Autonomous and Air-Ground Cooperative Onboard Systems for Surface Movement Incident Prevention

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Dedicated with deep gratitude to the memory of my grandfather

Heinrich FISCHER (1912 – 1992)

and my godfather

Wilhelm FISCHER (1941 – 2007)

who greatly supported and fostered my growing
fascination for technology and engineering.

Übersicht

An Verkehrsflughäfen stellt die fälschliche Benutzung von Start- und Landebahnen, die man als „Runway Incursion“ bezeichnet, eines der gravierendsten Risiken für die Flugsicherheit dar. Der bislang folgenschwerste Unfall in der Zivilluftfahrt, der Zusammenstoß zweier Boeing 747 auf Teneriffa im März 1977 mit 583 Toten, ist auf eine solche Runway Incursion zurückzuführen.
Bereits 1986 kam eine Studie des für die Untersuchung von Flugunfällen und Flugzwischenfällen zuständigen amerikanischen National Transportation Safety Boards (NTSB) zu dem Schluß, daß nicht technische Defekte, sondern menschliche Faktoren, landläufig als „menschliches Versagen“ bezeichnet, ursächlich für Runway Incursions sind. Dies ist insofern bemerkenswert, als das Rollen am Boden zwar zu den anspruchsvollsten Aufgaben im Cockpit gehört, Piloten in dieser kritischen Flugphase jedoch bislang nicht über ausgefeilte Assistenzsysteme verfügen, sondern sich nach wie vor im wesentlichen auf die Sicht aus den Cockpitfenstern und die Anweisungen der Flugsicherung über Sprechfunk stützen müssen. Als gesetzlich vorgeschriebene Hilfsmittel stehen zusätzlich lediglich Papierkarte, Kompaß sowie ein Ausdruck der den Flughafen betreffenden Nachrichten für Luftfahrer zur Verfügung.

Daher befaßt sich die vorliegende Arbeit mit der Frage, inwieweit sich Runway Incursions darauf zurückführen lassen, daß den Besatzungen notwendige Informationen nicht oder nur in inadäquater Form zur Verfügung gestellt werden, und wie die Bordausrüstung von Verkehrsflugzeugen ggf. ergänzt werden müßte, um das Unfallrisiko zu minimieren.
Nach einer Untersuchung der von Piloten und Fluglotsen am Flughafen anzuwendenden Prozeduren und Verfahren auf mögliche Schwachstellen erfolgt dazu eine eingehende Analyse von 40 Unfällen und schweren Zwischenfällen, anhand derer häufig wiederkehrende Kausalfaktoren ermittelt und kategorisiert werden.
Dabei zeigt sich, daß sich die untersuchten Runway Incursions – abgesehen von einigen Ausnahmen, die eindeutig fehlerhaften Anweisungen der Flugsicherung zuzuschreiben sind – hauptsächlich auf mangelndes Situationsbewußtsein der beteiligten Piloten zurückführen lassen. Hierfür sind unzureichende Navigationshilfen, fehlende Mittel zur Erfassung des umgebenden Luft- bzw. Bodenverkehrs und möglicher Konflikte, ungenügend aufbereitete Informationen über betriebliche Einschränkungen (wie z.B. die Sperrung von Start- und Landebahnen) sowie Mißverständnisse in der Kommunikation mit der Flugsicherung verantwortlich.

Um diese Defizite zu beheben, wird im Rahmen dieser Arbeit ein umfassendes Anzeige- und Warnkonzept erstellt, das alle für die Vermeidung von Runway Incursions notwendigen Informationen integriert, auf intuitive Weise darstellt und die Piloten warnt, sofern die reine Anzeige, beispielsweise aufgrund der Dynamik der Situation, nicht ausreicht, um drohende Gefahren abzuwenden. Als Grundlage dient mit der Airport Moving Map eine bereits kommerziell verfügbare datenbankgestützte digitalen Flughafenkarte. Eine prototypische Realisierung dieses Anzeige- und Warnkonzepts wird in Feldversuchen an den Flughäfen Frankfurt und Prag sowie abschließend im Flugsimulator des Instituts für Flugsysteme und Regelungstechnik der TU Darmstadt einer Validierung durch Verkehrspiloten unterzogen.

Abstract

At airports sustaining commercial operations, Runway Incursions, defined as the incorrect presence or manoeuvre of an aircraft, vehicle or person on a runway, constitute the most severe hazard to flight safety. In fact, the worst-ever accident in civil aviation to date, the collision of two Boeing B747s on Tenerife in March 1977 with 583 fatalities, was caused by a Runway Incursion.
As early as 1986, a special investigation report of the National Transportation Safety Boards (NTSB), which is responsible for investigating aviation incidents and accidents in the USA, concluded that Human Factors issues and not technical malfunctions were the primary causal factors of Runway Incursions. This is remarkable, because although surface movement is one of the most challenging cockpit tasks, pilots are currently not supported by sophisticated assistance systems in this critical phase of flight, but still mainly rely on visual acquisition of their environment and Air Traffic Control (ATC) instructions conveyed via radio. The only mandatory additional equipment consists of paper charts, compass and Notices to Airmen (NOTAM).

Consequently, the goal of this thesis is to investigate to what extent Runway Incursions can be attributed to an inadequate presentation or lack of required information on the flight deck, and how flight deck instrumentation will possibly have to be supplemented in order to increase safety in the airport environment.
Following a scrutiny of current procedures for surface movement with respect to potential deficiencies, an in-depth analysis of 40 incidents and accidents is conducted to identify and categorize generic, recurring causal factors of Runway Incursions.
Apart from several exceptions that can be attributed to incorrect ATC instructions or clearances, results clearly indicate that the investigated Runway Incursions were primarily caused by a lack of pilot situation awareness. The underlying reasons are a lack of suitable navigation aids, missing means of acquiring the surrounding traffic including potential conflicts, insufficient presentation of information on the airport operational environment (such as closed or restricted runways) or misunderstandings in the communication with ATC.

In order to address these deficiencies, a holistic flight deck visualisation and warning concept based on Airport Moving Map (AMM) technology, an already commercially available database-driven electronic airport chart presentation, is developed in the frame of this thesis, integrating all of the information required for Runway Incursion avoidance in an intuitive fashion. In case the mere presentation of information is not sufficient to prevent a hazardous situation, e.g. due to the dynamics of an emerging traffic conflict, pilots are alerted in a manner consistent with current flight deck alerting systems. A prototypic realisation of the resulting onboard surveillance system is validated with airline pilots in field trials at Frankfurt and Prague airport, using a Navigation Test Vehicle, followed by a further evaluation campaign employing a Research Flight Simulator.

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First and foremost, I would therefore like to thank Prof. Dr.-Ing. Wolfgang Kubbat for giving me the opportunity and the freedom to conduct the research that eventually led to this thesis, as well as his invaluable support, encouragement and patience in the past years. Besides, I am greatly indebted to Prof. Dr.-Ing. Ralph Bruder for being my co-advisor, and to Prof. Dr.-Ing. Uwe Klingauf for the leadership and continuity he provided as Head of the Institute.

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Abbreviations

AAPA	**A**ssociation of **A**sia **P**acific **A**irlines
AC	**A**dvisory **C**ircular
ACARE	**A**dvisory **C**ouncil for **A**eronautics **R**esearch in **E**urope
ACARS	**A**irborne **C**ommunications **A**ddressing and **R**eporting **S**ystem
ACAS	**A**irborne **C**ollision **A**voidance **S**ystem
ACC	**A**rea **C**ontrol **C**entre
ADS	**A**utomatic **D**ependent **S**urveillance
ADS-B	**A**utomatic **D**ependent **S**urveillance – **B**roadcast
ADS-C	**A**utomatic **D**ependent **S**urveillance – **C**ontract
ADS-R	**A**utomatic **D**ependent **S**urveillance – **R**e-broadcast
AEA	**A**ssociation of **E**uropean **A**irlines
AIP	**A**eronautical **I**nformation **P**ublication
AIRAC	**A**eronautical **I**nformation **R**egulation and **C**ontrol
AIS	**A**eronautical **I**nformation **S**ervice
AIXM	**A**eronautical **I**nformation E**x**change **M**odel
ALPA	**A**ir**l**ine **P**ilots' **A**ssociation
AMASS	**A**irport **M**ovement **A**rea **S**afety **S**ystem
AMDB	**A**erodrome **M**apping **D**ata**b**ase
AMM	**A**irport **M**oving **M**ap
AMMD	**A**erodrome **M**oving **M**ap **D**isplay
ANSP	**A**ir **N**avigation **S**ervice **P**rovider
AOC	**A**irline **O**perational **C**ontrol
AOCC	**A**irline **O**peration **C**ontrol **C**entre
AOM	**A**irplane **O**perations **M**anual
APU	**A**uxiliary **P**ower **U**nit
ARFF	**A**irport **R**escue and **F**ire **F**ighting
ARINC	**A**eronautical **R**adio **Inc**orporated
ARP	**A**erodrome **R**eference **P**oint
ASAS	**A**irborne **S**eparation **A**ssistance **S**ystem♣
ASDE	**A**irport **S**urface **D**etection **E**quipment
A-SMGCS	**A**dvanced **S**urface **M**ovement **G**uidance and **C**ontrol **S**ystem
ASRS	**A**viation **S**afety **R**eporting **S**ystem
ATA	**A**ir **T**ransport **A**ssociation
ATC	**A**ir **T**raffic **C**ontrol
ATCRBS	**A**ir **T**raffic **C**ontrol **R**adar **B**eacon **S**ystem
ATFM	**A**ir **T**raffic **F**low **M**anagement
ATIS	**A**utomatic **T**erminal **I**nformation **S**ervice
ATM	**A**ir **T**raffic **M**anagement
ATN	**A**eronautical **T**elecommunication **N**etwork
ATPL	**A**ir **T**ransport **P**ilot **L**icence
ATR	**A**vions de **T**ransport **R**égional
ATS	**A**ir **T**raffic **S**ervice
ATSA-SURF	**A**irborne **T**raffic **S**ituational **A**wareness on the Airport **Surf**ace
ATSU	**A**ir **T**raffic **S**ervices **U**nit

♣ ASAS was previously also referred to as "Airborne Separation Assurance System", cf. [Eur01].

BFU	**B**undesstelle für **F**lugunfall**u**ntersuchung
CAA	**C**argo **A**irline **A**ssociation
CAATS	**C**ooperative **A**pproach to **A**ir **T**raffic **S**ervices
CAPTS	**C**ooperative **A**rea **P**recision **T**racking **S**ystem
CAST	**C**ommercial **A**viation **S**afety **T**eam
CDS	**C**ockpit **D**isplay **S**ystem
CDTI	**C**ockpit **D**isplay of **T**raffic **I**nformation
CFR	**C**ode of **F**ederal **R**egulations (USA)
CIAIAC	**C**omisión de **I**nvestigación de **A**ccidentes e **I**ncidentes de **A**viación **C**ivil
CIC	**C**ontroller **i**n **C**ommand
CIS	**C**ommonwealth of **I**ndependent **S**tates
CMO	Boeing **C**urrent **M**arket **O**utlook
CMS	**C**entral **M**aintenance **S**ystem
CPA	**C**losest **P**oint of **A**pproach
CPDLC	**C**ontroller-**P**ilot **D**ata **L**ink **C**ommunications
CPL	**C**ommercial **P**ilot **L**icense
CRC	**C**yclic **R**edundancy **C**heck
CRM	**C**rew **R**esource **M**anagement
CST	**C**entral **St**andard **T**ime
CVR	**C**ockpit **V**oice **R**ecorder
CY	**C**alendar **Y**ear
D-ATIS	**D**ata link - **A**utomatic **T**erminal **I**nformation **S**ervice
DCDU	**D**ata link **C**ontrol and **D**isplay **U**nit
DF	**D**ownlink **F**ormat
DLIC	**D**ata **L**ink **I**nitiation **C**apability
D-OTIS	**D**ata link – **O**perational **T**erminal **I**nformation **S**ervice
ECAC	**E**uropean **C**ivil **A**viation **C**onference
ECAM	**E**lectronic **C**entralized **A**ircraft **M**onitoring
ECP	**E**IS **C**ontrol **P**anel
EFB	**E**lectronic **F**light **B**ag
EFIS	**E**lectronic **F**light **I**nstrument **S**ystem
EGPWS	**E**nhanced **G**round **P**roximity **W**arning **S**ystem
EIS	**E**lectronic **I**nstrument **S**ystem
Embraer	**Em**presa **Br**asileira de **Aer**onáutica
EMMA	**E**uropean Airport **M**ovement **M**anagement by **A**-SMGCS
ENAC	**É**cole **N**ationale de l'**A**viation **C**ivile
EPR	**E**ngine **P**ressure **R**atio
EPU	**E**stimated **P**osition **U**ncertainty
ETA	**E**stimated **T**ime of **A**rrival
ETNA	**E**lectronic **T**axiway **N**avigation **A**rray
EUROCAE	**Eur**opean **O**rganisation for **C**ivil **A**viation **E**quipment
FANS	**F**uture **A**ir **N**avigation **S**ystem
FCOM	**F**light **C**rew **O**perating **M**anual
FDR	**F**light **D**ata **R**ecorder
FIR	**F**light **I**nformation **R**egion
FMS	**F**light **M**anagement **S**ystem
FTK	**F**reight **T**on **K**ilometre

FY	**F**iscal **Y**ear
GDP	**G**ross **D**omestic **P**roduct
GMF	Airbus **G**lobal **M**arket **F**orecast
GNSS	**G**lobal **N**avigation **S**atellite **S**ystem
GPS	**G**lobal **P**ositioning **S**ystem
HFDL	**H**igh-**F**requency **D**ata **L**ink
HFOM	**H**orizontal **F**igure of **M**erit
HMI	**H**uman-**M**achine **I**nterface
IATA	**I**nternational **A**ir **T**ransport **A**ssociation
ICAO	**I**nternational **C**ivil **A**viation **O**rganisation
IFALPA	**I**nternational **F**ederation of **A**irline **P**ilots' **A**ssociations
ILS	**I**nstrument **L**anding **S**ystem
ISAWARE	**I**ncreasing **S**afety by collision **A**voidance **WAR**ning int**E**gration
ISAWARE II	**I**ncreasing **S**afety by enhancing crew situation **AWARE**ness
ISS	**I**ntegrated **S**urveillance **S**ystem
KCCU	**K**eyboard and **C**ursor **C**ontrol **U**nit
KLM	**K**oninklijke **L**uchtvaart **M**aatschappij N.V.
LH	**L**iquid **H**ydrogen
LNG	**L**iquefied **N**atural **G**as
LSK	**L**ine **S**elect **K**ey
LVP	**L**ow **V**isibility **P**rocedures
MCDU	**M**ultipurpose **C**ontrol **D**isplay **U**nit
MEL	**M**inimum **E**quipment **L**ist
MFDU	**M**ulti **F**unction **D**isplay **U**nit
MFK	**M**ulti-**F**unctional **K**ey
MMS	**M**oving **M**ap **S**tandalone (EMMA name of Airbus TDS)
MTOM	**M**aximum **T**ake-**O**ff **M**ass
MTOW	**M**aximum **T**ake-**O**ff **W**eight
NAC	**N**avigation **A**ccuracy **C**ategory
NACO	**N**ational **A**eronautical **C**harting **O**ffice
NASA	**N**ational **A**eronautics and **S**pace **A**dministration
ND	**N**avigation **D**isplay
NFDC	**N**ational **F**light **D**ata **C**enter
NIC	**N**avigation **I**ntegrity **C**ategory
NLR	**N**ationaal **L**ucht- en **R**uimtevaartlaboratorium
NOTAM	**No**tice to **A**ir **M**en
NTSB	**N**ational **T**ransportation **S**afety **B**oard
OANS	**O**nboard **A**irport **N**avigation **S**ystem
OEP	**O**perational **E**volution **P**artnership
OSED	**O**perational **S**ervices and **E**nvironment **D**ocument
PANS	**P**rocedures for **A**ir **N**avigation **S**ervices
PAPI	**P**recision **A**pproach **P**ath **I**ndicator
PAR	**P**recision **A**pproach **R**adar
PFD	**P**rimary **F**light **D**isplay
PIB	**P**re-flight **I**nformation **B**ulletin
PIC	**P**ilot-**I**n-**C**ommand
PKP	**P**assenger **K**ilometre **P**erformed
PSR	**P**rimary **S**urveillance **R**adar

PVD	**P**ara-**V**isual **D**isplay
QFU	Magnetic Runway Heading[♠]
R/T	**R**adio**t**elephony
RA	[TCAS] **R**esolution **A**dvisory
RAAS	**R**unway **A**wareness and **A**dvisory **S**ystem
RFMS	**R**esearch **F**light **M**anagement **S**ystem
RNAV	A**r**ea **Nav**igation
RPK	**R**evenue **P**assenger **K**ilometres
RTCA	**R**adio **T**echnical **C**ommission for **A**eronautics
RTO	**R**ejected **T**ake-**O**ff
RVR	**R**unway **V**isual **R**ange
RWY	**R**un**w**a**y**
SAE	**S**ociety of **A**utomotive **E**ngineers
SARPs	**S**tandards **A**nd **R**ecommended **P**ractice**s**
SARS	**S**evere **A**cute **R**espiratory **S**yndrome
SAS	**S**candinavian **A**irline **S**ystem
SATCOM	**Sat**ellite **Com**munications
SD	**S**tandard **D**eviation
SIA	**Si**ngapore **A**irlines [ICAO Code]
SID	**S**tandard **I**nstrument **D**eparture
SIL	**S**urveillance **I**ntegrity **L**evel
SMGCS	**S**urface **M**ovement **G**uidance and **C**ontrol **S**ystem
SMR	**S**urface **M**ovement **R**adar
SRC	[Eurocontrol] **S**afety **R**egulation **C**ommission
SRS	**S**peed **R**eference **S**ystem
SSR	**S**econdary **S**urveillance **R**adar
STAR	**St**andard Instrument **A**rrival **R**oute
TA	[TCAS] **T**raffic **A**dvisory
TACS	**Ta**xi **C**amera **S**ystem
TAWS	**T**errain **A**wareness and **W**arning **S**ystem
TCAS	**T**raffic Alert and **C**ollision **A**voidance **S**ystem
TDS	**T**axi **D**river **S**ystem (Airbus airport moving map prototype)
TIS-B	**T**raffic **I**nformation **S**ervice – **B**roadcast
TMA	**T**er**m**inal Control **A**rea
TWA	**T**rans **W**orld **A**irlines
UAT	**U**niversal **A**ccess **T**ransceiver
UF	**U**plink **F**ormat
UTC	**U**niversal **T**ime **C**oordinates
VASI	**V**isual **A**pproach **S**lope **I**ndicator
VDL	**V**HF **D**igital **L**ink
VHF	**V**ery **H**igh **F**requency

[♠] The abbreviation originates from the Aviation Q-code, which dates back to the time when the Morse code and radio telegraphy were widely in use in aviation.

Definitions

Accident
An occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which:

a) a person is fatally or seriously injured as a result of:
   - being in the aircraft, or
   - direct contact with any part of the aircraft, including parts which have become detached from the aircraft, or
   - direct exposure to jet blast,

   except when the injuries are from natural causes, self-inflicted or inflicted by other persons, or when the injuries are to stowaways hiding outside the areas normally available to the passengers and crew; or

b) the aircraft sustains damage or structural failure which:
   - adversely affects the structural strength, performance or flight characteristics of the aircraft, and
   - would normally require major repair or replacement of the affected component,

   except for engine failure or damage, when the damage is limited to the engine, its cowlings or accessories; or for damage limited to propellers, wing tips, antennas, tyres, brakes, fairings, small dents or puncture holes in the aircraft skin; or

c) the aircraft is missing or is completely inaccessible.

For statistical uniformity only, an injury resulting in death within thirty days of the date of the accident is classified as a fatal injury by ICAO. Furthermore, an aircraft is considered to be missing when the official search has been terminated and the wreckage has not been located [ICA01]†.

Aerodrome
A defined area on land or water (including any buildings, installations and equipment) intended to be used either wholly or in part for the arrival, departure and surface movement of aircraft [ICA01].

Aerodrome Traffic
All traffic on the manoeuvring area of an aerodrome and all aircraft flying in the vicinity of an aerodrome [ICA01].

† Unless indicated otherwise, the definitions in this section are quoted verbatim to prevent any unintended adulteration of the internationally accepted scope and content. In contrast to the remainder of this thesis, where verbatim quotations are presented *"with quotation marks and in italics"*, the definitions are presented in plain font here for improved readability. Any additions or explanations by the author are added after the reference in this section.

Aeronautical Information Publication (AIP)
A publication issued by or with the authority of a State and containing aeronautical information of a lasting character essential to air navigation [ICA04].

Aeronautical Information Service (AIS)
A service established within the defined area of coverage responsible for the provision of aeronautical information/data necessary for the safety, regularity and efficiency of air navigation [ICA04].

Air Traffic Service (ATS)
A generic term meaning variously, flight information service, alerting service, air traffic advisory service, air traffic control service (area control service, approach control service or aerodrome control service) [ICA01].

Aircraft Proximity
A situation in which, in the opinion of a pilot or air traffic services personnel, the distance between aircraft as well as their relative positions and speed have been such that the safety of the aircraft involved may have been compromised. An aircraft proximity is classified as follows:

> *Risk of collision*. The risk classification of an aircraft proximity in which serious risk of collision has existed.
>
> *Safety not assured*. The risk classification of an aircraft proximity in which the safety of the aircraft may have been compromised.
>
> *No risk of collision*. The risk classification of an aircraft proximity in which no risk of collision has existed.
>
> *Risk not determined*. The risk classification of an aircraft proximity in which insufficient information was available to determine the risk involved, or inconclusive or conflicting evidence precluded such determination [ICA01a].

Alternate Aerodrome
An aerodrome to which an aircraft may proceed when it becomes either impossible or inadvisable to proceed to or to land at the aerodrome of intended landing. Alternate aerodromes include the following:

> *Take-off alternate*. An alternate aerodrome at which an aircraft can land should this become necessary shortly after take-off and it is not possible to use the aerodrome of departure.
>
> *En-route alternate*. An aerodrome at which an aircraft would be able to land after experiencing an abnormal or emergency condition while en route.

ETOPS en-route alternate. A suitable and appropriate alternate aerodrome at which an aeroplane would be able to land after experiencing an engine shutdown or other abnormal or emergency condition while en route in an ETOPS operation.

Destination alternate. An alternate aerodrome to which an aircraft may proceed should it become either impossible or inadvisable to land at the aerodrome of intended landing [ICA01].

Apron
A defined area on a land aerodrome intended to accommodate aircraft for purposes of loading or unloading passengers, mail or cargo, fuelling, parking or maintenance [ICA01].

Apron Management Service
A service provided to regulate the activities and the movement of aircraft and vehicles on an apron [ICA01].

Cockpit Display of Traffic Information (CDTI)
A Cockpit Display of Traffic Information (CDTI) provides the flight crew with surveillance information about other aircraft, including their position. Traffic information for a CDTI may be obtained from one or multiple sources (including ADS-B, TCAS, and TIS-B) and it may be used for a variety of purposes. Any means of communicating the information is acceptable (aural, graphical, head-up, etc.) as long as the information is conveyed effectively [RTC02]. The CDTI may use a dedicated or a shared display device [RTC98].

Crew Resource Management
Crew Resource Management (CRM) deals with the cognitive and interpersonal skills required to manage flight within an organised aviation system, in particular the capabilities required to obtain and maintain adequate situational awareness, and techniques for joint problem solving and decision making. In particular, CRM intends to counteract a lack of situational awareness or a breakdown of efficient teamwork resulting from inadequate communication. CRM training was created to formalise education in these skills.

Incident
An occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of operation [ICA01].

Manoeuvring Area
That part of an aerodrome to be used for the take-off, landing and taxiing of aircraft, excluding aprons [ICA01].

Movement Area
That part of an aerodrome to be used for the take-off, landing and taxiing of aircraft, consisting of the manoeuvring area and the apron(s) [ICA01].

Navigation Accuracy Category (NAC)
The Navigation Accuracy Category is a parameter detailing the accuracy of a reported position (NAC_P) or velocity (NAC_V) to enable surveillance applications to determine whether reported data has an acceptable level of accuracy for the intended use. For position accuracy, NAC_P is bound to the Estimated Position Uncertainty (EPU), which defined as the radius of a circle, centred on the reported position, such that the probability of the true position being outside the circle is 0.05. When reported by a GPS or GNSS system, EPU is commonly called Horizontal Figure of Merit (HFOM). For velocity, a 95% confidence interval is used as well [RTC02].

Navigation Integrity Category (NIC)
The Navigation Integrity Category is a parameter between 0 and 15 enabling surveillance applications to determine whether the reported geometric position has an acceptable integrity containment region for the intended use. The categorised NIC integrity containment regions are described by the horizontal radius of containment (R_C) and the vertical protection limit (VPL). R_C is the radius of a circle centred on the reported position, within which the true position is assured to lie at the reported time of applicability. In the same fashion, VPL is the vertical bounding box. NIC is intimately associated with the Surveillance Integrity Level (SIL) [RTC06].

Notice to Airmen (NOTAM)
A notice distributed by means of telecommunication containing information concerning the establishment, condition or change in any aeronautical facility, service, procedure or hazard, the timely knowledge of which is essential to personnel concerned with flight operations [ICA04].

Obstacle
All fixed (whether temporary or permanent) and mobile objects, or parts thereof, that are located on an area intended for the surface movement of aircraft or that extend above a defined surface intended to protect aircraft in flight [ICA04].

Pilot-in-Command (PIC)
The pilot designated by the operator or owner of an aircraft as being in command and charged with the safe conduct of a flight. Irrespective of the crew role as a Pilot Flying (PF) or Pilot Not Flying (PNF), the pilot-in-command is ultimately responsible for the operation of the aircraft in accordance with the rules of the air, except that the pilot-in-command may depart from these rules in circumstances that render such departure absolutely necessary in the interests of safety. The pilot-in-command of an aircraft shall have final authority as to the disposition of the aircraft while in command [ICA90]. In most cases, the PIC is seated on the left side of the cockpit in fixed-wing aircraft.

Pre-flight Information Bulletin (PIB)
A presentation of current NOTAM and other urgent information of operational significance in plain-text language, prepared prior to flight [ICA04].

Revenue Passenger Kilometres (RPK)
The number of passengers multiplied by the number of kilometres they fly [Boe04].

Runway
A defined rectangular area on a land aerodrome prepared for the landing and take-off of aircraft [ICA01].

Runway Holding Position
A designated position intended to protect a runway, an obstacle limitation surface, or an ILS/MLS critical/sensitive area at which taxiing aircraft and vehicles shall stop and hold, unless otherwise authorized by the aerodrome control tower [ICA01].

Runway Visual Range (RVR)
The range over which the pilot of an aircraft on the centre line of a runway can see the runway surface markings or the lights delineating the runway or identifying its centre line [ICA01].

Serious Incident
An incident involving circumstances indicating that an accident nearly occurred [ICA01b].

Standard instrument arrival route (STAR)
A designated instrument flight rule (IFR) arrival route linking a significant point, normally on an ATS route, with a point from which a published instrument approach procedure can be commenced [ICA01a].

Standard instrument departure (SID)
A designated instrument flight rule (IFR) departure route linking the aerodrome or a specified runway of the aerodrome with a specified significant point, normally on a designated ATS route, at which the en-route phase of a flight commences [ICA01a].

Stopway
A defined rectangular area on the ground at the end of take-off run available prepared as a suitable area in which an aircraft can be stopped in the case of an abandoned take-off [ICA01a].

Surveillance Integrity Level
The Surveillance Integrity Level (SIL) defines the probability of the integrity containment region described by the NIC parameter (see definition above) being exceeded for the selected geometric position source [RTC06].

Taxiway
A defined path on a land aerodrome established for the taxiing of aircraft and intended to provide a link between one part of the aerodrome and another, including:

a) *Aircraft stand taxi line*. A portion of an apron designated as a taxiway and intended to provide access to aircraft stands only.
b) *Apron taxiway*. A portion of a taxiway system located on an apron and intended to provide a through taxi route across the apron.
c) *Rapid exit taxiway*. A taxiway connected to a runway at an acute angle and designed to allow landing aeroplanes to turn off at higher speeds than are achieved on other exit taxiways thereby minimizing runway occupancy times [ICA01a].

Terminal Control Area (TMA)
A control area normally established at the confluence of ATS routes in the vicinity of one or more major aerodromes [ICA01].

Threshold
The beginning of that portion of the runway usable for landing [ICA01a].

Visibility
Visibility for aeronautical purposes is the greater of:

a) the greatest distance at which a black object of suitable dimensions, situated near the ground, can be seen and recognized when observed against a bright background;
b) the greatest distance at which lights in the vicinity of 1000 candelas can be seen and identified against an unlit background [ICA01a].

Visibility Condition
For surface operations, the ICAO Manual on A-SMGCS discriminates the following four generic visibility conditions [ICA04a]:

> **Visibility Condition 1:** Visibility is sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, and for personnel of control units to exercise control over all traffic on the basis of visual surveillance.
>
> **Visibility Condition 2:** Visibility is sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, but insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance.
>
> **Visibility Condition 3:** Visibility is sufficient for the pilot to taxi, but insufficient for the pilot to avoid collision with other traffic on taxiways and at intersections by visual reference, and insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance. For taxiing, this is normally taken as visibilities equivalent to an RVR of less than 400 m but more than 75 m.
>
> **Visibility Condition 4:** Visibility is insufficient for the pilot to taxi by visual guidance only. This is normally taken as a RVR of 75 m or less♣.

It should be noted that the above visibility conditions apply for both day and night operations. The precise criteria for determining the transition between visibility conditions are a function of local aerodrome and traffic characteristics [ICA08].

♣ According to an airline captain based at Frankfurt Airport (EDDF), Visibility Condition 4 is only encountered in approximately 3-4% of all flights.

1 Introduction

1.1 Motivation

Surface movement is one of the most challenging phases of flight. Particularly at complex airports, at airports the flight crew is not familiar with or in degraded visibility conditions, with airport markings potentially obscured by snow, taxiing an aircraft may cause excessive workload and thus increase the risk of errors. This does not only impair the efficiency of surface operations, but can also lead to serious incidents and accidents, of which Runway Incursions are the by far most safety-critical. In fact, the worst-ever accident in civil aviation to date, the collision of two Boeing B747s on Tenerife in 1977 with 583 fatalities, was caused by a Runway Incursion [ICA80].

Runway Incursions unquestionably pose the greatest threat to aviation safety at aerodromes, particularly in view of the continuous worldwide growth in air traffic.
In recent years, accidents and a growing number of Runway Incursion incidents, including several near-misses, have led to the initiation of various Runway Safety initiatives and research programmes around the globe, often focusing on ground-based measures ranging from (often local) changes in Air Traffic Management (ATM) procedures and improved surveillance technologies, e.g. multilateration, to airport layout considerations such as perimeter taxiways [Eur04, FAA04].
The urgency of the problem is also illustrated by the fact that the National Transportation Safety Board (NTSB) has had a technical solution to give "*immediate warnings of probable [runway] collisions/incursions directly to flight crews in the cockpit*" on its "Most Wanted" list since it was established in 1990, with the measures taken by the Federal Aviation Administration (FAA) so far still classified as "unacceptable" [NTS07a].

As early as 1986, an NTSB Special Investigation Report concluded that Runway Incursions are a human factors problem, since no single Runway Incursion to date had been caused by a technical malfunction [NTS86]. In fact, a detailed analysis of various Runway Incursion accident and incident reports yields that deficiencies in flight crew situational awareness are almost always a causal factor in these occurrences. Crew disorientation due to a lack of situational awareness played a substantial role in three recent fatal Runway Incursion accidents in Taipei, Milano-Linate and Lexington [ANS04, ASC02, NTS07]. In the first two cases, crew disorientation was at least partially caused by adverse weather conditions and the non-conformance of airport lights, signs or markings to ICAO regulations.

In response to the crew disorientation issue, the electronic airport moving map display as supplement or substitute for conventional paper charts has evolved in research and, subsequently, industry over the past decade. It is now widely accepted as the core technology to increase the flight crew's situational awareness in terms of position on the airport surface, and commercially available both as fully integrated line-fit solution on the Airbus A380 or as Electronic Flight Bag (EFB) application by various manufacturers, such as ACSS or Jeppesen.

However, situational awareness on the ground encompasses much more than mere position awareness. Awareness of relevant traffic on surrounding taxiways and traffic in the runway environment is essential to understand traffic patterns and to anticipate potential conflicts. Currently, flight crews use a combination of visual acquisition and monitoring Air Traffic Control (ATC) clearances issued to other traffic, the so-called 'party line effect', to build a mental model of traffic in the airport environment. If visibility deteriorates such that traffic can no longer be acquired visually, or if both local languages and English are used, this becomes increasingly difficult.

Emerging advanced traffic surveillance technologies such as ADS-B and TIS-B [RTC02, RTC03], which are now seeing large-scale implementation programs in several regions of the world, have the potential of providing surface traffic data with high resolution, integrity and accuracy. The availability of traffic surveillance data in the cockpit in suitable form could potentially help flight crews to maintain traffic situational awareness under adverse weather conditions. In addition to this, it might also aid pilots in detecting mistakes made by other flight crews or controller errors. In fact, controllers erroneously clearing two aircraft for the same runway were the key causal factors in both the 1991 Los Angeles and the 2000 Paris Charles-de-Gaulle accidents. In the latter case, the use of two different ATC languages prevented the crew of a British Shorts 330 from noticing the controller error [BEA01].

Furthermore, numerous cases of flight crews deviating from the assigned taxi route, failing to hold short of a runway or taking off without clearance illustrate that situational awareness regarding the ATC clearances assigned by the controller is crucial. After all, due to a misunderstanding with Tenerife tower, the captain of KLM 4805 erroneously believed that his flight had been cleared for take-off [ICA80].
Last but not least, there is a third aspect of situational awareness that needs to be addressed, the operational environment. Currently, like paper charts, the airport moving map is limited to quasi-static airport information, because the underlying aerodrome database is envisaged to be updated only every 28 days with the regular AIRAC cycle. Nonetheless, information on short-term and temporary changes is essential for flight safety, e.g. when relating to runway closures, because choosing a closed runway may have catastrophic consequences, as the Singapore Airlines Flight SQ006 accident at Taipei in 2000 shows. In other incidents, such as UPS Flight 896 at Denver in 2001 departing from a closed runway, a disaster was only narrowly avoided [NTS03]. Today, information on short-term and temporary changes, e.g. runway closures, is mainly conveyed through the Pre-Flight Information Bulletin (PIB), a plain-language compilation of current Notices to Airmen (NOTAM) and other information of urgent character. However, the accessibility of this information is limited: a typical PIB for an intercontinental flight often exceeds 30 A4 pages (including alternate airports), and the flight crew has to create the mental picture of the respective airport environment by locating and combining PIB with aerodrome mapping information.

This brief survey clearly indicates that there are, apparently, significant unsolved human factors issues with current surface movement operations, which become increasingly problematic once external visual references fail due to visibility limitations. Consequently, improved flight crew situational awareness should be a key element of any attempt to address the problem of Runway Incursions. The motivation for this thesis is to make a contribution to the mitigation or solution of this problem.

To obtain a better understanding of the nature and scope of the Runway Incursion problem, the next section is dedicated to a survey of existing definitions of what constitutes a Runway Incursion, and performs a down-selection of the definition to be used for this thesis.

1.2 The Problem of Runway Incursions

In order to maintain safe operations on the runway, strict procedures and rigorous surveillance are employed. Current operating procedures on the ground require explicit approval from ATC to cross or enter the runway surface and its associated protection zone, and additional clearances are required for line-up and take-off. Outside the United States, landing clearances to arriving aircraft may typically only be issued if all other traffic has vacated the runway. A violation of these procedures may result in Runway Incursions. Until recently, however, there were various diverging and evolving definitions of a Runway Incursion, converging only in the point that any collision of two aircraft – or an aircraft and a vehicle – on the runway surface constitutes a Runway Incursion.

Systematic investigation of Runway Incursions dates back to the late 70s and early 80s. After NASA's Aviation Safety Reporting System (ASRS) had been established in 1976, systematic studies of "runway transgressions", defined as "*any erroneous occupation of a runway at a controlled airport by an aircraft or other controlled vehicle*", were performed by NASA in 1978 and 1984 [NTS86]. The 1984 study concluded that "*there does not appear to be any pattern to the causes […] other than human errors on the part of both air traffic controllers and pilots*" and revealed difficulties with clearances, communications, orientation and preoccupation as key factors in pilot-induced incursions. Multiple intersecting runways and restricted visibility frequently appeared as factors in both pilot- and controller-induced incursions. The Federal Aviation Administration (FAA) later narrowed the scope to events involving an at least abstract collision hazard, using the following definition in its Runway Safety Reports [FAA05, FAA08] until Financial Year 2008:

> *A runway incursion is any occurrence in the airport runway environment involving an aircraft, vehicle, person, or object on the ground that creates a collision hazard or results in a loss of required separation with an aircraft taking off, intending to take off, landing, or intending to land.*

This definition formed the basis of all Runway Incursion statistics in the United States for years and dominated the overall perception of the problem well beyond North America. It is based on the concept of a protection zone ("*bubble*") around any aircraft entering the runway, the size of which corresponds to the required separa-

tion from other aircraft and any other objects. In this concept, any penetration of the protection zone is regarded as a Runway Incursion, and the depth of penetration serves as a measure for the severity of the incursion [FAA01].
However, this definition is not unproblematic, because it requires a loss of separation or collision hazard, and thus the presence of at least one other aircraft, vehicle or person. If a flight crew operates the aircraft on a runway without corresponding authorisation by ATC (as e.g. in case of erroneous runway entry) and there is no other traffic in the vicinity, this does not constitute a Runway Incursion according to this FAA definition, but is merely considered as a general surface movement incident.

It is important to note, however, that an erroneous runway entry or usage, and not a loss of separation, is the crucial step leading to a Runway Incursion, because the presence of and the distance to any other aircraft – and thus the collision hazard – is largely determined by chance, especially in low visibility conditions or whenever visibility is impaired due to a particular airport layout (e.g. runway profile)[1]. In these cases, neither pilot nor controller might be able to detect an impending danger visually. In other words, the collision risk is the ultimate consequence of a Runway Incursion, not the cause.

Since November 2004, a more global definition of Runway Incursions by the International Civil Aviation Organisation (ICAO) is effective [Eur04], replacing the various local definitions:

> *Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take off of aircraft.*

The wording chosen is somewhat reminiscent of the FAA definition, but due to the use of "*incorrect presence*" instead of "*collision hazard*" and "*loss of separation*", the ICAO definition emphasizes the main cause of Runway Incursions, albeit at a generic level, whereas the FAA definition is merely descriptive of the incursion symptoms. The term "*incorrect presence*" also takes into account controller errors, such as the violation of separation minima set forth in ICAO Doc 4444 [ICA01a].
Consequently, the ICAO definition significantly extends the scope of Runway Incursions compared to the FAA definition: taking off or landing on a wrong (and potentially unsuitable) runway or using a closed runway is now also considered a Runway Incursion, even if there is no traffic hazard.

However, there is an important case that is **not** explicitly covered by the ICAO definition: taking off without clearance, as in the Tenerife accident [ICA80]. If line-up has been approved, the presence of the aircraft on the runway is both intended and correct. Nonetheless, a Runway Incursion is caused by the unauthorised take-off. Therefore, it may be necessary to amend the ICAO definition slightly, e.g. to "*…incorrect presence* ***or manoeuvre*** *of an aircraft...*", to incorporate this case explicitly.

[1] As an example, at Rome-Ciampino Airport (CIA), RWY 15/33 is sloped such that aircraft lined up on RWY 15 cannot see any aircraft at the other end of the runway.

In conclusion, this thesis will apply the ICAO definition, under the assumption that incorrect runway manoeuvres are implicitly covered as well. Furthermore, as an extension of the ICAO definition, the case of erroneously using a taxiway for take-off or landing will be considered, because this may result in situations equally hazardous as Runway Incursions.

1.3 Other Surface Incidents and Accidents

Due to the high speeds involved in take-off and landing, Runway Incursions are associated with a significantly higher risk of multiple fatalities than other surface movement incidents outside the runway, and can thus be regarded as the by far most serious threat to flight safety in the airport environment. By contrast, with the exception of erroneously using a taxiway as a runway, there is only a small probability that collisions on the taxiway system will lead to fatal injuries among aircraft passengers and crew[2].

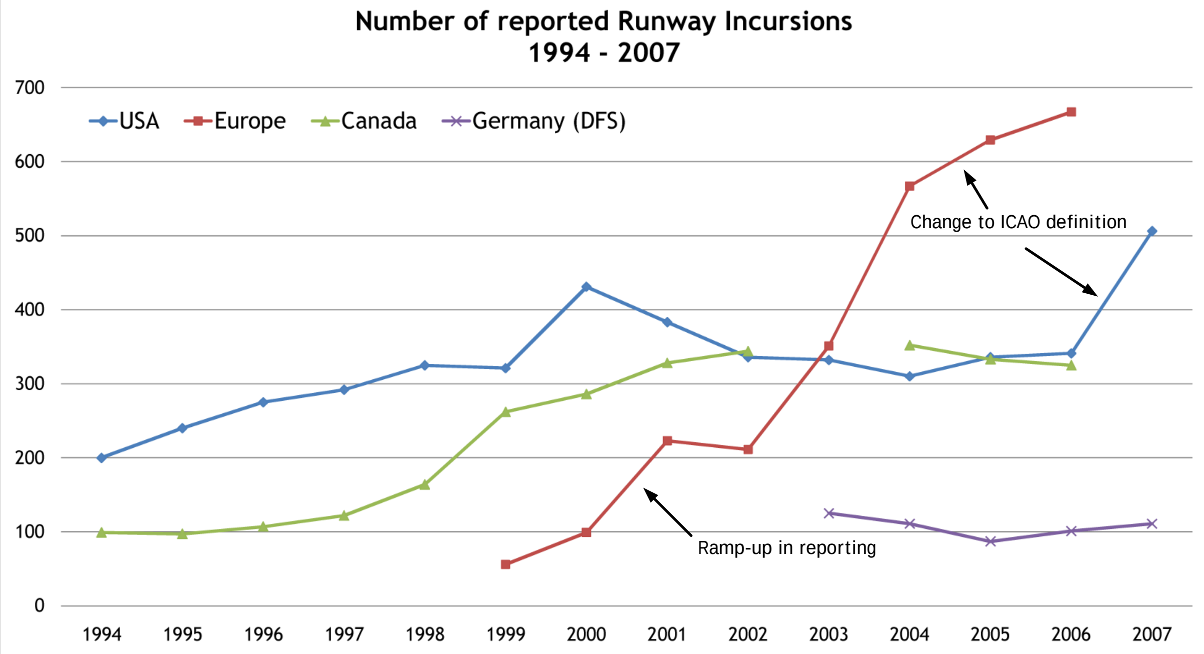
However, incidents and accidents outside the runways occur more frequently than Runway Incursions. In the calendar years 2000 and 2001, for example, there were 1391 and 1250 surface incidents at airports in the US National Airspace System, compared to 423 and 328 Runway Incursions, respectively [FAA02, FAA02a].

Aircraft damage resulting from collisions outside the runways is tremendous, and besides, any collision will have a severe operational impact for airlines. The aviation insurance industry estimates that the damage to aircraft during ground operations is in excess of US $4 billion per year alone for the direct costs (spare parts and repair), which corresponds to a weekly sum of US $77 million. A conservative estimate is that the indirect costs (e.g. revenue losses) are at least as high as the direct costs. The majority of ground mishaps resulting in major damage in 2004 involved large jet aircraft and occurred predominantly in Europe. Although there were no fatalities, there is clearly a large potential for serious or fatal injuries to persons in or around the aircraft [IAT05].

It is also noteworthy that, in contrast to the ICAO definition, the FAA definition of a Runway Incursion includes foreign objects on the runway as well. This, however, violates the fundamental distinction between human-controlled, consciously moving traffic on one side and inanimate, non-fixed obstacles on the other side. Although the consequences of foreign objects on the runway can be dire, as the loss of the Air France Concorde near Charles de Gaulle airport in 2000 [BEA00] shows, this type of runway incident/accident will not be considered here, since there are virtually no commonalities with Runway Incursions caused by aircraft, vehicles or persons, which are generally the result of erroneous surface movement operations.

[2] Nonetheless, abrupt braking to avoid a collision or the impact itself will most likely lead to injuries among the cabin crew, who might not be seated and buckled up yet if the aircraft is taxiing out. The risk of fatalities increases with relative speed and cannot be fully excluded, e.g. if the wing of an aircraft damages the forward fuselage of another one, or if the collision results in a fire, particularly if an aircraft taxiing to the runway for a long-distance flight, and thus heavily loaded with fuel, is involved. Generally, though, the risk of severe or even fatal injuries is much higher for vehicle drivers involved in collisions with aircraft [IAT05].

1.4 Statistical Data on Runway Incursions



Sources: FAA Runway Safety Reports, FAA Administrator's Fact Books, Eurocontrol Performance & Safety Review Reports DFS Mobilitätsbericht, Transport Canada, NAV Canada

Figure 1: Comparison of reported annual Runway Incursions in Europe, Canada and the USA

To obtain a better understanding of the magnitude of the overall problem, this section is dedicated to a review of Runway Incursion statistical data and an analysis of their implications and limitations. Both the absolute number of occurrences and the rate of incursions per million operations are valid metrics for a quantitative assessment of the severity of the Runway Incursion problem and its development in recent years.
First of all, it should be noted that there are no Runway Incursion statistical data covering worldwide operations, comparable to the data published by Boeing for commercial jet airplane accidents, cf. [Boe07]. Consequently, the analysis in this section is based on data for selected individual countries and regions. Figure 1 shows the development of reported Runway Incursions in Europe, Canada and the United States, as far as data is available.

1.4.1 United States

In the United States, Runway Safety Reports have been published on an annual basis since 2001 by the FAA's Office of Runway Safety [FAA01], providing the best and most exhaustive statistical coverage of Runway Incursions in the world. Data are continuously and consistently available over the whole 1994 – 2007 period, although a change of the reporting period from Calendar Year (CY) to Fiscal Year (FY) in the Runway Safety Reports published after 2002 necessitates the use of data from the FAA Administrator's Fact Book for the years 2002 – 2007 to prevent double counting of events [FAA02a]. It is evident from Figure 1 that the number of Runway Incursions was steadily rising from 1994 to 1999, and exhibiting a steep increase in 2000.

The decline in 2001 and 2002 can be partially attributed to the post-9/11 crisis of US aviation, which resulted in fewer flight operations, but also to the first immediate measures taken in the scope of the US Runway Incursion Prevention programmes. Since 2002, incursion numbers have stabilized, albeit at a high level, which is a clear indication that the measures taken so far are insufficient to achieve a significant reduction in the number of Runway Incursions. On the contrary, on a smaller time scale, there are even signs that the situation is deteriorating again. Between FY 2004 and FY 2007, the Runway Incursion rate has risen from an average 5.2 to 6.1 Runway Incursions per million operations, which corresponds to an increase of 17%, thus exceeding the 12% increase in the absolute number of incursions in the same period, because the total number of operations dropped by roughly two million operations to 61,131,629 in 2007 [FAA08].
While there appears to be another dramatic surge in the number of incursions from 2006 to 2007, the true reason behind this apparent increase is the adoption of the ICAO definition of Runway Incursions with the beginning of FY 2008, starting October 1st, 2007 [FAA08][3]. When comparing data on a FY basis, the increase is even more prominent, from 370 incursions in FY 2007 to 1,009 in FY 2008, corresponding to an increase of at least 273 %. Until FY 2008, consequently, all Runway Incursions involving just one aircraft or vehicle are statistically shrouded in the general "surface incident" category. The ramp-up after the change to the ICAO definition, however, gives an impression of the magnitude of the dark figure of events previously not listed in the Runway Incursion statistics.

1.4.2 Europe

Unfortunately, there is no holistic publication comparable to the Runway Safety Report in Europe. Statistical data on Runway Incursions has to be retrieved from various sources, such as the Eurocontrol Performance Review Reports, cf. [Eur08], and the Annual Safety Reports by the Safety Regulation Commission (SRC), cf. [Eur08a]. Due to the fragmentation and various national responsibilities, the data presented in Figure 1 are heavily influenced by the completeness of reporting. The fact that Paris Charles-de-Gaulle Airport alone registered 20 Runway Incursions between January and June 2000 [BEA01] provides strong evidence that the 99 incursions reported in Europe for the whole year do not portray the situation adequately. Likewise, the huge increase in the number of incursions between 2002 and 2004 does not reflect an actual deterioration of runway safety, but merely an improvement in the coverage of incidents through the unified reporting schemes enforced by Eurocontrol. Prior to November 25th, 2004, when the new ICAO definition of Runway Incursions became effective, there were at least 14 different definitions of a Runway Incursion in use in the European Civil Aviation Conference (ECAC) area alone. Since neither the reporting rate nor the exact definition used by the individual states are known, European Runway Incursion data up to 2004 are not usable for a statistical comparison with US or Canadian data, and do not permit any conclusion on the actual development of runway safety in Europe. Due to the uncertainty about the homogeneity of definitions and reporting rate, it is also unclear whether the increase from 2004 to 2005 can be attributed to the change of definition or other factors. As a result, the only reliable

[3] The FAA had originally planned to change its definition to comply with ICAO in 2006 [IAT05].

information deducible from Eurocontrol statistics is that there were 667 Runway Incursions in Europe in 2006, a significant increase over the 629 incidents registered in the previous year.
For Germany, Deutsche Flugsicherung (DFS) GmbH reports between 87 and 125 Runway Incursions for the 2003 to 2007 period in its mobility report [DFS08], as shown in Figure 1. By contrast, the annual reports of the Bundesstelle für Flugunfalluntersuchung (BFU) list between three and nine Runway Incursions per annum for the 2003 – 2007 period, with the maximum in 2005. The apparent contradiction is due to the fact that BFU covers severe incidents only and is limited to aircraft with a Maximum Take-off Weight (MTOW) above 5.7 t, i.e. aircraft typically used for commercial operations.
While there is no clearly observable tendency towards fewer or more frequent incidents, and there is too few data for a sound statistical analysis, a total number of 27 Runway Incursions rated as severe incidents within five years is certainly non-negligible. In this context, it is noteworthy that the BFU still uses a definition close to the FAA's, mandating a collision hazard as prerequisite for categorization and reporting of an incursion as a severe incident [BFU04, BFU05, BFU06, BFU07, BFU08].

1.4.3 Canada

Transport Canada could not identify any single factor or combination of factors that could serve as an explanation of the dramatic increase in the number of Runway Incursions at Canadian airports between 1996 and 1999 [TC00]. Using a definition close to the one later officialized by ICAO, a dedicated sub-committee on Runway Incursions collected and analysed statistical data for the 1993 to 1999 period from various sources. Since older data did not appear to be sufficiently detailed and reliable, the analysis focussed on the 1997 – 1999 period and the first five months of 2000. It was found that the trend towards more Runway Incursions was valid and real, and not caused by more diligent reporting due to the increased focus on Runway Incursions. Further data presented in Figure 1 have been extracted from the monthly Operational Performance Reports issued by NAV Canada, cf. [NAV08]. Generally, the situation is comparable to the United States with incursion numbers stagnating at a high level.

1.4.4 Conclusion

The statistical data show that Runway Incursions are generally on the rise in the United States and Canada. Due to the different definitions in use until October 2007 and the reporting ramp-up artefacts in the European data, a comparison of the situation in Europe and the USA is currently not possible, and the number of valid conclusions to be drawn from European Runway Incursion statistics in general is very limited. There is a Runway Incursion problem in Europe, and there is no proof that the countermeasures so far, such as the European Action Plan for the Prevention of Runway Incursions [Eur04, Eur06], have led to any reduction or at least stabilisation of incursion numbers.

1.5 Runway Incursions and Air Traffic Growth

The general tendency that Runway Incursions are on the rise, as identified in the previous section, raises the fundamental question whether and to what extent this correlates with the development of air traffic over the same period.

Since the late 1950s, the rate of fatal aviation accidents has dropped considerably in spite of a significant increase in air traffic. Averaged over the last decade, there were 0.5 fatal accidents per million departures in scheduled commercial operations, with only slight annual variations [Boe07]. Since the accident rate – which is a valid objective safety metrics – appears to have stabilized at this very low level, it can be expected that further air traffic growth will, in the absence of additional safety efforts, lead to an increasing number of incidents and accidents. This constitutes a significant challenge to aviation, because the ultimate goal of safety efforts is the prevention of individual accidents. Besides, the public, which is highly sensitive to aviation safety issues[4], will perceive a deterioration of flight safety. Therefore, the objective is achieving a reduction of accidents with the number of flight operations increasing.
However, the considerations above are based on the assumption that the current level of flight safety (in terms of accident rate) can be maintained even though more and more aircraft operate at the same time. Potential interaction effects due to increased traffic density are completely neglected. For aspects of technical reliability, maintenance and basic flight training standards, this seems appropriate. But with respect to ATM incidents in general, there is considerable evidence that their number increases with traffic, cf. Figure 3 [Eur08]. Given the complex influence of human factors aspects on the problem of Runway Incursions, it is necessary to take a closer look at the development of air traffic and its impact on airports, and to analyze potential correlations between Runway Incursions and traffic growth.

1.5.1 Background: Air Traffic Growth

In the age of globalisation, the interdependence of trade and industries from all around the world tightens. While the aviation industry has always assumed a pioneering role in internationalisation[5], even industry branches traditionally nationally oriented in terms of the supply chain, like e.g. the automotive industry[6], experience an increase in international ties.

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4 This high degree of sensitivity can be deemed almost irrational compared to the sensitivity for safety issues regarding other modes of transport. In 2005, more people (986) were killed in road accidents in the state of Bavaria [StB06] than in commercial airplane accidents (805) worldwide [Boe06]. Due to the large average number of fatalities in airline accidents, airline accidents usually receive international media coverage, whereas public information on road accidents scarcely goes beyond the level of the local newspaper.

5 The Junkers F13, the world's first all-metal passenger aircraft, which first flew in 1919, was exported, among others, to Afghanistan, Argentina, Australia, Bolivia, Brazil, Canada, Chile, China, Colombia, Ecuador, Finland, Hungary, Japan, Persia, Poland, South Africa, the Soviet Union, Turkey, Uruguay and the USA. Hugo Junkers co-founded several airlines, among them a Persian airline, and, of course, Junkers Luftverkehr AG (ILAG). In 1925, with 178 aircraft, 100,000 passengers and shares in no less than 29 national and international airlines, Junkers Luftverkehr AG – which was subsequently fused with Deutscher Aero Lloyd (DAL) on January 6, 1926 to form the Deutsche Lufthansa – was de facto the world's largest airline [Wag96].

6 The production plants of the major German car manufacturers are embedded in regional clusters of suppliers. This spatial proximity ensures a smooth flow of production and makes the roughly 5,500 suppliers of the automotive industry in Germany competitive in spite of comparatively high wages [IDW04]. However, the

Both global trade and modern manufacturing strategies such as the just-in-time stock distribution concept rely on the ability of airlines, particularly specialized cargo carriers, to deliver freight to almost any international destination within 24 hours.
As a consequence, the annual volume of goods transported by air has tripled between 1970 and 2002, when scheduled airline flights and dedicated air cargo operators handled 30.2 million tonnes, 18.2 million of which on international routes. There was an average annual increase in air cargo of 7% since 1980, and today, its overall share in worldwide transport, measured by value of the world's manufactured exports, lies around 40% [ICA02]. Production processes and trade are so deeply interwoven internationally that high-priced goods are usually transported by aircraft and not by ship. High-tech goods airlifted from Asia to Europe and North America represent 40% of total exports by tonnage, but account for almost 75% by value [Air04]. Furthermore, air transport of perishables has fundamentally changed consumption patterns – typical summer fruits and vegetables are now available all year. To a certain extent, the availability of air cargo transport can thus be regarded as a prerequisite and driver of globalisation.
Nonetheless, with just 1,644 dedicated freighter aircraft in service at the end of 2005, compared to 17,153 passenger aircraft, the vast majority of commercial flight operations are scheduled passenger flights. However, their cargo component, belly-loaded freight, currently accounts for 42% of the world's air cargo transport [Air06][7].
In spite of increasingly sophisticated means of electronic communication, it seems business travel remains an elementary need of all industry branches worldwide. Furthermore, recreational travel also contributes significantly to the overall growth in air traffic. As air travel became more affordable and the number of holidays increased in the course of the last decades, people started to prefer holiday resorts far away and to travel more than once per year. While travelling across the Alps with their private Volkswagen beetle car to Italian holiday resorts epitomised the holiday dream for many Germans in the 1950s and 1960s, Caribbean and Far Eastern beaches are reality for millions today. Even European holiday regions are mostly reached by airplane, and for some places like the Canaries, the existence of affordable air travel was a precondition for their success in mass tourism. In 2001, almost 40% of all international tourists used air transport [ICA02].

As a result, air travel reached a first peak in 2000, when more than 1.63 billion passengers (equivalent to 26% of the world's population) boarded scheduled flights, 181 times the 9 million airline passengers carried on scheduled services in 1945. For the 1970–2002 period, the volume of worldwide domestic traffic increased four times, from 298 million Passenger Kilometres Performed (PKP) in 1970 to 1.2 billion PKP in 2002. International air traffic experienced an even more dramatic growth of roughly 11 times in the same period, from 162 million PKP to 1.7 billion PKP. As a result, the share of international air services in total passenger traffic rose from 35% to almost 60% during the same period [ICA02]. In view of these facts, Airbus claims that air travel has become a basic human need [Air04].

share of national suppliers in the procurements of the Volkswagen Group is slightly larger than 50% in recent years [VW05].

[7] Combi aircraft, another option to combine freight and passengers in a single aircraft, are not mentioned by the quoted Airbus document, which explicitly refers to "belly holds" only; neither are mail flights of airliners.

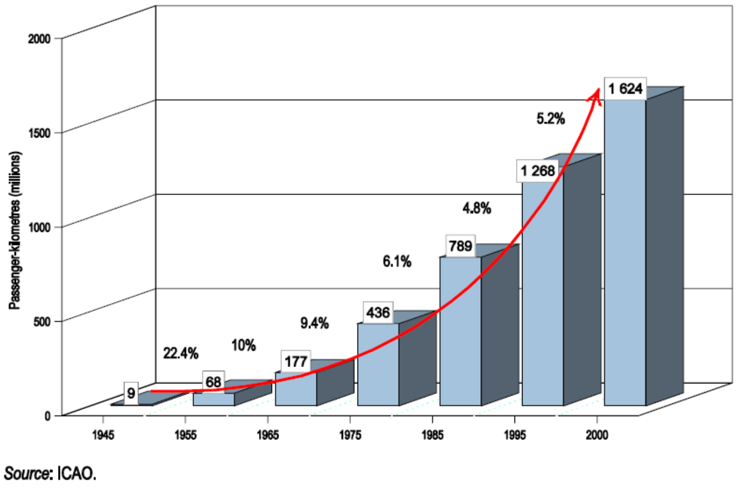

Figure 2: Development of passenger air travel in ICAO contracting states from 1945 to 2000 [ICA02]

Even terrorist activities and major international crises, like the terrorist attacks of September 11th, the two Iraq Wars and the SARS epidemic, had only a temporary impact on the growth in air traffic and did not mitigate the overall rate of increase, but merely shifted the curve of growth (i.e. the long-term demand) by 1.5 years [Air03]. In 2004, for example, airlines transported a little more than 2 billion passengers with some 18,000 jet aircraft of western origin, which corresponds to an estimated increase of 6% in comparison to 2003 [IAT05]. Other sources even speak of an increase in Revenue Passenger Kilometres (RPK) of 11.4% from 2003 to 2004 [Air04][8], and an overall annual growth in air traffic of 14% in 2004, the largest within the last 25 years [Air06], which they mainly attribute to a powerful rebound from the 9/11/2001 and Iraq war crisis.

The reasons for this growth are comparatively simple. First of all, there is a lack of competitive alternative modes of transport, except for the short-haul segment, where road and rail transport represent viable alternatives. In other words, air travel is the only practically feasible option for intercontinental travel, and there is a choice between car, rail and airplane only for short distances. Second, air fares have dropped, initially also due to the lack of demand, but mainly because of the emergence of low cost carriers, which stipulated interest while making airline customers increasingly sensitive to the ticket price at the same time.

Consequently, overall air travel increased by nearly 30% from 2000 to 2006, a recovery unprecedented in aviation history, driven mainly by a strong economy, new airlines, emerging markets and increasing liberalisation [Air06].

1.5.2 Impact of Traffic Growth on Airports

The growth of air traffic poses an immense challenge to civil aviation. Since the capacity of the Air Traffic Management (ATM) system, particularly airports, is limited, larger traffic volumes must be managed while maintaining both safety and efficiency in spite of the increasing traffic density, and under almost all weather conditions.

With growing demand for flights, airports have increasingly turned into the bottlenecks of the air transport system. According to recent ATC studies, cf. [Eur08], the share of delays generated by airports has risen compared to delays attributable to the

[8] It should be noted, though, that the Airbus statistics is based on ICAO data for the first three quarters of 2004, figures for the last quarter are extrapolated. Note also that the basis for the IATA numbers appears to be the absolute number of passengers, while the ICAO/Airbus data are based on RPK.

en-route sectors. Admittedly, though, the introduction of Reduced Vertical Separation Margins (RVSM) has helped to create more capacity in the en-route sector, with a positive impact on delays.

Within the last decade, the number of flights in Europe has increased with an average rate of 3.5% per year. At the same time, average en-route Air Traffic Flow Management (ATFM) delays for the summer period (May – October), of which 77% were capacity-related, have significantly decreased from 5.5 minutes in 1999 to 1.6 minutes per flight in 2007 [Eur08]. Nonetheless, absolute overall ATFM delay increased by an average 3.7% p.a., which at first glance suggests that delay grows at essentially the same rate as traffic. A second glance, however, shows huge annual variations which eventually cancel one another. By contrast, airport-related ATFM delays[9] exhibit an average annual growth of 6.3%, almost 1.8 times the average traffic growth.
Thus, airport ATFM delay grows faster than both traffic and overall traffic delay. Consequently, the share of airport ATFM delay has increased considerably from 23% in 1997 to 44% in 2007. With 91%, nearly all of this airport ATFM delay was attributed to arrival [Eur04a]. Furthermore, it is noteworthy that 15 European airports accounted for 69% of airport delays in 2007 [Eur08].

Additional capacity on the ground requires substantial investments. Nonetheless, limited funding is not the main reason why airport enhancements cannot keep pace with air traffic demand. In Western democracies, airport expansion programmes face high bureaucratic hurdles and are subject to an often decade-long decision making process. The amount of time and money involved in this process is tremendous, often dwarfing the actual construction effort. Since airport needs must be balanced fairly against overall societal needs considering environmental, noise abatement and legal factors, or any combination of these, this effort is justified. Frequently though, airport extension plans are blocked by politics or non-governmental organisations, who exploit the subject for political or ideological reasons. One of the most prominent examples is the planned expansion of Frankfurt Airport [Fra07].
Consequently, particularly short- and medium term capacity enhancements can only be achieved through a more efficient utilization of existing airport infrastructure and optimized processes, cf. e.g. [Fra07]. Generally, if actual or forecast traffic demand exceeds the capacity of an ATM system, the first step is thus always to maximize the use of existing system capacity, before measures to increase capacity by other means are taken [ICA01a]. In 2007, 93 airports were already capacity constrained: these airports accommodate 64% of worldwide air traffic [Air07], with a majority located in Europe.
As a consequence, particularly the big hub airports will see a significant increase in air traffic over the next decades which cannot fully be balanced by a corresponding enhancement of their infrastructure. Demand is thus quickly outgrowing capacity gains through potential expansions. Therefore, the resources of airports are exhausted and brought to their limits first when air traffic increases, and consequently,

[9] Airport ATFM delays occur when flights have to be delayed due to capacity limitations. Arrival ATFM delays are experienced at the departure airport, but are in fact caused by a lack of capacity at the destination airport. As a consequence, flights are held on the ground at the departure airport until arrival capacity at the destination airport is assured.

the only feasible way of coping with increasing air traffic at airports is to increase the efficiency of the existing infrastructure. Even high-level strategy papers such as Vision 2020, although expecting threefold air traffic by 2020 and demanding 99% punctuality, state that the construction of new airports and runways should be avoided as far as possible [Bus01].

If there is, as Airbus predicts, an increase in hub-and-spokes operations for economic and logistic reasons, the bottleneck role of the hub airports will be intensified far beyond the basic structural level outlined above. Even if the Airbus prognosis that ticket price will be the driving factor proves wrong eventually, the development of large metropolitan areas with more than 20 million inhabitants will necessitate high-capacity airports at these cities to satisfy travel demand, which will increase further with growing wealth of these areas. As an example, it is expected that aircraft movements at Beijing airport will grow from 250,000 per annum today to about 700,000 by 2023, making it one of the world's busiest airports [Air04].

The bottleneck role of airports, however, is not limited to efficiency, but also encompasses safety. Although only 18% of the flight time is typically spent on the ground and in the airport vicinity, 80% of hull losses and/or fatal accidents occur in the corresponding flight phases [Boe04a][10]. There is a dominance of landing accidents (45%), which encompasses both runway incursions and excursions.

1.5.3 Analysis of Correlations between Traffic Growth and Runway Incursions

Based on empirical 1990s data from the United States, it has been suggested that the rising number of Runway Incursions correlates with traffic growth [Lou99]. Likewise, Transport Canada (TC) attributed the observed increase in Runway Incursions to traffic growth [TC00]. Recent data for 15 European States, cf. Figure 3, apparently also support this model [Eur08][11].

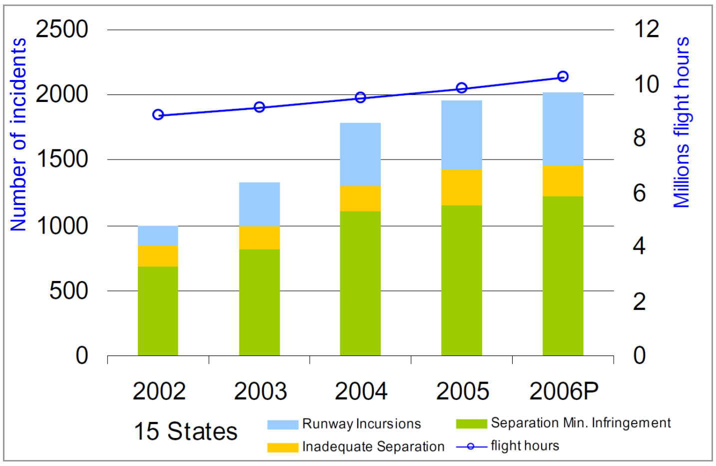

Figure 3: Development of reported ATM incidents in 15 European States [Eur08]

However, a direct correlation between the development of air traffic and Runway Incursions is difficult to prove for current data from the United States concerning the 1999 to 2007 period [FAA03, FAA08]. Since the FAA's statistics is limited to occurrences involving traffic conflicts, any traffic-related effects should be clearly evident in this data.

But, as an example, the number of Runway Incursions in the USA increased by 12.1% from previously 330 to 370 in 2007, while the number of operations decreased by -0.3% in the same period. On average, there was a slight reduction in traffic (-1.3%) between 1999

[10] It should be noted, though, that Boeing's *Statistical Summary of Commercial Jet Airplane Accidents* excludes both CIS-manufactured aircraft and regional jets or turboprops with a mass less than 60,000 lbs (27,200 kg).

[11] Only the 2004-2006 period is considered due to the reliability issues discussed in Section 1.4.

and 2007, whereas the number of Runway Incursions increased by 2.1% over the same period. This indicates that there is no simple mathematical relation between Runway Incursions and the development of traffic, all the more as Runway Incursions are, compared to the number of operations, relatively rare events, and annual variations in the number of Runway Incursions in the USA are well within 2σ of the mean value.

Furthermore, a closer look at the Transport Canada study quoted above reveals that its findings are solely based on a theoretical model for the number of potential Runway Incursion scenarios as a function of traffic. However, the predictions of this model, that the potential for Runway Incursions increases more rapidly than traffic itself, were not systematically validated with the empirical data collected by Transport Canada. The only conclusion drawn was that the model could potentially account for the trend observed [TC00].

Figure 4 shows the annual Runway Incursion rates per million operations, averaged over the 2003 – 2006 period for the so-called Operational Evolution Partnership (OEP) airports, i.e. the 35 airports that form the backbone of U.S. commercial aviation. Together, they account for 32% of all Runway Incursions and 25% of all operations [FAA07]. In the figure, airports are sorted by decreasing overall number of operations.
If the number of Runway Incursions were proportional to traffic volume, one would expect to see a constant incursion rate in the figure. This would mean that the probability for Runway Incursions is independent of traffic density, which is, at least in first approximation, a reasonable assumption, since the rules of the air and applicable separation minima are not changed as traffic increases.

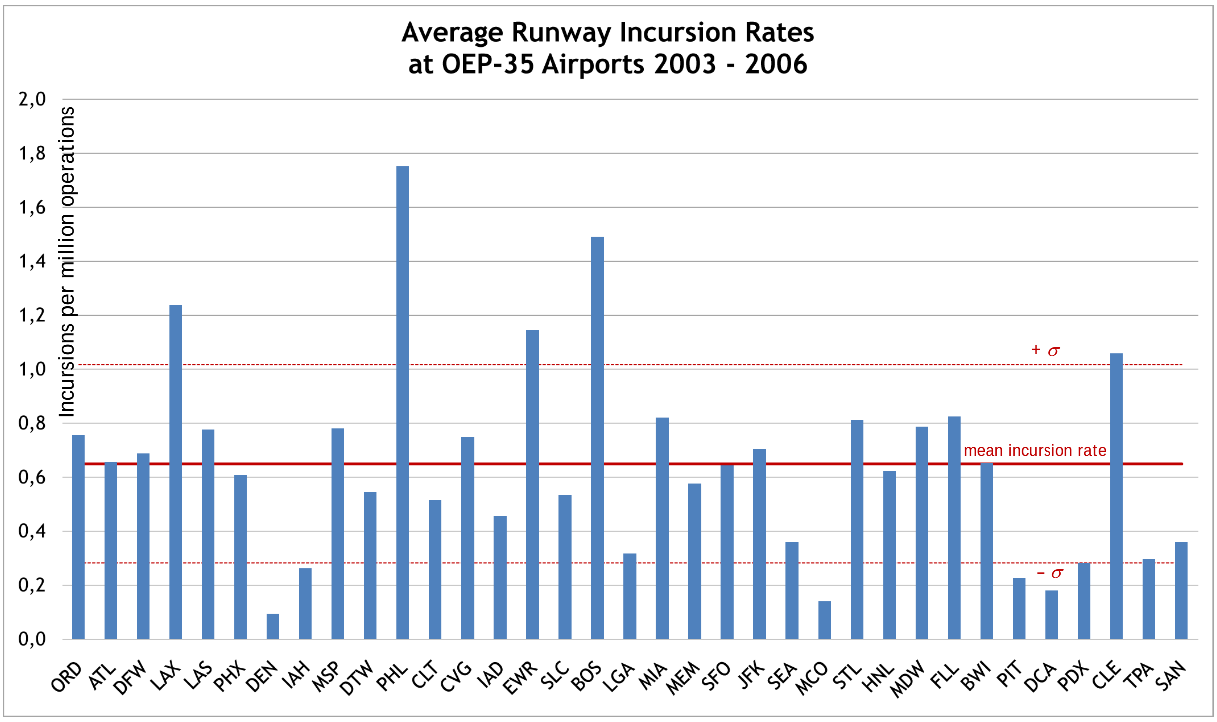

Figure 4: Development of average Runway Incursion Rates at OEP-35 airports [FAA07]

Conversely, any hypothesis that runway incursions grow larger than proportional with traffic density is based on the assumption that larger traffic volumes result in higher – and potentially excessive – workload for both pilots and controllers, and thus degrade performance to the point where errors become more frequent. In Figure 4, this would correspond to a decreasing incursion rate of some sort[12].

Although the number of values within one σ (dashed red line) of the mean incursion rate (solid red line) is consistent with a normal distribution, a simple linear model cannot account for the oscillatory behaviour exhibited by the actual incursion rates. While statistical noise is to be expected due to the low numbers of incursions compared to literally millions of operations, particularly the upward spikes for Los Angeles (LAX), Philadelphia (PHL), Newark (EWR) and Boston (BOS) are remarkable. An analysis of the airport diagrams reveals that there are no simple structural factors, such as the number of runways or runway intersections, that could account for the observed differences. As an example, Chicago O'Hare Airport (ORD) has seven runways and four runway intersections, and is one of the most complex airports in the United States. Nonetheless, its incursion rate is only slightly above average. Furthermore, only one of the three fatal U.S. Runway Incursion accidents involving airliners within the last 30 years occurred at an airport with a significantly above average incursion rate, Los Angeles.

This suggests that the occurrence of Runway Incursions depends on a more complex combination of factors. While some of them could potentially be site-specific, particularly the impact of flight crew situational awareness outlined initially could be dependent on factors independent of, or beyond the control of individual airports, such as flight deck instrumentation or visibility. Besides, some of the human factors aspects – such as disorientation – are not dependent on traffic density at all.

1.5.4 Conclusion

In conclusion, there is an observable tendency that the number of Runway Incursions is increasing, but no statistically sound evidence that this development is strongly coupled to the variations in the number of flight operations, let alone for a simple interrelation of traffic growth and rising numbers of Runway Incursions. Nonetheless, the fact that even fewer operations may eventually result in a higher number of incursions is alarming, and illustrates the criticality and urgency of the problem.

In line with this observation, a 1986 study by the NTSB revealed that 12 of 17 incursion incidents classified as controller-induced occurred in light traffic, and only two in heavy. Frequently, a lack of coordination between controllers contributed to incursions. Combined with the findings of a 1984 NASA study that multiple intersecting runways and restricted visibility frequently appeared as causal factors in both pilot- and controller-induced incursions [NTS86], this suggests that the complexity of operations and infrastructure – and thus a derivative of traffic demand – is an important factor as well. Further – albeit theoretical – evidence for the influence of operational complexity can be found in the aforementioned Transport Canada study,

[12] Since the change in overall operations is not equidistant between airports, obtaining a valid functional relation is not possible.

which analytically determined that airports operating near the capacity limit are particularly vulnerable to the occurrence of Runway Incursions, especially when capacity-enhancing procedures are applied at aerodromes with intersecting runways [TC00]. This could explain why the number of incursions is apparently not influenced by small variations in the number of operations. Nonetheless, a more detailed analysis of Runway Incursion causal factors is required.
In view of the historic development of air traffic and the expected further increase, chances to limit the complexity of air traffic operations and infrastructure are low. It is therefore worthwhile to focus on the human factors aspects of the Runway Incursion problem, in order to give stakeholders better tools to handle complex operations. In line with the research focus of the Institute of Flight Systems and Automatic Control, this thesis approaches the problem from the perspective of the flight crew. The particular challenge of this approach is that the solution must be sufficiently generic to be applicable for myriads of different airport configurations and local procedures.

1.6 Goals, Scope and Structure of this Thesis

The goal of this thesis is to identify potential deficiencies of current flight deck instrumentation contributing to Runway Incursion incidents and accidents, and to assess the conditions and the extent to which onboard systems can contribute to enhanced safety in the airport environment. While the idea of onboard systems for the prevention of Runway Incursions is anything but new, cf. Kubbat *et al.* [Kub99], a holistic concept for an onboard functionality encompassing all aspects relevant for Runway Incursion avoidance is still missing.

Therefore, focussing on runway safety[13], advantages and disadvantages of an onboard solution are weighed against other technological approaches such as ground-based systems, and scenarios requiring air-ground cooperative systems are identified. Based on an analysis of causal factors in Runway Incursion incidents and accidents, requirements for onboard technologies are developed, leading to the concept for a novel surveillance-type onboard Surface Movement Awareness and Alerting System (SMAAS).

Since the primary goals of such a holistic system approach are improved situational awareness and pro-active conflict detection, and not necessarily the addition of new alerts to the flight deck, particular emphasis is given to possibilities to improve the flight crew's situational awareness to avoid hazardous situations strategically and proactively. Nonetheless, because there could be situations in which the flight crew is busy with other crew duties or otherwise distracted, the feasibility of safety-net type tactical alerting in cases where increased situational awareness alone might not be sufficient to maintain flight safety or to prevent conflicts must be studied as well.

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13 As discussed previously, runway safety is not limited to Runway Incursions, but also includes issues such foreign objects or debris on the runway surface, wildlife straying onto the runway, and birds on meadows surrounding the runway. However, this thesis focuses on traffic, i.e. the controlled, deliberate movement of aircraft, vehicles, or persons.

The problem of Runway Incursions is an urgent one, requiring immediate attention and countermeasures to be put in place. In view of the number of near-misses, one should not be deceived by the fact that the number of fatal airliner accidents is currently at a historic minimum [Boe07], since this might be accidental, because it is well within statistical noise.

Consequently, the concept for a future onboard system for Runway Incursion avoidance will have to satisfy various constraints. While avoiding the pitfalls of a quick fix, it must have a realistic operational perspective, which limits the technologies to be used to existing and near-future ones, while maximizing the use of technologies available today. Another important aspect is that the approach must be evolutionary rather than revolutionary, enabling integration into both existing airliner cockpits and the present ATM system, both from a technical and procedural perspective. Furthermore, the concept must be modular, such that it can be tailored to the potentially distinct requirements and constraints of different airframe classes. Additionally, a modular system also allows a gradual or step-wise transition from today's systems.
Wherever in this thesis a model or straw man aircraft was required, the Airbus single aisle/long range family was used, mainly because it is well proven in millions of flight hours, with thousands of aircraft on the market and on order, enabling both a retrofit and line-fit perspective on system integration. Besides, sufficiently detailed technical information on these aircraft is readily available.

In the frame of this thesis, the envisaged components of the SMAAS were realised as software prototypes. The goal of this realisation was a proof of concept for the novel surveillance system and its individual interrelated and interacting components. Accordingly, this thesis primarily tries to validate the necessity and impact of having an information or alert in a certain condition, rather than validating that this information or alert is conveyed in an optimum manner. Consequently, the assessment of the Human-Machine Interface (HMI) itself is only a secondary objective. However, in practice, making this distinction can be very difficult. Since information is necessarily perceived through an HMI, special care must be exerted in designing the prototypic HMI. It must be sufficiently well-designed to enable an evaluation of the concept without disturbances due to issues related to immature HMI design. Otherwise, there is a significant risk that an inadequate HMI distorts and falsifies the results on the concept itself.
Subsequently, the prototypic SMAAS setup was validated with pilots using two different evaluation platforms, the Institute's Navigation Test Vehicle and the Fixed-Base Research Flight Simulator, mainly to gather feedback on the operational relevance and desirability of the proposed solution, in line with the objectives stated above.

This first chapter has given an introduction to the problem complex of Runway Incursions as the most safety-critical example of surface movement incidents in general. Potential impacts of increasing air traffic, high-capacity operations and the bottle-neck role of airports were reviewed, and the necessity for a more detailed analysis of causal factors identified.

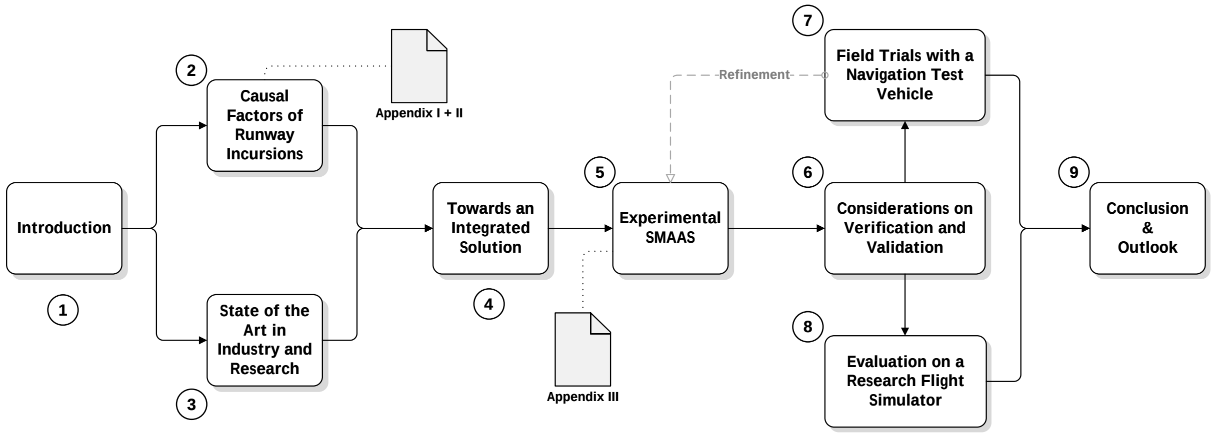

Figure 5: Structure of this thesis

Therefore, **Chapter 2, "Causal Factors of Runway Incursions"**, aims at a detailed analysis of current operations at aerodromes to identify the underlying causes, mechanisms and schemes leading to Runway Incursions and other surface movement incidents. It commences with an analysis of current ground operations from a procedural point of view and scrutinizes them for potential deficiencies. A survey of existing high-level reports focussing on Runway Incursion, e.g. the FAA and Eurocontrol, is used as a starting point for a classification of Surface Movement Incidents and Runway Incursions in particular. Eventually, an analysis of selected accidents and incidents is used to conclude on the common, generic causes of Runway Incursions with special emphasis on the role of situational awareness, communication and surveillance. This results in five ***High-Level Requirements*** on information required for Runway Incursion avoidance from an operational perspective.

Chapter 3, "State of the Art", starts with a survey of existing solutions for better situational awareness on the ground and Runway Incursion avoidance. Current onboard traffic surveillance technologies (TCAS, ADS-B and TIS-B) are addressed as well. Some of these systems will later be used as building blocks or supporting technologies for the solution devised by this thesis. The remainder of the chapter is dedicated to brief review of current ATM surveillance technologies and concepts, such as the Advanced Surface Movement Guidance and Control System (A-SMGCS).

Chapter 4, "Towards an Integrated Solution", derives the functionality required for a holistic, onboard-centric solution for Runway Incursion avoidance and identifies areas where research is required to realise it. The chapter commences by devising strategies for Runway Incursion avoidance, which subsequently serve as a framework for addressing the individual deficiencies and limitations of current flight deck instrumentation identified in Chapter 2. For each of the operational ***High-Level Requirements***, Chapter 4 then discusses the advantages and disadvantages of onboard versus ground-based technologies, and identifies scenarios in which an air-ground cooperative approach is required. The backbone of air-ground cooperative systems is a digital communication between flight deck and Air Traffic Control (ATC), the so-called Controller Pilot Data Link Communication (CPDLC). These considerations on a useful distribution of future Runway Safety Net functionality between the onboard and ground domain start at the situational awareness level and progress towards flight deck alerting aspects. In this context, the issue whether alerting should provide the flight crew with TCAS-style resolution advisories and whether there are valid evasive strategies in every situation is of paramount importance.

Chapter 5, "Experimental Surface Movement Awareness and Alerting System", is the central chapter of this thesis. Based on the requirements and constraints identified in the previous chapters, the system concept for the novel Surface Movement Awareness and Alerting System (SMAAS) proposed by this thesis is outlined and discussed. Subsequently, the individual components of the SMAAS are described in detail, with focus on functionality and crew interface. The discussion commences with a description of the modular sub-functions dedicated to an improvement of situational awareness, and then progresses to a discussion of the alerting parts. This chapter provides a detailed rationale for trigger conditions and alert design.

Chapter 6, "Considerations on Verification and Validation", commences by outlining the generic validation objectives applicable to both the campaign with the Navigation Test Vehicle and the Research Flight simulator, as well as the overall strategy selected to achieve these. After considerations on participants and experimental factors, this chapter concludes with a survey of existing methods and metrics for measuring e.g. situational awareness and workload, and scrutinizes them for applicability.

Chapter 7, "Field Trials with a Navigation Test Vehicle", is dedicated to the validation campaign conducted with the Institute's Navigation Test Vehicle at Frankfurt Airport (EDDF) and Prague Airport (LKPR). Following a brief description of the objectives, the validation platform, its particular setup for the evaluation and the scenarios are outlined. The results obtained in the evaluation are then presented, analysed and discussed.

Chapter 8, "Evaluation on a Research Flight Simulator", describes the evaluation campaign with the Institute's fixed-base Research Flight Simulator, which partially re-validated the results of the field trial campaign while already taking into account some refinements resulting from the assessment on the Navigation Test Vehicle. However, the focus of this second campaign was on the traffic alerting functionality, which had already been conceived, but not yet been realised at the time of the field trials. After an overview of the objectives, the validation setup and the scenarios, the results of this evaluation campaign are presented, analysed and discussed.

Chapter 9, "Conclusion", summarizes the findings of this thesis and concludes on the results, with particular emphasis on the findings of the evaluation campaigns from the previous chapters.

Finally, this thesis is complemented with three appendices.

2 Causal Factors of Runway Incursions

This chapter, which is dedicated to a detailed analysis of Runway Incursion causal factors, commences with a review of current surface operations from an organisational and procedural perspective (Section 2.1). Apart from an identification of potential deficiencies inherent in the way surface operations are presently conducted, this review also sets the scene for an in-depth analysis of surface movement incidents and accidents in the following section (Section 2.2), which - in the absence of technical defects and malfunctions - can be equated to an at least partial breakdown of procedures and/or organisational structures.

While this thesis focuses on Runway Incursions, the whole context of airport operations must be considered. Otherwise, there is a high risk that important contributing factors are excluded by an a-priori limitation to the immediate runway environment. After all, runways are not isolated, foreign objects within the aerodrome structure, but an integral, central part of the airport. Since there is considerable evidence that a large number of Runway Incursions is caused by disorientation, cf. [ICA07], the sequence of events for most runway-related incidents and accidents consequently begins on the manoeuvring area.

In the second part of this chapter, an incident and accident analysis is performed with the ultimate goal of identifying Runway Incursion causal factors and the underlying mechanisms. As a first step, a review of existing incident and accident classifications is conducted (Section 2.2.1). Then, selected individual incidents and accidents are investigated, focussing on flight crew Human Factors aspects (Section 2.2.2).

The causal factors thus identified are subsequently further categorized, and the results serve as basis for an analysis of potential deficiencies in current avionics and flight deck instrumentation (Section 2.3). However, it is essential to determine the limitations of a technology-oriented approach, since there may very well be domains where a change of procedures or other measures could be superior to the introduction of additional systems. Another important aspect in this context is an assessment to what extent Runway Incursions and other surface movement incidents have common causes and may thus be mitigated through similar solutions.

Eventually, based on these considerations, five ***High-Level Requirements*** for the prevention of Runway Incursions from a flight deck perspective are derived and discussed. These ***High-Level Requirements*** will subsequently be used as basis for a discussion of potential mitigations and solutions.

2.1 Analysis of Current Surface Operations

When navigating on the airport surface, both pilots and vehicle drivers rely on visual aids, such as airport markings, signage and lighting (see Appendix II: Visual Aids to Surface Navigation), for guidance along an assigned route and the identification of intersections and holding positions. Visual aids are usually complemented by the respective paper chart in the cockpit (cf. Section 2.1.3.2) and Notices to Airman (NOTAM, cf. Section 2.1.3.1). Combined with information from previous experience (if available), this is intended to ensure that they have sufficient understanding of their environment. If these sources of information are correctly provided and suitably embedded in flight crew procedures, they add multiple layers of redundancy and thus safety to an aviation system.

Irrespective of the type of operation, the class of aircraft and the phase of flight, ICAO Annex 2, Rules of the Air, requires pilots to use visual observation as the fundamental method of acquiring the surrounding traffic and detecting potential conflicts [ICA90]. As an additional challenge, surface traffic encompasses not only other aircraft, but also vehicles performing a large variety of functions, often on the manoeuvring area, i.e. on taxiways and runways.
Consequently, independent of whether an airport is controlled or not, pilots and other surface traffic operators use visual observation as the primary cue for orientation, navigation and collision avoidance ('see and avoid'). This principle, which is often also referred to as 'see and be seen', forms the foundation of ground operations today. Since the majority of airline aircraft operate predominantly from controlled airfields, the description in this chapter will focus on controlled aerodromes.

Generally, the primary goal of air traffic services is the prevention of collisions between aircraft, both airborne and on ground. In the latter case, collisions between aircraft, vehicles and obstructions on the ground are in the scope as well. Expediting and maintaining an orderly flow of air traffic is an essential, but secondary objective of air traffic services, which usually comprise Air Traffic Control (ATC), Flight Information Service (FIS) and alerting service[14]. At controlled airfields, the ATC services applicable to ground operations are mainly the aerodrome control service and, to a lesser extent, the approach control service [ICA01].

A consistent description of ground operations today is a formidable task, because there are, despite international standardisation, myriads of variations in the organisation and procedures of handling traffic on the ground, particularly outside the manoeuvring area, i.e. on the apron. However, ICAO Annex 11, Air Traffic Services [ICA01], the PANS-ATM [ICA01a] and various other ICAO documents describe a common framework, which is briefly presented in the following.

[14] The scope of the alerting service as defined by Annex 11 is the alerting of rescue units on the ground when an aircraft is known to have technical or other significant problems (i.e. when it is in the uncertainty, alerting or distress phase), and the management of the corresponding emergencies from an ATC point of view. The provision of alerts to the flight crew via voice communication of an imminent collision is apparently not in the scope of this definition of 'alerting' [ICA01]. Therefore, on the ground, the alerting service is currently limited to a mobilization of the rescue and fire-fighter units if deemed appropriate by the controllers or on explicit flight crew request [ICA01a].

2.1.1 Organisation of ATC at the Airport: Aerodrome Control Service

At controlled airports, Aerodrome Control Service is provided by the aerodrome control tower ('tower'). The tower is responsible for issuing clearances and information to all aircraft under its control "*to achieve a safe, orderly and expeditious flow of air traffic on and in the vicinity of an aerodrome*". This responsibility also extends to vehicles and personnel on the manoeuvring area. Surveillance of all traffic is generally performed by visual observation. In low visibility conditions, surveillance is augmented by radar[15] where available [ICA01a]. However, this does not preclude the use of radar as supplement in excellent visibility.

Nonetheless, visual acquisition dominates current surveillance, as evidenced e.g. by the aircraft lighting procedures suggested as part of Advisory Circular AC 120-74A [FAA03a], which recommends using different combinations of exterior aircraft lights not only to make aircraft operating on the airport surface more conspicuous, but also to convey the location (taxiway or runway) and intent. As an example, different light combinations are proposed to signal whether an aircraft is on the runway but holding for take-off clearance, crossing an active runway, or taking off. However, an important drawback of these lighting procedures is that they are not an agreed international standard and voluntary even in the USA.

According to the PANS-ATM [ICA01a], the functions of an aerodrome control tower are often performed by different control or working positions, such as:

- **aerodrome controller**, normally responsible for operations on the runway and aircraft flying within the area of responsibility of the aerodrome control tower[16];
- **ground controller**, normally responsible for traffic on the manoeuvring area outside the runways;
- **clearance delivery position**, normally responsible for the delivery of start-up and ATC clearances to departing IFR flights.

Depending on airport complexity and traffic density, these positions can be subdivided further. For example, where parallel or near-parallel runways are used for simultaneous operations, individual aerodrome controllers are usually responsible for operations on each of the runways or sets of runways.
The responsibility of ATC on an aerodrome is limited to the manoeuvring area. Services on the aerodrome aprons, known as Apron Management Services (see Section 2.1.2.3), are usually performed by a separate unit, but may also be assigned to the aerodrome control tower, depending on the local situation.

The aerodrome control tower is also responsible for the selection of the runway-in-use, i.e. the runway considered to be most suitable for use by the types of aircraft expected to be operated at the airport. Usually, aircraft land and take off into the wind, unless safety, runway configuration, available instrument approaches, weather conditions or the general traffic situation render a different direction preferable. Of

[15] Radar can be supplemented by more recent surveillance technologies such as Mode S multi-lateration.
[16] In the United States, the aerodrome controller is commonly referred to as 'local controller'.

course, several runways can be in use at the same time, and it is common at most airports that separate runways are designated as runway-in-use for arriving and departing aircraft. At any rate, flight crews may ask for take-off or landing on a different runway if they consider the current runway-in-use not suitable. If circumstances permit, crews should then be cleared to use the runway of their choice [ICA01a].
In addition to essential information on aerodrome conditions, ATC also has to provide the flight crew of any arriving or departing aircraft with timely information on so-called "essential local traffic". Any other aircraft, vehicle or person on the manoeuvring area or in the aerodrome vicinity that might constitute a collision hazard must be reported in a fashion allowing an easy identification of the traffic concerned.

Likewise, the aerodrome controller has to take action in case a Runway Incursion occurs or wildlife is detected on the runway after take-off or landing clearances have been issued. Unless other action is deemed favourable, the controller will typically react as follows [ICA01a]:

a) The controller informs all aircraft concerned by the Runway Incursion or other obstruction of the situation and location of the obstacle/obstruction.
b) The controller cancels the take-off clearance for an aircraft which has not commenced its take-off roll.
c) The controller instructs any landing aircraft to go around, if still considered possible.

2.1.2 Procedures for Aerodrome Control Service

2.1.2.1 Communication and Phraseology

In the vicinity of aerodromes, communication between ATC and aircraft is generally established by two-way VHF radiotelephony (RT). The aerodrome control service has to be capable of communication with aircraft at any distance within 25 NM (45 km) of the airport [ICA01a]. Since ICAO recommends using separate channels for traffic on the manoeuvring area, aerodrome control service typically encompasses several distinct frequencies, reflecting the organisational structure of ATC at a particular airport [ICA01]. Consequently, separate frequencies are commonly used for controlling different parts of the airport. In times of light traffic, e.g. during the night hours, several controller working positions may be combined and worked by a single controller, but different controllers never share a single frequency.

For brevity, clarity and unambiguous mutual understanding, voice communication between ATC and flight crews follows formalized procedures [ICA06]. The standardized curriculum of prescribed words and phrases to be used in communication is referred to as phraseology [FAA04b]. Any station on the ground serving international air traffic must provide ATC services in English on request. Generally, radiotelephony communications are conducted in either English or "*in the language normally used by the station on the ground*" [ICA01d][17].

[17] In several countries, such as France and Italy, this leads to a situation where a controller uses English for instructions to foreign aircraft and the local language to control the aircraft of national operators. Since this may

Compared to normal language, ATC phraseology is simplified, truncated to the essential information, and employs fixed semantics. Phraseology includes specific rules for pronunciation of numbers and letters, and sometimes re-defines the meaning of words to disambiguate communication. As an example, 'NEGATIVE' is used in lieu of 'NO' [ICA01d]. However, phraseology is not intended to cover every conceivable situation that may arise. Therefore, while phraseology should always be used where applicable [ICA06], this does not preclude using plain language where appropriate to establish efficient communication [FAA09]. ICAO explicitly encourages the use of plain language in non-routine situations, and mandates sufficient plain language proficiency for users [ICA06]. Phraseology and communication procedures are defined in ICAO Annex 10, Vol. 2 [ICA01d], and the PANS-ATM [ICA01a].

As part of these communication procedures, the flight crew has to read back safety-relevant parts of ATC clearances to the controller. Route clearances and instructions to enter, land on, take off on, hold short of, cross taxi and backtrack on any runway always have to be read back [ICA01a]. Likewise, any conditional clearances and any critical information, such as altimeter settings or runway-in-use have to be confirmed by the crew.

Data link technology is emerging as means of ATC communication and currently used for en-route clearances in oceanic airspace, departure clearances or to convey ATIS information. However, unless specified otherwise by the responsible ATS unit, Controller Pilot Data Link Communication (CPDLC) messages are not read back by voice, i.e. there is no mix of data link and voice [ICA01a].

2.1.2.2 Manoeuvring Area Control

Use of the manoeuvring area is, with few exceptions, restricted to aircraft, and the capability to establish two-way radiotelephony communication with ATC is a prerequisite for all traffic.

2.1.2.2.1 Taxi Instructions

Taxi instructions should be as precise and concise as possible to provide the flight crew with adequate information to follow the assigned route correctly. Collisions with other aircraft or objects and inadvertent entry of an active runway have to be avoided under all circumstances. Therefore, if a taxi clearance contains a taxi limit beyond a runway, it has to contain an explicit clearance to cross or an instruction to hold short of the respective runway[18]. Wherever practicable, the authorities should define standard taxi routes and publish them in the corresponding national Aeronautical Information Publication (AIP). If no standard taxi routes are available, a taxi clearance will usually be described by a sequence of taxiway and runway designators. It is also quite common that information on aircraft to follow or to give way to is included in a taxi clearance.

lead to a situation where particularly foreign pilots will not be aware of clearances issued to other aircraft in the local language, this procedure is frequently criticized, and has been cited as causal factor in the Paris accident in 2000 (cf. Appendix I-8) and the Linate disaster (cf. Appendix I-11).

18 In the United States, non-active runways may be crossed without explicit ATC approval [FAR07], but the NTSB re-iterated a safety recommendation to require explicit ATC authorisation for all runway crossings in the wake of the Comair accident [NTS07].

Under special circumstances, and provided that no risk or delay to other aircraft will occur, aircraft may be permitted to taxi on the runway-in-use in order to expedite the flow of traffic. A special case is the so-called 'back-tracking' on a runway, where an aircraft taxis to the end of the runway, turns and takes off in the opposite direction. An aircraft using an active runway as a taxiway will usually be requested to report when it has vacated the runway. This report should be made when it is well clear of the runway [ICA01a].

2.1.2.2.2 Take-off and Landing Clearances

The take-off clearance is not issued until the ATC en-route clearance, which is required prior to take-off in most cases, has been transmitted to and acknowledged by the flight crew. Therefore, an initial ATC clearance is typically requested before an aircraft starts to taxi [ICA01a].

Once a departing aircraft has reached the assigned runway and is ready for take-off, it is usually first instructed to line up and wait on the runway, and then cleared for take-off in a second step. To reduce the potential for misunderstanding, line-up and take-off clearances must include the designator of the departure runway. However, to expedite traffic, a clearance for immediate take-off may be issued to an aircraft before it enters the runway. When accepting such a clearance, the aircraft is obliged to taxi onto the runway and take off in one continuous movement [ICA01a].

Take-off clearances may only be issued if the traffic situation permits, i.e. if there is reasonable assurance that there will be sufficient separation. Typically, the preceding departing aircraft should have crossed the end of the runway-in-use or started a turn, and any preceding landing or crossing aircraft must be clear of the runway.

Approach control typically guides arriving aircraft to the designated runway-in-use via Standard Instrument Arrival Routes (STARs). Where necessary, radar vectoring is used to establish aircraft on the desired approach with at least the required minimum separation from preceding traffic. After transfer to the tower, aircraft on final approach are cleared to land once all other traffic is clear of the runway; conditions are the same as for departing aircraft [ICA01a]. Only in the United States, current procedures permit controllers to clear more than one arriving aircraft for landing if sufficient separation is anticipated [FAA04a].

To expedite traffic flow, a landing aircraft may be requested to hold short of an intersecting runway after landing (so-called LAHSO operations requiring dedicated authorisation), to land beyond the touchdown zone of the runway or to vacate the runway at a specified exit taxiway. When requesting a landing aircraft to perform a specific landing/roll-out manoeuvre or to expedite vacating the runway, the controller needs to consider the prevailing weather conditions, the type of aircraft, runway length and the reported braking action. However, if the pilot-in-command considers it impossible to comply with the requested operation, it can be rejected, provided that the controller is advised without delay.

Whenever a runway is in use for landing operations, no aircraft may enter the approach end of this runway for line-up whenever another aircraft is approaching, unless the landing aircraft has passed the point of intended holding [ICA01a].

2.1.2.2.3 *Handling of Vehicles*

As a general principle, no vehicles or pedestrians are allowed on the manoeuvring area without prior authorisation by the aerodrome control tower, and the entry to a runway or any deviation from the authorised operation requires explicit permission[19]. If an aircraft is landing or taking off, vehicles must either respect the currently applicable holding position or, if located elsewhere near the runway, maintain a separation at least equal to that of the runway holding position.
Although aircraft generally[20] have the right of way over vehicles and pedestrians [ICA01a, ICA04b], there are numerous cases where visibility restrictions and/or a lack of conspicuousness of either aircraft or vehicles has lead to the breakdown of visual traffic acquisition, and thus accidents and incidents, cf. Section 2.2.2.
Therefore, the number of vehicles permitted on the manoeuvring area should be strictly limited to vehicles essential from an operational point of view, such as

- ATS or aerodrome operational vehicles (e.g. runway inspection)
- emergency vehicles (e.g. fire fighters, rescue vehicles),
- aircraft tugs,
- follow-me cars, and
- runway maintenance vehicles (e.g. friction testing) or sweepers [ICA04a].

Depending on the season and region, however, there will also be an armada of snow clearing vehicles on taxiways and runways. At some airports, de-icing takes place close to the runway, and the corresponding vehicles are thus seasonally also allowed on the manoeuvring area. An additional aspect is that vehicles authorised to operate on the manoeuvring area must be expected to operate not only on taxiways, runways and dedicated vehicle roads, but also on unhardened areas like grass strips [Ber04].
Most airports feature a network of dedicated vehicle roads, which may also run through parts of the manoeuvring area. When authorised vehicles operate on these roads, they are typically not controlled by the tower. In Low Visibility Procedures, however, vehicle operation on certain roads may be restricted or suspended, depending on local arrangements [ICA04a].

2.1.2.3 Apron Management Service

ICAO defines Apron Management Service as a service providing apron instructions to regulate the activities and movement of traffic and any other vehicle operating on the apron (typically handling services). While the aerodrome control tower can be assigned to perform the Apron Management Service, it is quite common that it is performed by a separate unit. Depending on local arrangements, apron management can be solely performed by the local Air Navigation Service Provider (ANSP), the airport authority or joint operations, and sometimes even the airlines themselves. At Memphis Airport (KMEM), for example, the main airport users, Federal Express and Delta Airlines, provide apron management for their respective aprons.

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[19] Vehicles not equipped with two-way radio communication must either be accompanied by another vehicle with the required communication capabilities (e.g. a follow-me car), or there has to be a special pre-arranged procedure not requiring voice communication for these operations [ICA01a].

[20] Only emergency vehicles responding to an emergency have priority [ICA04b].

2.1.2.4 Low Visibility Procedures (LVP)

At aerodromes, Low Visibility Operations are conducted in conditions of visibility that prevent the control tower from applying visual separation between aircraft or between aircraft and vehicles [ICA01a].
Consequently, to ensure that these operations can be undertaken safely, additional measures are required. The special procedures defined to support these operations are known as Low Visibility Procedures (LVP) [ICA08]. These procedures are put in effect through the aerodrome control tower when the Runway Visual Range (RVR) decreases to a predetermined value, which is typically between 400 m and 600 m [ICA04a]. Additionally, LVP are required whenever CAT II/III precision approach and landing operations or departure operations in RVR conditions of less than 550 m are in progress[21]. Consequently, a key objective of LVP is to protect the physical area around the runway, including any landing system guidance signals that may be used during these operations [ICA01a, ICA08]. Therefore, Low Visibility Operations typically require specific additional markings and lighting, such as Stop Bars at runway access points and Runway Guard Lights, as specified in Annex 14, cf. [ICA04b].

Aerodromes must be certified for Low Visibility Operations. When designing LVP, a safety assessment must be carried out to ensure that the level of safety is maintained during these operations. In doing so, the probability of hazards such as Runway Incursions must be considered, taking into account the increased difficulty for aircraft and vehicles to navigate in low visibility [ICA08]. Generally, where LVP are in effect, persons and vehicles operating on an apron must be restricted to the essential minimum [ICA04b]. Due to the more demanding nature of Low Visibility Operations, additional measures are typically required to maintain the safety of operations. A common approach to achieve this is to restrict the operation of the aerodrome, e.g. by limiting the choice of taxi-routing or, additionally, number and type of movements. The predominating factor limiting the movement rate in approach and landing operations is that the previous aircraft must have vacated the landing system sensitive area, which is substantially larger than in CAT I. Particularly at aerodromes where traffic density is high, such restrictions will lead to a dramatic reduction of capacity while LVP operations are in force.

However, the precise measures required to establish LVP will significantly vary from aerodrome to aerodrome, depending on the physical layout, size and complexity, as well as on the availability and sophistication of surveillance technologies. Other factors include the characteristics of the aircraft using the aerodrome and the movement rate required. As a general principle, the necessity for restrictions can be reduced or removed by technological means [ICA01a, ICA08].
Visibility at an airport may be subject to considerable local variations, particularly in low visibility conditions. Consequently, even before the RVR drops below 550 m, the visual range may be significantly lower in other parts of the movement area. Furthermore, for aerodromes covering large areas, visibility may vary so much that different types of CAT operations could be applicable for different runways [ICA08].

[21] It should be noted that some aircraft operators employ Low Visibility Take-Off Procedures only when the RVR falls below 400 m. In any case, the departure runway does not have to be equipped for CAT II/III approach and landing [ICA08].

Last but not least, it should be noted that not only aerodromes, but also aircraft and flight crews need authorisation to conduct Low Visibility Operations. For aircraft, this mainly encompasses equipage with CAT II/III certified Instrument Landing System (ILS) technology, and crews are specifically trained for these approach types and low visibility operations on the ground.

2.1.3 Dissemination of Aeronautical Information

Airline operations take place in an environment that is subject to rapid change, with conditions varying on a daily basis, hourly or even more frequently. Obviously, weather has a major share in these operational variations, but the air traffic infrastructure itself is not static, either. To cope with these changes, all relevant aeronautical information, irrespective of whether it is distributed electronically or on paper, is updated every 28 days at fixed common dates agreed within the framework of Aeronautical Information Regulation and Control (AIRAC). Consequently, significant operational changes can only become effective at these previously fixed dates, and the corresponding information must be available at the airline (or any other recipient) at least 28 days in advance of the effective date. Furthermore, it is recommended that all major changes are distributed 56 days in advance.

However, it is not possible to cover all operationally relevant changes through this system. In the airport environment, for example, construction work to maintain installations, to refurbish traffic-worn pavements or to improve and expand the aerodrome often takes place in parallel to normal flight operations, because this is virtually the only way airport operators can handle current demand, keep the aerodrome serviceable and prepare for the expected increase in commercial air traffic. As a result, frequently changing temporary closures or restrictions of runways and taxiways are reality at many airports. To minimize impact on traffic throughput, both scheduled maintenance and urgent repairs are often carried out during night hours or whenever demand for flight operations is low. It is unrealistic to assume that all of this work can always be planned weeks ahead, since it might become necessary on very short notice (equipment failure etc.).

Consequently, all short-term and temporary changes[22] **not** persisting for the full 28 day period are explicitly excluded from the AIRAC distribution, and must be handled differently. The same applies to operationally relevant permanent changes occurring between AIRAC effective dates [ICA04].

2.1.3.1 Current handling of short-term and temporary changes

Today, information on short-term changes and temporary changes to infrastructure or operational procedures is typically conveyed by publication via the following services, depending on the timeframe of validity and the available ahead-warning time (shortest to longest):

[22] Short-term changes are alterations that occur between AIRAC effective dates; the changes may be either of temporary or permanent nature.

- **Air Traffic Control (ATC):** Short-term, tactical notification of the crew, either via conventional Radio Telephony (R/T) or Controller Pilot Data Link Communications (CPDLC), e.g. in case a runway is closed because of snow clearing activities, urgent repairs, accidents etc. This service is commonly used to relate information on changes immediately after they have occurred, i.e. when pilots have no other way of knowing.
- **Automatic Terminal Information Service (ATIS)**: Continuous service providing information on the operational status of an aerodrome, such as the runways currently in use for take-off and landing, and prevailing meteorological conditions. ATIS service, which is updated whenever significant changes occur, can either be provided as a pre-recorded voice transmission on a dedicated frequency, via data link (D-ATIS), or both. ATIS may also contain information on runway closures and other important restrictions of the aerodrome movement area[23], see Section 3.4.2 for details.
- **Notices to Airmen (NOTAM)[24]:** Notification of all relevant short-term changes (temporary or permanent), typically as Pre-flight Information Bulletin (PIB) during the pre-flight briefing [ICA04]. Unless they relate to equipment failures and other unforeseen events, NOTAM are typically released several hours before the changes they announce become effective. Information conveyed by NOTAM may be valid for several hours, days or weeks, and is thus mainly used at a strategic level.
- **Aeronautical Information Publication (AIP) Supplements:** temporary changes of longer duration (3 months and beyond), e.g. runway closure for several months due to pavement replacement.

If temporary changes are valid for three months or longer, they are published as an AIP Supplement. Alternatively, in case extensive text and/or graphics is required to describe information with shorter validity, this will also require an AIP Supplement. AIP supplements often replace NOTAMs and then reference the corresponding serial number of the NOTAM [ICA04].

The information from the services above, the first three of which are routinely directly available to flight crews, is complementary and partially redundant, since e.g. runway closure information might be reported by all of the services listed above. NOTAM information, however, forms the strategic baseline for flight planning, flight preparation and decision making, and therefore deserves special attention.
With the exception of some AIP Supplements, all of these services provide textual (or, in the case of ATC, verbal) information only.

[23] In this context, it should be noted that D-ATIS as defined by ICAO Doc 9705 already contains machine-readable information on the runways in use and potential runway contaminations, whereas closure information is still provided via the free-text section of the transmission only. Furthermore, it should be noted that runway closure information is optional, not mandatory content of ATIS transmissions, irrespective of whether voice or data link are used.

[24] According to ICAO Annex 15, NOTAM should preferably be distributed by means of telecommunications, but a list of all valid NOTAM in plain text must be provided in print on a monthly basis. NOTAM transmitted via telecommunications are usually referred to as Class I, whereas those distributed in print are Class II.

2.1.3.2 Aerodrome Charts

To facilitate surface movement of aircraft, flight crews must be provided with Aerodrome Charts, which also have to provide essential operational information on the airport. ICAO Annex 4, Aeronautical Charts, gives guidance on the contents of Aerodrome Charts, which have to depict, among others,

- all runways including those under construction with designation number, dimensions, directions, type of surface and markings;
- all taxiways with designations, width, lighting, markings, including runway-holding positions and stop bars or other visual guidance and control aids;
- all aprons with aircraft stands, lighting, markings and other visual guidance and control aids, including location and type of visual docking guidance systems;
- aircraft servicing areas and buildings of operational significance;
- location and type of the visual approach slope indicator systems;
- radio communication facilities;
- the boundaries of the air traffic control service;
- obstacles to taxiing; and
- any part of the depicted movement area permanently unsuitable for aircraft.

Additionally, the coordinates of the aerodrome reference point as well as the elevations of all precision approach runway thresholds and touchdown zones have to be supplied.

Where, due to congestion of information, details necessary for surface movement along taxiways and between taxiways and aircraft stands cannot be shown with sufficient clarity on the Aerodrome Chart, a supplementary Aerodrome Ground Movement Chart with a larger scale is required to support aircraft movement to and from the aircraft stands, including the parking/docking process.

For airports where, due to the complexity of the terminal facilities, this still does not provide sufficient detail for aircraft parking and docking operations, an additional Aircraft Parking/ Docking Chart providing additional detail has to be supplied [ICA01e].

The main commercial providers of aeronautical charts with worldwide activities are Jeppesen Sanderson and Lufthansa FlightNav.

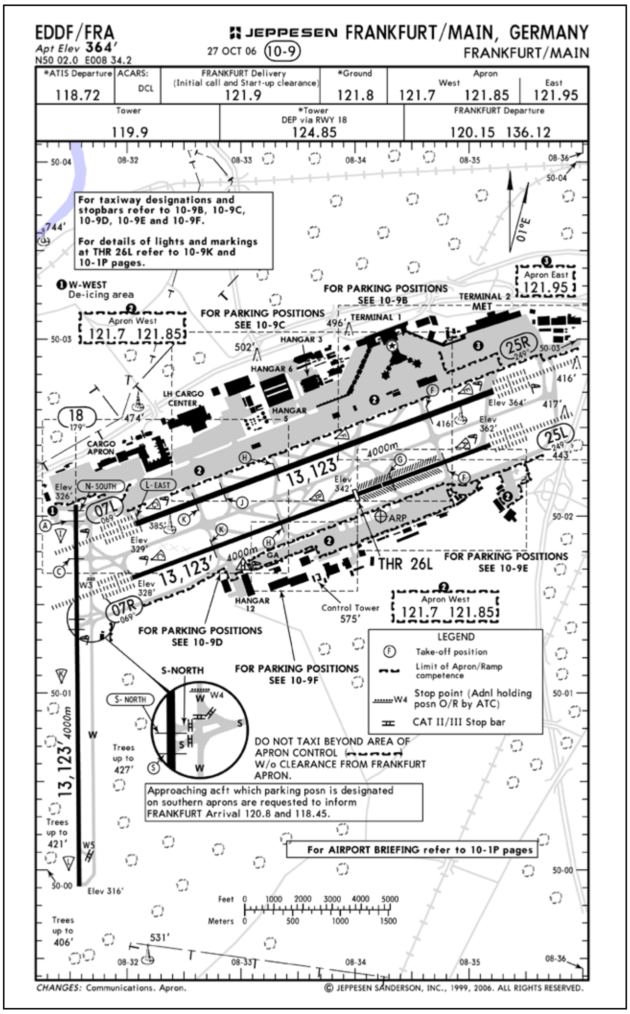


Figure 6: Sample Aerodrome Chart of Frankfurt/Main Airport (EDDF) by Jeppesen

2.2 Analysis of Runway Incursion Incidents and Accidents

2.2.1 Classification of Surface Movement Incidents and Accidents

This section surveys existing classification schemes for surface movement incidents and accidents, focussing on Runway Incursions. The objective of this analysis is to assess whether and to what extent these classifications provide additional insight into common causal factors and the mechanisms leading to mishaps. This is based on the assumption that any useful categorization requires an at least basic understanding of a problem and its scope, and may thus serve as a starting point for a solution, or at least help to identify the domains where improvement is most urgently needed.

2.2.1.1 Classification by Stakeholder

The FAA suggests to divide Runway Incursions into three "error types", resulting in the categories "Operational Errors/Deviations" (i.e. ATC errors), "Pilot Deviations" and "Vehicle/Pedestrian Deviations" [FAA01]. This classification has its origin in the FAA's incident reporting requirements. Until 1986, the FAA did not study Runway Incursions systematically, since there was no corresponding common database; incident reports were, accordingly, either categorized as operational error reports, controller deviation reports or Near Mid-Air Collision (NMAC) reports [NTS86][25].

Between 2000 and 2003, 57% of all Runway Incursions in the US were classified as pilot deviations, whereas only 23% were attributed to operational errors/deviations [FAA04]. For the percentage of pilot deviations, there was only a slight change to 55% within the FY 2004 to FY 2007 period, whereas the fraction of ATC errors rose to 29% [FAA08][26]. Based on this data, one might be tempted to conclude that the majority of Runway Incursions is caused by pilots and vehicle operators. ATC errors, by contrast, seem to play only a minor role, although they appear to be on the rise, while the share of incursions due to vehicle/pedestrian deviations has been reduced.

The only further subdivision the FAA provide in statistics based on this classification is by type of operation, commercial or general aviation[27]. However, categories such as "*Runway Incursion Types Involving at Least One Commercial Aircraft*" in the FAA's Runway Safety Reports (cf. e.g. [FAA02]) are of little more than taxonomic value, because there is no distinction to what extent the commercial aircraft, the general aviation aircraft, the controller or the interactions between these three contributed to the Runway Incursion, which is important to know for an identification of structural or system-immanent problems and a subsequent development of countermeasures.

[25] The NTSB found that human performance aspects were not covered by the operational error reports, and that pilot deviation reports often relied, contrary to FAA requirements, on informal counselling [NTS86].

[26] It should be noted that the underlying data cover both general aviation and commercial aviation operations at towered airports.

[27] While commercial aviation operations form a relatively uniform group, consisting of jet and commuter aircraft scheduled or chartered for the transport of passengers and cargo flown by individuals with at least a Commercial Pilot License (CPL), general aviation operations represent a very inhomogeneous group, as they encompass all activities from leisure flying with a single-engined propeller aircraft to business travel with highly sophisticated jet aircraft, often adaptations of airliners. The level of education and professionalism of the pilots involved can vary on an equally large scale. Conversely, aircraft typically intended for General Aviation use may be operated commercially as well [FAA04].

These considerations indicate that a classification of Runway Incursions according to the FAA's scheme is not necessarily an indication of the actual causes, and might only be of limited use when it comes to their identification.
First of all, the categorization by error type typically refers to the last event in a chain of controller, pilot, and/or vehicle operator actions that eventually led to the Runway Incursion, cf. [FAA04]. Aviation incidents and accidents, however, usually have no single cause, but result from a combination of several technical and/or procedural errors, often in conjunction with deviations from Standard Operating Procedures (SOP)[28]. Further complexity is added by the fact that causal factors are often not isolated, but may have an interdependence of some kind, like e.g. visibility and situational awareness. There are, however, several generic incident/accident models in the literature, which can be employed after some adaptation.

One of the most famous of these generic accident models is the so-called "Swiss Cheese" model described by Reason [Rea90, Rea00], cf. Figure 7. A number of safety barriers, which can be either technical, procedural or organisational, offer protection against a hazard, e.g. of a Runway Incursion. However, these barriers are not perfect, but have occasional holes, like a Swiss Cheese. Reason imagined, however, that unlike in a real cheese, these holes are not stationary, but rather opening, shutting and shifting location permanently. As a result, the presence of a hole in any one of the barriers, or even successive barriers, does not present an issue. An incident/accident can only occur when the holes are momentarily arranged in such a fashion that **all** of the safety barriers simultaneously fail, permitting a so-called "trajectory of opportunity" to pass through [Rea00]. In a way, therefore, Reason's model is a visualisation of the term "unfortunate sequence of events".
Causal factors can be seen as holes in the safety barriers in this model, thus increasing the probability that a particular barrier fails. Of course, certain causal factors could influence more than one barrier.

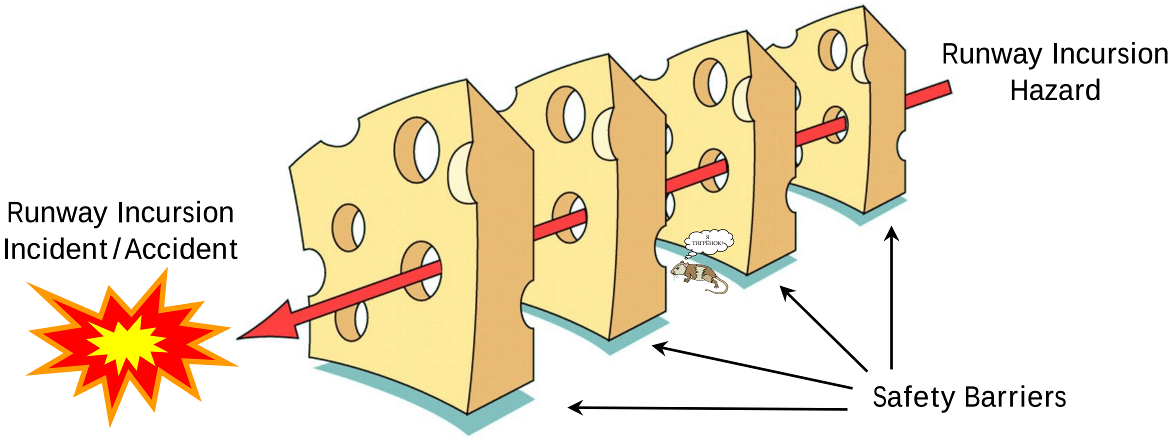


Figure 7: Swiss Cheese accident model (after [Rea90, Rea00])

[28] As an example, aircraft can be dispatched without certain equipment due to malfunctions, which is, on the one hand perfectly within the limits prescribed by the Minimum Equipment List (MEL), but might on the other hand require special attention and altered procedures from the crew. Likewise, shutting down and re-starting the engines at a de-icing station causes additional workload for the crew. These non-standard situations may divert the crew's attention and thus increase the risk of oversight and errors.

Since only the last element is considered, the combination of events leading to a Runway Incursion is not reflected by the FAA classification, not even within the flight crew, vehicle driver or controller domain. It is therefore poorly suited to model the complex interactions between controllers, pilots and other stakeholders in surface operations. As early as 1986, accordingly, the National Transportation Safety Board (NTSB) expressed its concern that 26 Runway Incursion incidents and accidents classified by the FAA as either "pilot-induced" or "controller-induced" actually involved combinations of pilot and controller factors [NTS86].

The most serious limitation of the FAA classification scheme, which was temporarily also adopted by Transport Canada and Eurocontrol, however, is that it limits itself to assigning "human error" to different types of individual operators, rather than giving an indication **why** the corresponding deviation from an ATC instruction or another type of error occurred, and what the effects of interaction between the stakeholders were in this process.
Consequently, there is a significant risk that potential systemic issues underlying "human errors" such as a pilot deviation are masked by the FAA classification, and that the true reasons for the incursion remain in the darkness. This inadequacy to determine causes and to derive requirements for potential solutions, in turn, might prevent the development of efficient countermeasures, or even lead to fallacious, superficial "solutions".

Although surface movement incidents and accidents outside the runway have a large commercial impact, there do not seem to be any coordinated initiatives specifically dealing with taxiway or apron incidents and accidents so far. Consequently, there are neither internationally harmonized definitions nor classifications. A mere subdivision into "runway incursions" and "non-runway-incursions" as proposed by the first FAA Runway Safety Report [FAA01] is not sufficient.

2.2.1.2 Classification by Severity

Runway Incursions can also be classified by the severity of individual incidents, which, in turn, raises the question of suitable metrics.
Commonly, the severity of Runway Incursions is assigned in proportion to the risk of an accident. This is based on the assumption that the structural, system-inherent causes of Runway Incursions are best reflected by, or are more apparent in, accidents and serious incidents, while they might be masked by sporadic errors and general "noise" in minor incidents. The deficiencies thus identified could then be used to deduce design criteria and guidelines for a solution intended to avoid Runway Incursions. This purely descriptive approach, would, in other words, use the intensity of the symptoms to determine severity.
When dealing with incursions involving traffic conflicts, various external parameters such as speed, separation, visibility and the level of remedial action that was taken to avoid an accident could be used to calculate the potential of an accident.

Since there can be a significant accident hazard even without the presence of another aircraft or vehicle, e.g. if the flight crew uses a closed or otherwise unsuitable runway, one could look at the chain of events as an alternative, and determine incursion severity by the number and interdependence of operational errors, equipment failures and ineffective safety mechanisms that caused the incident. This more analytic approach would yield a theoretical potential for a hazardous or catastrophic event. Clearly, this potential is higher if a pilot error remains undetected by a controller, in comparison to a situation where both parties are aware of the mishap and can take remedial action.

With its first Runway Safety Report in 2001, the FAA introduced new metrics to assess the severity of Runway Incursions. Five key parameters were selected to assess the relative severity of Runway Incursions and to determine the margin of safety associated with each event [FAA01]:

- **Available Reaction Time:** considers how much time pilots, controllers and/or vehicle operators had to react to the situation based on aircraft type, phase of flight and separation distance
- **Evasive or Corrective Action:** considers the need for and the type of evasive or corrective manoeuvre required to avoid a collision.
- **Environmental Conditions:** considers visibility, surface conditions and light conditions (e.g. night/day).
- **Speed of Aircraft and/or Vehicle:** considers speed as a function of aircraft type and phase of flight (taxi, take-off, landing)
- **Proximity of Aircraft and/or Vehicle:** considers the proximity, or the separation distance from one another.

Over the years, additional factors to be considered were apparently added to this original severity categorization [FAA04]:

- **Location of aircraft:** considers whether aircraft or vehicle were on the runway itself or on a taxiway inside the runway holding position markings
- **Knowledge of the other party's location**
- **Status of radio communications**

Using these parameters, the FAA suggests four categories of severity, labelled A to D, ranging from near collisions or accidents to minor incidents. Categories A and B represent major Runway Incursions with a significant collision risk, while categories C and D contain minor incursions with little or no danger of collision. An official description of these categories follows below [FAA05]:

Category D	Category C	Category B	Category A
Little or no chance of collision, but meets the definition of a Runway Incursion	Separation decreases, but there is ample time and distance to avoid a potential collision	Separation decreases and there is a significant potential for collision	Separation decreases and participants take extreme action to narrowly avoid a collision, or the event results in a collision

Table 1: Runway Incursion Severity Categories [FAA05]

However, the collision risk is the ultimate consequence of a Runway Incursion, not the cause, and thus not suitable as sole metrics for severity, as it would filter all events not involving the presence of a second aircraft.
Since FY 2008, a slightly modified variant of the FAA safety classification is effective. Category A is now supplemented by an additional "accident" category. Category B is largely unchanged, while the new category C now encompasses all incidents previously rated as either C or D. The new severity category D encompasses all incursions involving only one movement, with "*no immediate safety consequences*" according to the FAA [FAA08]. Nonetheless, the accidents at Taipei and Lexington, prove that safety may very well be compromised even if there is no risk of colliding with another aircraft, vehicle or person.
Another criticism concerning the FAA classification scheme is that the severity categories above leave the individuals classifying the incidents some room for interpretation. While a tool for calculating the severity category from a set of spatial proximity and visibility parameters, supplemented by a number of discrete scenarios and error types, has been developed and validated [She04], an important missing step in this approach is the transition from estimates to data directly extractable from the Flight Data Recorder (FDR). On the other hand, a post-hoc severity classification of Runway Incursions cannot solely rely on the availability of FDR data, which may not have been downloaded at the time.

2.2.1.3 Conclusion on Existing Classification Schemes

In conclusion, the existing classification schemes do not provide much insight into Runway Incursion causal factors, and thus cannot be used to derive guidelines for the development of future Runway Incursion avoidance functionality or the allocation of its components between air and ground.

To obtain this insight, the complete chain of events leading to an incident or accident has to be analysed, focusing on factors contributing to what seem to be, in hindsight, procedural deviations and errors. It is therefore necessary to analyse individual incidents and accidents in detail, see Section 2.2.2.

Although the FAA classification of incursions according to stakeholder oversimplifies the situation, the finding that "Pilot Deviations" apparently account for more than half of all Runway Incursions provides further evidence that it is particularly worthwhile to investigate flight deck-related causal factors in Runway Incursions. Accordingly, the interdependency of these factors with aircraft equipment and flight training aspects, such as Crew Resource Management (CRM), must be considered. Last but not least, operating procedures themselves have to be scrutinized for systemic errors.

Notwithstanding the above, the analysis in this section has also clearly shown that, in developing a solution, it may not be sufficient to support the stakeholders involved in surface movement within their respective domains, but that additional measures to improve the interaction between these stakeholders might be required as well.

2.2.2 Analysis of Selected Incidents and Accidents

2.2.2.1 Principles of Incident & Accident Investigation

The main paradigm of aviation safety research is that a thorough analysis of accidents and incidents will help to reveal the underlying causes and contributing factors, thus giving indications where improvement is necessary to avoid similar occurrences in the future. Accordingly, ICAO Annex 13, "*Aircraft Accident and Incident Investigation*", states that the sole objective of an accident or incident investigation is the prevention of further accidents and incidents, not a determination of blame or liability [ICA01b]. In fact, any judicial or administrative proceedings to that extent should be conducted completely separately from the investigation under the provisions of Annex 13. This is intended to ensure that a non-punitive environment is maintained throughout the investigation to ensure full cooperation of the individuals involved, without fear that the information they relate may be used for subsequent disciplinary, civil, administrative or criminal proceedings. As a result, since limited access to relevant information on account of potential judicial activity impedes the investigation process and might even prevent an efficient determination of the causes, with serious impact on flight safety, accident and incident investigation is given priority[29].

Another principle of Annex 13 is to carry out investigation with all key stakeholders involved to ensure an optimum flow of information between them. While the state where the accident or incident occurred (State of Occurrence) usually conducts the investigation[30], the state in which the aircraft was registered (State of Registry), the State of the Operator, the State of Design and the State of Manufacture may appoint accredited representatives to the investigation commission. Furthermore, the key stakeholders are required to provide all relevant information available on aircraft and flight crew involved in the accident or serious incident to the State of Occurrence. Besides, the involvement of aircraft designers and manufacturers eventually ensures an optimum dissemination of the investigation findings, particularly if they are related to technical failure. Likewise, the institution concerned with the investigation may issue safety recommendations to airlines, manufacturers or other aviation authorities if the findings point towards structural or organizational deficiencies in aviation that are of general interest.
The generalisation of investigation findings beyond the local context of the individual event, in which they are unquestionably valid, is another important paradigm, because there is no formal system-theoretical approach proving that the analysis of aviation accidents and incidents is a suitable means of **systematically** identifying structural deficiencies in aviation, or that these general deficiencies should become especially evident in serious incidents and accidents. Since aviation accidents and severe incidents are fortunately very rare events, with only few occurrences per million flight operations, it is also very difficult to employ statistics to validate the general significance of investigation findings. Nonetheless, this generalisation is reason-

[29] Unfortunately, though, this principle is not universally applied by all ICAO member states.

[30] The State of Occurrence is responsible for instituting and conducting the investigation, but may partially or even completely delegate the investigation to another ICAO state by mutual agreement and consent. As an example, the read-out of flight recorders is often delegated to authorities of another state if the state in charge of the investigation does not have the appropriate facilities.

able and commonly accepted particularly when it comes to technical defects. If, for example, structural fatigue of a certain aircraft component is identified as causal factor in an accident, an inspection of this component in other aircraft of the same type is often ordered as a precautionary measure by the authorities and/or the manufacturer. It should be noted, however, that this strategy is ultimately only able to prevent copycat occurrences of an incident/accident, whereas further effort is required to characterize the superordinate problem, such as hitherto unknown effects in material science, manufacturing or maintenance issues.

2.2.2.2 Human Factors in the Investigation Process

Nonetheless, the brief initial survey of Runway Incursion incidents and accidents conducted in Chapter 1 as well as the review of the high-level literature such as the FAA Runway Safety Reports leads to the initial hypothesis that Runway Incursions are virtually never the result of technical problems or structural failures, but always result from inadequate application of safety procedures or erroneous decisions taken by the flight deck, the tower or by airport personnel (e.g. vehicle drivers). In either case, it is assumed that Human Factors aspects play a key role. In the Human Factors domain, however, a generalisation, let alone an identification of higher level deficiencies, is even more difficult to achieve than in the field of technology. In fact, the validity of Human Factors conclusions drawn from the current investigation process has been challenged, e.g. by Dekker [Dek06], because there is substantial evidence that outcome knowledge affects the perceived relevance and judgement of factual information; this general psychological phenomenon is called "hindsight bias" [Fis75], and it was found that its intensity increases with the complexity of the scenario studied [Pen81].

In aviation incident/accident investigation, meticulous, in-depth scrutiny of factual evidence is required to identify the probable cause. This typically encompasses both technical aspects and human performance. However, when analysing crew behaviour, investigators commonly have several weeks or months to assess potential alternative courses of crew action that might have helped to realise a problem and to prevent an incident/accident, whereas the flight crew actually had to make their decisions within seconds or minutes. This additional temporal dimension further increases the innate vulnerability of the investigation process to confirmation bias.

Ultimately, this may lead to an inadequate, biased conclusion, because investigators usually attempt to determine a crew behaviour that would – in hindsight – have prevented the accident, and then identify deviations from this ideal course of action as "human error" in the actual sequence of the flight crew's actions and decisions, instead of explaining why certain decisions were eventually taken by the crew, i.e. why they seemed reasonable from the flight crew's perspective at the time (this is often referred to as local rationality). However, only the latter can help to identify the deceptions, misperceptions or lack of information that led to the – in hindsight – erroneous decisions/actions, whereas the first approach gives rise to the common misbelief that further automation is the panacea to eliminate human error from aviation.

In identifying, understanding and classifying Human Factors issues in aviation incidents or accidents, a number of concepts from behavioural science and cognitive psychology, such as situational awareness, cognitive fixation or confirmation bias/ plan continuation, have proven to be particularly helpful.

The most famous and most important of these is clearly situational awareness. While there are myriads of definitions for situational awareness and the term has been criticized as "*the buzzword of the 90s*", cf. [Wie93], Endsley's somewhat abstract definition of situational awareness as "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*" [End95] is most commonly used today.

However, employing this generic definition of situational awareness in an aviation context leads to difficulties, mainly because it is undefined which of the elements in the environment are relevant for the flight task at hand.
This elusiveness of the basic term 'situational awareness' is perhaps best characterised by the fact that it is virtually never used by itself, but always in conjunction with additional explanatory attributes. Accordingly, Endsley claims that "*maintaining a high level of situation awareness*" is critical for "*achieving successful performance in aviation*" [End99]. Conversely, in the context of incidents and accidents, frequent reference is made to 'a lack of situational awareness' or even "*a loss of situation awareness*" (e.g. in [NTS07]).

In line with these considerations, Endsley states that in an aviation context, situational awareness can be regarded as "*internalized mental model of the current state of the flight environment*", which forms the basis for all decisions and actions. In aviation, therefore, situational awareness is related to the perception of "*critical factors*" and comprehending what they mean "*in relation to the flight crew's goals*" [End99]. This constitutes a significant extension of the original definition, because it implies that the task at hand defines the critical elements in the environment to be perceived and comprehended. Consequently, situational awareness is meaningful only in the specific context of a certain task or goal.
In this context, it should be noted that the frequently used term 'loss of situational awareness' is misleading and should not be used, cf. [Dek06], since an individual can only lose situational awareness by becoming unconscious or incapacitated in a similar manner. Even the realisation that one is 'lost' implies a certain level of situational awareness. In fact, while situational awareness may be inadequate to achieve certain task, a correct self-assessment of one's level of situational awareness implies a higher degree of situational awareness than an unrecognized, unreflected erroneous perception and mental model of the environment.
With regard to the interrelation of situational awareness and mental model, most of current literature suggests a significantly more intricate interdependency than the simple equivalence claimed by Endsley, cf. [BR04], but a more detailed discussion is beyond the scope of this thesis. Additionally, the precise interrelation is highly dependent on the nature of the task, particularly on the dynamics and the degree to which the long-term memory is involved. Consequently, there will be differences between an airport navigation and a traffic surveillance task.

With these clarifications, situational awareness is an extremely powerful concept to characterise a flight crew's perception and understanding of their situation, including the resulting mindset. In this thesis, the following conventions have been adopted: 'adequate situational awareness' is always used in the meaning of having (an) adequate (level of) situational awareness for the flight task at hand (including a correct self-assessment of one's level of situational awareness); a 'lack of situational awareness' will be used to characterise an inadequate level of situational awareness (and inadequate self-assessment). Furthermore, e.g. 'situational awareness with respect to position' will be abbreviated as 'position awareness'. Furthermore, a term like 'lack of situational awareness' is used in a purely factual sense in this thesis and does not imply blame, i.e. the term is not used as a synonym for 'pilot error'.

Cognitive fixation refers to an unbalanced diversion of attentional resources to a certain task, resulting in a lack of attention to other and potentially more pertinent tasks. Confirmation bias is a tendency to interpret and to obtain information in such a fashion that it confirms an existing preoccupation or hypothesis, and to systematically overlook or neglect any evidence providing contradictory indications. In other words, the mind tries to fit new or additional information into the current concept, rather than scrutinizing the concept itself. Essentially, a flight crew subject to confirmation bias might subconsciously only search for information that confirms their present understanding of the situation. There is evidence that this phenomenon is caused by emotional constraints on rational thinking[31].

2.2.2.3 Overview of Incidents and Accidents Analysed

As outlined previously, it is essential to analyse individual incidents and accidents to obtain insight into Runway Incursion causal factors with the goal of determining general, recurring patterns. Aside from the severity-of-symptoms aspects outlined above, it must be noted that typically only accident reports and some incident reports provide sufficient detail on the sequence of events and the prevailing conditions to enable a meaningful post-hoc analysis on Human Factors and flight deck instrumentation aspects; this finding is also confirmed by ref. [EEC04]. In contrast to accident investigation, where flight data recorder (FDR) and cockpit voice recorder (CVR) data are typically one of the main sources of information for investigators, the corresponding data are frequently not even secured for analysis of severe incidents, cf. [BFU09], which limits the reconstruction of events in the cockpit to the flight crew's recollection.

Starting with the Tenerife accident, an analysis of all major fatal Runway Incursion accidents within the last 30 years involving airline aircraft was performed in the frame of this thesis, with focus on Europe and North America. In addition, a number of noteworthy incidents were also covered by this analysis; these were mainly selected based on the availability of suitably detailed investigation reports allowing a thorough analysis of the sequence of events and causal factors.

[31] Recent neurophysiologic studies have shown, albeit for the field of politics, that confirmation bias and related phenomena can be attributed to activity in brain areas predominantly responsible for emotion, whereas domains associated with analytical thinking remain inactive [WBH06].

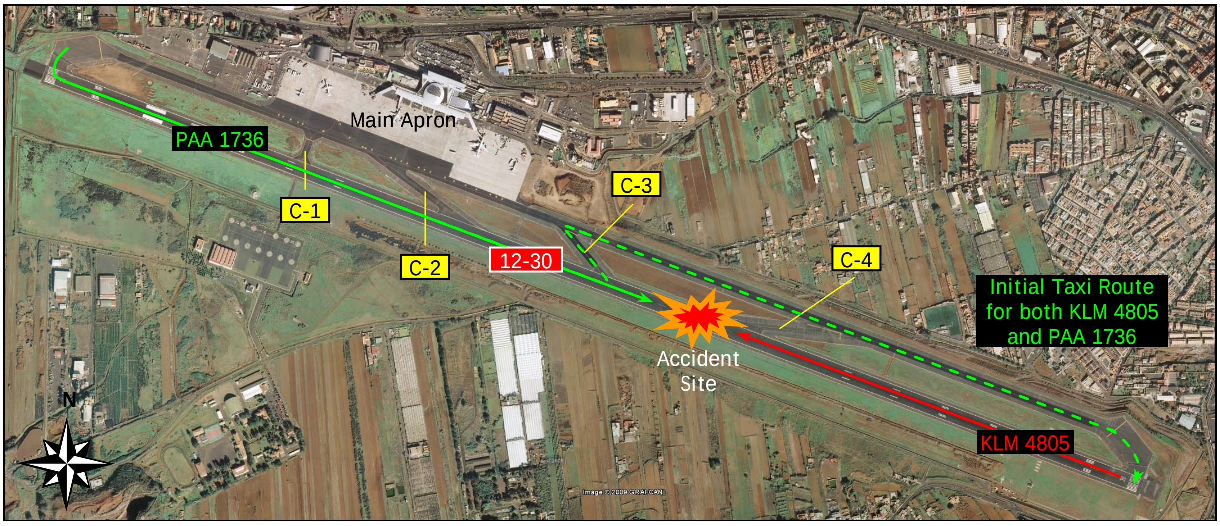


Figure 8: Runway Incursion accident at Tenerife's Los Rodeos Airport (1977)

Table 2 provides a synopsis and an overview of the key findings for the 24 selected Runway Incursion incidents (grey background) and accidents (beige background) that form the backbone for the determination of causal factors within this thesis. In the table, causal factors are in **bold face**, whereas important contributing factors are underlined.

A more detailed analysis of these occurrences can be found in Appendix I, where the sequence of events is briefly presented for each accident[32], strictly following the official reports[33]. By contrast, the corresponding analysis and probable cause part provides a summary and critical review of the investigation results, focussing on Human Factors aspects. This is supplemented by a conclusion on flight deck instrumentation aspects for each accident.

In total, investigation reports on 40 incidents and accidents in the 1977 – 2007 period were reviewed. For six incidents, however, the data available did not contain sufficient detail for an unambiguous analysis of causal factors. These are briefly surveyed in Appendix I-17, along with several incidents that bore so many similarities with others already presented in detail that providing an exhaustive description of those would have been of little additional value. Furthermore, one incident was analysed solely on the basis of a personal account, and is therefore not part of Table 2, either.

32 The only accident that is not discussed in detail in Appendix I is the 1990 runway collision at Atlanta-Hartsfield International Airport [NTS91b], because the scenario is very similar to the Los Angeles accident, which was far more severe in terms of fatalities and therefore selected for detailed presentation.

33 The structure of this presentation is similar to that of an accident report, which typically also contains a presentation of the sequence of events, an analysis of the gathered facts and the determination of the probable cause as individual chapters in this order.

Date	Location	Aircraft #1	Aircraft #2	†	Meteoro-logical Conditions	Description, Causal and Contributory Factors
27.03.1977	Los Rodeos Airport (GCXO) Tenerife	KLM B747-200 PH-BUF KLM 4805	PanAm B747-100 N736PA PAA 1736	583	Daytime IMC Fog and low clouds	During take-off in dense fog, the KLM Boeing 747 collided with the PanAm aircraft, which was still back-tracking RWY 30 (cf. Figure 8) because all taxiways were crammed with other aircraft after a mass-diversion [ICA80]. ❖ The KLM crew was not aware that PanAm was still on the runway (**Lack of Traffic Awareness**). ❖ The KLM captain commenced take-off erroneously believing he had the appropriate clearance (Issue with **ATC Instructions/Clearances**). ❖ There was a misunderstanding as to whether ATC clearance included T/O clearance or not. R/T communication impaired by squeal (**Communication Issue**).
07.12.1983	Madrid Barajas Airport (LEMB)	Iberia Boeing 727 EC-CFJ IB350	Aviaco DC-9 EC-CGS Flight 134	93	Daytime IMC Fog	During its take-off run on RWY 01, the Iberia Boeing 727 collided with the Aviaco DC-9 which had inadvertently taxied onto the runway in dense fog [CIA84]. ❖ In visibilities partially as low as 20...30 m, the Aviaco flight crew did not make a sufficiently strong right turn at a complex intersection, thus ending up on a taxiway leading them straight onto the runway (**Disorientation**). ❖ The taxiway guidance line associated with the correct turn had not been repainted and was thus hardly discernible on the wet pavement (**Inadequate Airport Markings**). ❖ Communication between the Aviaco flight crew and ATC was minimalist, and the pilots failed to share their concerns regarding their location with ATC (**Communication Issue**).
19.12.1983	Anchorage International Airport (PANC) Alaska	Japan Airlines B747-200F J8151	**Vehicle** Pickup Truck	–	Night IMC	The Japan Airlines Boeing 747 collided with a pick-up truck while landing on RWY 6R [NTS84]. ❖ The local controller could not recall whether or not he had acknowledged the ground controller's request to cross the pick-up truck (**Controller Error**). ❖ With the RVR in the order of 600...800 ft and the nose gear still in the air when the collision occurred, the flight crew could not visually acquire the vehicle (<u>Lack of Traffic Awareness</u>).
20.12.1983	Sioux Falls Airport (KFSD) South Dakota	Ozark Air Lines DC-9	**Vehicle** Snow Sweeper	1	Daytime IMC Blowing Snow	The Ozark Air Lines DC-9 struck a snow sweeper while landing on RWY 03 [NTS85]. ❖ The controller did not advise the flight crew of the ongoing snow removal operations when clearing the flight to land (**Controller Error**). ❖ Since the snow sweeper truck was shrouded in the snow raised by its operation, the flight crew could not visually acquire the vehicle (<u>Lack of Traffic Awareness</u>). ❖ Due to the blowing snow reported by the ATIS and the absence of any information on the ongoing snow removal, the flight crew mistook what they perceived as weather phenomenon (<u>Inadequate Information on Operational Environment</u>).

Table 2: Overview of analysed Runway Incursion incidents and accidents

Date	Location	Aircraft #1	Aircraft #2	†	Meteorological Conditions	Description, Causal and Contributory Factors
23.12.1983	Anchorage International Airport (PANC) Alaska	Korean DC-10 HL7339 KAL 084	Southcentral Piper PA-31 N35206 SCA 59	–	Daytime IMC Fog	While erroneously attempting to take off from RWY 24R in prevailing fog, the Korean DC-10 collided head-on with the Piper, which was lined up and waiting for its take-off clearance on RWY 6L [NTS85]. ❖ In the fog and with the airport surface covered by snow, ice and frost, most airport markings were illegible. Additionally, airport signage was inadequate, and therefore the flight crew of KAL 084 essentially operated without external information to assist them while taxiing. They eventually ended up on an intersection of RWY 24R instead of RWY 32 (**Disorientation, Inadequate Airport Signage**). ❖ The captain of the DC-10 decided to take off although he was uncertain whether he was on the correct runway, and failed to realise that the aircraft heading was inconsistent with RWY 32, the runway chosen. The segment of RWY 24R ahead of the DC-10 was too short for a successful take-off.
31.03.1985	Minneapolis St. Paul International Airport (KMSP)	Northwest DC-10 NW 51	Northwest DC-10 NW 65	–	Night VMC	By performing an early rotation, the captain of NWA 51 narrowly averted a collision with the other DC-10, which was crossing RWY 29L while NWA 51 was taking off [NTS86]. ❖ Due to a breakdown of controller coordination (**Communication Issue**), NWA 51 was cleared for take-off by the local controller while the ground controller had instructed NWA 65 to cross RWY 29L, with this crossing yet to take place (**Controller Error**). ❖ Both controllers failed to recognize the hazardous situation in time to take corrective action (**Controller Error**).
18.01.1990	Atlanta-Hartsfield International Airport (KATL)	Eastern Boeing 727 N8867E Flight 111	Beechcraft King Air A100 N44UE	1	Night IMC	While landing on RWY 26R, the Boeing 727 struck the Beechcraft King Air, which had landed shortly before and was turning off the runway [NTS91b]. ❖ The local controller, probably distracted by addressing communication difficulties with a third aircraft, failed to ensure separation of the two aircraft arriving to RWY 26R (**Controller Error**). ❖ The local controller failed to issue the required preceding traffic information to EA 111 along with the landing clearance, thereby depriving the flight crew of a stimulus to visually search for the preceding traffic and of knowledge of the slower approach speed of N44UE (**Controller Error**). ❖ In the prevailing visibility conditions, with some of the King Air's anti-collision lights inoperative, the Eastern Airlines pilots had no chance of seeing the other aircraft in time (<u>Lack of Traffic Awareness</u>).
03.12.1990	Detroit Metropolitan Wayne County Airport (KDTW)	Northwest DC-9 NWA 1482	Northwest B-727 NWA 299	8	Daytime IMC Fog	The Boeing 727 was on its take-off roll on RWY 3C, when it collided with the DC-9 which had inadvertently entered the same runway in dense fog [NTS91]. ❖ The DC-9's pilots became increasingly disoriented in the fog and failed, partially due to a reversal of crew roles, to follow both the initially assigned taxi route as well as the updated taxi instructions, and did not notify ATC when they noticed that they had taxied onto a runway (**Disorientation, Crew Resource Management, Communication Issue**). ❖ The controller's updated route led an already disoriented crew through one of the most complex intersections at the airport, which was inadequately signed (**Inadequate Airport Signage**). ❖ The pilots of the Boeing 727 were not aware that the DC-9 had taxied onto the runway and, due to the deteriorating visibility, had no chance of visually acquiring the other aircraft until it was too late (**Lack of Traffic Awareness**). Given that the visibility was visibly lower than the required (and reported) ¼ mile (400 m), the Boeing 727 should not have taken off (<u>Poor Decision Making</u>).

Date	Location	Aircraft #1	Aircraft #2	†	Meteorological Conditions	Description, Causal and Contributory Factors
01.02.1991	Los Angeles International Airport (KLAX)	USAir B737-300 N388US USA 1493	Skywest Metroliner N683AV SKW 5569	34	Night VMC	While landing on RWY 24L, the Boeing 737 collided with the Metroliner, which was lined up and waiting for the take-off clearance at an intersection some 500 m down the runway [NTS91a]. ❖ Apparently, the local controller, potentially distracted by non-routine communication (accidental departure from frequency) with a Wings West flight, eventually confused the Skywest flight with a further Wings West flight still holding short of the runway, and thus believed RWY 24L was free of traffic when clearing USA 1493 to land (**Inadequate Air Traffic Management, Controller Error**). ❖ The flight crew of the Boeing 737 had virtually no chance to discern the Metroliner against the background of runway lighting (<u>Lack of Traffic Awareness</u>).
22.11.1994	Lambert St. Louis International Airport (KSTL)	TWA MD-82 N954U TWA 427	Cessna 441 N441KM	2	Night VMC	During take-off on RWY 30R, the MD-82 collided with the Cessna, which had erroneously lined up further down the same runway at the intersection with taxiway R, instead of RWY 31 as instructed [NTS95]. ❖ Most likely, the Cessna pilot was not disoriented, but erroneously believed that RWY 30R was his assigned departure runway, potentially encouraged by the fact that RWY 31 was not on the ATIS (Issue with **ATC Instructions**, **Communication Issue,** Inadequate information on **Operational Environment**). ❖ The MD-82 flight crew only saw the Cessna when it was illuminated by their own lights, and thus had no chance of avoiding a collision (<u>Lack of Traffic Awareness</u>).
10.12.1998	Amsterdam Airport Schiphol (EHAM)	Delta Boeing 767 N193DN DAL39	**Towed** KLM B747-400	–	Day IMC	The flight crew of the Boeing 767 successfully aborted take-off on RWY 24 when they observed that the Boeing 747-400 was being towed across the runway, accompanied by an airport authority van [RVT01]. ❖ Because of a misunderstanding when coordinating with the assistant controller, the controller clearing the Boeing 767 for take-off was in a wrong mindset concerning the direction of the planned runway crossing of the aircraft under tow, and therefore, based on the ground radar picture, considered the crossing complete before it had actually begun (**Communication Issue**, **Controller Error**). ❖ The Delta flight crew could only detect the conflicting runway traffic because there was sufficient visibility (<u>Traffic Awareness Issue</u>). A disaster was solely prevented due to the pilot' quick and proficient reaction.
25.05.2000	Paris Charles-de-Gaulle Airport (LFPG)	Air Liberté MD-83 F-GHED Flight 8807	Streamline Aviation Shorts 330 G-SSWN 200	1	Night VMC	While lining up for an intersection take-off on RWY 27, the Shorts 330 was struck by the MD-83, which was in its take-off roll on the same runway [BEA01]. ❖ As a result of an incomplete coordination between controllers (**Communication Issue**), the local controller developed an erroneous mental picture of the traffic situation and believed that the Shorts 330 was (and would line up) somewhere behind the MD-83 (**Controller Error**). ❖ The Shorts 330 flight crew was not sure which aircraft the "number 1" in their conditional line-up instruction referred to, but commenced line-up in spite of this uncertainty (Issue with **ATC Instructions**). Due to the simultaneous use of both French and English, the Shorts crew were not aware that the MD-83 had been cleared for take-off on RWY 27 only seconds before they were instructed to line up (**Communication Issue**). ❖ Due to the geometry of the taxiway-runway intersection, and restrictions of the view from the cockpit, the Shorts 330 pilots could not visually acquire the MD-83. Light pollution from a construction area obscured the Shorts 330 from the MD-83 pilots (**Lack of Traffic Awareness**).

Date	Location	Aircraft #1	Aircraft #2	†	Meteorological Conditions	Description, Causal and Contributory Factors
31.10.2000	Taipei Chiang Kai-Shek International Airport (RCTP) Taiwan	Singapore Airlines B747-400 9V-SPK SQ006	–	83	Night IMC Heavy Rain	Instead of taking off from RWY 05L as planned, the flight crew inadvertently lined up on the parallel, partially closed RWY 05R and crashed into construction equipment during take-off in 450 m RVR [ASC02]. ❖ The pilots were preoccupied with weather-related tasks - such as crosswind calculations and discussions on the status of alternate airports - during taxi, and eventually ceased using their airport diagrams. Airport signs were hardly readable due to the heavy rain (**Disorientation**). ❖ Taxiway guidance lights did not meet ICAO standards at the location where disorientation occurred, resulting in bright, deceptive lead-on lights towards RWY 05R and much less conspicuous and partially defective lights towards RWY 05L (cf. Figure 12). Furthermore, there was no signage or lighting at the threshold of RWY 05L indicating the construction area some 1200 m down the runway (**Inadequate Airport Signs, Markings and Lights; Inadequate Information on Operational Environment**).
25.09.2001	Denver International Airport (KDEN)	UPS Boeing 757 UPS 896	–	–	Night VMC	The Boeing 757 erroneously took off from the closed RWY 8, eventually passing within roughly 10 m of a temporary light fixture illuminating a construction area on an adjacent taxiway [NTS03]. ❖ The controller responded positively to a request of the flight crew to change the departure runway from RWY 35L to RWY 8, although the latter runway was closed, and cleared the flight for take-off (**Controller Error**). ❖ Although runway closure information was correctly present on the ATIS transmission, the crew was not aware that RWY 8 was closed and did not become suspicious when seeing the construction area. There was, however, no NOTAM on the closure (**Inadequate Awareness of Operational Environment**).
08.10.2001	Milano Linate Airport (LIML)	SAS MD-87 SE-DMA SK 686	Cessna Citation D-IEVX	118	Daytime IMC Dense Fog	When rotating during its take-off on RWY 36R, the MD-87 collided with the Cessna Citation, which had inadvertently taxied onto the runway from the General Aviation apron in dense fog (Figure 10) [ANS04]. ❖ The Cessna flight crew was only qualified for CAT I operations and should neither have initiated nor been authorised to conduct the flight in the prevailing CAT III conditions. ❖ Since the Cessna was not fitted with a CVR, it remains unclear whether the pilots became disoriented in the fog, or whether they were pre-occupied by the idea that they would taxi to RWY 36R on the same route they had used to taxi in (**Disorientation/Misinterpretation of ATC Instructions**). ❖ Signage, lights and markings at the airport were not in accordance with ICAO standards, including the presence of a permanently lit stop bar and undocumented holding positions, possibly not only catalysing disorientation, but also creating confusion in the communication between the Cessna flight crew and ATC (**Inadequate Airport Signs, Markings and Lights**; **Communication Issue**). ❖ Due to the meteorological conditions, neither aircraft had the possibility to visually acquire the other one and to take corrective action in time (<u>Lack of Traffic Awareness</u>).
25.01.2002	Anchorage International Airport (PANC) Alaska	China Airlines Airbus A340 B-18805 Flight 011	–	–	Night VMC	The A340 took off from taxiway K instead of RWY 32, but managed to get airborne successfully [NTS02]. ❖ According to their statements, the flight crew members were deceived by the bright taxiway centreline lights on taxiway K, which made them think they were already on the runway. However, the investigation could find no anomalies with the taxiway lighting. ❖ Before take-off, the flight crew failed to cross-check their heading, which would have given them a chance to realise that they could not possibly be on RWY 32 (**Disorientation**).

Date	Location	Aircraft #1	Aircraft #2	†	Meteoro-logical Conditions	Description, Causal and Contributory Factors
03.05.2004	Munich F.-J.-Strauß Airport (EDDM)	KLM Boeing 737	Air Dolomiti ATR 42-500	—	Night VMC	During landing on RWY 08R, the Boeing 737 nearly collided with an ATR 42-500, which was lining up on the same runway via a high-speed exit [BFU09]. ❖ Due to the taxiway geometry, the ATR flight crew was unable to see landing or departing runway traffic before it passed directly in front of them. ❖ Given these limitations, the controller should not have used a conditional line-up instruction in the prevailing conditions. Furthermore, the controller did not unambiguously identify the aircraft she was referring to (**Controller Error, Communication Issue**). ❖ The ATR pilots therefore believed that a departing A321 which had just passed by on the runway was the aircraft they were permitted to line up behind, while the controller was referring to the Boeing 737 still on final approach (**Lack of Traffic Awareness)**. ❖ A catastrophic accident was only prevented because the flight crew of the Boeing 737 saw the other aircraft sufficiently early to initiate an evasive manoeuvre, eventually avoiding the ATR 42 by a few metres. ❖ The incident scenario bears a striking resemblance with the accident at Paris CDG airport in 2000.
09.06.2005	Boston Logan International Airport (KBOS)	Aer Lingus Airbus A330 EI-ORD EIN132	US Airways Boeing 737 N394US USA1170	—	Daytime VMC	The A330 and the Boeing 737 nearly collided when simultaneously taking off from the intersecting runways RWY 15R and RWY9; the Boeing 737 flight crew managed to keep their aircraft's nose down to avert a collision [NTS05]. ❖ Due to a controller error potentially related to workload, both aircraft were simultaneously cleared for take-off from the two intersecting runways (**Controller Error**). ❖ Given the prevailing daytime VMC conditions, the US Airways flight crew was able to detect the con-flicting runway traffic and to avert a collision; an accident would have been unavoidable in less favour-able visibility conditions (Traffic Awareness Issue).
05.11.2005	Anchorage International Airport (PANC) Alaska	EVA Air MD-11F BR635	—	—	*unknown*	The MD-11F erroneously took of from taxiway Y, which is parallel to the runway actually intended for departure, RWY 32. ❖ The flight crew apparently became disoriented following two consecutive runway changes (RWY 32, RWY 07L and then again RWY 32), and made a pre-mature left turn, aligning with taxiway Y instead of RWY 32 as instructed (**Disorientation**).
12.01.2006	Frankfurt Airport (EDDF)	China Air-lines B747-200F	Aer Lingus A320	—	Night IMC	The Boeing 747 freighter erroneously crossed RWY 07L while the Airbus A320 was landing. The A320 was able to decelerate sufficiently to prevent a collision hazard [BFU09a]. ❖ The Boeing 747 flight crew repeatedly failed to provide a correct read-back of the controller's instruc-tions, mistook his corrections/repetitions for an update, and thus erroneously believed they were al-lowed to cross RWY 07L (**Misinterpretation of ATC Instructions**, **Communication Issue**). ❖ The controller failed to notice that the last read-back of the Boeing 747 flight crew was wrong again, and that the pilots had apparently understood they were approved to cross RWY 07L (Controller Error). ❖ An accident was prevented because the A320 flight crew could see the intruding Boeing 747 and decel-erate their aircraft (Traffic Awareness Issue).

Date	Location	Aircraft #1	Aircraft #2	†	Meteoro-logical Conditions	Description, Causal and Contributory Factors
27.08.2006	Lexington Blue Grass Airport (KLEX)	Comair CRJ-100 N431CA Flight 5191	–	49	Night VMC	The CRJ-100 erroneously took off from RWY 26 instead of RWY 22 as planned (see Figure 9), and crashed due to the fact that RWY 26 was too short for a successful take-off [NTS07]. ❖ The flight crew confused RWY 22 and RWY 26. This was most likely induced by the fact that, as a result of the ongoing construction activities, the airport taxiway designations and layout did not correspond to the aerodrome charts available to the pilots (**Disorientation**); the pilots seemed to be slightly inattentive, though, since there were multiple minor lapses in pre-flight activities. ❖ Due to partially missing NOTAM information, the flight crew was largely unaware of the challenges resulting from the construction activities. Additionally, there was a slight misinterpretation of the NOTAMs relating to the RWY lighting system (**Inadequate Information on Operational Environment**). ❖ The fact that the controller cleared the flight for take-off when they were holding short of RWY 26 may have served as an unintended affirmation of the flight crew's belief that they had indeed reached their departure runway. The controller turned to paperwork after the take-off clearance.
28.10.2006	Newark Liberty International Airport (KEWR) New York	Continental Boeing 757 N17105 Flight 1883	–	–	Night VMC	After a circling approach, the Boeing 757 erroneously landed on taxiway Z in parallel to RWY 29, the runway actually intended for landing [NTS07d]. ❖ Apparently deceived by the non-standard Precision Approach Path Indicator (PAPI) lights of RWY 29, which were on the right side of the runway rather than on the left (and thus appeared to be "correct" when on approach to the taxiway), the crew confused taxiway and runway (**Disorientation**). ❖ Taxiway Z lights were set to a higher illumination level than those of the neighbouring RWY 29 at the time of the incident (**Inadequate Airport Lighting**), which may have contributed to the confusion.
05.01.2007	Denver International Airport (KDEN)	Key Lime Air Metroliner N425MA LYM 4216	Frontier Airbus A319 N915FR FFT 297	–	Daytime Blowing Snow	The Metroliner erroneously taxied onto RWY 35L while the Airbus A319 was cleared to land. The A319 flight crew conducted a go-around, eventually clearing the Metroliner by roughly 15 m [NTS07e]. ❖ When taxing to RWY 34, the Metroliner flight crew encountered significant difficulties in finding their way due to blowing snow and snow-covered taxiway markings and lights. Eventually, they missed a left turn and inadvertently entered RWY 35L (**Disorientation**). ❖ Initially, the A319 pilots believed the runway was clear. They perceived the Metroliner, which was some 600 m down the runway, only in the last moment, because the other aircraft had been obscured from their view by blowing snow and propeller wash (Traffic Awareness Issue).
02.02.2007	Denver International Airport (KDEN)	United Boeing 737 N928UA UAL1193	**Vehicle** Snowplough	–	Daytime VMC	The Boeing 737 nearly collided with a snowplough when landing on RWY 8, but managed to bring the aircraft to a halt employing significant brakes and reverse thrust [NTS07b]. ❖ The snowplough driver initiated crossing the runway without clearance. ❖ An accident was only prevented because visibility was good; consequently the flight crew was able to see the snowplough sufficiently early (Traffic Awareness Issue). ❖ The controller apparently did not see the snowplough, and the system intended to alert him of Runway Incursions (AMASS, cf. Section 3.5.1.3) did not raise an alert.

2.3 Key Findings & Flight Deck Instrumentation Aspects

The analysis of Runway Incursion incidents and accidents presented in the previous section yields the important result that limited visibility, particularly due to fog or other meteorological phenomena, is a predominant factor in all fatal accidents examined, cf. Table 2. None of these occurred in daytime VMC conditions: the Tenerife, Madrid, Anchorage (Korean Airlines), Detroit and Linate accidents happened in foggy conditions, the Taipei disaster was in heavy rain and darkness, and the Atlanta, Lost Angeles, St. Louis, Paris and Lexington accidents occurred at night. Limited visibility prevented at least one of the flight crews involved in each of these mishaps from maintaining adequate situational awareness with respect to their position and/or the location of other relevant traffic. By contrast, in all those incidents where collisions on the runway could be averted, there was sufficient visibility for a last-minute visual detection of the emerging collision hazard.

This may serve as substantial evidence that conventional airport navigation and traffic acquisition techniques are prone to failure in adverse visibility, even if flight crews are familiar with an airport, and that current flight deck instrumentation does not provide pilots with adequate support for operations under these meteorological conditions. Another recurring problem in this context are deficient airport signs and markings, being cited as causal factors e.g. in the Madrid, Anchorage (Korean Airlines), Detroit, Taipei and Linate accidents. This is consistent with earlier findings of the NTSB, which identified not only limited visibility, but also inadequate signs and markings as recurring causal factors in an analysis of 26 Runway Incursion incidents [NTS86].

A further remarkable finding is the significant role of communication deficiencies, which encompass a broad spectre of causal and contributory factors. Within the ATC domain, deficient coordination between controllers has frequently resulted in Runway Incursions through erroneous instructions and clearances, as in the Anchorage (Japan Airlines) and Paris accidents or the Minneapolis, Amsterdam and Boston incidents. Nevertheless, the primary concern in this context is the communication between pilots and ATC. Inefficiencies resulting from the use of multiple languages in an ATC environment have contributed to both the Paris and Linate accident. While a complete breakdown of communication between pilots and controller as in Linate is relatively rare, not sharing essential information or concerns has frequently either led to a misinterpretation of ATC instructions/clearances or missed opportunities to prevent accidents. Even in accidents with other primary causes, communication issues have aggravated the situation and worsened the outcome. Several accidents were caused by insufficient information on the operational configuration of the airport, in particular on the operational use and availability (or closure) of runways.

Generally, most of the Runway Incursion causal factors identified through the incident and accident analysis are not independent, but exhibit an intricate interrelation. This insight permits to categorize causal factors in a hierarchical structure, such that each incident and accident can be attributed to at least one of the following high-level root cause categories, which are introduced and explained below:

2.3.1 Runway Incursions caused by Disorientation

Nearly all Runway Incursions involving inadvertent entry into an active runway, runway confusion or take-off and landing operations on taxiways can be attributed to spatial disorientation. In the fatal accidents in Madrid (see Appendix I-2 for details), Detroit (Appendix I-5), Taipei (Appendix I-9), Linate (Appendix I-11) and Lexington (Appendix I-12), crew disorientation due to a lack of situational awareness played a substantial role. Essentially, the impact of limited visibility on flight crews is that it degrades situational awareness of ownship position due to a lack of external "landmark" references and limited overview, both caused by restricted visual range, which may eventually result in spatial disorientation. Inadequate airport signs, markings and lights can be confusing or deceptive, thus catalysing disorientation. Additionally, they may aggravate emerging disorientation or prevent crews from noticing that their mental model of the aircraft's position is not correct. Last but not least, the Lexington accident demonstrates that discrepancies between charted and actual taxiway designations also have the potential to induce confusion (cf. Figure 9).

Another very noteworthy aspect derivable from the accident reports is that the pilots involved did not use all available instrument cues for consistency checks on their position. The NTSB report on the Detroit accident notes that the pilots did not refer to heading for an identification of their position. Likewise, the flight crew of the accident aircraft in Lexington failed to note the heading discrepancy that would have told them they were on the wrong runway. Due to the VFR character of surface operations, it seems that visual cues, however sparse they may be, dominate on the ground, whereas heading, apparently, is not always intuitive enough in combination with paper charts to enable fail-safe airport navigation. More subtle cues such as the misalignment of the Para-Visual Display (PVD) in the Taipei accident, which could have told the flight crew they had made the wrong choice of two parallel runways, were not correctly interpreted by the flight crew, either.

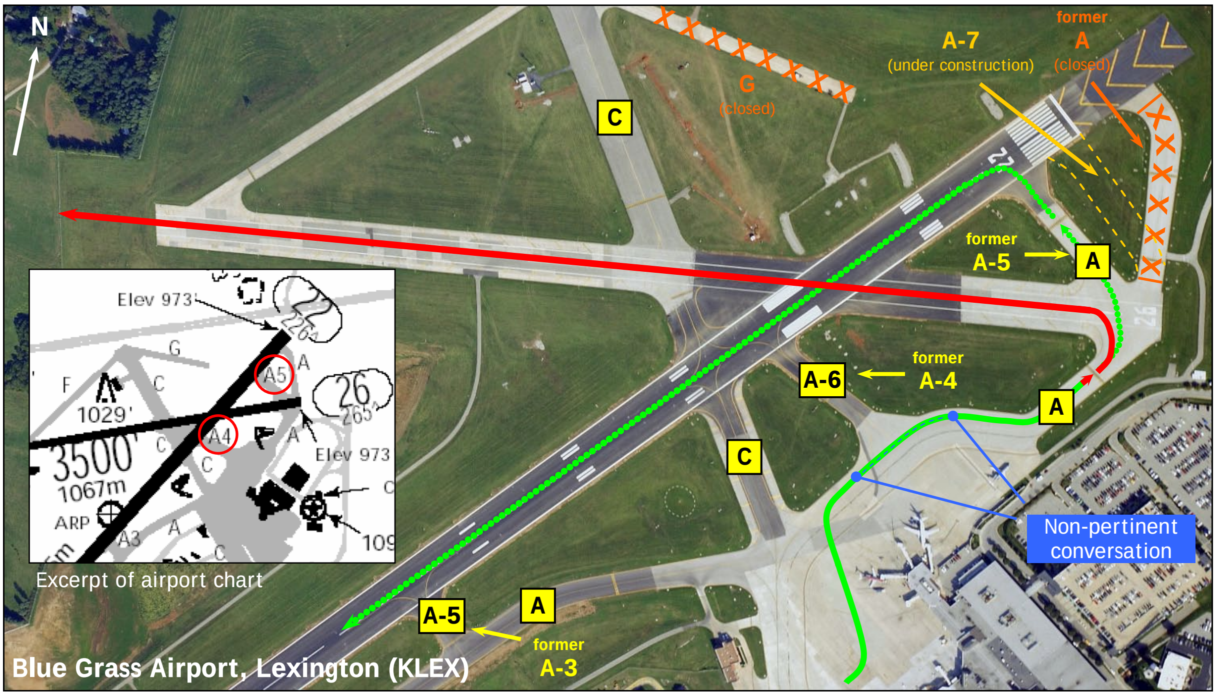


Figure 9: Take-off from wrong runway at Lexington Blue Grass Airport (2006)

Recently, regulators and airports have devoted their attention to improved, more conspicuous markings, such as the enhanced taxiway centreline markings in the vicinity of the runway proposed by the FAA [FAA08], or at least tried to make existing signs and markings compliant with ICAO standards. While this is certainly a valid and worthwhile approach, full efficiency is only achieved in fair visibility conditions. No matter how much effort is invested into perfecting signs and markings, visibility restrictions caused by heavy precipitation or fog will limit their readability, and additionally, the reflectivity of wet pavements generally decreases the conspicuity of markings. Besides, snow, slush or a thin layer of ice may easily render markings entirely unreadable, as evidenced e.g. by the 1983 Korean Airlines Anchorage accident (Appendix I-3). Consequently, the efficiency of signs and markings can be easily annihilated, particularly in conditions when they would be needed most. Last but not least, they do not provide an independent source of position information.
It is furthermore noteworthy that with the exception of the Linate accident, disorientation occurred when flight crews made required turns too early (as in Lexington) or did not turn far enough to intercept the intended taxiway. The resulting angular error was small in most cases, resulting in a situation where a shallow angle error in heading eventually resulted in disorientation. Since the printed airport diagrams currently used for surface navigation rely on the availability of visual cues and signs/markings for reference and position identification, they may easily fail, as the analysis of selected incidents and accidents has shown.

In conclusion, current cockpit and ground-based aids to surface navigation cannot provide adequate support in all weather conditions, and are actually prone to fail in limited visibility or otherwise adverse weather conditions, when they would be needed most. Even worse, it is evident that the detection and isolation of surface navigation errors is even harder to achieve in these conditions.
Consequently, the main systemic issue is not the occurrence of disorientation, but the inadequacy of current flight deck instrumentation and procedures to reliably detect, manage and resolve surface navigation errors, irrespective of their cause, i.e. independent of whether they result from e.g. low visibility, operational distractions, non-standard aerodrome signage or erroneous aeronautical information. In fact, all accidents involving disorientation could have been prevented by a means of indicating ownship position with respect to the aerodrome layout to the flight crews involved.

What flight crews need, consequently, is an independent source of airport mapping and position information that can help to overcome visibility limitations and potential airport signage/marking (conspicuousness) issues (***High-Level Requirement I***).

At first glance, the occurrence of Runway Incursions due to disorientation seems to be entirely unrelated to traffic density, since the surrounding traffic obviously has no impact on a flight crew's ability to navigate in an airport environment. Nevertheless, there is a subtle interrelation: airport complexity, which certainly has an impact on disorientation, is a result of traffic demand. Nonetheless, since airports evolve over longer periods of time, short- or medium-term variations of traffic density do not have any impact on incursions due to disorientation. Even if the number of traffic operations changes, airport complexity will still remain the same.

2.3.2 Runway Incursions due to Undetected Traffic Conflicts

Degraded visibility not only increases the risk of disorientation, but also hampers visual traffic acquisition, which is currently the only means of traffic surveillance for flight crews on the ground. Nevertheless, it is important to note in this context that not only meteorological limitations to visibility, such as fog, are a factor. Particularly the Paris accident (Appendix I-8) and the Munich incident in 2004 (Appendix I-16) demonstrate that view restrictions resulting from either airport or cockpit geometry, or a combination of both, can also lead to the breakdown of collision avoidance by “see and avoid”.

While additional information on surrounding traffic may be obtained from the so-called party line effect, i.e. radio transmissions of other aircraft under the control of the same ATC unit, and TCAS information on arriving and departing aircraft[34], this information is not continuously available and does not provide the same degree of coverage and reliability as direct visual observation. Apart from the volatile nature of R/T transmissions, obtaining traffic information via the party line effect has the additional disadvantage that building up an accurate mental image of the surrounding traffic in this way requires familiarity with the airport or airspace (location of taxiways, waypoints etc.) and the procedures being used[35].

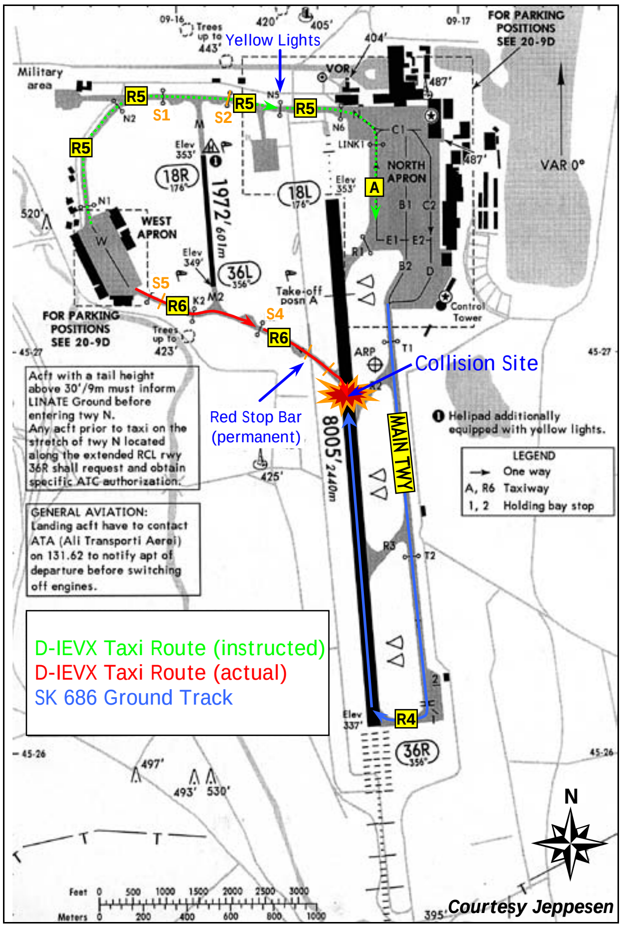


Figure 10: Accident at Milano-Linate (2001)

Additionally, the investigation of the Atlanta, Los Angeles (cf. Appendix I-6) and St. Louis (Appendix I-7) accidents revealed that bright runway lighting may easily outshine standard aircraft lights, thus reducing conspicuity and detectability of aircraft on runways even in night VMC conditions. While strobes considerably increase aircraft conspicuity even in a runway environment with high-intensity lighting, their use is typically delayed until the take-off clearance has been received in consideration to other pilots’ night vision [NTS95]. Furthermore, particularly in foggy conditions, reflections from ownship strobes may cause discomfort. Again, while improvements to aircraft lighting are desirable, it requires at least some residual visibility to be efficient.

Traffic conflicts may result from myriads of possible scenarios and causes, involving, among others, disorientation (see previous section) and communication issues. With the exception of the Taipei and Lexington accidents, which did not in-

[34] This constitutes an unintended function, since TCAS is certified for airborne collision avoidance only.
[35] Personal communication with EADS flight test department, June 2009.

volve any other traffic, all accidents discussed in the previous section could have been prevented, or at least been mitigated in their consequences, if at least one of the parties involved had possessed knowledge of the presence and location of the other aircraft, irrespective of the cause of the traffic conflict. If they had been aware that other traffic was on the runway, the crews of e.g. KLM Flight 4805 in Tenerife (see Figure 8 and Appendix I-1), NWA Flight 299 in Detroit or TWA Flight 427 in St. Louis would not have commenced take-off, and there might have been a chance for the crews of Scandinavian Flight 686 in Milano-Linate (cf. Figure 10), Iberia Flight 350 in Madrid and USAir Flight 1493 in Los Angeles to take efficient remedial action. For all of the collision accidents studied in Section 2.2.2, timely awareness of the other traffic on the runway might have prevented the collision. Conversely, for virtually all of the Runway Incursions involving a traffic conflict that did not result in an accident, timely detection of the incursion through visual acquisition of the other traffic and appropriate remedial action prevented disaster.

In conclusion, therefore, undetected traffic conflicts in the runway environment have the highest potential for an accident. Consequently, an independent source of information on the surrounding traffic would have helped the flight crews to establish and maintain adequate traffic awareness, particularly concerning the presence of other traffic on the runway. Additionally, given the dynamics of the Paris and Linate accident or the Munich incident, traffic conflict detection and subsequent alerting are certainly an invaluable supplement to traffic information.

Relevant surrounding traffic on the airport surface and the runway environment, including potential traffic conflicts, must be brought to the attention of flight crews in a suitable form (***High-Level Requirement II***).

If, for whatever reason, a Runway Incursion occurs, the risk of a collision accident increases with the overall number of runway operations and thus the percentage of time the runway is used for take-off or landing. However, the probability that a traffic conflict remains undetected does not seem to be directly related to traffic density, because visibility, both meteorologically and geometrically, is the dominant factor from a flight deck perspective. Additionally, on the ATC side, the availability of airport surveillance equipment is an essential factor. Only in situations where excessive controller workload decreases performance, the probability of conflict detection may depend on traffic density.

2.3.3 Runway Incursions due to Insufficient Airport Information

The Runway Incursions at St. Louis, Taipei, Denver, Lexington and Newark demonstrate that additional support in identifying the runway intended for take-off or landing might help to prevent accidents and hazardous situations. Especially the Taipei and Lexington disasters, as well as the Denver incident, additionally indicate that up-to-date information on the airport environment, particularly on the runways in use and on short-term or temporary changes, is crucial for safe and efficient flight operations. Nevertheless, the deficiencies in the current system of communicating short-term and temporary changes to pilots are well established, cf. [HJK04, Ver08].

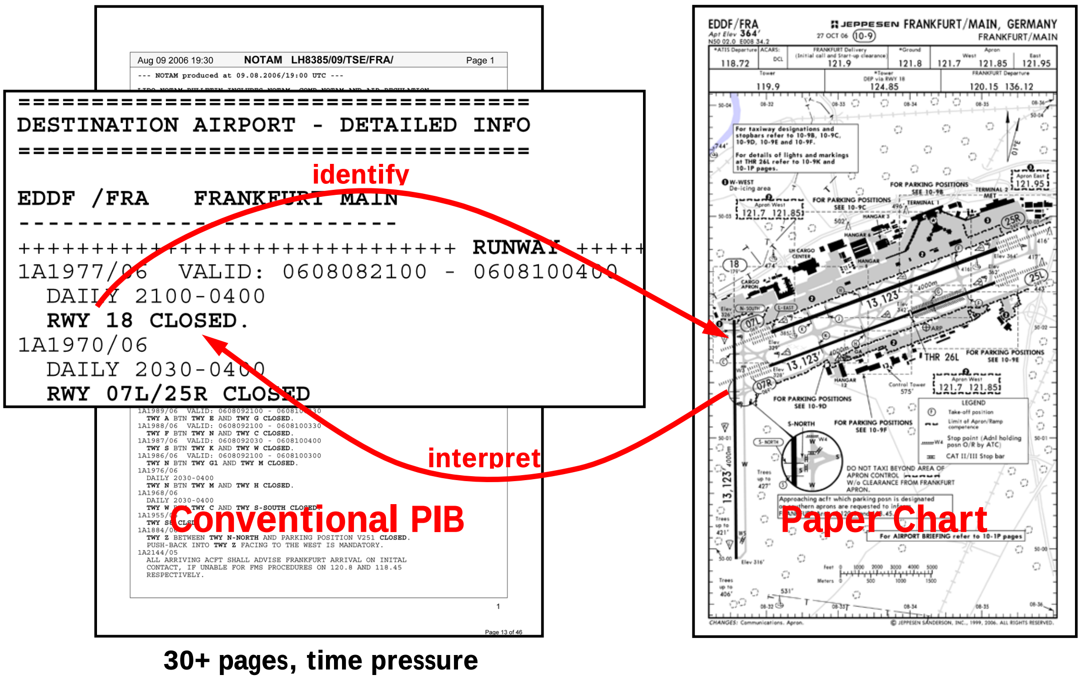


Figure 11: Fragmentation of information with conventional Pre-Flight Information Bulletin

Today, crews receive a plain-text language compilation of current NOTAM and other urgent information of operational significance prior to flight that is called 'Pre-Flight Information Bulletin (PIB)' and required by ICAO Annex 15[36] [ICA04]. Usually, it is prepared by the flight dispatcher and handed out to the crew on paper or an electronic equivalent such as PDF. Typically, for an intercontinental flight, this conventional NOTAM package consists of some 30 or more A4 pages, because all take-off, en-route and destination alternates need to be covered[37]. This has a variety of disadvantages, e.g. that

- the accessibility of the NOTAM information is somewhat limited, particularly if the crew has to find a certain information under time pressure, since pilots often need to browse several pages to locate information on e.g. a particular alternate airport;
- the information is fragmented, and needs to be combined with other sources like paper charts and the flight deck displays to create a complete mental model and a sufficient level of situational awareness (cf. Figure 11)[38];

[36] According to current ICAO regulations, a compilation of current NOTAM and other information of urgent character shall be made available to flight crews in the form of plain-language Pre-flight Information Bulletins [ICA04].

[37] In this context, it must be noted that decisions on the necessity of issuing or distributing a NOTAM are not purely driven by operational considerations; legal aspects such as liability issues are an important factor as well. This may result in a decision in favour of a NOTAM to be legally on the safe side, even if the information contained is not essential from an operational perspective.

[38] NOTAMs concerning aerodromes often reference closures or restrictions relative to other airport locations, and therefore require either a high degree of familiarity with an airport, or charts for an accurate decoding and interpretation. As an example, the information that taxiway N is closed between taxiways M and H at Frankfurt Airport (EDDF) requires knowledge on the location of M and H relative to N. Furthermore, due to the huge local variations in taxiway naming conventions, the fact that the closure in the above example encompasses just one taxiway segment between the parallel taxiways M and H is not deducible in a logic and intuitive fashion.

- the information is not prioritized, and pilots need further knowledge, such as the terminal/apron their airline routinely uses and the taxi route to be expected, to determine whether a NOTAM is relevant for them or not;
- the information is not available to any aircraft system, and can thus not be displayed or used to create alerts, e.g. for closed runways, malfunctioning Navaids or restricted airspaces.

Furthermore, the time the crew commonly has for the briefing is not sufficient for a detailed review of all this information. Thus, there is a small, but non-vanishing risk that important information, e.g. on runway closures or restrictions, is simply overlooked [Ver08]. Last but not least, the readability of NOTAM still suffers from the extensive use of abbreviations and uppercase letters, which is a relict from the 1930s and 1940s, when the original NOTAM format was defined taking into account the limitations of teletype technology. Although teletype machines have disappeared, the non-intuitive NOTAM format has never been updated substantially [HJK04].

One of the lessons to be learned is that the current way of conveying runway closure information is not the optimum solution. The Taipei accident investigation revealed that the flight crew of SQ006 had reviewed NOTAM information and was aware that RWY 05R was closed, but the disorientation leading to the assumption that they were on RWY 05L while they had, in fact, lined up on RWY 05R rendered this information useless (see Figure 12 and Appendix I-9). Likewise, at Denver airport, both controller and flight crew of UPS Flight 896 apparently missed the fact that RWY 8 was closed due to construction work on an adjacent taxiway, although they had been notified of the closure by airport operations personnel and the ATIS broadcast (cf. Appendix I-10). These two exemplary Runway Incursions, which can also be attributed to inadequate flight crew situational awareness[39], clearly illustrate the limitations and deficiencies of the current system of conveying short-term and temporary changes.

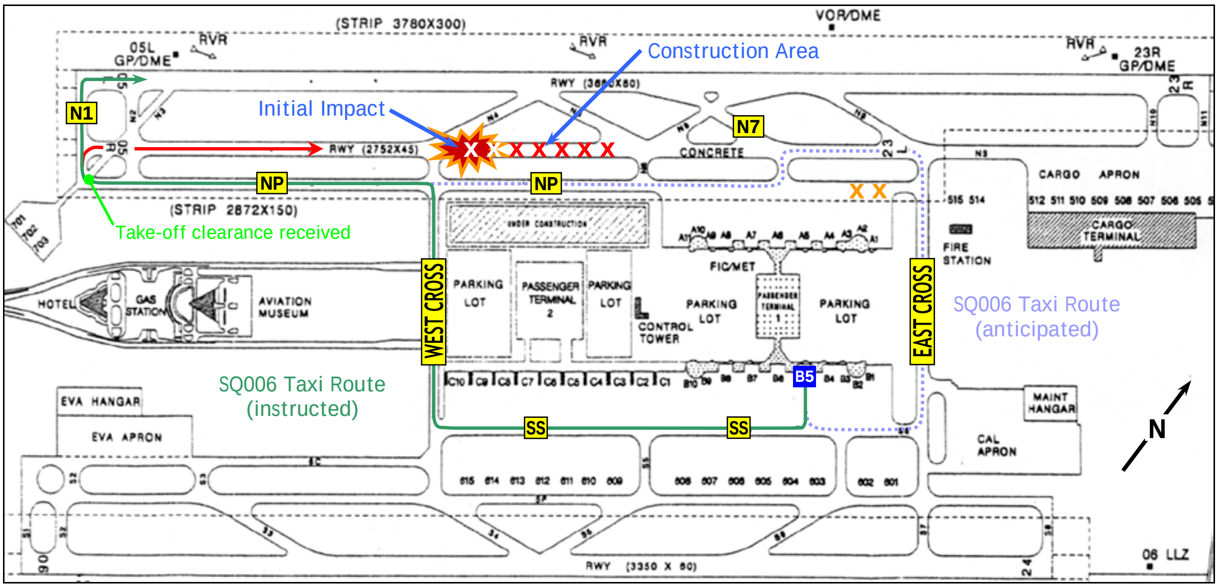


Figure 12: Singapore Airlines Flight SQ006 accident at Taipei airport (2000)

[39] Of course, particularly the Denver incident suggests that an integral representation of short-term and temporary changes is of equal importance for controller situational awareness, but beyond the scope of this thesis.

Conveying runway closure and other PIB/NOTAM information in textual form is indeed vulnerable to failure, since any disorientation on the airport surface means that the flight crew can no longer apply this information correctly. Conversely, even if the flight crew is perfectly aware of their precise location on an aerodrome, the Denver incident demonstrates that the risk of oversight is reality with the current system, and by no means limited to NOTAM as a medium, since e.g. (D-)ATIS transmissions suffer from the same limitations.

From a flight safety perspective, however, it is essential for safe and efficient surface movement operations that flight crews are aware of the operational status and configuration of an aerodrome and its installations, such as potential runway closures or restrictions. Erroneously taking off or landing on a closed or otherwise unsuitable runway is extremely likely to have catastrophic consequences, mainly due to potential collisions with construction equipment, as illustrated by the Singapore Airlines Flight SQ006 accident at Taipei in 2000 (cf. Appendix I-9).

Relevant and sufficiently up-to-date information on the operational status and configuration of an aerodrome and its installations must be brought to the attention of flight crews in a suitable form (***High-Level Requirement III***).

2.3.4 Runway Incursions as a Result of Communication Deficits

Communication between pilot and controller is a critical link in the ATC system, but it can be broken with surprising speed and disastrous results [FAA09]. The Tenerife catastrophe (cf. Figure 8) is exemplary of a Runway Incursion accident where a misunderstanding between the flight crew and the air traffic controller was the main causal factor. Likewise, ambiguities in the use of conditional clearances, particularly with respect to the identification of the other aircraft the clearances referred to, were decisive factors both in the Paris accident and the Munich incident. In this context, runway-related ATC clearances and instructions are especially critical, because they constitute the last line of defence against Runway Incursions. Any failure of this safety barrier will immediately result in a hazardous situation, cf. Figure 7, unless a comparison with the traffic situation immediately reveals that there must be a mistake or misunderstanding.

Furthermore, many of the other Runway Incursions investigated feature indications of deficient communication between flight deck and controllers, such as the Detroit and Linate accident (Figure 10), in which flight crews were not able to execute the clearances assigned by ATC as intended, mainly due to disorientation. Therefore, information on the assigned taxi route, potentially including an advisory or alert upon deviation, might serve as additional, redundant cue to prevent disorientation by making the inevitable discrepancy between the instructed and the actual taxi route more palpable.

An important first conclusion from these considerations is that multiple redundant sources of information permitting cross-checks are essential in preventing Runway Incursions.

Beyond the incident and accident analysis, there is further evidence on the significant role of communication deficiencies in Runway Incursions. The already quoted mid-80s NTSB study concluded that miscommunication played a significant role in Runway Incursions, with the main issues in this context identified as improper phraseology and read-back of clearances not fully understood by the pilots [NTS86]. In the period from fiscal years 2000 to 2003, the FAA identified the following most common errors contributing to the so-called 'Pilot Deviations':

- Pilots read back controllers' instructions correctly but do not comply with the instructions;
- Pilots fail to hold short of the runway as instructed and cross or taxi into position on the runway;
- Pilots accept clearances issued to an aircraft other than their own [FAA04].

Investigating Runway Incursion incidents at Paris Charles-de-Gaulle in the first half of the year 2000, the BEA arrived at the following remarkably similar error scenarios:

- Aircraft cross the runway or go past a holding point;
- Aircraft line-up in front of an aircraft on take-off or on final, instead of lining up behind;
- There is a confusion in call-signs, which leads to an aircraft other than the one intended by the controller moving.

Furthermore, as one of the main phraseology aspects, it was noted that the holding points are not always clearly identified, and that call signs often resemble each other, thus promulgating confusion [BEA01].

In conclusion, this may serve as substantial evidence that situational awareness on the ground is not limited to positional and traffic awareness or awareness of operational aspects, but includes clearance awareness as well. More recently and more generally, IATA estimated that deficient flight crew communication played a significant role in 28% of all airliner hull losses in 2004, which makes it No. 4 of the most significant factors [IAT05]. Generally, radio voice communications between tower and crew can be impaired by the following factors:

- white noise, acoustical problems in understanding clearance
- crowded frequency, confusing call signs
- language problems in understanding clearances
- use of non-standard phraseology

Leaving aside technical problems for the moment, these communication deficits can be divided into two groups. The first group consists of communication problems due to the language used and associated language proficiency. In terms of situational awareness, everybody is usually aware of the communication problem and can use extra vigilance to avoid incidents.

For the second group, the deficiencies are far more difficult to unveil, because communication is apparently working, and the parties involved are not aware that they are talking about different things. Such communication deficits can also result from incorrect or not internationally accepted phraseology. A major concern in this context is the widespread use of "*Taxi Into Position and Hold*" in North America and by North American crews instead of the international ICAO PANS-ATM standard phrase "*Taxi to the Holding Point, Runway XY*". The resulting confusion has lead to several Runway Incursion incidents worldwide [IAT05].

In view of these shortcomings, one can draw the conclusion that both crew situational awareness and the interaction of controllers and pilots have to be improved. Since communication between flight deck and ATC concerns mainly the assignments of routes and clearances, this is, as the above examples show, the domain most severely influenced by a breakdown of communication. A key issue in this context is the volatile nature of information related by ATC and pilots through voice communication. Instructions and clearances are typically transmitted once; they cannot be retrieved and reviewed whenever the flight crew feels the need to do so. Of course, there is always the possibility to ask ATC again, but this requires awareness that information is incomplete or has not been understood properly. Particularly when dealing with an illusion of efficient communication, information once erroneously captured may therefore be extremely difficult to correct.

Both taxi route assignments and clearances related to surface movement or other runway operations must be conveyed to flight crews in a fashion unambiguously reflecting the controller's intention. Furthermore, route and clearance information must be continuously accessible and robust against phraseology or language proficiency issues, and conditional clearances must unambiguously identify the aircraft they refer to (***High-Level Requirement IV***).

2.3.5 Runway Incursions caused by Surveillance and ATC Errors

Controllers erroneously clearing two aircraft for the same runway were the causal factors in both the 1990 Atlanta (Appendix I-17), 1991 Los Angeles and the 2000 Paris accidents. In the latter case, the use of two different languages by ATC prevented the crew of a British Shorts 330 from noticing the controller error [BEA01]. Furthermore, the Sioux Falls accident (Appendix I-14) occurred because the controller cleared the flight crew to land in spite of the ongoing snow removal operation.

Multiple intersecting runways were identified as a factor frequently associated with controller-induced Runway Incursions, while traffic was light or moderate in 12 of 17 Runway Incursions attributed as "controller-induced" by a 1986 NTSB study [NTS86]. Another finding was that coordination between controllers, specifically ground controller and local controller, was often insufficient in the incidents.
As an example, in the 1985 Minneapolis incident (Appendix I-4), the controller allowed traffic to build up until the limits of the airport were exceeded. For this incident, the Boston incident and the Paris accident, a lack of coordination between ground controller and local controller was at the root of the Runway Incursions.

Likewise, in the Anchorage (Japan Airlines) runway collision, the local controller could not recall whether he had given the ground controller permission to cross the accident vehicle or not. Last but not least, a misunderstanding during coordination between controllers was also the reason for the Amsterdam Runway Incursion incident (see Appendix I-14 for details).
As with airport lighting, signage and markings, the issue of potential ATC errors is obviously beyond the control of individual flight crews. From the perspective of an air carrier supporting worldwide operations, the risk of ATC errors can never be fully excluded.

Consequently, a system that enables pilots to anticipate and mitigate potential controller errors, irrespective of whether they result from a lack of appropriate surveillance equipment or controller human factors issues, such as a lack of coordination between controllers, is required (***High-Level Requirement V***).

2.3.6 Impact of Airport Infrastructure & Organisational Deficiencies

The role of inadequate signs, markings and lighting, which clearly constitutes an airport infrastructure deficiency, has already been discussed in conjunction with disorientation, cf. Section 2.3.1.
The most egregious airport organisational deficiencies have been identified in the Linate accident, where undocumented holding positions were used, preventing efficient error trapping. Another noteworthy organisational issue concerns intersection take-offs, and in particular the use of high-speed exits for line-up. Both the Paris accident and the Munich incident have shown that the resulting lack of physical visibility onto the runway from the cockpit in conjunction with conditional clearances results in an extreme risk of an accident. Other factors identified in the analysis of incidents and accidents were missing surveillance equipment and inadequate local ATC procedures. Again, these infrastructure and organisational issues are beyond the control of individual flight crews.

2.3.7 Conclusion on Runway Incursions and Human Factors Aspects

As early as 1986, the NTSB concluded that Runway Incursions are a human factors problem [NTS86]. To this date, no Runway Incursion accident has been caused by technical malfunctions, as evidenced by the analysis earlier in this chapter. This section contains some considerations to elucidate why human factors and human performance aspects appear to be the dominant factor in Runway Incursions.

When reading through aviation accident reports, one is confronted with an apparent paradox: Airline pilots are among the most carefully selected, best-trained and re-trained, most thoroughly assessed, medically scrutinized individuals that operate technology on this planet. Nonetheless, errors that appear to be basic at first glance, e.g. in airport navigation or disorientation occur, such as in the already mentioned Lexington and Taipei accidents. Outside the domain of surface movement, the recent Helios airways accident (cf. [AAI06]) raises similar questions, in particular when considering the following:

- Pilots are down-selected in thorough selection process, individuals with high cognitive skills.
- Pilots are scrutinized medically, to ensure that medical problems do not impair their performance.
- Pilots are very carefully trained, probably more than any other operators of technology. Frequent refreshers, intricate system of proficiency checks, both in the simulator and on the line.
- Apart from the General Aviation aircraft involved in the Linate disaster, all of the accidents discussed in this thesis occurred involved aircraft from airlines with a high reputation from countries where qualification is generally not considered a problem.
- All pilots in accidents discussed in the previous sections were rated as average or above average pilots by their supervisors.

Under the assumption that the assessment system for airline pilots is efficient, and that there are no significant deficiencies in pilot training, the number of options offering a satisfactory explanation for the observed errors shrinks.
Besides difficulties with clearances, communications, orientation, a 1984 NASA study also revealed preoccupation as another key factor in pilot-induced incursions [NTS86]. Consequently, the role of pilot distraction should not be underestimated. Therefore, the FAA advised with Advisory Circular AC 120-74A that the “sterile cockpit” philosophy should be applied. This means that flight crew members must be able to focus on their duties without being distracted by non-flight related matters, such as eating meals, engaging in non-essential conversation, or reading material not related to the safe and proper operation of the aircraft [FAA03a].
However, the operational context itself can be distracting as well. Rather often, pilots have to complete checklists while taxiing simultaneously. In response to the FAA recommendations, but going beyond the Advisory Circular AC 120-74A, a major US airline mandated that all of its pilots have to complete all checklists before taxiing [FAA04]. Furthermore, programming the Flight Management System (FMS) or configuring the aircraft for take-off (or cleaning up the configuration after landing), use of the Airborne Communications Addressing and Reporting System (ACARS) and radio calls with the airline company might also add to the distraction of pilots. Therefore, AC-120-74A recommends that all such activity be terminated when approaching the entrance of an active runway.
Nevertheless, with the exception of the Lexington accident, there are no hints in the investigation reports analysed that would make distraction appear as a satisfactory explanation of flight crew actions and flight crew performance in Runway Incursion incidents and accidents. Additionally, there were no conclusive indications for a variability of individual performance due to fatigue or personal problems in any of the Runway Incursion accidents investigated. Since surface movement is one the least automated phases of flight, it is very unlikely that “complacency”, an issue often quoted in connection with deficient crew vigilance in during a highly automated phase of flight, was of any influence. Additionally, a closer look reveals that errors that seem to be basic at first glance often turn out as wrong decisions taken in a deceptive, unforgiving environment on the basis of inadequate and insufficient information.

Consequently, in view of the information deficits identified in the previous sections, the only logical and conclusive explanation for the sometimes seemingly egregious pilot errors that remains is the inadequacy of “flight guidance tools” for surface movement. The deficiencies in flight deck instrumentation, in turn, result in a less than adequate situational awareness for the task at hand, and potentially also in excessive workload and task saturation, as e.g. in the Detroit accident [NTS91].
When applied in the aviation domain, situational awareness implies and encompasses knowledge and awareness of any relevant factor that might potentially affect the safety of the flight. With this and the categories identified above in mind, a lack of crew situational awareness on the aerodrome surface can be subdivided further into:

- Lack of **position awareness**. The crew is either not sure of the position on the airfield and gets lost, or believes the aircraft to be elsewhere on the airport, particularly in situations of poor visibility. Especially the latter case can lead to inadvertent entry into a runway (e.g. entering or crossing the wrong runway, e.g. 30L instead of 30R).
- Lack of **traffic awareness**. The crew lacks awareness of the position, intention and cleared manoeuvres with respect to relevant traffic in the vicinity of the aircraft.
- Lack of **operational awareness**. The crew lacks awareness of the operational environment and configuration of the airport, i.e. they are not aware of closed runways or taxiways, or of the runways in use.
- Lack of **clearance awareness**. The crew is not fully aware what the current clearance mandates or allows them to do, or whether an appropriate clearance for the intended manoeuvre has been requested or issued. This includes the crew being in the wrong ‘mindset’ and failing to request clearance for the manoeuvre; having a false impression of being cleared for the manoeuvre (e.g. to enter runway, to land or to take-off) and failure to correctly execute an ATC sequencing instruction.

It is essential to note that the factors identified above may exacerbate each other: in bad visibility, a breakdown of communication between pilot and controller may start out from a subtle misunderstanding, but subsequently cause an air disaster, cf. [ICA80].

In conclusion, this proves the initial hypothesis that there are indeed **deficiencies in flight deck instrumentation** with respect to surface movement**,** and that inadequate reference to human performance limitations in the selection of current means (paper charts, visual acquisition) is the main high-level cause of Runway Incursions**.**
Thus, the main goal to be achieved from an onboard perspective is a global increase in crew situational awareness, supplemented by alerting in situations where the enhanced awareness is not sufficient to avoid hazardous situations. This approach is in line with the European Action Plan [Eur04].

2.3.8 Summary of High-Level Requirements

This chapter concludes with a brief summary and overview of the high-level requirements identified:

Flight crews need an independent source of airport mapping and position information that can help to overcome visibility limitations and potential airport signage/marking (conspicuousness) issues (***High-Level Requirement I***).

Relevant surrounding traffic on the airport surface and the runway environment, including potential traffic conflicts, must be brought to the attention of flight crews in a suitable form (***High-Level Requirement II***).

Relevant and sufficiently up-to-date information on the operational status and configuration of an aerodrome and its installations must be brought to the attention of flight crews in a suitable form (***High-Level Requirement III***).

Both taxi route assignments and clearances related to surface movement or other runway operations must be conveyed to flight crews in a fashion unambiguously reflecting the controller's intention. Furthermore, route and clearance information must be continuously accessible and robust against phraseology or language proficiency issues, and conditional clearances must unambiguously identify the aircraft they refer to (***High-Level Requirement IV***).

Consequently, a system that enables pilots to anticipate and mitigate potential controller errors, irrespective of whether they result from a lack of appropriate surveillance equipment or controller human factors issues, such as a lack of coordination between controllers, is required (***High-Level Requirement V***).

While many incidents and accidents could have been prevented with just one of the above ***High-Level Requirements*** fulfilled, it is important to note in this context that redundancy is essential in preventing Runway Incursions, given the criticality and severity of the issue. Relying on a single source or measure will often fail to prevent hazardous or catastrophic situations, particularly in case of erroneous or misunderstood ATC instructions/clearances. Only cross-checking with the surrounding traffic can detect the error in this case.

3 State of the Art in Industry and Research

3.1 Onboard Systems for Better Ground Situational Awareness

The idea of onboard systems for the prevention of Runway Incursions is anything but new, cf. [Kub99]. Over the past decade, the electronic Airport Moving Map (AMM) has evolved in research and, subsequently, industry and is now widely accepted as the core technology to increase the flight crew's situational awareness in terms of position on the airport surface. In a comprehensive Runway Incursion risk mitigation study, the Commercial Aviation Safety Team (CAST) found airport moving map displays to be a highly effective safety enhancement for reducing the risk of Runway Incursions caused by pilot error [FAA04]. Furthermore, research by the Cargo Airline Association (CAA) and NASA, not surprisingly, concluded that efficient surface traffic awareness is hardly possible in the absence of an airport moving map [BAO00]. In addition, it has been argued that an airport moving map integrated into the aircraft's Electronic Flight Instrument System (EFIS) should form the basis of any surveillance-type system providing Runway Incursion alerting [Ver07].
Consequently, it is not surprising that accident investigators have already suggested its large-scale introduction, e.g. in the wake of the SQ006 accident [ASC02] and, more recently, after the Comair Flight 5191 disaster [NTS07] to address the issue of flight crew disorientation on the airport surface.

At present, there are three airport moving map solutions of industrial relevance. On the Airbus A380, the so-called Onboard Airport Navigation System (OANS) provides an airport moving map display on the Navigation Display (ND) screen, as detailed in Section 3.1.1. Furthermore, Boeing subsidiary Jeppesen offers an airport moving map as an Electronic Flight Bag (EFB) application, which is discussed in Section 3.1.2. Last but not least, Aviation Communications and Surveillance Systems (ACSS), a joint venture of L-3 Communications and Thales, has recently developed another EFB application named SafeRoute encompassing airport moving map and CDTI functionality (Section 3.1.3).

Generally, Electronic Flight Bags are electronic display systems intended to reduce or eliminate the need for paper and other reference materials in the cockpit by replacing hard copy material, such as paper charts, that pilots typically find in their flight bags. According to FAA Advisory Circular 120-76A, EFB devices can be subdivided into three different classes [FAA03b]:

- **Class 1 EFB:** Portable Commercial-Off-The-Shelf (COTS)-based computer systems used for aircraft operations, such as flight crew laptops, that are not interconnected to aircraft systems, and do not require certification.
- **Class 2 EFB:** Portable and typically COTS-based systems connected to the aircraft during normal operations. As a minimum, data connections to aircraft systems, power supply and mounting devices require formal certification.
- **Class 3 EFB:** Fully installed equipment that requires formal certification.

Initially, airport moving map applications showing ownship position were limited to Class 3 EFB devices [FAA03b, FAA03c]. However, in view of the high number of Runway Incursions and the safety benefits expected by the use of airport moving map technology, the FAA eventually revised its policy in 2007 and now also permits airport moving maps with an ownship symbol on Class 2 EFBs [FAA07a]. This can be expected to result in a more widespread application of EFB-based airport moving maps, and has already lead to an increasing number of products on the market.

3.1.1 A380 Onboard Airport Navigation System (OANS)

Figure 13: A380 Cockpit Overview

The Airbus A380 is the first airliner offering an airport moving map integrated into the Electronic Flight Instrument System (EFIS).
The so-called Onboard Airport Navigation System (OANS) is capable of presenting an airport moving map supporting the conventional ARC, ROSE and PLAN modes on the Navigation Display (ND) screen on pilot request. As for the classic ND, range and mode are controlled via the corresponding selectors on the EFIS control panel in the glareshield. The airport moving map can be viewed in five fixed ranges of 5, 2, 1, 0.5 and 0.25 NM. Additionally, using the Keyboard and Cursor Control Unit (KCCU), pilots can call up a dedicated tab menu with additional soft controls in the display area immediately below the airport moving map, as shown in Figure 14. Among others, this menu enables pilots to select a different airport for display by entering ICAO code, IATA code or city name.
On the A380, the airport moving map can be used in conjunction with the so-called Taxi Camera System (TACS), a composition of several video streams showing an aircraft overview from the vertical stabilizer and the landing gear. The TACS, which can be displayed on the PFD screen on the ground as shown in Figure 14, is intended to improve awareness of the location of the aircraft and landing gear with respect to the taxiway edges. It was first introduced to support surface movement on the Airbus A340-600.

From a conceptual perspective, the A380 OANS is the closest realisation of the airport moving map concept proposed by the Institute of Flight Systems and Automatic Control since the late 1990s, cf. [Kub99]. Furthermore, in the years to follow, there has undeniably been mutual influence and exchange of information between Airbus and TUD through various European research projects such as ISAWARE, VICTORIA, ISAWARE II, EMMA, EMMA II and FLYSAFE.

Figure 14: Airbus A380 Onboard Airport Navigation System (OANS)

The OANS functionality is hosted on a dedicated line replaceable unit supplied by Thales and Diehl Aerospace, which feeds the airport moving map image into the EFIS via a video link.

3.1.2 Jeppesen Electronic Flight Bag – Taxi Position Awareness

Jeppesen's Electronic Flight Bag (EFB) is a solution for a paperless cockpit and mainly intended to replace paper charts. It can be hosted on different hardware platforms, depending on customer needs and airframer constraints. The EFB currently supports electronic, vector-graphics versions of Approach, Aerodrome and Airspace Charts, including Standard Instrument Departure (SID) and Arrival Route (STAR) procedures. Furthermore, Jeppesen offers a variety of additional functions for the EFB, ranging from cabin video surveillance to electronic aircraft and flight operations manuals. In the context of this thesis, however, the most interesting function is an airport moving map initially designated 'Taxi Position Awareness' (TPA), cf. [Jep05], which has been a featured application on Boeing's Class 3 EFB (Figure 15) since its introduction in 2003. At this time, it was the first product of its kind available for commercial aviation [Jep08, Psc08]. It is intended to support flight crews in orienting on the aerodrome surface by displaying the aircraft's position on the ground in relation to runways, taxiways and airport structures. In addition, the product brochure states that the airport moving map could contribute to a reduction or elimination of runway incursions by enhanced position awareness and decreased pilot workload, and also enhance the efficiency of ground operations [Jep05].

If the aircraft is on the ground, the Jeppesen airport moving map application is capable of auto-loading the AMDB for the appropriate airport, which is determined using the aircraft position from the Flight Management System and/or the GPS signal.

Figure 15: Boeing Electronic Flight Bag (EFB) with Jeppesen airport moving map on a B-777

Figure 16: Jeppesen airport moving map of Paris Charles-de-Gaulle Airport on EFB

Pilots can choose between two basic modes, a Track-up Mode displaying the aircraft position at the centre of the screen, with the map beneath appropriately moved and rotated, or a stationary Planning Mode in North-up orientation without ownship position [Jep05]. Figure 16 details the Human-Machine Interface (HMI) of the Jeppesen airport moving map on a Boeing Class 3 EFB in a Boeing 777. The display, manufactured by Astronautics, features a series of fixed-function keys on the upper and lower display frame, whereas the side frames are equipped with multi-functional keys (MFKs). These may be associated with different functions, depending on the chosen mode or the operational context.

Using the keys on the lower frame, the flight crew can zoom and pan the airport moving map as desired. Panning is presumably limited to the Planning Mode.
For zooming, there is a choice of four discrete ranges (0.5, 1, 2 NM and 'all airport') [Psc08]. With the lowest MFK on the right display frame, a menu with the main application options can be displayed and hidden. When activated, the applicable menu items are displayed in text boxes next to the MFKs, partially overlaying the airport moving map. Pilots can then use the MFKs to alternate between Track-up and Planning Mode, to show range rings or to search and select other airport maps available on board.

In 2008, Boeing had delivered Class 3 EFB to 48 customers for 345 aircraft; the precise fraction of aircraft also equipped with the Jeppesen airport moving map was not made public. However, after the FAA revised its policy to allow the visualisation of ownship position on airport moving maps hosted on Class 2 EFB devices, Jeppesen was also the first company to receive formal approval for an airport moving map application hosted on a NavAero Class 2 EFB, with Continental Airlines as launch customer [Jep08]. It can therefore be expected that the Jeppesen solution will see more widespread application in the retrofit market in the future.

3.1.3 ACSS SafeRoute

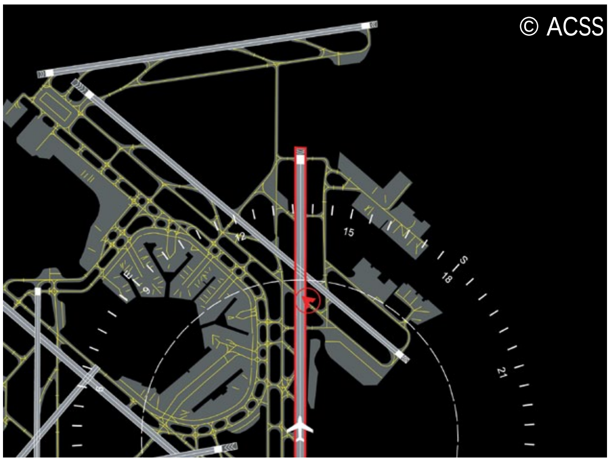


Figure 17: Initial SafeRoute Design (2005)

ACSS offers an EFB-based application named SafeRoute, which provides an airport moving map called Surface Area Movement and Management (SAMM) and a series of ADS-B based functions, including a Cockpit Display of Traffic Information (CDTI), a Merging and Spacing (M&S) application for arrival management and CDTI-assisted visual separation (CAVS). The use of TIS-B data as back-up is also possible.
Airport moving map and CDTI are hosted on a Boeing Class 3 EFB supplied by Astronautics Corporation of America, featuring software also developed by Astronautics according to ACSS specifications. The system uses databases supplied by Jeppesen.
On the ground, the EFB display can be switched to the airport moving map presentation, which visualises the aircraft's precise position/heading and the surrounding traffic. SafeRoute features a basic Runway Incursion prevention functionality based on ADS-B or TIS-B traffic data. Whenever ownship is approaching a runway that is used for take-off or landing, its outline is highlighted in red. The outline is changed to yellow when a landing aircraft is decelerating after touchdown[40]. Figure 17 shows the initial SafeRoute design presented when development was officially announced at the Paris Air Show in 2005 [ACS05]. SafeRoute received a supplementary type certificate in 2007 [ACS07].

Currently, the main SafeRoute customer is United Parcel Service (UPS), who was also strongly involved during the development phase. UPS is planning to install the system on its entire Boeing B-757 and B-767 fleets by the end of 2009. Figure 18 illustrates the location of the EFB with the SafeRoute application in the cockpit of a UPS Boeing 757 [Ger07]. Additionally, UPS intends to use the application to decrease taxi delays or inefficient routing to and from the parking positions at its Louisville (KSDF) hub [Flt07].

Figure 18: EFB with SafeRoute in a UPS B-757

It is important to note that the SafeRoute HMI has evolved considerably and in parallel to the work performed in the scope of this thesis. This aspect is discussed further in Section 9.2 on p. 384.

[40] This suggests that position information and a speed-based threshold are used to determine whether a runway is being used by traffic.

3.1.4 Aerodrome Mapping Databases (AMDB)

A crucial prerequisite for the development of the airport moving map from initial concepts to an operationally usable product was the availability of sufficiently standardised airport databases, which evolved in parallel to the airport moving map format concepts, cf. [Fri08]. In the future, these airport databases will also increasingly be used in the production of aerodrome charts [Psc08].

In order to achieve international standardisation and to enable an industrial-scale production of Aerodrome Mapping Databases (AMDBs), a number of standards have been created in recent years. The fundamental standard, RTCA DO-272/EUROCAE ED-99 "User Requirements for Aerodrome Mapping Information" [RTC01], predominantly influenced and created by the Institute of Flight Systems and Automatic Control, defines AMDB requirements regarding airport features and related attributes to be considered (i.e. content), including quality and processing. It has recently been superseded by a version A [RTC05].
This standard is supplemented by RTCA DO-291/EUROCAE ED-119 "Interchange Standards for Terrain, Obstacle, and Aerodrome Mapping Data" [RTC04], which defines in the meta-data and feature catalogue coding standards for the data, which enables data integrators and data originators to exchange AMDBs, provided that the database complies with these specifications [ARI06].
Based on these two standards, ARINC Specification 816 "Embedded Interchange Format for Airport Mapping Database" [ARI06] defines both coding, pre-processing (triangulation) and a physical file format for embedded avionics systems with the aim to give airlines as end-users a choice of different database providers irrespective of the avionics supplier.

In ARINC 816, the individual AMDBs (destinations and alternates) required for the operation of a defined fleet within an airline are assembled in a so-called "Airport Database" (ADB), which consists of the AMDB files of the individual airports and a configuration file containing available data. The configuration file is supplemented by a **C**yclic **R**edundancy **C**heck (CRC) file that also contains the CRCs of the individual AMDB files. As with the FMS navigation database, the aircraft always carries two AIRAC cycles of AMDB data. It is estimated that two AIRAC cycles of some 300 airports in medium resolution will roughly require 200 MB of storage space [ARI06].

3.2 Onboard Traffic Surveillance and Alerting Systems

3.2.1 Airborne Collision Avoidance System (ACAS)

To prevent airborne mid-air collisions, all turbine-engined aircraft with a maximum certified take-off mass in excess of 15,000 kg or authorisation to carry more than 30 passengers must be equipped with an Airborne Collision Avoidance System (ACAS II) since January 1st, 2003. As of January 1st, 2005, this worldwide mandate was extended to aircraft with a maximum take-off mass greater than 5,700 kg or more than 19 passengers, and ICAO recommends equipping all aircraft [ICA01c].

ACAS is a system based on air traffic control transponder technology. It interrogates the transponders of aircraft in the vicinity, analyses the replies to determine potential collision threats, and generates a presentation of the surrounding traffic for the flight crew. If other aircraft are determined to be a threat, appropriate alerts are provided to the flight crew to assure separation. Basic performance criteria for ACAS are defined in ICAO Annex 10 [ICA02a]. Currently, there are three ACAS versions: ACAS I is limited to the visualisation of proximate traffic and alerting to potential collision threats, whereas ACAS II is additionally capable of providing vertical escape manoeuvres to avert a collision. ACAS III is a projected future system offering horizontal escape manoeuvres as well.

Currently, the only ACAS implementation fulfilling the criteria of the ICAO ACAS mandate is the Traffic Alert and Collision Avoidance System (TCAS II), version 7, as described in RTCA DO-185A [RTC97]. It requires a Mode S transponder, but offers some backward compatibility with the older Mode A/C transponders. Therefore, the discussion in subsequent sections focuses on TCAS II as the current state-of-the-art[41].

3.2.1.1 Technical Realisation and Capabilities

Each Mode S transponder has a unique ICAO 24 bit address, which serves two purposes, unambiguous identification and the possibility to address communication to a specific aircraft. Interrogations from secondary surveillance radars (SSR) are transmitted on the 1030 MHz uplink frequency, whereas transponder replies and other transmissions are made on the 1090 MHz downlink frequency. Mode S communication occurs via 25 different up- and downlink formats (UF/DF) of either 56 or 112 bit overall length, serving the various surveillance purposes [ICA02a]. Mode S also encompasses data link capabilities with a maximum bandwidth of 4 Mbit/s [RTC97].

3.2.1.1.1 Traffic Surveillance

TCAS uses the Mode S and Mode C interrogation replies of other aircraft to calculate bearing, range and closure rate for each so-called 'intruder'. By combining this data with altitude information from transponder replies where available, three-dimensional tracks for at least 30 surrounding aircraft are established. Vertical speed estimates are derived from the change in altitude [RTC97]. These tracks are then used

[41] For the remainder of this thesis, all references to ACAS/TCAS without detailing a version are understood to relate to ACAS II or TCAS II, version 7, respectively.

to create a representation of the surrounding traffic for the flight crew (see Section 3.2.1.2) and analysed to determine potential collision threats.

Depending on aircraft configuration and external conditions, TCAS detection is typically limited to a range of 30…40 NM and encompasses a maximum vertical range of ± 9,900 ft (± 3,000 m) above and below ownship [Air05][42]. TCAS ranges are fairly accurate and usually determined with errors less than 50 m. However, the bearing error may be quite large: for elevation angles within ± 10°, the maximum permissible bearing error is 27°, and it may be as high as 45° for higher elevation values [RTC97].

3.2.1.1.2 *Conflict Detection and Resolution*

By extrapolating the acquired tracks for the surrounding traffic, TCAS calculates the Closest Point of Approach (CPA) and the estimated time τ before reaching this point for each intruder. Alerts are generated if the CPA for an intruder is within a certain τ and altitude threshold such that it might represent a collision hazard. To take into account the situation where aircraft tracks converge with low closure rates, there are additionally small fixed minimum distances (< 2,500 m) at which alerts are triggered irrespective of τ. For aircraft not reporting altitude, it is assumed that they are flying at the same altitude as ownship.

TCAS features two alert levels. It typically first generates a so-called Traffic Advisory (TA), a caution alert that there is potentially conflicting traffic. If the collision threat becomes real, TCAS determines an appropriate vertical evasive manoeuvre and triggers a Resolution Advisory (RA) warning, which identifies the intruder causing the conflict as well as the vertical manoeuvre and vertical rate required to resolve the conflict. In certain situations, depending on the geometry of the encounter or the quality and age of the vertical track data, an RA may be delayed or not selected at all. RAs are only generated for intruders reporting altitude.

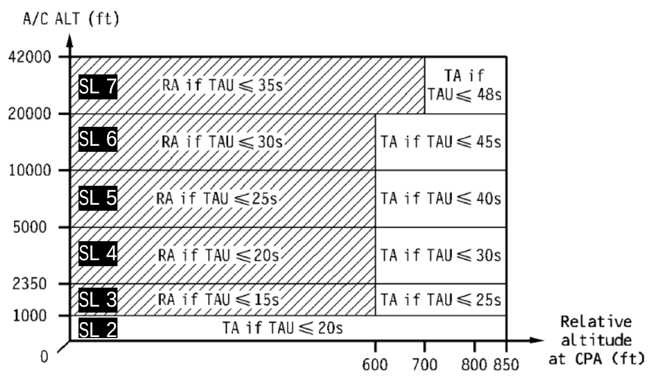


Figure 19: τ thresholds for TCAS TA and RA alerts as function of altitude [Air05]

The decision whether a Traffic Advisory or a Resolution Advisory alert is triggered essentially depends on the τ and relative altitude values presented in Figure 19.

The τ thresholds for triggering TA or RA alerts are dependent on aircraft altitude and vertical separation with the intruder at the CPA to obtain an optimum balance between efficient protection and a limitation of unnecessary alerts. To achieve this, seven discrete TCAS Sensitivity Levels (SL) have been defined, as shown in Figure 19. Sensitivity Level 2 only triggers Traffic Advisories for τ ≤ 20 s. Sensitivity Level 1 can only be selected manually by the crew (see below) and constitutes a special case, since TCAS interrogations are entirely inhibited.

[42] The required minimum values are 14 NM and ± 3,000 ft (± 1,000 m) [RTC97].

The collision avoidance logic used in determining nature and strength of the vertical evasive manoeuvre for Resolution Advisories is very complex due to the numerous special conditions. Additional complexity originates from the fact that TCAS is capable of handling multiple threat encounters. An exhaustive description of the TCAS logic can be found in Volume 2 of DO-185A [RTC97].

For intruders identified as threats, an appropriate Resolution Advisory evasive manoeuvre is determined, depending on the precise geometry of the encounter and a variety of other factors, such as range/altitude thresholds and aircraft performance. The evasive manoeuvre eventually chosen is instructed using one of the aural annunciations in Table 3, and the vertical rate range required to obtain safe separation is indicated on the vertical speed indicator, as detailed in Section 3.2.1.2 below.
Initially, TCAS will issue positive instructions, i.e. instruct a vertical rate to be flown, typically ± 1,500 ft/min. If necessary, e.g. if one of the flight crews involved fails to respond to the alert, the initial RA will be modified as required. This may result in negative instructions, e.g. in limiting the vertical speed, an increase of the climb or sink rate to 2,500 ft per minute. Even a complete reversal of the RA sense is possible. Eventually, when safe separation has been achieved, an explicit 'CLEAR OF CONFLICT' advisory is issued [FAA00, RTC97].

All Resolution Advisories are automatically converted into Traffic Advisories below 1,100 ft (340 m) radio altitude in climb and 900 ft (270 m) in descent. Furthermore, any TCAS callouts are inhibited below 500 ft (150 m) radio altitude. Additionally, in case of degraded performance (e.g. engine failure) or when operating in the vicinity of closely spaced runways, the flight crew can manually select a TCAS operational mode allowing only Traffic Advisories (Sensitivity Level 2). In this case, τ is set to a fixed value of 20 s, irrespective of altitude, and no vertical speed commands are generated. This TA-only mode is typically also selected automatically in the presence of the higher-prioritized windshear, stall or Terrain Awareness and Warning System (TAWS) warnings; in this case, all audio callouts are inhibited [Air05].

3.2.1.1.3 Coordination of Resolution Advisories

TCAS is capable of coordinating conflict resolution with other TCAS-equipped aircraft. To achieve this, the vertical sense selected for conflict resolution will be transmitted in negative form. As an example, the other aircraft will be sent a 'DON'T CLIMB' complement if ownship TCAS intends to solve the conflict by climbing, in order to restrict the other aircraft's choice of vertical sense.
Since TCAS-equipped aircraft will, for the vast majority of cases, classify each other as threats at slightly different points in time, coordination is usually straightforward: the first aircraft selects and transmits its geometry-based sense and, slightly later, the second aircraft, taking into account the first aircraft's coordination message, selects and transmits the opposite sense. In certain special cases such as simultaneous coordination, both aircraft may select and transmit a sense independently based on the perceived encounter geometry. If these senses turn out to be incompatible, the aircraft with the higher Mode S address will reverse its sense, displaying and announcing the reversed RA to the pilot [RTC97].

3.2.1.2 Flight Crew Interface

The flight crew interface of TCAS encompasses three major components, the traffic display, a control panel and means of presenting resolution advisories.

3.2.1.2.1 *Traffic Display*

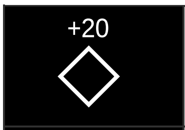
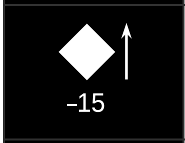
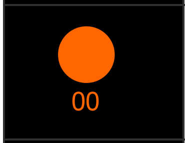
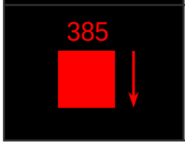
	**Other Traffic:** Basic TCAS traffic symbol, a white[43] or cyan diamond.
	**Proximate Traffic:** Traffic within 5 NM horizontally and 1500 ft vertically, a filled white or cyan diamond.
	**Traffic Advisory:** All traffic for which a TA is pertinent shall be presented by an amber or yellow circle.
	**Resolution Advisory:** Traffic causing a resolution advisory shall be indicated by a red square.

Figure 20: TCAS symbology (after [RTC97])

The TCAS traffic display is intended to aid pilots in the visual acquisition of traffic, including the differentiation of intruder threat levels, to provide situational awareness and to instil confidence in the presented resolution advisories.
The traffic display function must be capable of displaying at least eight other aircraft, called 'intruders' in TCAS terminology. Since all traffic tracked by TCAS is ranked by the collision avoidance logic, intruders are sent to the display in a prioritized order, thus ensuring that those intruders most relevant to collision avoidance are displayed.
Traffic is displayed in relation to a symbol reflecting ownship position[44], on a display featuring range rings, see Figure 21. The representation of other traffic is typically limited to a vertical volume of ± 2700 ft, and the symbology used depends on alert state and proximity of the corresponding traffic, as shown in Figure 20.

Figure 21: Airbus A320 family EFIS with TCAS traffic presented on ND

[43] The preferred colour, where specified, is underlined.
[44] DO-185A specifies cyan as the preferred colour for the ownship symbol, but neither Airbus (yellow), Boeing (magenta), Bombardier nor Embraer (white) comply with this standard. However, at least the basic requirement that ownship symbol must be coloured differently than other/proximate traffic is fulfilled.

Traffic symbols are supplemented by a two-digit altitude data tag in the same colour as the intruder symbol, indicating the altitude of the intruder aircraft relative to ownship in hundreds of feet. For traffic above the own aircraft, the tag is placed above the traffic symbol and preceded by a '+', whereas other aircraft below ownship feature the tag below the symbol with a '–' as prefix. For traffic at the same altitude, '00' is displayed, and the position of the tag depends on whether the respective traffic has closed in from above or below[45]. The absence of the altitude data tag indicates a non-altitude reporting intruder. Optionally, on pilot selection, the reported intruder altitude may be indicated in lieu of the relative altitude. Actual altitude tags are be positioned above or below the traffic symbol in a manner consistent with the relative altitude data tags. If other traffic is climbing or descending with a rate of 500 ft/min or more, an upward or downward arrow in the same colour as the intruder symbol is displayed to the right of the symbol.

In case bearing information is unavailable for traffic generating either a TA or RA alert, alpha-numeric information is presented on the traffic display for up to two intruders, usually centred below the ownship symbol. Information is presented in the format threat level – range (in NM) – altitude (in 100 ft, consistent with absolute/relative altitude setting) and, if applicable, an intruder vertical speed arrow. As an example, "TA 5.2 –06↑" represents an intruder causing a TA at 5.2 NM with a relative altitude of –600 feet, which is climbing with 500 ft/min or more[46].

With a TA or RA in progress, the aircraft causing the alert and all proximate traffic within the selected display range is shown. However, it is recommended that all other traffic is displayed as well to increase the probability that pilots visually acquire the aircraft actually causing the alert.

3.2.1.2.2 TCAS Control Panel

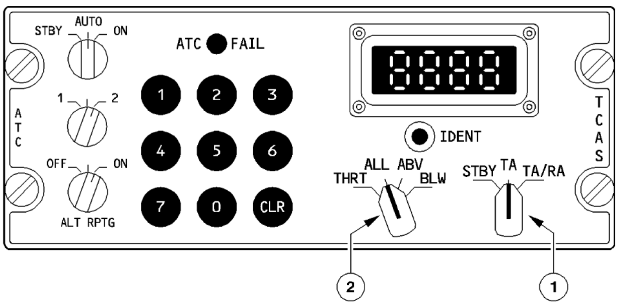


Figure 22: Airbus A320 ATC/TCAS Control Panel [Air05]

Flight crews must be provided with controls to select an automatic mode of operation for ACAS, a mode in which only TAs can be issued (SL 2), and a standby mode (SL 1), which inhibits interrogation of other traffic. Controls for ACAS may be integrated with those for the Mode S transponder, provided that a transponder-only mode is available [ICA02a].

On Airbus A320 family and A330/340 aircraft, TCAS operation and the display of TCAS traffic are controlled by the so-called ATC/TCAS panel located in the centre pedestal, cf. Figure 22, which integrates transponder and ACAS controls. Apart from controls for the TCAS mode of operation as described above (1), the panel contains another selector (2) providing the crew with three pre-defined settings to adjust the

45 If no trend information is available, the co-altitude altitude data tag is displayed below the traffic symbol.

46 For a non-altitude reporting intruder, the corresponding part of the string is removed, i.e. "TA 5.2" would be displayed in the above example.

vertical extension of the traffic "volume" to be displayed, 'ABOVE', 'ALL' (also called 'NORMAL' on some other aircraft) and 'BELOW'; turning the selector to "THREAT" will only show traffic in case a TA or RA alert is present [Air05].

3.2.1.2.3 Presentation of Alerts

Resolution Advisory Type	Aural Annunciation	Visual Alert[47]
Corrective Climb	*Climb, Climb*	CLIMB
Corrective Descend	*Descend, Descend*	DESCEND
Altitude Crossing Climb (Corrective)	*Climb, Crossing Climb — Climb, Crossing Climb*	CROSSING CLIMB
Altitude Crossing Descend (Corrective)	*Descend, Crossing Descend — Descend, Crossing Descend*	CROSSING DESCEND
Corrective Reduce Climb	*Adjust Vertical Speed, Adjust*	ADJUST V/S
Corrective Reduce Descent	*Adjust Vertical Speed, Adjust*	ADJUST V/S
Reversal to a Climb (Corrective)	*Climb, Climb NOW — Climb, Climb NOW*	CLIMB NOW
Reversal to a Descend (Corrective)	*Descend, Descend NOW — Descend, Descend NOW*	DESCEND NOW
Increase Climb (Corrective)	*Increase Climb, Increase Climb*	INCREASE CLIMB
Increase Descent (Corrective)	*Increase Descent, Increase Descent*	INCREASE DESCENT
Initial Preventive RAs	*Monitor Vertical Speed*	MONITOR V/S
Non-crossing, maintain rate RAs (Corrective)	*Maintain Vertical Speed, Maintain*	MAINTAIN V/S
Altitude crossing, maintain rate RAs (Corrective)	*Maintain Vertical Speed, Crossing Maintain*	MAINTAIN V/S CROSSING
Weakening of Corrective RAs	*Adjust Vertical Speed, Adjust*	ADJUST V/S
Clear of Conflict	*Clear of Conflict*	CLEAR OF CONFLICT

Table 3: TCAS RA Aural Annunciations and Visual Alerts [RTC97]

Table 3 details the aural annunciations for the different types of Resolution Advisories. In some implementations, aural annunciations are supplemented by textual messages (essentially repeating the callout) at a prominent location in the flight deck.
In the presence of multiple RAs, the presentation of alerts to the flight crew is combined, such that the most demanding active RA is displayed. Figure 23 shows a TCAS vertical speed range indicated on the vertical speed scale of a PFD. The presentation details whether an RA requires corrective action, or merely warns against initiating an action that could lead to inadequate vertical separation.
All positive RAs are displayed with a green "fly-to" indication detailing the corrective action. By contrast, vertical speed ranges to be avoided, including all negative RAs, are represented in red [RTC97]. In the example shown, the flight crew would have to (maintain) descent with 2,500 ft/min.

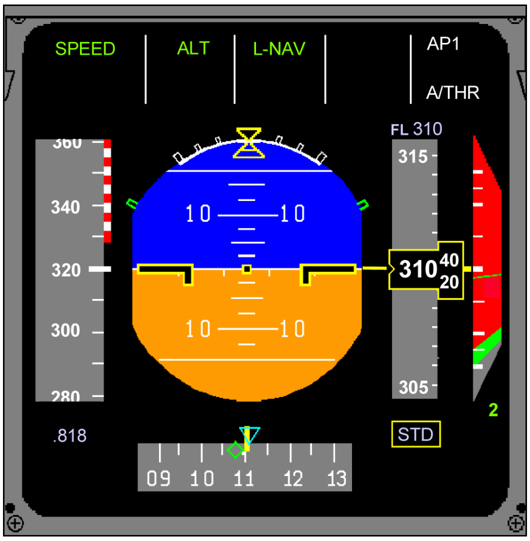


Figure 23: TCAS vertical speed command indication on a PFD [FAA00]

[47] A visual indication of these text messages is not mandatory.

3.2.2 Automatic Dependent Surveillance – Broadcast (ADS-B)

Automatic Dependent Surveillance – Broadcast (ADS-B) is a function enabling aircraft, irrespective of whether they are airborne or on the ground, and other relevant airport surface traffic, to periodically transmit their state vector (horizontal and vertical position, horizontal and vertical velocity) and other surveillance information for use by other traffic in the vicinity or users on the ground, such as Air Traffic Control or the airline. This surveillance information, which is dependent on data obtained from various onboard data sources, such as the air data or navigation system, is broadcast automatically and does not require any pilot action or external stimulus. Likewise, the aircraft or vehicle originating the broadcast does not receive any feedback on whether other users within range of this broadcast, either aircraft or ground-based, decode and process the ADS-B surveillance information or not. ADS-B was conceived to support improved use of airspace, reduced ceiling and visibility restrictions, improved surface surveillance, and enhanced safety, such as conflict management [RTC03]. As an example, ADS-B may extend surveillance coverage and provide ATS services in airspace currently not served by radar-based surveillance systems, or support advanced concepts, such as Free Flight, in all airspace while maintaining a high level of flight safety [RTC02].
There will be ADS-B mandates in Australia, Canada, Europe and the United States in the foreseeable future [Eur08b, FAA07b], since ADS-B is a core technology for the future ATM concepts currently under development, as discussed in Section 3.5.3.

3.2.2.1 Technical Realisation and Capabilities

In principle, ADS-B defines a set of data to be exchanged and is independent of any particular type of data link. The only requirement on the data link is that it must be capable of all-weather operations and fulfil the basic ADS-B capacity and integrity requirements. ADS-B system capacity was derived based on 2020 traffic estimates for the Los Angeles basin. It is assumed that, for a high density scenario, there will be approximately 2,700 other aircraft within 400 NM, of which 1,180 are within the core area of 225 NM, and 225 on the ground. The nominal ADS-B range is between 10…120 NM, depending on the type of emitter. ADS-B integrity, i.e. the probability of an undetected error in an ADS-B message although source data are correct, must be 10^{-6} or better on a per report basis [RTC02].

3.2.2.1.1 Implementation via Mode S Extended Squitter

The ADS-B implementation that will eventually become an international standard is based on the Mode S transponder. Apart from the normal, periodically transmitted Mode S squitters (DF = 11), which are, among others, used by multi-lateration installations and ACAS, there is an additional 112 bit Mode S Extended Squitter (ES) message (DF = 17), which is broadcast via the 1090 MHz downlink frequency[48]. Apart from the broadcasting aircraft's unique ICAO 24 bit address and a capability code, it contains a 56 bit message field (ME) that can be filled with one of the following sub-messages, according to the schedule and the conditions specified below [RTC03]:

[48] For this reason, the Mode S implementation of ADS-B is commonly referred to as "1090 ES".

- **Airborne Position Message (0.4…0.6 s[49]):** As soon as the aircraft is airborne, it automatically transmits its position, encoded via latitude/longitude, and altitude. Position information is supplemented by a Horizontal Containment Radius Limit (R_C), expressed via the Navigation Integrity Category (NIC).
- **Surface Position Message (0.4…0.6 s):** While the aircraft is on the ground[50], it broadcasts this message containing a specifically encoded ground speed, heading or track, latitude /longitude and the Containment Radius (RC), instead of the Airborne Position Message. If the aircraft's position changes by less than 10 m in 30 s, the transmission interval is increased to 4.8 … 5.2 s. With increasing ground speed, the quantisation interval increases from 0.125 kts to 5 kts, and the highest encodable ground speed is 175 kts. Up to 70 kts, speed resolution is 1 kt or better; this halves until 100 kts, and speed resolution degrades to 5 kts above 100 kts.
- **Aircraft Identification and Type Message (4.8…5.2 s):** Irrespective of flight status, a message containing an 8 character field for the aircraft flight-plan call-sign (e.g. an airline flight number) if available, or the aircraft registration, is broadcast. For surface vehicles, the radio call sign is used. The message also contains the ADS-B emitter category, permitting a distinction between aircraft (including different wake vortex categories), gliders/balloons and vehicles, where e.g. service and emergency vehicles can be distinguished. When the surface position message is broadcast at the low rate, the transmission rate of this message is lowered to once every 9.8…10.2 s.
- **Airborne Velocity Message (0.4…0.6 s):** While airborne, ADS-B equipped aircraft transmit their vertical and horizontal velocity, including information on the Navigation Accuracy Category (NAC_V). For subsonic aircraft, horizontal speed is encoded using heading/track and groundspeed, providing a resolution of 1 knot between 0 and 1021 kts.
- **Target State and Status (conditional, 1.3…1.4 s):** This message conveys an aircraft's target heading/track, speed, vertical mode and altitude. In addition, it contains a flag detailing ACAS operational status, and an emergency flag that can be used to announce presence and type of an emergency (i.e. medical, minimum fuel, or unlawful interference). However, the message is only transmitted when the aircraft is airborne, and if target status information is available and valid.
- **Aircraft Operational Status (conditional, every 2.4…2.6 s):** This message provides an exhaustive overview of an aircraft's operational status, including both equipment aspects (such as the availability of a CDTI) and navigation performance, e.g. the Navigation Integrity Category (NIC), the Navigation Accuracy Category (NAC) and the Surveillance Integrity Level (SIL). This is intended to enable surveillance applications to determine whether the reported position etc. has an acceptable accuracy and integrity for the intended function. On the ground, the transmission interval is reduced to 4.8…5.2 seconds, but can also be increased for 24 seconds following a significant change.

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[49] The ADS-B message update rate specified in this fashion means that messages are sent at random intervals (in relation to the preceding transmission), which are uniformly distributed over the specified time range, using a time quantization of no more than 15 ms [ICA02a, RTC03].

[50] Typically, an aircraft's air/ground logic or switch is used to determine that it is on the ground. Alternatively, with either groundspeed or airspeed smaller than 100 kts, or radio altitudes below 50 ft, the aircraft is supposed to be on the ground, and the Surface Position Message is broadcast [RTC06].

In addition, besides status and test messages, several further formats are envisaged for future growth potential, such as the exchange of trajectory data. Non-transponder broadcasters, such as airport vehicles, use a different downlink format (DF = 18), and DF=19 is reserved for military aircraft and applications.
Since transponders must currently be limited to 6.2 ADS-B messages per second, there are on average two Airborne Position Messages, two Airborne Velocity messages and 0.2 Identification messages, supplemented by up to two event-driven messages. Position messages have priority over velocity, identification and conditional messages [RTC03].

For surface operations, a positional accuracy of 2.5 m (root mean square, from the certified navigation centre of the aircraft) and a velocity accuracy of 0.3 m/s (RMS) are required. The ADS-B latency of the reported state vector information must be less than 1.2 s with 95% confidence, except for high accuracy/integrity reports ($NAC_P \geq 10$ or $NIC \geq 9$), where latency is required to be below 0.4 s [RTC02].

3.2.2.1.2 Limitations

The main issue with the 1090 MHz Extended Squitter ADS-B implementation is the undesirable overlap with other ATC transponder transmissions. Although sophisticated message reception techniques detailed in DO-260A provide a high probability of correct reception even when the desired squitter is overlapped with an interfering Air Traffic Control Radar Beacon System (ATCRBS) reply of equal or greater power. Nonetheless, in some high interference environments, such as Los Angeles or Frankfurt, there is a relatively high probability that the desired squitter signal will be overlapped with two or more ATCRBS replies, thus reducing the effective air-to-air range as a result of this interference [RTC03].

3.2.2.1.3 Alternative realisations and variants

This section gives a very brief overview of alternative ADS-B realisations and variants that are considered for General Aviation or were tested as alternatives to Mode 1090 ES [RTC02].

Universal Access Transceiver (UAT)

In the United States, the so-called Universal Access Transceiver (UAT) is foreseen as the general aviation ADS-B implementation, because the associated equipment is more affordable than the 1090 ES solution. UATs operate at a frequency of 978 MHz.

ADS-R

The fact that two different ADS-B implementations, UAT and Mode 1090 ES, will coexist in the United States for different types of aircraft operating in the same airspace raises the question of how particularly onboard ADS-B users will be capable of obtaining a complete traffic surveillance picture. The solution envisaged by the FAA is to use ADS-B Re-Broadcast (ADS-R). Ground-based transceivers will be used to broadcast ADS-B messages received via Mode S Extended Squitter over the UAT frequency, and vice versa. Conceptually, ADS-R is therefore sometimes seen within the scope of Traffic Information Service – Broadcast (TIS-B), cf. Section 3.2.3.

VDL Mode 4

An ADS-B implementation using VDL Mode 4 was primarily used in European research programmes, such as the NEAN project family [RTC00a]. The obvious advantage of a VDL Mode 4 solution is that it relieves the Mode S channel, which might become increasingly crowded in terminal airspace (cf. Section 3.2.2.1.2), since it uses an entirely different frequency band. However, this results in the obvious disadvantage that additional radio equipment and antennas are required for an ADS-B implementation via ADS-B, which is the reason why the 1090 ES solution was eventually favoured and has become the de-factor standard.

3.2.2.2 Proposed Applications

3.2.2.2.1 Cockpit Display of Traffic Information (CDTI)

The basic ADS-B application from an onboard perspective is a CDTI, which is mainly intended to improve awareness of proximate traffic, both in the air and on the ground. In addition, depending on how complete the coverage of surrounding traffic is, a CDTI may also serve as an aid to visual acquisition, thus supporting normal "see and avoid" operations. A CDTI is not limited to a single or particular source of traffic data. Therefore, information from TIS-B or TCAS can be integrated as well.

It is important to note that a CDTI is conceptually not limited to traffic presentation, but can also be used to visualise weather, terrain, airspace structure, obstructions, detailed airport maps or any other static information deemed relevant for the intended function. Last but not least, a CDTI is required for a number of envisaged future onboard applications (see below), particularly Free Flight operations [RTC02].

3.2.2.2.2 Airborne Collision Avoidance

ADS-B is seen as a valuable technology to enhance operation of Airborne Collision Avoidance Systems (ACAS), e.g. by increased surveillance performance, more accurate trajectory prediction, and an improved collision avoidance logic. In particular, the availability of intent information in ADS-B is seen as an important means of reducing the number of unnecessary alerts. Furthermore, DO-242A proposes extended collision avoidance below 1000 ft above ground level and the ability to detect Runway Incursions as potential ADS-B applications and benefits [RTC02].

3.2.2.2.3 Conflict Management and Airspace Deconfliction

Aircraft conflict management functions are envisaged to be used in support of cooperative separation whenever responsibility has been delegated to the aircraft. Airspace deconfliction based on the exchange of intent information will be used for strategic separation. Since pilot and controller share the same surveillance picture, resolution manoeuvres are expected to be better coordinated [RTC02].

3.2.2.2.4 ATS Conformance Monitoring

ATS conformance monitoring is the process of ensuring that aircraft maintain on the assigned or agreed trajectory, both in the air or on the ground, with an acceptable degree of deviation. Conformance monitoring occurs for all controlled aircraft or airspace, and includes monitoring of simultaneous approaches or departures to/from multiple runways and surface operations [RTC02].

3.2.2.2.5 Other Applications

Other potential ADS-B applications mentioned in DO-242 A include general aviation operations control, improved search and rescue, enhanced flight following, and additional functions addressing Aircraft Rescue and Fire Fighting (ARFF) or other airport ground vehicle operational needs [RTC02].

3.2.3 Traffic Information Service – Broadcast (TIS-B)

The fundamental idea behind TIS-B is to extend the use of traffic surveillance data readily available on the ground, which are typically derived from ATC surveillance radars, multi-lateration installations or other ground-based equipment, to enhanced traffic situational awareness and surveillance applications aboard aircraft or airport vehicles. Essentially, TIS-B is therefore a function in which transmitters on the ground provide aircraft, airport vehicles or other users with information about nearby traffic [RTC03].

When based on ATC surveillance data, TIS-B enables pilots, vehicle drivers and controllers to share the same traffic picture, which is important in the context of ATM concepts promulgating collaborative decision making. Likewise, TIS-B addresses the essential problem of non-cooperative traffic, and thus the issues concerning the completeness and quality of the traffic surveillance picture available onboard, particularly in a transition phase with ADS-B equipage levels still low. In fact, TIS-B is sometimes regarded only as an interim or back-up solution [RTC03].

Apart from ground-based surveillance sensors, TIS-B information might also be based on received ADS-B Messages originally transmitted on a different data link [RTC03]; from this perspective, TIS-B would include ADS-R. For the purpose of this thesis, however, these services are considered separately, under the notion that ADS-R is a simple repeater function, whereas TIS-B typically involves sophisticated sensor data fusion.

3.2.3.1 Technical Realisation and Capabilities

Originally, like ADS-B, TIS-B is a data exchange concept not specifying a particular data link or exchange protocol. However, as for ADS-B, the use of the Mode S data link capability is defined in RTCA DO-260A [RTC03].

Consequently, TIS-B data are broadcast via the Mode S downlink frequency of 1090 MHz, using 112 bit messages (DF = 18). TIS-B ground-to-air transmissions use essentially the same signal formats as 1090 MHz ADS-B and can therefore be accepted by a 1090 MHz ADS-B receiver:

- **TIS-B Fine Airborne Position Message:** corresponds to the ADS-B Airborne Position Message
- **TIS-B Fine Surface Position Message:** corresponds to the ADS-B Surface Position Message
- **TIS-B Identification and Type Message:** corresponds to the ADS-B Identification and Type Message, but will only be used for targets with a 24 bit aircraft address
- **TIS-B Airborne Velocity Message:** corresponds to the ADS-B Airborne Velocity Message
- **TIS-B Coarse Airborne Position Message:** this message does not correspond to any ADS-B message.
- **TIS-B Coarse Airborne Velocity Message:** this message does not correspond to any ADS-B message.

Technically, the main difference between ADS-B and TIS-B is that the aircraft address field can also contain a 12 bit Mode A address and a 12 bit track file number in case the target transmitted via TIS-B is not equipped with a Mode S-transponder and was acquired by radar.

Each TIS-B message contains information on a single aircraft or vehicle, i.e. the Mode S message load increases dramatically in high-density airspace.
Another concern related to TIS-B is that its update rate will typically be significantly lower than the ADS-B update rate, because secondary surveillance radars, depending on their rotation speed, only provide updates every 5-12 seconds. Additionally, it is believed that latency effects will limit the operational usability of TIS-B data.

TIS-B should not be confused with Traffic Information Service (TIS), another Mode S data link service capable of providing information on up to eight traffic targets within 5 nautical miles and 1,200 ft (370 m) AGL, which seems to have become obsolete with the advent of TIS-B [RTC97a, RTC98]. With a possible range quantisation of 1/8 NM (~ 230 m) and bearing encoded in 6° steps, TIS is obviously not a suitable source for aerodrome traffic surveillance.

3.2.3.2 Proposed Applications

The proposed applications are essentially the same as for ADS-B; see Section 3.2.2.2.

3.3 Onboard Systems for Runway Incursion Avoidance

3.3.1 Honeywell's Runway Awareness and Advisory System (RAAS)

In the domain of alerting systems, Honeywell offers a Runway Awareness and Advisory System (RAAS), packaged as an add-on to EGPWS that provides aural advisories and alerts with respect to runway operations. The RAAS provides the flight crew with five 'routine' advisories intended to reduce the risk of a Runway Incursion, three of which are triggered regularly during normal operations. These include an "Approaching Runway" and "On Runway" aural advisory that is immediately followed by an announcement of the corresponding runway identifier. Furthermore, the third routine aural advisory announces the runway distance remaining. Additionally, a feature intended to prevent flight crews from taking off on a taxiway provides an alert if a certain speed limit is exceeded outside the runway [Hon03]. Last but not least, the system is also capable of alerting flight crews if the available runway distance is not sufficient for take-off.

One of the main features of RAAS is the fact that it interfaces with the flight crew solely through the audio channel. This poses the risk of an undesirable level of interference with crew procedures during the taxi phase (check lists, cabin report etc.) and communication with ATC over R/T. In addition to this, the advisories are unspecific and do not take into account the operational situation and clearances, i.e. the crew will hear the "Approaching Runway" and "On Runway" audio messages irrespective of whether they are cleared to enter the runway in question or not. This might, eventually, result in crew complacency towards the advisory.

3.3.2 NASA's Runway Incursion Prevention System (RIPS)

Last but not least, more in the field of research, NASA's Runway Incursion Prevention System (RIPS) has to be mentioned. Using the FAA definition of Runway Incursions as a starting point, it focuses on the detection of potential traffic collision hazards on the runway and provides visual and aural alerts in case of conflict.
The underlying Runway Safety Monitor (RSM) algorithm uses information on the runway and a customizable, three-dimensional protection zone around it to determine whether ownship is in conflict with other ADS-B equipped traffic on the same runway, a crossing runway or an intersecting flight path. If this is the case, a single alert is issued irrespective of the hazardous situation triggering it, and the system is not yet capable of providing conflict resolution guidance [Gre06].

Alerts when deviating from a taxi route assigned via CPDLC or crossing a holding position without appropriate clearance were briefly reported in connection with the RIPS recently, but these seem to have played a minor role in recent flight test evaluations carried out with the RIPS [Jon05]. Flight test results for the RIPS indicate that onboard alerting for conflicting runway traffic is feasible, and RIPS is certainly one of the most advanced projects in this domain, with first flight tests back in 2000.

3.3.3 Honeywell/Sensis Uplink of ASDE-X Alerts via Mode S

ATC surveillance systems like AMASS or the ASDE-X Safety Logic are capable of alerting air traffic controllers of potential Runway Incursions, see Sections 3.5.1.3 and 3.5.1.4. Currently, however, these alerts are presented to controllers only, who must subsequently warn pilots via voice, which results in less than optimal response times.

In an effort to overcome this limitation, Honeywell and Sensis demonstrated the feasibility of up-linking Runway Incursion alerts generated on the ground by the ASDE-X Safety Logic directly to the flight deck in August 2007.
With the demonstrated technology, a Runway Incursion detected by ASDE-X will not only be conveyed to the air traffic controller, but also be up-linked to the aircraft involved in the conflict via unused existing Mode S message fields. Upon receipt, the modified TCAS software aboard the aircraft will trigger an aural alert to warn pilots of the potential Runway Incursion. Details on the callouts or operational procedures envisaged for using the system are currently not publicly known, and it appears that there are currently no plans to develop a product based on this technology demonstration.

A benefit of the demonstrated solution is that it allows a simultaneous presentation of Runway Incursion alerts to both air traffic controllers and pilots. An additional advantage of this solution is that it uses existing ground and avionics systems, which limits the required equipment changes to software modifications. However, a presentation of the conflicting traffic in the cockpit is not possible, and the alerting capability would initially only be available at the 35 high traffic density airports that are in the progress of receiving ASDE-X installations [Sen07].

3.4 Existing and Emerging Data Link Functionality

This section is dedicated to a brief review of existing and emerging data link functionality currently in use to exchange information between aircraft systems and ground installations. Generally, the use of data link services aboard aircraft can be grouped in two categories, communication with Airline Operations Control (AOC) and interfacing data link Air Traffic Services (ATS), the latter consisting of Controller-Pilot Data Link Communication (CPDLC), Automatic Dependent Surveillance (ADS) and Data Link Flight Information Services (FIS). Along with aviation routine weather reports (METAR), D-ATIS is currently the only data link FIS of practical relevance [ICA99]. In virtually all cases, the introduction of data link communication is driven by the need to decrease frequency congestion and communication workload. The latter also encompasses the automation of routine status messages, as in the case of ADS, which enables automated position reporting to ATC based on a Global Navigation Satellite System (GNSS) in areas inaccessible to radar surveillance without flight crew interaction.

The usage of data link was pioneered in the domain of AOC communication by the Airborne Communications Addressing and Reporting System (ACARS), which was introduced in 1978 using a low-speed Very High Frequency (VHF) data link and a character-based transmission protocol limited to a bandwidth of 2.4 kBit/s, which is also referred to as VHF Digital Link (VDL) Mode A [Air04a]. ACARS applications can be customized and may encompass automated on block/off block messages, flight plan upload, the exchange of brief text messages between cockpit and AOC, or the automatic transmission of maintenance data. Due to bandwidth constraints, an alternative VHF data link protocol, VDL Mode 2, nominally operating at 31.5 kBit/s, was eventually developed. However, since VHF is limited to line-of-sight coverage with a range of approximately 240 NM (440 km) at 30,000ft, additional ACARS implementations via High-Frequency Data Link (HFDL), featuring only 1.8 kBit/s, but a range of more than 4000 km and better availability than HF voice, as well SATCOM (64 kBit/s or more) were subsequently introduced to satisfy airlines' worldwide communication needs.
In parallel, the ICAO council tasked its special committee on Future Air Navigation Systems (FANS) to make recommendations concerning the upgrade of communications, navigation and surveillance systems to cope with increasing world wide air traffic [Air04b]. Among others, these activities resulted in the definition of a standardised Aeronautical Telecommunication Network (ATN) for ATS applications, also based ob VDL Mode 2. Nevertheless, the development and introduction of the ATN was delayed; it is currently entering service in Europe. Consequently, ACARS has been used in the meantime to obtain ATIS and METAR information from ATS via AOC. Besides, the ACARS infrastructure is even used for initial CPDLC applications [Air04a].

The following two sections give a brief overview of the current status of the two data link applications of highest relevance for this thesis, CPDLC and the retrieval of information on the operational environment, which is illustrated using the FANS A/B CPDLC implementation (see Figure 25) and D-ATIS as most prominent examples.

3.4.1 CPDLC and Future Air Navigation System (FANS)

Concerning the interaction with Air Traffic Services, CPDLC and ADS first emerged in an operational context over the South Pacific Ocean, cf. [Bil96], an area inaccessible to the means of Air Traffic Control commonly employed in continental airspace. Previously, the absence of radar surveillance and the fact that aircraft operate beyond the range of VHF stations required procedural ATC using HF radio, which only has very poor voice quality due to fading, and relying on crew reports at certain predefined waypoints. This resulted in an inflexible system necessitating very large safety distances between adjacent aircraft.

By contrast, CPDLC permits to sustain data link communications between pilot and controller, particularly in areas where voice communications are difficult. Like conventional R/T, CPDLC is based on the exchange of standardized message elements, which can be combined to complex messages if necessary. The philosophy that the crew is obliged to read back all safety-related ATC clearances is retained in a CPDLC environment [ICA01a] by the implementation of a dedicated acknowledgement process [FAN06]. The approximately 180 pre-formatted CPDLC message elements defined for the FANS A (via ACARS) and B (ATN) implementations are analogues of the existing ICAO phraseology, with the important difference that CPDLC messages are machine-readable. This is achieved by allocating a certain identification code to each individual message element, and permitting certain parameters such as flight level, heading or waypoint names to be transmitted separately as variables [FAN06].

Until today, the main application of CPDLC is in oceanic airspace. Besides, it is widely used in conveying pre-departure clearances to aircraft at airports to avoid radio frequency congestion and to reduce the chances of errors in the clearance delivery process. It is important to note that operational use is currently limited to fields where the interaction between pilot and controller is not time critical.

In Europe, CPDLC is currently envisaged as supplementary means of communication and not intended to replace voice as primary means of communication. Rather, it will be used for an exchange of routine, non-time critical instructions, clearances and requests between flight crew and controller.

Figure 24: Location of DCDU equipment in an Airbus A330 cockpit

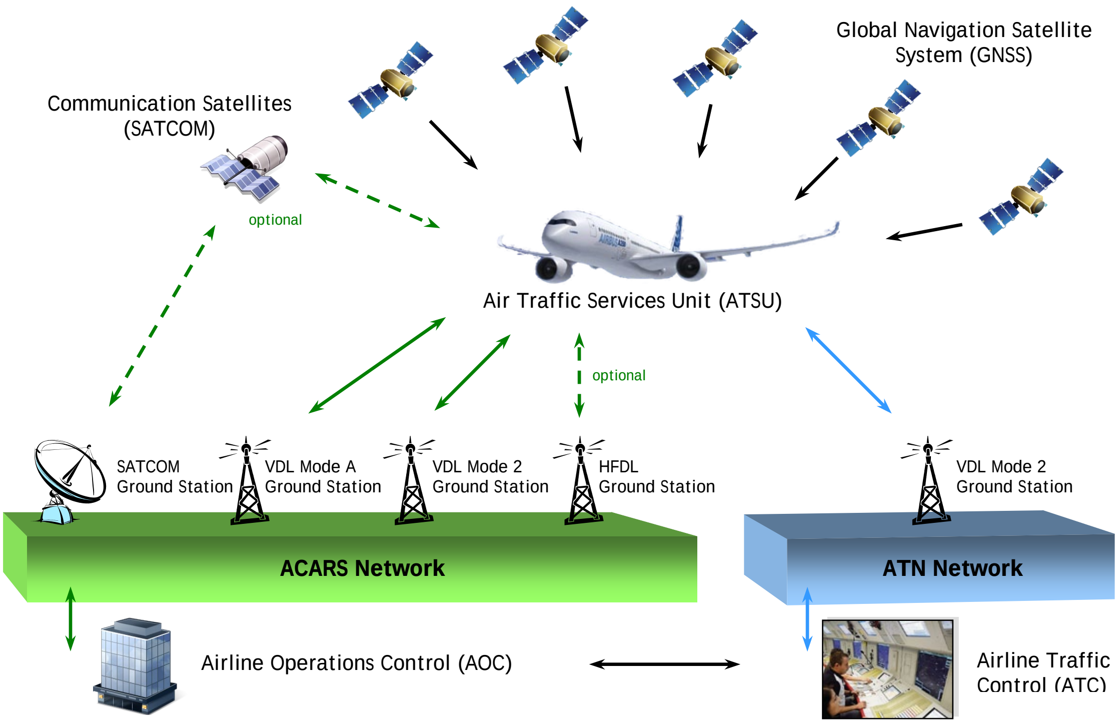

Figure 25: FANS B architecture for CPDLC and AOC communication (after [Air08])

Initially, it will be applied to upper airspace control above FL 285 [Eur09]. Accordingly, initial trials using the ATN are taking place at Maastricht UAC. From 2013 to 2015, the ATM-side introduction will take place. For aircraft, a forward fit of new airframes is foreseen from 2011, and retrofit by 2015. In any case, the operational decision to use CPDLC rests with the flight crew and the controller.

Figure 25 shows a typical FANS B architecture. Aboard the aircraft, a so-called Air Traffic Services Unit (ATSU) manages communication with AOC and ATC via the various available data links, some of which are customer options. The main difference compared to FANS A is that communication with ATC occurs via the ATN instead of ACARS. In the cockpit, the flight crew is notified of a new incoming ATC message by an indicator on the glareshield and a ringing sound. Pilots may then review the ATC instruction and acknowledge it, reject it or ask for more time to assess its impact. On the Airbus A320/A330/A340 aircraft families, the so-called Datalink Control and Display Unit (DCDU), illustrated in Figure 24, is used to review and acknowledge ATC CDPDLC messages. In case the flight crew need to initialize a request to ATC, the Multipurpose Control Display Unit (MCDU) is used to compose the CPDLC message, which is the forwarded to the DCDU for review prior to transmission [Air08, FAN06].

Advantages and drawbacks of CPDLC have been discussed at length for some years. CPDLC reduces misunderstandings and errors pertaining to poor voice quality, fading or language issues, and ensures that flight crews do not erroneously react to instructions intended for another aircraft (e.g. due to similar callsigns). Furthermore, the possibility to recall messages makes ATC clearances and instructions continuously accessible, and transcription errors are reduced by the possibility to transfer CPDLC information directly to the FMS. On the other hand, particularly the preparation of a request to ATC takes much longer with CPDLC, and any party line information (see e.g. Section 2.3.2) is lost. Last but not least, the introduction of CPDLC transfers additional information to the already heavily loaded visual channel [Air04b].

3.4.2 D-ATIS

According to ICAO Annex 11, Automatic Terminal Information Service (ATIS) has to be provided at aerodromes whenever there is a need to reduce frequency congestion and air traffic controller workload in the terminal area. ATIS contains information pertaining to operations relevant to all aircraft, such as meteorological conditions, runway(s) in use and further information which may affect the departure, approach and landing phases of flight, thus eliminating the need of transmitting the corresponding items individually to each aircraft as part of ATC communication. ATIS messages are updated at fixed intervals (usually 30…60 min) and whenever a change of meteorological or operational conditions results in substantial alterations to their content. In order to make consecutive ATIS transmissions distinguishable and to enable controllers to confirm with flight crews that they have the most recent information available, each ATIS broadcast is identified by a single letter of the ICAO spelling alphabet, which is assigned consecutively in alphabetical order [ICA99, ICA01].

Conventional ATIS transmits a voice recording typically lasting less than one minute over a published VHF frequency in the vicinity of the aerodrome [ICA99]. To ensure that broadcasts do not exceed, wherever practicable, 30 seconds, larger airports offer different ATIS services for departing and arriving aircraft [ICA01]. Wherever D-ATIS and voice ATIS are provided simultaneously, both content and format of the messages should be identical, which also implies that they must be updated at the same time [ICA01].

```
.D-ABET ---- DLH9YV          28JUL06 0735Z
ATIS BRE

ATIS E RWY: 27 TRL: 70 SR: 0336 SS: 1927
METAR 280720 EDDW 20004KT 7000
NSC 21 /20
1012
TEMPO 4000 TSRA BKN030CB
SUSAN EXPECT ILS APCH ATTN ATTN NEW DEP
FREQ 1 2 4 DECIMAL 8

CONTRACT ACTIVE
```

Figure 26: Sample D-ATIS for Bremen airport

Mandatory content encompasses aerodrome identification (ICAO), a departure or arrival indicator and the already mentioned ATIS designator, followed by the runway-in-use, the types of approach to be expected, significant runway surface conditions and – if appropriate – braking action as well as visibility and, when applicable, RVR. Furthermore, a summary of present weather must be provided, including clouds below 1 500 m (5 000 ft) or below the highest minimum sector altitude (whichever is greater). Besides, any cumulonimbus has to be reported and, if the sky is obscured, vertical visibility when available. Additionally, surface wind direction and speed, air temperature, dew point temperature and altimeter setting need to be provided [ICA01]; see Figure 26 for an example. This compulsory information can be supplemented by free-text information on significant meteorological phenomena in the approach and climb-out areas, including wind shear and observations on recent weather of operational significance.

It is expected that D-ATIS will result in reduced flight crew workload, because ATIS information does not need to be copied by hand any longer, and pilots do not have to divert attention from ATC frequencies to listen to the ATIS broadcast. Besides, there should be reduced ambiguity in the transmitted information, since D-ATIS eliminates potential misinterpretation resulting from poor transmission quality. Last but not least, D-ATIS might increase the accessibility of ATIS information.

3.5 Air Traffic Management Technology and Concepts

3.5.1 Airport ATC Surveillance Technology

Air Traffic Controllers are supported in visual traffic acquisition by surveillance technologies of varying sophistication, to which this section gives a very short introductory overview.

3.5.1.1 Surface Movement Radar (SMR)

In the aerodrome area, an X-band Primary Surveillance Radar (PSR) called Surface Movement Radar (SMR) is commonly used to provide situational awareness to the controller. However, due to the nature of the environment, the SMR does not provide adequate separation awareness in manoeuvres conducted in confined spaces such as those in the gate area and in queuing before take-off. As the policy of most airports was[51] to have transponders turned to standby when aircraft are on ground[52], SSR techniques were not used at airports [ICA04a].

3.5.1.2 Airport Surface Detection Equipment (ASDE)

ASDE is a high resolution ground surveillance radar system capable of displaying aircraft and vehicle traffic on the airport surface on one or more displays in the control tower. The system is designed to augment visual acquisition of traffic to enable controllers to detect, locate and track surface activity. ASDE–3 was the first surface detection system to become operational [NTS95].

3.5.1.3 Airport Movement Area Safety System (AMASS)

AMASS is a software enhancement to the Airport Surface Detection Equipment (ASDE), providing a logic for predicting the path of departing and landing aircraft, as well as aircraft and/or vehicle movements on runways. When a potential collision is detected, visual and auditory alerts to the controller are activated. As an example, AMASS will alert controllers to a potential collision when an aircraft or vehicle is occupying a runway and when arriving or departing aircraft cross a certain threshold or attain a certain speed. The system processes surveillance data from ground radar, predicting possible conflicts based on the position, velocity, and acceleration of arriving or departing aircraft and vehicles [NTS07e]. In 2008, AMASS was operational at 34 airports in the United States [FAA08].

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51 Airports equipped with ASDE-X in the U.S. require pilots to leave the transponder "ON" because ASDE-X uses SSR / multi-lateration techniques.

52 The reason for this is to avoid that aircraft are still displayed as airborne on the SSR used for approach. ICAO Document - Annex 10 - Volume 4, Amendment 77 [ICA02a], states as recommendation in § 3.1.2.10.3.10.2 that Mode A/C replies should be inhibited when the aircraft is on the ground to prevent interference when in close proximity to an interrogator or other aircraft. However, Mode S discretely addressed interrogations do not give rise to such interference and may be required for data link communications with aircraft on the airport surface. Acquisition of squitter transmissions may be used for passive surveillance of aircraft on the airport surface (Mode S multi-lateration). Most modern aircraft have the transponder connected to a Weight-on-Wheels switch. When the aircraft is on the ground and the transponder set to "ON", Mode A/C replies are inhibited, while the Mode S reply capability as well as extended squitter ADS-B messages remain enabled [ARI89].

3.5.1.4 Airport Surface Detection Equipment - Model X (ASDE-X)

ASDE-X is a multi-sensor next-generation surface surveillance system which the FAA is acquiring for airports in the United States. At the end of 2008, it was in use at 12 airports and projected to be operational at 35 airports by the end of 2010 [FAA08]. The system is designed to provide high resolution, short-range, clutter free surveillance and identification information on both moving and stationary traffic located on or near the airport surface under all weather and visibility conditions.
ASDE–X introduces multi-lateration transponder-based surveillance capability, both ground-based and airborne, which allows the system to provide much more reliable overall surveillance than the ASDE–3 AMASS system. By processing sensor reports into a single target, which is then displayed on a high resolution colour monitor, ASDE-X provides controllers with a seamless picture of all operations on the airport surface. This sensor data fusion ensures that the most accurate information about aircraft or vehicle location is received in the tower, which is intended to increase surface safety and efficiency [FAA09]. ASDE-X also contains a so-called Safety Logic, which is an additional software functionality capable of alerting air traffic controllers of potential traffic conflicts, including Runway Incursions [Sen07].

3.5.2 Surface Movement Guidance and Control System (SMGCS)

Today, most aerodromes employ some form of a Surface Movement Guidance and Control System (SMGCS) as described in the corresponding ICAO Manual on A-SMCGS (Doc 9476) [ICA86]. In their simplest form, these systems hardly go beyond standard ICAO aerodrome markings. However, more advanced installations use switched taxiway centrelines (‘follow the greens’) and illuminated stop bars at holding positions, which emphasize the instruction to hold given to crews via radio by a series of red lights [ICA04a]. Unless these lights are switched off, pilots must never cross such a stop bar [ICA08].
However, in Low Visibility Operations, LVP as described in Section 2.1.2.4 are employed. These procedures may differ from airport to airport, but in general, pilots and vehicle drivers feel that their ability to apply ‘see and be seen’ is severely impaired under these conditions. Although current procedures allow aircraft to land in conditions down to zero visibility, and take-off is possible in a RVR down to approximately 75 m, Doc 9476 does not contain any concept beyond the provisions for standard LVP to facilitate safe and expeditious operations in all weather conditions. This is the major shortcoming of the SMGCS concept [ICA04a].

3.5.3 Advanced SMGCS (A-SMGCS)

In recent years, the well-known limitations of SMGCS and the necessity for major airports to invest in more efficient use of the existing infrastructure have lead to the development of new ATM concepts, since both increased traffic and infrastructural complexity require a more efficient organisation of traffic flows on the ground. These improved SMGCS concepts are commonly designated as Advanced Surface Movement Guidance and Control Systems (A-SMGCS). Initial steps towards an international standardization of A-SMGCS have taken place and are documented in ICAO Doc 9830, the Manual on A-SMCGS [ICA04a].

A-SMGCS aims at increasing both safety and efficiency of operations on the aerodrome surface. From an economic point of view, it is expected that A-SMGCS will significantly contribute to increased capacity and reduced delays in all weather conditions, even when taking into account the predicted increase in surface movement operations. However, the presentation in this section focuses on safety aspects.
In this context, one of the high-level goals behind A-SMGCS is to provide increased situational awareness to controllers, pilots and vehicle drivers regardless of visibility conditions, traffic density or aerodrome layout. This implies better surveillance, improved guidance and enhanced visual aids.
Another major innovation is that A-SMGCS should be capable of conflict prediction, detection and resolution, which also includes Runway Incursion avoidance. The ICAO manual requires that an A-SMGCS should assist ATC at least in the prevention of incursions of aircraft and vehicles onto runways and taxiways, as well as collisions between aircraft, vehicles and obstructions on the manoeuvring area in all visibility conditions.

3.5.3.1 The A-SMGCS Concept

To achieve the goals outlined above, A-SMGCS has to provide more precise guidance and control for aircraft and vehicles in the movement area in all weather conditions, and should also be able to ensure spacing between all moving aircraft and vehicles, especially in conditions which prevent manual spacing.

Unless the total number of aircraft and vehicles permitted to operate on the movement area at a given time is strictly limited, such a task is beyond the capability of a controller even if aided by conventional surface movement radar (SMR), cf. [ICA04a]. New surveillance technology will therefore be required in order to provide a better situational awareness to all airport movement stakeholders. Most likely, this will lead to reallocation of responsibilities for various system functions, as less reliance is placed on the ability of the pilot or control authority to provide visual surveillance. Furthermore, the ICAO manual explicitly states that A-SMGCS design should not be constrained by existing allocations of responsibility. The use of automation to assist controllers in their tasks is therefore envisaged, but the ultimate responsibility for the safety of an aircraft will always remain with the pilots. This implies that pilots must be provided with the means of exercising this authority. The four primary A-SMGCS functions surveillance, routing, guidance and control, which are intended to satisfy all of the above requirements, are briefly outlined below:

Surveillance
The A-SMGCS surveillance function provides accurate information on the position and the identity of all aircraft and vehicles operating within the airport movement area, irrespective of weather conditions. Not only moving, but also static aircraft and vehicles should be covered. The surveillance function is the fundamental A-SMGCS function, as it provides the three other functions with essential input; they cannot work if surveillance data is not available. Furthermore, the surveillance information is intended to be used in refining the traffic planning functions associated with predicting taxi throughput and arrival/departure times.

Routing
The A-SMGCS routing function, which can be operated manually or automatically, assigns a route to each aircraft and vehicle within the movement area. Of course changes to this assigned route and the destination have to be possible at all times. Furthermore, the routing function should not constrain the crew's choice of a suitable runway exit after landing. If the routing function is automatic, both controllers and crew should have sufficient possibilities to interfere manually. An additional goal of this function is to minimize both taxi distances and crossing conflicts, the former clearly with a focus on economical aspects.

Guidance
The main purpose of the guidance function is to provide clear indications to pilots and vehicle drivers to allow them to follow the route that has been assigned to them, and to enable them to maintain situational awareness of their position on this route. Of course, the guidance functions should also be capable of accepting route changes any time, and it should be able to indicate routes and areas restricted or not available for use.

Control
The control function is the most complex A-SMGCS function. It should be capable of detecting conflicts, providing alerts and suggesting resolutions for all kind of surface movement conflicts, most prominently Runway Incursions, while keeping controllers, pilots and vehicle drivers in the loop. Alerting should cover both short and medium term alerts. Furthermore, this function is responsible for longitudinal spacing, taking into account various parameters such as speeds, jet blast effects, human and system response times, deceleration performance and aircraft dimensions.

The introduction of these A-SMGCS functions should not result in an overall risk level in excess of the probability of one fatal accident per 10^7 operations[53].
A-SMCGS is conceived as a modular system to facilitate tailoring and adaptation to all types of aerodromes and their specific needs, and to permit a gradual transition from SMGCS to A-SMGCS. As part of this modular approach, five different implementation levels are defined by the ICAO Manual on A-SMGCS, which mainly differ in the level of automation used in conflict detection, conflict resolution, routing and guidance [ICA04a]. Changes of operational procedures with the introduction of A-SMGCS are desired to achieve clearly defined roles and responsibilities for controllers, pilots and vehicle drivers in order to eliminate procedural ambiguities. Additionally, particularly the more sophisticated functions might require that aircraft have to be suitably equipped to benefit from A-SMCGS.

With the introduction of A-SMGCS, it is expected that communication will migrate into a mix of voice and data link usage. Controller-Pilot Data Link Communications (CPDLC) will be introduced to supplement radiotelephony for clearances and rout-

53 Given the fact that the current fatal accident rate, averaged between 1996 and 2007, is 0.5 per one million departures, and that three of 89 fatal accidents in this period were attributed to Runway Incursions, cf. [Boe07], this is not a particularly ambitious goal, since the current Runway Incursion-related fatal accident rate is consequently already as low as 1.7 per hundred million departures.

ings that are not subject to time critical transmission or do not require instantaneous action. Thus, there will be a general decrease in voice communication, but it will still be used where necessary [ICA04a], e.g. in case urgent matters need to be addressed.

3.5.3.2 Considerations on Flight Crew Awareness

According to the ICAO Manual on A-SMGCS, pilots should be provided with the following information to safely taxi the aircraft in all operational conditions and to enhance flight crew situational awareness [ICA04a]:

a) information on location and direction at all times;
b) continuous guidance and control during the landing roll-out, taxiing to the parking position and from the parking position to the runway-holding position, to line up at any take-off position and the take-off roll;
c) indication of the route to be followed, including changes in direction and indication of stops;
d) guidance in parking, docking and holding areas;
e) indication of spacing from preceding aircraft, including speed adjustments;
f) indication of spacing from all aircraft, vehicles and obstacles in Visibility Condition 4;
g) indication of the required sequencing;
h) information to prevent the effects of jet blast and propeller/rotor wash;
i) identification of areas to be avoided;
j) information to prevent collision with other aircraft, vehicles or known obstacles;
k) information on system failures affecting safety;
l) the location of active runways;
m) alert of incursion onto runways and taxiways; and
n) the extent of critical and sensitive areas.

Surprisingly, the manual states in a note that **most of these requirements might be satisfied by ground visual aids.** Generally, the A-SMGCS concept, like SMGS, is a concept focussing on the ground infrastructure side, as it considers all issues from an aerodrome and ATC perspective. Improved visual aids are regarded as the primary concept for enhanced surface guidance in A-SMGCS. This ground infrastructure perspective is particularly evident when a note in the ICAO Manual on A-SMGCS states that "*the guidance function will primarily be based on standardized ground visual aids*", and rather diffusely mentions that "*additional equipment or systems*" aboard aircraft to supplement these visual aids are only required in Visibility Condition 4. Consequently, additional avionics, like an airport moving map, a Cockpit Display of Traffic Information (CDTI) or an enhanced vision system are, according to the ICAO Manual, only envisaged for low visibility operations [ICA04a].

This is, of course, highly questionable from a conceptual point of view, because the capabilities of such onboard displays to provide the crew with an optimum situational awareness and other benefits of this technology would lie idle in good visibility if this principle was strictly applied.

Although the list of information requirements above is originally intended for ground systems, it will subsequently have to be compared to the findings of Chapter 2, "Causal Factors of Runway Incursions". This analysis will yield to what extent the items listed may serve as an additional requirements for an onboard system for surface movement support and Runway Incursion avoidance.

3.5.3.3 Prediction and Detection of Conflicts

Since one of the main objectives of A-SMCGS is the prevention of collisions between aircraft, vehicles and objects on the manoeuvring area, an alerting functionality is envisaged as part of the control function. However, alerting is not limited to traffic conflicts, but also encompasses intrusion into restricted areas, e.g. the runway protection zone, or deviations from assigned routes. In the corresponding requirements, the ICAO Manual on A-SMGCS distinguishes detected conflicts, which require immediate action to prevent a collision, and predicted conflicts, which necessitate expeditious action to avoid the development of an imminent situation. A-SMGCS should be capable of providing alerts to controllers for the following types of runway conflicts:

1. aircraft arriving to, or departing aircraft on, a closed runway
2. arriving or departing aircraft with traffic on the runway (including aircraft beyond the runway holding positions)
3. arriving or departing aircraft with moving traffic to or on a converging or intersecting runway
4. arriving or departing aircraft with opposite direction arrival to the runway
5. arriving or departing aircraft with traffic crossing the runway
6. arriving or departing aircraft with taxiing traffic approaching the runway (predicted to cross the runway-holding position)
7. arriving aircraft exiting runway at high speed with converging taxiway traffic
8. arriving aircraft with traffic in the sensitive area (when protected)
9. aircraft exiting the runway at unintended or non-approved locations
10. unauthorised traffic approaching the runway
11. unidentified traffic approaching the runway

As the Manual admits, this list merely contains several possible conflict scenarios and is not exhaustive. The same is true for the taxiway conflicts that have to be handled:

1. aircraft on a closed taxiway;
2. aircraft approaching stationary traffic;
3. aircraft overtaking same direction traffic;
4. aircraft with opposite direction traffic (head-on conflict);
5. aircraft approaching taxiway intersections with converging traffic;
6. aircraft taxiing with excessive speed;
7. aircraft exiting the taxiway at unintended or non-approved locations;
8. unauthorised traffic on the taxiways;
9. unidentified traffic on the taxiways;
10. crossing of a lit stop bar.

Last but not least, the A-SMGCS should also provide alerts for further conflicts on both aprons and taxiways, such as the loss of wing-tip spacing due to manoeuvring, unauthorised entry to a taxiway or apron, or failure to comply with instructions to hold or to give way to other traffic. In this context, the Control function should also be able to handle deviations from assigned routes and events imposing operational changes, such as runway changes or closure of taxiways for maintenance. Additionally, prediction should also cover route conflicts, i.e. the situation where there are at least two routes prone to cause a conflict. Nevertheless, Runway conflict alerting is given priority over taxiway and apron alerting [ICA04a].

It is noteworthy in this context that the concept of alerts outlined by the manual shows little familiarity with the alerting concepts commonly applied in aircraft cockpits. As an example, the manual suggests "*a warning*" alert associated with a predicted conflict, while, in the cockpit, the correct corresponding alert level would be an advisory or caution, depending on the severity.
Likewise, it is surprising that, while calling for a minimization of false and nuisance alerts, the Manual also prescribes general 'reminder' alerts to controllers in situations where more than one aircraft or vehicle is detected within the monitored runway area at the same time, irrespective of the precise traffic constellation [ICA04a].

In conclusion, the alerting functionality proposed by A-SMGCS is entirely based on use cases, since it merely defines a minimum set of conflict situations to be covered. The risk associated with such an approach is that the solution might eventually work sufficiently well only for traffic scenarios covered by the use cases, and exhibit substandard performance or fail for all other situations. Additionally, while it is envisaged that flight crews involved in traffic conflicts are alerted via controllers by voice or even directly by up-linking A-SMGCS-generated alerts to the aircraft systems, the alerting concept proposed by A-SMGCS exhibits a lack of harmonisation and compatibility with the way alerts are handled on the flight deck today.

Therefore, although A-SMGS envisages several onboard functions, it nevertheless remains a concept centred on ground-based systems, ranging from improved ATC surveillance to advanced, automated surface guidance by lighting systems on the ground. Only the Level 5 A-AMGCS includes mandatory onboard functions for guidance, but these are seen in the context of ground installations and highly dependent on these from a functional perspective. Consequently, their usability is limited by the required availability of a corresponding ground infrastructure; this is the reason why A-SMGCS is not used as a starting point for this thesis.

3.5.4 Airborne Separation Assistance System (ASAS)

The Airborne Separation Assistance System (ASAS) is an Air Traffic Management (ATM) concept for future operations based on additional aircraft capabilities, enabling flight crews to maintain separation to other aircraft and providing flight information concerning surrounding traffic. The primary means of ASAS traffic surveillance is ADS-B (see Section 3.2.2), which may be supplemented by TIS-B (Section 3.2.3) traffic data for non-ADS-B equipped traffic where necessary.

However, the main focus of ASAS is on operational procedures for controllers and flight crews, so-called ASAS applications, which employ these future aircraft systems for better traffic situational awareness, for achieving and maintaining an assigned spacing with other aircraft, or for a delegation of separation responsibility from the controller to the flight crew in certain well-defined scenarios [Eur01].
Since these ASAS applications have different levels of maturity and are associated with different operational issues, it was decided to allocate them to different implementation packages. ASAS Package 1 is a coherent set of Airborne and Ground Traffic Surveillance applications that can realistically be realised within the next 5-10 years [Eur02]. It encompasses various Airborne Traffic Situational Awareness (ATSA) applications aimed at enhancing the flight crews' knowledge of the surrounding traffic situation both in the air and on the airport surface, and thus improving the flight crew's decision process for the safe and efficient management of their flight. For these awareness applications, no changes in separation tasks or responsibility are intended [Eur01].
For the purposes of this thesis, the most important ASAS Package 1 function is enhanced traffic situational awareness on the airport surface (ATSA-SURF), which aims at improving traffic awareness on the airport surface for both taxi and runway operations in all weather conditions. Its objectives are to improve safety, e.g. at taxiway or runway intersections, and to reduce taxi time particularly during low visibility conditions or at night
For a realisation of ATSA-SURF, it is envisaged that at least position and identification of the surrounding traffic, which could include both aircraft and airport vehicles, are displayed to flight crews on a Cockpit Display of Traffic Information (CDTI). It is explicitly stated that traffic needs to be displayed on an airport moving map. Furthermore, an onboard functions advising flight crews when approaching an active runway, e.g. in case traffic is located on the runway, is envisaged [Eur02].

Consequently, in contrast to the A-SMCGS concept, the ASAS Package 1 function ATSA-SURF is an onboard-centred concept relying on the availability of an onboard moving map and traffic data via ADS-B or TIS-B. Alerting, allocated to ATC as ground-based functionality in A-SMGCS, is seen as an onboard function in the scope of ATSA-SURF. However, both the onboard airport moving map and the associated traffic presentation are foreseen in both ASAS and A-SMGCS.

3.5.5 Runway Status Lights

Runway Status Lights automatically switched by the airport's surveillance system are currently being studied. They are intended to indicate to flight crews whether it is safe to enter a runway, or to take off and land. At runway-taxiway intersections, taxiway centreline lights are supplemented by so-called red Runway Entrance Lights that will illuminate whenever traffic is taking off or landing on the runway. Likewise, the runway centreline near the thresholds features red Take-Off Hold Lights that will be switched on whenever other traffic on the runway makes it unsafe to take off or land. The concept has been evaluated using RWY 18L/36R at Dallas-Fort Worth Airport (KDFW) and RWY 09/27 at San Diego Airport (KSAN). An installation is also scheduled for Boston Logan International Airport (KBOS) [FAA09].

4 Towards an Integrated Solution

One of the main goals of this thesis is to analyse the features required for future onboard systems to enable a significant contribution to Runway Incursion avoidance and thus enhanced safety in the airport environment. As a first step towards this goal, the analysis of accidents and incidents in Chapter 2 has revealed areas where the unavailability or a lack of readily accessible information, and in consequence a lack of flight crew situational awareness, has been a causal factor in Runway Incursions. Particularly with respect to Runway Incursions caused by inadequate position awareness, there is substantial evidence that current flight deck instrumentation does not provide pilots with adequate assistance to prevent, detect and resolve disorientation in all weather conditions.

Generally, the findings in Section 2.3 suggest that enhanced flight deck instrumentation might have prevented virtually all of the investigated occurrences, or at least averted a catastrophic outcome. In fact, the necessity to improve flight crew situational awareness in the airport environment to prevent Runway Incursions is well-established and frequently quoted, particularly in connection with airport moving maps [RTC03a, RTC05], and the idea of employing onboard systems for the prevention of Runway Incursions is not new, with first concepts emerging more than a decade ago, cf. Kubbat *et al.* [Kub99].
However, as the brief review in Chapter 3, "State of the Art", has shown, the various existing and emerging onboard solutions only address isolated aspects of the Runway Incursion problem. There appears to be a focus on position awareness, traffic visualisation and traffic conflict detection. A holistic, systematic concept for an onboard functionality encompassing all aspects relevant for Runway Incursion avoidance, as identified by the ***High-Level Requirements*** in Chapter 2, is still missing. Based on the fundamental considerations on Runway Incursion avoidance below and the ***High-Level Requirements***, this chapter therefore derives the functionality required for a holistic onboard solution and identifies areas where research is necessary to realise it. The main goal is to enhance and to complement current operations, with neither core roles nor responsibilities of controllers and flight crews changed. Nevertheless, procedures may be adapted or enhanced where necessary to enable a safe and efficient use of the additional systems on the flight deck and at ATC facilities, or to ensure that the system is used according to its intended function. Conversely, it is not intended that technology replaces current safety procedures and good airmanship in routine operations, such as the visual check the crew performs to ensure that the approach areas are clear before entering a runway.

Nonetheless, in developing mitigations for the issues identified in Chapter 2, a narrow focus on entirely aircraft-based solutions must be avoided. First of all, there is no reason to develop a complex and potentially expensive onboard technology if there is a relatively simple ground-based or procedural solution. More importantly, though, Runway Incursions involving a breakdown of communication or misunderstanding between flight crew and air traffic controller cannot be addressed by an onboard solution alone, because taxi route assignments and clearances related to runway operations may hardly be conveyed to flight crews in an efficient way in the absence of a data link between aircraft and ground systems. Likewise, ATIS, NOTAM or other information on the operational configuration of the aerodrome must necessarily have its origins in the respective facilities on the ground. Hence, there is a clearly identified intrinsic need for an air-ground cooperative system in the domains where communication with ATC or short-term and temporary changes to the operational condition of the aerodrome are concerned.

Additionally, a key external driver for air-ground cooperative systems is the need for interoperability with future ATM installations and procedures. The majority of Runway Safety initiatives and emerging ATM concepts focuses on either ground-based measures or systems consisting of both ground-based and onboard elements.
As an example, U.S. and European Runway Safety programmes propose a variety of airport enhancements from improved surveillance technologies such as multilateration to enhanced markings and perimeter taxiways [Eur04, FAA04]. Furthermore, cooperative ATM concepts like A-SMGCS and ASAS employ ground-based as well as onboard technologies (cf. Section 3.5), which raises and drives the issue of standardization. In addition, some ground-based surveillance systems such as ASDE-X, its predecessor ASDE-3 with AMASS supplement and A-SMGCS comprise ground-generated alerts to the controller if there is a risk of a Runway Incursion. As discussed in Section 3.3, there has already been a technology demonstration uplinking these alerts directly to the flight deck.

In view of these concurrent onboard and ground-based technology developments, a fundamental research issue is the distribution and allocation of future Runway Safety Net functionality between the ground and onboard segment, and the required interaction. Nevertheless, since the target level of safety in civil aviation is to reduce the probability of a catastrophic failure to 10^{-9} per flight hour, every effort to incorporate redundancy should be made. The coexistence of onboard solutions and ATM systems serving essentially the same purpose is therefore desirable in principle, provided that this does not eventually result in conflicting instructions to flight crews.
However, with respect to the goals and scope of this thesis (Section 1.6), the findings on incident and accident causal factors (Section 2.3), and for the reasons laid down in the following section, this thesis pursues an onboard-centric approach for Runway Incursion avoidance functionality. The major challenge associated with the distribution of functionality concerns the capability of onboard systems to support both stand-alone and air-ground cooperative operation. In this context, 'stand-alone' means that the onboard system can be operated independently of any specific ATM ground infrastructure with at least basic features available. Consequently, both necessity and scope of stand-alone functionality for onboard systems have to be established. Additionally, from a human factors perspective, a key issue is how the flight crew can unambiguously discern whether the onboard system (or part thereof) is operating in a standalone or air-ground cooperative mode. To address these issues, this chapter first devises strategies for Runway Incursion avoidance. Subsequently, by relating these strategies to the previously identified ***High-Level Requirements***, it is analysed whether they can best be met by onboard or ground-based technologies, and where air-ground cooperative solutions are required.

4.1 Rationale for an Onboard-Centric Approach

Runway Incursions are a worldwide problem and can, in principle, occur everywhere. From a flight crew or aircraft operator perspective, therefore, the level of protection against Runway Incursions should have no or only minimal dependence on the airports served.

Consequently, if the distribution of Runway Incursion avoidance functionality between aircraft and ground-based systems is shifted towards ATM technology as with A-SMGCS (see Section 3.5), full functionality can only be provided as long as the corresponding ground infrastructure is available on a worldwide basis. If the ground-based part does not exist or is inoperative at a particular airport, the overall system is increasingly likely to become ineffective, and the fundamental criterion above cannot be fulfilled.

Conversely, from an ATM or airport operator perspective, a system focussing on ground-based technologies as core elements of a future Runway Safety Net may solve the problem of Runway Incursions at the particular airports where it is installed, but from a pilot or airline perspective, the worldwide deployment of the required ground installations at aerodromes of all categories is indeed a major concern. After all, airlines have only very limited influence on airport infrastructure outside their major hubs. Potential deficiencies in airport signage, markings and air traffic control, let alone the introduction of sophisticated ground-based surface movement systems such as A-SMGCS, are therefore very often, if not nearly always, beyond the influence of aircraft operators. By contrast, the deployment of e.g. an airport moving map, which has emerged as basic onboard Runway Incursion avoidance functionality, cf. Section 3.1, is completely under an airline's control and it can be used at any airport, provided that an appropriate aerodrome mapping database (AMDB) and Global Navigation Satellite System (GNSS) coverage, e.g. GPS, are available.

Although it is predictable that most of the large hub airports of the so-called 'Western Hemisphere' will see a full-scale deployment of A-SMGCS or equivalent candidate technologies for the ground part of the Runway Safety Net in the near future, one of the most interesting trends in aviation is that more and more low-fare carriers and regional airlines push onto the market [FAA03]. Their business model usually includes offering point-to-point travel to small airfields close to the tourist regions or to reliever airports (as opposed to large hub airports) in order to save airport fees. It is unlikely that these airfields will be among the first A-SMGCS equipped aerodromes, because one may argue that only large and complex airports will gain significant operational and economic benefit from A-SMGCS. At the same time, hub airports will most probably either have sufficient financial resources of their own, or, alternatively, enough political weight to acquire this technology.

Irrespective of whether Boeing's direct connection philosophy, the hub-and-spoke concept of Airbus or a mixture of both will eventually prevail, at least one airport will not be a hub for a significant share of future airline flights. However, many of these smaller airfields with low traffic density and simple structure will most likely

be equipped with a more basic A-SMGCS implementation and lower priority, if at all. In addition, it can be assumed that several more decades will pass until these technologies will reach all the international airports of developing nations[54].
Nevertheless, particularly the Tenerife accident suggests that the danger of Runway Incursions is lurking everywhere. Likewise, a more recent development, the advent of large numbers of Very Light Jets (VLJs), does not only have the potential to re-shape the aviation market even more dramatically than low cost carriers, but will also require additional effort in terms of flight safety at small airports.

Furthermore, as the Tenerife disaster and the closure of US airspace following the terrorist attacks of September 11, 2001 show, even carriers shuttling between hubs equipped with every imaginable ground-based technology for Runway Incursion avoidance may suddenly find themselves diverting to small airfields due to terrorist threats. Moreover, further occurrences such as ATC strikes, weather hazards, volcanic activity, medical emergencies or a technical problem aboard the aircraft might also cause such a diversion.
In the event of a mass-diversion to a small airfield, there is subsequently a high risk that neither airport infrastructure nor controllers will be able to handle this sudden increase in traffic properly. Even if advanced ground-based technology is available, the site-specific tailoring may not cover the mass-diversion case, which could lead to incomplete surveillance, nuisance alerts or complete outages. Additionally, controllers working at smaller airports will gradually lose their capability of handling 40 a/c per hour, even if their original training covered high-density airports.

Consequently, for Runway Incursion avoidance, pilots and aircraft operators cannot rely on enhanced ATC surveillance in all visibility conditions and ground-based alerting tools everywhere in the world. Likewise, advanced services such as Controller-Pilot Data Link Communications (CPDLC) services or fused traffic data broadcast by Traffic Information Services (TIS-B) might not be available, either.
By contrast, the main advantage of an aircraft-based solution is that it is, at least in principle, available and usable everywhere, providing crew support independently of systems on the ground. Although limitations to this independence apply, this approach is fundamentally different from looking at onboard systems from an ATM perspective as with A-SMGCS, where the perception of aircraft-based technology is more that of an onboard front-end of the global air-ground infrastructure.

[54] If one takes the availability of the Instrument Landing System (ILS), which was commercially introduced in Europe and the United States in the sixties, as an indicator, several generations will pass until all international airports support A-SMGCS. Some major African airports, among them e.g. Alexandria/Egypt (HEAX), are still not equipped with ILS.

4.2 Strategies for Runway Incursion Avoidance

This section analyses which strategies for avoiding Runway Incursions, and particularly potential subsequent accidents, are available in principle. The advantages and limitations of these strategies are discussed, permitting an identification of the implications for a holistic approach towards an integrated solution. Concerning the resolution of runway traffic conflicts, the avoidance manoeuvres feasible in principle are sketched, and examples of their successful application from the incident analysis in Section 2.2 are reviewed to obtain initial insight into the feasibility of and the margins available for providing system-generated conflict resolution guidance.

4.2.1 Prevention of Ownship Runway Incursions

By definition, as discussed in Section 1.2, taking effective countermeasures against *the incorrect presence or manoeuvre of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take off of aircraft* will prevent Runway Incursions. From this perspective, Runway Incursions are not primarily, but only in last consequence, a problem of conflicting traffic [Ver06].
This insight shifts the focus of Runway Incursion avoidance, i.e. the prevention of Runway Incursion incidents and accidents, from the detection of runway traffic conflicts to the elimination of the operational and procedural errors causing the incursion. After all, at least at controlled airfields, the occurrence of Runway Incursions implies a failure of the invisible safety net that procedures and surveillance span around the runway. Besides, detecting a dangerous situation instead of preventing it in the first place might be taking the second step before the first.

Consequently, preventing Runway Incursions before they develop into a traffic conflict situation potentially resulting in a significant collision hazard is the first and crucial step to improve runway safety. Instead of attempting to cure the symptoms, traffic conflicts, flight crews must be prevented from actively causing Runway Incursions, e.g. by entering a runway or the associated protection zone without the required authorisation, by using a closed or otherwise unsuitable runway, or by taking off or landing without clearance.

To achieve this, the flight crew has to be provided with sufficient and adequate situational awareness concerning position (***High-Level Requirement I***), operational environment (***High-Level Requirement III***) and ATC instructions/clearances (***High-Level Requirement IV***). Apparently, it is much easier and safer to prevent Runway Incursions at this stage than to cope with a subsequent traffic conflict on the runway, with potentially few options and little margin for resolution, as evidenced by the discussion in Section 4.2.3 below.

4.2.2 Reaction to Existing and Emerging Runway Incursions

Nonetheless, measures for Runway Incursion prevention alone are not sufficient to avoid accidents, because they do not cover the case where a Runway Incursion is emerging or has already occurred. Particularly if other traffic is incorrectly present or operating within the confines of the runway or its associated protection zone, it is essential for flight safety that any resulting traffic conflicts and collision hazards are immediately brought to the attention of the flight crew (***High-Level Requirement II***).

Although it may seem at first glance that equipping all aircraft with preventive Runway Incursion avoidance functionality should eliminate such situations, this assumption proves to be neither realistic nor correct. In view of the experience with TAWS/ACAS, an equipment level of 100% is unrealistic even after the end of the transition period towards a mandate, because there are typically exceptions for certain types of operation and aircraft below a given threshold mass (cf. Section 3.2.1), which usually affect General Aviation aircraft. In view of the accidents at Atlanta, St. Louis or particularly Linate, and taking into account that 72% of the Runway Incursions in the United States between 2003 and 2006 involved at least one General Aviation aircraft, similar limitations are clearly unacceptable for effective Runway Incursion prevention. Additionally, more than 10% of Runway Incursions in the same period were attributed to vehicles [FAA07]. Thus, a mandate would not only have to be more restrictive with respect to exceptions, but also need to be extended to vehicles.
More importantly, though, Runway Incursion prevention functionality does not offer protection against controller errors (***High-Level Requirement V***), since even a better awareness of ATC instructions and clearances does not necessarily reveal such mistakes to the flight crew.

Therefore, once the preventive approach has failed – e.g. if surrounding traffic or a controller error has caused a Runway Incursion – the focus shifts to the mitigation of the consequences. As a result, to avoid accidents, Runway Incursion prevention functionality must be complemented by a reactive component capable of detecting and eliminating – or at least mitigating – potential traffic collision hazards. Runway Incursion (accident) avoidance therefore encompasses not only prevention, but also this reactive component.

In conclusion, there are two key research issues for the reactive Runway Incursion avoidance functionality. The primary question is how Runway Incursions involving conflicting traffic and potential collision hazards can be detected reliably. For obvious reasons, the system should neither miss critical situations nor bring false or spurious conflict indications to the attention of flight crews – both would at least undermine pilots' confidence, if not prevent certification of the system for operational use altogether. The second key issue is how reactive Runway Incursion avoidance functionality can subsequently contribute to the mitigation or resolution of the detected conflicts. This encompasses not only the desirability from an operational point of view, but particularly the feasibility from a technical and airworthiness perspective. Therefore, to understand the implications of conflict resolution for this functionality, the following section reviews the options a flight crew currently has for avoiding an accident when encountering a Runway Incursion involving conflicting traffic.
Both of the above issues are also closely related to the question of whether alerting functionality is required. Since this is also of paramount importance for preventive Runway Incursion avoidance functionality, this question is addressed in a dedicated subchapter, Section 4.4 "Considerations on Alerting".

4.2.3 Options for the Resolution of Runway Traffic Conflicts

4.2.3.1 Runway Incursion while ownship is airborne

In case a Runway Incursion occurs on final approach while the aircraft is still airborne, the execution of the missed approach procedure is the standard conflict resolution today. If the controller observes a Runway Incursion or any other obstruction on the runway after the landing clearance has been issued, the landing aircraft must be advised of the imminent danger and will be instructed to go around [ICA01a]. Likewise, the standard procedure for flight crews is also to initiate a go-around if they detect a Runway Incursion themselves. This has actually helped to prevent accidents, as evidenced e.g. by the 2007 Denver incident, cf. Appendix I-16.5.
There might be rare situations, such as an emergency landing due to an engine fire, or an aircraft low on fuel, where this manoeuvre could lead to disaster, but in these cases, the runway is usually reserved for the landing aircraft, cf. [ICA01a], thus minimizing the risk of an additional Runway Incursion. It can thus be regarded as proven that a valid Runway Incursion conflict resolution exists for virtually all scenarios in which ownship is airborne.

4.2.3.2 Runway Incursion during ownship take-off

The situation is completely different for Runway Incursions occurring while ownship is manoeuvring on the ground, especially for traffic conflicts emerging during the take-off run. Both the severity of the conflict and feasible resolutions depend on positions, speeds and closure rate of the traffic involved. Conflict resolutions fall in two categories, centred around the fundamental decision to continue take-off or to abort.

4.2.3.2.1 Rejected Take-Off

Currently, if conflicting runway traffic is visually detected in the early stages of the take-off roll, the flight crew will typically decide to abort take-off; this manoeuvre is commonly referred to as a 'Rejected Take-Off' (RTO). It is usually also performed if ATC advises pilots of a Runway Incursion or cancels the take-off clearance for other reasons, cf. [ICA01a]. In general, aborting take-off can be regarded as the most advantageous conflict resolution for low speeds, and has been credited with preventing collisions in the Runway Incursion incidents at Philadelphia (1985), Amsterdam (1998) and Hamburg airport (2004), see Appendices I-14.3 and I-17.

Nevertheless, rejecting take-off is a viable option only up to the so-called take-off decision speed V_1, which is determined as part of the take-off performance calculations. Attempting to stop the aircraft beyond V_1 is very likely to result in a runway excursion, which is associated with a significant risk of a hull loss, injuries and fatalities among passengers or crew.
In an accident of a Kalitta Air Boeing 747-200 at Brussels airport in May 2008, for example, the flight crew's decision to reject take-off six seconds after the V_1 callout resulted in a runway overrun and hull loss of the aircraft. While the take-off speeds had been determined for a wet runway, aborting take-off in dry conditions at a speed 12 kts above the calculated V_1 of 138 kts, together with a reduction of the effective

take-off distance available by 300 m to ~90% of the overall runway length (line-up from an intersection), resulted in an accident [AAU09]. This may serve as an illustration of the narrowness of the margins involved. At speeds greater than V_1, an RTO is therefore only performed if the aircraft is not considered flyable at all [FAA93].
In general, the risks associated with an RTO significantly increase with speed. For better risk assessment and decision making, the take-off roll is divided in a low-speed and a high-speed regime, which typically begins at 80 or 100 kts. While still in the low-speed regime, pilots may reject take-off whenever they encounter unexpected environmental situations or system malfunctions, such as tyre failures, unusual noise or vibration [Air05a]. By contrast, in the high-energy regime, an RTO is only performed in a very limited number of situations, which are usually defined in the Airplane Operations Manual (AOM) and typically encompass [DLH97]:

- Airplane not controllable or flyable
- Sudden loss of engine thrust
- Engine or APU fire warning
- Unsafe configuration
- **Runway Incursion/Intrusion**
- Bird strike danger (flocks of birds)
- Windshear

Although the transition at 80 or 100 kts seems somewhat arbitrary at first glance, it has been demonstrated in the frame of a worst case calculation that full braking as required for a RTO might already result in damage to the brakes/tyre system slightly above 100 kts, with potentially significant operational consequences [DLH97]. As the speed approaches V_1, damage to brakes and tyres is almost inevitable. The most critical situation, a rejected take-off initiated at the V_1 and take-off mass combination resulting in maximum kinetic energy, has to be demonstrated during aircraft certification with the brakes worn[55] (§25.109[56]). The braking disks usually absorb so much energy that the tyres are destroyed within minutes, mainly by heat radiation. Regulations require that the parking brake remains functional for three minutes and that neither wheels, tyres nor brake assembly catch fire[57] for at least five minutes to ensure a safe evacuation of the aircraft (§25.735). Tyres have to maintain pressure for 10 minutes before they deflate, because aircraft should be able to vacate the runway under their own power [EAS06, FAR07].
Nevertheless, the main concern associated with a rejected take-off in the high-speed regime is the risk of runway excursions and overruns. Particularly if the take-off is limited by the available acceleration-stop distance[58], past experience has confirmed this risk even for an RTO below V_1 with all performance calculations correct [Air05a].

[55] The brakes must be within 10% of the allowable wear limit for all wheels.

[56] Part 25 of the US Federal Aviation Regulations (FAR) [FAR07] and the EASA Certification Specification for Large Transport Aeroplanes (CS-25) [EAS06] are virtually identical in structure and content. For reasons of simplicity, the more compact US-style referencing, e.g. §25.101, is used synonymously with CS 25.101, instead of an awkward 'CS/§25.101' notation. Significant discrepancies between FAR and EASA are noted explicitly.

[57] To ensure that tyres are not inflamed easily, they must be inflated with dry nitrogen or another inert gas containing less than 5% oxygen on aircraft with certified MTOW above 34.119 kg (75.000 lbs) according to §25.733.

[58] According to the provisions of §25.109 for the accelerate-stop distance, a distance equivalent to 2 seconds at v_1 is added in take-off speed calculations to account for the operational variability in the time it takes the flight crew to deploy the retarding devices (e.g. brakes, thrust reduction/reversers, spoilers) [EAS06, FAR07].

One of the reasons is that the actual braking performance - and thus the achievable stopping distance - depends on a multitude of different factors. These include (but are not limited to) runway braking action or contamination level, condition and texture of the runway pavement (e.g. bumps, dents, and attrition from aircraft tyres), runway slope, wind speed and direction, as well as wear of aircraft tyres and brakes.

To add further complexity, most of the runway-related parameters are not homogenous over the whole length of the runway, but may show considerable variation. In convective weather or otherwise swiftly changing meteorological conditions, these parameters may be subject to rapid change on the timescale of minutes or even seconds. This does not only concern turning or gusting wind, but also runway contaminants.

With current ATIS or ATC reports typically limited to a categorized description of braking action, 'dry' (not reported), 'good', 'medium/fair', 'poor' and 'nil', which are largely based on subjective pilot reports, and objective methods to derive braking action directly from aircraft data still in their infancy, cf. [RW02], an accurate prediction of braking performance in all meteorological conditions therefore still constitutes a major unsolved challenge.

In conclusion, therefore, rejecting take-off is an often viable, but by no means universally valid method of resolving a runway traffic conflict. It is only feasible if the remaining distance to the conflicting traffic is still sufficiently large. From a take-off performance perspective, a Runway Incursion by other traffic corresponds to a sudden decrease of the available acceleration-stop distance compared to the unobstructed runway; the maximum speed at which take-off can be successfully aborted is therefore lower than the calculated V_1 in most cases.
However, as e.g. the 2004 Munich incident (cf. Appendix I-16) shows, completely stopping the aircraft may not always be required to avoid a collision. Depending on the type of intruder, its precise location and the runway width, a substantial deceleration could be sufficient for a controlled swerve around the conflicting traffic or a diversion into a taxiway/high speed exit, if available.

Nevertheless, at a high closure rate and with little distance to the intruding traffic, there might be no margin left to resolve the conflict in this manner, if at all. Under these circumstances, even unorthodox conflict resolutions, like vacating the runway into the grass and their consequences need to be assessed very carefully. However, in view of the fact that the Kalitta Boeing 747 left the runway surface at a speed of approximately 80 kts, this involves a high risk of injuries to passengers/crew and at least substantial damage to the airframe, if not a total hull loss. Close to V_1 the consequences of leaving the runway could be equally catastrophic for passengers and crew as colliding with the intruder.

4.2.3.2.2 Continued take-off

Continuing take-off is the second fundamental option to resolve runway traffic conflicts for departing aircraft, and in fact the only viable conflict resolution beyond V_1. Particularly in the high-speed regime, it will be safer than attempting to bring the aircraft to a stop in certain cases even for speeds below V_1.

Generally, the decision to continue take-off means that ownship must become airborne sufficiently early to be able to climb free of the intruding traffic, which apparently cannot be relied upon to leave the runway in time. Consequently, from a flight performance perspective, the presence of an intruder on the runway results in an instantaneous additional requirement to achieve a certain minimum altitude at a given distance from the runway threshold.

However, most take-off operations use reduced thrust or de-rated take-off thrust to minimize operating costs as well as tear and wear on the engine. Furthermore, this has substantial benefits in terms of engine reliability. Consequently, there is typically some performance margin in terms of available thrust. Additionally, it has to be demonstrated during certification that an aircraft can successfully rotate 7% or 10 kts (whichever is less) below the calculated rotation speed V_R without marked increase of the take-off distance (§25.107). Nevertheless, since it is desirable to climb free of intruding traffic on the runway with maximum vertical margin, it is assumed that the maximum available thrust will be set as soon as the decision to continue take-off has been made.

Continuing take-off and climbing over the intruding traffic has been successful in avoiding accidents in several cases, such as the Minneapolis incident involving two DC-10s in March 1985 (cf. Appendix I-4), another occurrence at the same airport in June 1985, and a Runway Incursion at Chicago Midway Airport also in 1985, with vertical margins between 15 and 60 m (see Appendix I-17 for details on these and the incidents below).
Nonetheless, rotating earlier or stronger than usual inherently bears the risk of a tailstrike, as evidenced e.g. by an incident at Dallas-Fort Worth International Airport in 2001. During take-off, a Delta flight crew observed a Boeing 737 taxiing across the runway. They succeeded in avoiding a collision by applying full power and rotating early, but their aircraft sustained minor damage due to a slight tailstrike.

However, an early rotation may not be sufficient in all cases to avoid a collision, and an additional lateral manoeuvre might be required. In an incident at Chicago O'Hare International Airport in 1999, the captain of a Korean Air Boeing 747 lifted off earlier than normal and banked left to avoid striking an Air China Boeing 747 that had erroneously taxied onto RWY 14R.
Banking at low altitude is, nevertheless, an inherently dangerous manoeuvre. Furthermore, an additional problem with both the early rotation and the banking manoeuvre is that they may, depending on the precise situation, require exceptional pilot skills for a safe completion, and are even then associated with a significant risk of failure with narrowing margins, whereas §25.101 requires that all procedures associated with take-off and landing must be flyable by crews with average skills.

Additionally, since these manoeuvres will typically bring the aircraft close to the boundaries of its flight envelope, it will become more vulnerable to any gusts, variations in wind direction or engine performance, and windshear encountered during take-off.

Nevertheless, as for the rejected take-off, there may be insufficient margin to prevent an accident. In the Tenerife accident, the KLM flight crew attempted to climb over the PanAm Boeing 747, cf. Appendix I-1, but failed. Likewise, at Linate, the SAS pilots immediately pulled up the nose of their aircraft when they spotted the Cessna during rotation, but since they detected the other aircraft only seconds before the collision due to the fog, this was not successful, either (Appendix I-11).

In conclusion, therefore, there may be situations in which neither rejecting nor continuing take-off will prevent an accident. This once more confirms the necessity of preventing Runway Incursions before they result in traffic conflicts, and underlines the importance of detecting emerging conflicts as early as possible to maximise the chances that there is sufficient margin for conflict resolution.
Table 4 summarizes the options a crew has to resolve a Runway Incursion conflict during the take-off run. Manoeuvres are listed with the respective constraints of applicability and the definite consequences associated with their application. Additional risks caused by the avoidance manoeuvre are specified as well. The main underlying danger for all of these manoeuvres is that they fail to prevent a collision with the traffic causing the Runway Incursion, either due to a situation that will inevitably lead to an accident, or due to an inappropriate choice of the evasive manoeuvre.

4.2.3.3 Runway Incursion during ownship landing and roll-out

If a runway incursion traffic conflict develops once the aircraft has touched down and decelerated such that a go-around remains no longer possible, the options for conflict resolution are essentially the same as for the abort scenarios of the take-off case, see previous section and Table 4. Consequently, the same considerations concerning risk apply, particularly with respect to vacating the runway in the grass.

In 1979, a landing Flying Tiger Boeing 747-F veered off RWY 9R at Chicago O'Hare International Airport, and thus successfully avoided a collision with a Delta Boeing 727 which had erroneously been cleared across the runway. However, the Boeing 747 incurred substantial damage due to the excursion. In several other cases, though, such as the 2006 Frankfurt incident and a 2007 Denver incident involving a snowplough on the runway, flight crews were able to prevent a collision by increasing deceleration only, see Appendix I-17.

Generally, the chances of avoiding a collision are, for any given aircraft type, speed and distance, somewhat higher during the landing roll-out compared to the take-off run, because the aircraft is already decelerating and commonly significantly below MTOW. Additionally, an aircraft produces more drag in the landing configuration with its flaps extended and aerodynamic retarding devices typically deployed.

<table>
<tr><th colspan="5">Runway Incursion Conflict Resolution Options (Take-off)</th></tr>
<tr><th></th><th>Manoeuvre</th><th>Constraints</th><th>Consequences</th><th>Risks</th></tr>
<tr><td rowspan="18">Abort</td><td rowspan="6">Bring aircraft to a full stop on the runway</td><td rowspan="6">Distance to conflicting traffic must be sufficiently large</td><td colspan="2">v < 100 kts</td></tr>
<tr><td>—</td><td>—</td></tr>
<tr><td colspan="2">v > 100 kts</td></tr>
<tr><td>—</td><td>Damage to brakes and tyres</td></tr>
<tr><td colspan="2">v ~ v_1</td></tr>
<tr><td>Damage to brakes and tyres</td><td>Runway excursion
Injuries to passengers and flight crew</td></tr>
<tr><td rowspan="6">Brake and exit runway at high-speed exit or taxiway

Brake and swerve around conflicting traffic</td><td rowspan="6">Availability of suitable exit or taxiway

Sufficient runway width and space for evasion</td><td colspan="2">v < 100 kts</td></tr>
<tr><td>—</td><td>Collision with traffic on taxiways</td></tr>
<tr><td colspan="2">v > 100 kts</td></tr>
<tr><td>Damage to brakes and tyres</td><td>Damage to landing gear due to overstress
Runway/taxiway excursion</td></tr>
<tr><td colspan="2">v ~ v_1</td></tr>
<tr><td>Damage to brakes and tyres</td><td>Damage to landing gear due to overstress
Runway/taxiway excursion
Injuries to passengers and flight crew</td></tr>
<tr><td rowspan="6">Vacate runway into the grass</td><td rowspan="6">—</td><td colspan="2">v < 100 kts</td></tr>
<tr><td>Runway excursion
Damage to landing gear</td><td>Damage to airframe
Injuries to passengers and flight crew</td></tr>
<tr><td colspan="2">v > 100 kts</td></tr>
<tr><td>Runway excursion
Damage to airframe</td><td>Hull loss
Injuries to passengers and flight crew
Fatalities</td></tr>
<tr><td colspan="2">v ~ v_1</td></tr>
<tr><td>Runway excursion
Damage to the airframe</td><td>Hull loss
Injuries to passengers and flight crew
Fatalities
Complete loss of control and collision with other traffic or buildings</td></tr>
<tr><td rowspan="3">Continue</td><td>Continue take-off as planned, potentially with added thrust if available</td><td>Distance to conflicting traffic must be sufficiently large</td><td>—</td><td>—</td></tr>
<tr><td>Continue take-off with early rotation/steep climb</td><td>Distance to conflicting traffic must be sufficiently large
$v > v_R - 10$ kts</td><td>—</td><td>Tailstrike
Loss of control
Crash
Hull Loss
Fatalities</td></tr>
<tr><td>Avoid conflicting traffic by rotating and banking</td><td>Distance to conflicting traffic must be sufficiently large
$v > v_R - 10$ kts</td><td>—</td><td>Loss of control
Crash
Hull Loss
Fatalities</td></tr>
</table>

Table 4: Options for Runway Incursion conflict resolution during take-off

4.2.3.4 Runway Incursion during ownship line-up, crossing or back-track

Conflicting runway traffic may not only occur during take-off and landing, but also when ownship is backtracking, crossing or lining up on a runway.
With ownship already on the runway surface, it will be best in the majority of cases to expedite crossing or to vacate the runway. If exiting the runway via an adjacent or nearby taxiway is not feasible, leaving the runway surface anywhere must be considered as well. The considerations concerning vacating the runway into the grass remain essentially the same as in all other situations. Typically, though, the speeds achievable in such a vacation manoeuvre are sufficiently low to prevent serious injuries among passengers and flight crew.

With ownship beyond the applicable holding position, but not yet physically on the runway surface, conflict resolution becomes more subtle. Depending on whether crossing or line-up is intended, there might be situations in which an expedited crossing may be favourable over an attempt to stop. Resolution options are also dependent on airport geometry in this case. As an example, the possibility to turn an intended line-up manoeuvre into a runway crossing to avert a collision with conflicting traffic is dependent on the availability of a suitable taxiway opposite of the taxiway used for line-up. Again, there may be situations in which conflict resolution is not possible irrespective of the manoeuvre chosen, or requires unorthodox manoeuvres.

4.3 Compensation of Existing Deficiencies and Limitations

Compensating the existing deficiencies and limitations in flight deck instrumentation, as outlined by the five ***High-Level Requirements*** in Section 2.3, is crucial for Runway Incursion avoidance. Nevertheless, individually addressing each requirement may eventually yield a patchwork solution, which is clearly not desirable. For a holistic approach, it is therefore essential to scrutinize the ***High-Level Requirements*** in the light of the strategies for Runway Incursion avoidance devised in Section 4.2 - they provide structure and context for the derivation of the required onboard, ground and cooperative functionality. The following sections survey candidate technologies for an integrated solution and identify the associated key research issues.

4.3.1 Prevention of Disorientation and Enhanced Position Awareness

Disorientation due to insufficient flight crew position awareness, mostly in adverse weather conditions, is one of the most frequent causal factors in Runway Incursion incidents and accidents, as discussed in Section 2.3. Consequently, according to ***High-Level Requirement I***, an independent source of aerodrome mapping and position information that can help to overcome visibility limitations and potential issues with airport signage, markings and lights (conspicuousness, adherence to standards) is required. This cannot be achieved with ground-based measures, cf. Section 2.3.

Based on the analysis in section Sections 2.2.2 and 2.3, the only area where cues currently available on the Flight Deck were not efficiently used by incident or accident flight crews concerns heading. To facilitate double-checking whether current heading is consistent with the perceived location on an aerodrome, it seems useful to relieve flight crews from mental arithmetic. But apart from adding taxiway orientation information to airport charts, there seems to be hardly any room for improvement within the current system. Besides, while possibly improving a detail of current operations, this clearly would not address all of the identified issues.

By contrast, an independent source of aerodrome mapping information can be achieved by extending the scope of navigational information currently displayed on electronic moving map displays. In line with the concepts proposed by Kubbat *et al.* [Kub99], and taking into account the recommendations issued by investigators in the wake of the Taipei and Lexington accidents, an airport moving map imposes itself as basic solution for the disorientation and position awareness issue. This approach is consistent with the current State of the Art (cf. Section 3.1) and ongoing activities in the field of Synthetic Vision. Furthermore, there is a substantial number of references outlining the potential of an airport moving map in preventing Runway Incursions by enhanced flight crew situational awareness, cf. [RTC05], but only very few elaborate on this subject or provide a rationale.
According to DO-257A [RTC03a], the intended function of an Aerodrome Moving Map Display (AMMD) is "*to assist flight crews in orienting themselves on the airport surface by enhancing the pilots' awareness of ownship position on the airport surface and to improve pilot position awareness with respect to taxi operations*", which is in reasonable agreement with ***High-Level Requirement I***.

An airport moving map display is, in principle, usable at every airport, provided that an Aerodrome Mapping Database (AMDB) according to RTCA DO-272A [RTC05] can be made available, and provided that Global Navigation Satellite System (GNSS) coverage is available, conditions which can be presumed as fulfilled for all airports used by commercial aviation. It is therefore independent of any particular ATM infrastructure on the ground, i.e. a stand-alone onboard system.
Nonetheless, like paper charts or their electronic equivalents, it is dependent on the availability, validity and currency of Aeronautical Information Services (AIS) data, particularly with respect to the designations of taxiways and other aerodrome features.

For the purpose of Runway Incursion avoidance, however, an airport moving map is believed to be more robust against taxiway charting discrepancies than paper charts, provided that it offers sufficient positional integrity.
As long as information concerning the location of the runway(s) is correct and the presented airport structure is not substantially changed, even occasional errors in taxiway, stand or apron naming should not significantly hamper the value of this independent source of airport information for Runway Incursion prevention, although usability for airport navigation will be significantly degraded. Nonetheless, provided that the flight crew can trust the presented ownship position, it is assumed that this will enable pilots to detect the perceived inconsistencies as charting discrepancies, instead of attempting to reconcile the inconsistent information with the perception of their position.

The main concern associated with the use of this technology, a potential increase of head-down times, frequently expressed by flight crew members participating in previous airport moving map assessments [RM01] or when discussing the technology [And95], has been somewhat rebuted by eye-tracking experiments performed by Graeber and Andre [GA99] and, both more recently and more conclusively, by Biella [Bie05]. Biella could demonstrate that the presence of an airport moving map display in the cockpit merely shifts attention from the conventional paper charts to the display, but does not increase overall head-down time. In designing the system and, even more importantly, the associated procedures, it must be nonetheless ensured that any potential tendency of the crew to focus on the displays in limited visibility conditions, thus possibly missing external cues that are not shown on the display for whatever reason, is addressed appropriately.

In conclusion, therefore, the airport moving map is regarded as the core element of onboard functionality for the prevention of disorientation and, thus, Runway Incursions; this must be validated in a representative environment (see Chapter 6).
The technology itself already has a high degree of maturity (cf. Section 3.1), and most fundamental issues from a systems and Human Factors perspective have been addressed. Consequently, the main research interest in the frame of this thesis concerns the repercussions and implications an integrated solution for Runway Incursion avoidance has on airport moving map design, particularly in terms of display formats and flight deck integration.

4.3.2 Enhanced Traffic Awareness and Traffic Conflict Detection

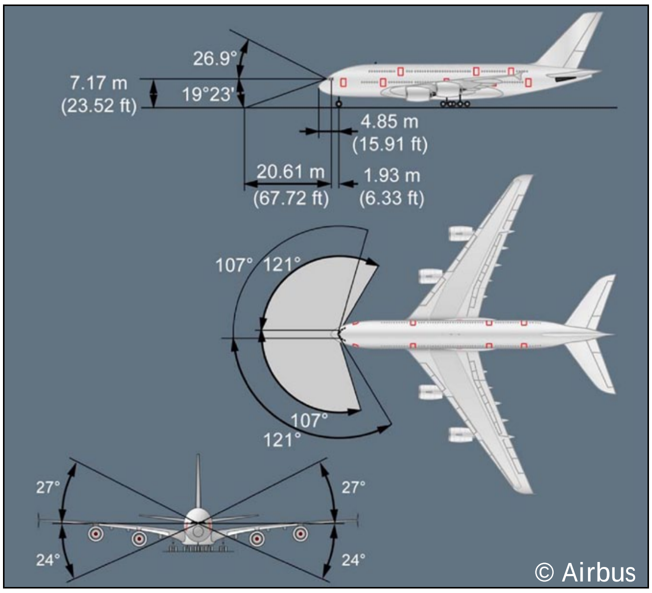

Figure 27: Airbus A380 Cockpit Field of View

High-Level Requirement II mandates that relevant surrounding traffic on the airport surface and the runway environment, including potential traffic conflicts, must be brought to the attention of flight crews in a suitable form.

Improving traffic awareness by enhancing visual acquisition is certainly a valid approach. In this context, enhanced aircraft lighting procedures, cf. [FAA03a], or improved lighting can doubtlessly increase aircraft conspicuity on the ground.

Nonetheless, as shown in Figure 27, the flight crew's field of view is limited by cockpit geometry, which may physically prevent the visual acquisition of relevant and potentially conflicting traffic. Additionally, geometrical restrictions resulting e.g. from sloped runways or buildings must be taken into account. As the accident at Paris Charles-de-Gaulle (LFPG) in 2000 (Appendix I-8) and the Munich incident in 2004 (Appendix I-16) clearly demonstrate, approaching traffic can be virtually impossible to acquire visually if high-speed taxiways are used to feed runway operations. Likewise, when lined up on a runway, landing traffic approaching from behind as in the case of the Los Angeles accident (Appendix I-6) is clearly outside the flight crew's field of view. In conclusion, therefore, visual acquisition is not only limited by meteorological conditions, but also by geometrical restrictions. Enhancing aircraft conspicuity is consequently not sufficient to fulfil ***High-Level Requirement II***.

4.3.2.1 Methods of conveying traffic information to flight crews

Classic airport signs and markings are static and therefore apparently not suitable for conveying dynamic traffic information. However, as the example of Runway Status Lights (see Section 3.5.5) illustrates, switchable airport lights can in principle be used to indicate occupancy of runways, taxiways or other airport areas, and thus provide indirect traffic awareness. Runway Status Lights are automatically switched on by the airport's surveillance system to inform pilots that it is unsafe to enter a runway, to take off or to land due to other traffic. While initial evaluation results were apparently positive, cf. [FAA09], indicating both runway traffic status and ATC instructions (as with stop bars) by red in-pavement lights may potentially be confusing. Furthermore, since the Runway Status Lights as envisaged provide exclusively negative feedback, the presence of these lights at some airports and their absence at others might eventually result in crews erroneously perceiving runway operations as safe if the system is not installed (or not working) at an airport. Besides, the effectiveness of Runway Status Lights in advising aircraft approaching in CAT II/III conditions that there is runway traffic must be questioned. Last but not least, Runway Status Lights only provide information on the presence of traffic, not on its precise location.

Another aspect is that airport lighting and light colour can be deceptive, particularly in foggy conditions. In fact, in the wake of the Madrid accident, a study on colour perception under foggy conditions conducted with 100 air transport pilots revealed that 88% of the participants failed to identify the colour white correctly. The participants, who had been carefully selected by filtering for normal vision and colour perception, most commonly mistook white for yellow (42%), light brown (10%) and green (9%). When white was shown in combination with either red or green, the error rates were 70% and 77%, respectively. The most frequent error was to identify only a single colour in the combination, i.e. either red (56%) or green (61%) [CIA84].

In conclusion, there is no solution based on ground-based visual aids that can provide adequate traffic awareness on relevant surrounding traffic. Consequently, an onboard solution is mandatory to fulfil the traffic awareness part of ***High-Level Requirement II***. Furthermore, if relevant traffic is displayed in the cockpit, crews may be able to anticipate potentially hazardous situations themselves.
As discussed in Section 3.2.2.2, the main goals of any Cockpit Display of Traffic Information (CDTI) application are improved traffic situational awareness and enhanced visual traffic acquisition, compared to unaided visual search. Thus, taking into account the current state of the art and the emerging ASAS Package 1 concept ATSA-SURF (cf. Section 3.5.4), a CDTI presenting operationally relevant traffic in relation to an airport moving appears to be the solution of choice, cf. [BAO00, RTC02, SAE03]. Accordingly, a US study by the Cargo Airline Association (CAA) and NASA concluded that efficient surface traffic awareness is hardly possible in the absence of an airport map [BAO00]. In this case, it is very difficult - if not impossible - for the crew to identify the exact position of surface traffic presented on the display if visibility is reduced.

The introduction of a CDTI for aerodrome traffic can therefore be regarded as a further rationale for an airport moving map. Consequently, DO-242A explicitly requires an "*airport surface moving map as underlay*" when using a CDTI for enhanced situational awareness of airport traffic (including runway and final approach occupancy awareness). Additionally, this standard outlines the need for sufficiently detailed display ranges and resolutions to determine unambiguously whether a traffic target is on the runway or not. Nevertheless, it is emphasized that a CDTI is not intended to replace visual navigation and traffic acquisition on the airport surface [RTC02].

4.3.2.2 Suitable sources of traffic data

The choice of a CDTI immediately leads to the question of potential sources of traffic data. Due to the large maximum permissible bearing angle of 27° [RTC97], TCAS is not suitable for traffic surveillance on the ground, even if TCAS traffic surveillance was not, as currently, suppressed on the ground, cf. Section 3.2.1.1. Assuming, with ownship lined up on the runway, a bearing error of 27° and a standard runway protection zone extending 75 m from the runway centreline (see Appendix II-2), basic geometric considerations yield that for intruder distances of approximately 150 m and beyond, TCAS traffic data is too inaccurate to indicate whether an intruder is within the runway protection zone or not.

While active sensors such as radar would allow truly autonomous onboard traffic surveillance, they can be excluded as potential source of airport surface traffic data for several reasons. Assuming an installation collocated with the weather radar in the aircraft nose, the only installation not requiring extensive airframe modifications, a radar sensor will suffer from similar geometrical limitations as cockpit vision. Other arguments against radar sensors are equipment costs, potential radiation hazards or undesirable electromagnetic interference. Electro-optical sensors, irrespective of whether they are active or passive, are not capable of working in all relevant atmospheric conditions due to signal attenuation [Jur85].

By contrast, ADS-B and, where available, TIS-B, are by design capable of providing traffic data with sufficient accuracy and integrity to enable a traffic awareness representation on an airport moving map, cf. Sections 3.2.2 and 3.2.3. Furthermore, since an ADS-B mandate is emerging in several countries, among them the key players in aviation, it can be regarded as the traffic surveillance technology of the future in civil aviation [Eur08b, FAA07b]. Although equipment and adherence to the published ADS-B standards are still voluntary, many aircraft are already equipped with ADS-B out capability. This enables an avionics approach to aerodrome traffic awareness and, subsequently, traffic conflict detection independent of ground-based infrastructure.
However, a key issue for the effectiveness of such a solution is equipage of other aircraft (and vehicles), especially in the transition phase towards a mandate. Particularly in the United States, TIS-B is seen as a 'gap filler' technology in terminal airspace and on the ground until all transport category aircraft are equipped. Nonetheless, in view of the emerging ADS-B mandate, the following assumptions regarding the availability of traffic surveillance data are made in this thesis:

- All transport category aircraft are equipped with an ADS-B out installation that is capable of providing the ADS-B messages described in Section 3.2.2. Likewise, any other aircraft operating at airports serving scheduled airline operations are presumed to either feature these ADS-B out capabilities, or be included in TIS-B.
- For airborne traffic, both ADS-B and TCAS data are available, whereas aircraft on the ground transmit only ADS-B data.
- Additionally, TIS-B traffic information may be available at certain airports or in selected airspaces, irrespective of whether traffic is on the ground or in the air.
- Since it is highly undesirable to display a single traffic target multiple times, it is assumed that aircraft are equipped with a traffic computer capable of fusing ADS-B, TIS-B and ACAS traffic data and providing a consolidated best position estimate; corresponding devices are already available on the market, cf. [ACS07].
- All airport vehicles operating on the manoeuvring area are equipped with ADS-B transmitters, and covered by ground traffic surveillance and included in the TIS-B traffic broadcast where available. In either broadcast, they are unambiguously identified as vehicles (DF = 18), cf. Section 3.2.2.1.
- Any other airport vehicles, such as service vehicles operating on the apron only, may also be equipped to transmit ADS-B data, but it is assumed that there will not be an ADS-B out mandate for all airport vehicles.

- All aircraft under electrical power continue to transmit ADS-B signals (position and identity) even when parked at a gate or parking stand[59] and during pushback. In the long term, it is expected that information on unpowered parked aircraft could be included in TIS-B broadcasts, either based on SMR data or because the airport operator's logistics systems have the information which aircraft is parked where, and can forward this information to the TIS-B service provider. In the short term, the absence of data on some parked aircraft may be an issue.
- For unpowered aircraft under tow, only primary radar can currently make the distinction between a tug and a tug-aircraft combination.

Aside from accuracy, there is a fundamental difference between ADS-B, TIS-B and TCAS traffic data: accuracy and integrity of ADS-B and TIS-B data depend on the equipment installed aboard 3rd party aircraft or on the ground, whereas TCAS traffic data are calculated onboard and only require a working transponder aboard the surrounding aircraft, i.e. equipment that is already mandatory. Therefore, although TCAS traffic data is unusable for display on an airport moving map, it could be used to perform consistency checks on the ADS-B or TIS-B data received.

4.3.2.3 <u>The issue of traffic conflict detection</u>

When a Runway Incursion results in a traffic conflict and potential collision hazard, immediate awareness, ideally of both involved flight crews and controllers[60], of this potentially very dangerous situation is essential, and appropriate countermeasures are crucial. As an example, another aircraft or vehicle could enter, fail to vacate or otherwise operate within the runway protection zone while ownship is cleared for take-off or landing on the same runway. Furthermore, there could be conflicting traffic taking off or landing on the runway while pilots are approved to cross or to perform a line-up. Additionally, there are a number of potential conflict scenarios for intersecting runways, including LAHSO operations.

For this reason, ***High-Level Requirement II*** explicitly includes enhanced awareness of potential traffic conflicts. Therefore, apart from collecting further evidence that a CDTI is a suitable means of increasing traffic awareness, a key research issue is how traffic conflicts can be detected, in particular whether a mere presentation of the surrounding traffic enables pro-active traffic conflict detection, or if alerting is required in addition. In this context, it is noteworthy that all of the CDTI guidance documents referenced above state that traffic alerting might be necessary, but do not give any details on potential alert conditions or Human-Machine Interface (HMI) requirements. This confirms the necessity to restudy traffic conflict alerting in an aerodrome environment in more detail.

Nevertheless, the question whether providing enhanced situational awareness is sufficient to prevent hazardous situations in the aerodrome environment is not endemic to conflicting traffic, but also applies to the domains addressed by the other ***High-Level Requirements***. It is therefore addressed in a dedicated subchapter, Section 4.4.

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59 This behaviour could be confirmed during trials with ADS-B live traffic at Frankfurt airport (EDDF) for the European project EMMA, see Chapter 7.

60 The ICAO Manual on A-SMGCS acknowledges the need to raise the corresponding alerts to both pilots and controllers, but does not provide any further details on this matter [ICA07].

A further important research issue concerning the presentation of traffic and potential traffic alerts is the impact on airport moving map design. In this context, there are a number of very interesting HMI issues resulting from the need to integrate the CDTI with existing flight deck systems, particularly how consistency with TCAS as existing mandatory traffic surveillance system can be achieved in terms of symbology while, at the same time, utilising the enhanced traffic information provided by ADS-B and TIS-B.
Likewise, the influence of an incomplete traffic surveillance picture resulting from less than 100% equipage on the usability of a CDTI and traffic alerting (if required) must be established. Another important aspect concerns the down-selection of operationally relevant traffic that might be necessary in high density traffic environments to limit display clutter.

4.3.3 Improved Information on Aerodrome Operational Status and Configuration

For safe and efficient surface movement operations, it is essential that relevant and sufficiently up-to-date information on the operational status and configuration of an aerodrome and its installations, such as potential runway closures or restrictions, is brought to the attention of pilots in a suitable form (***High-Level Requirement III***).

Due to the strategic nature of this information and its importance in decision making, current international standards necessitate the availability of a compilation of current NOTAM and other information of urgent character on the flight deck in the form of a plain-language Pre-flight Information Bulletin (PIB) [ICA04]. Nevertheless, the PIB and all other current sources of short-term and temporary aeronautical information[61] are either text-based or verbal, and not sufficiently intuitive. These and other limitations have been discussed extensively in Section 2.3.3.

In most cases, though, information on construction areas or runway closures is also conveyed by on-site ground based means, such as signs, lights, barricades and markings, but these may be absent particularly in case of short-term and temporary closures, as discussed in Appendix II-2.1, and suffer from the same limitations as any airport signs, lights and markings even when present.

4.3.3.1 Challenges associated with an onboard presentation

In conclusion, therefore, an onboard solution is required to overcome the limitations of the current system with its immanent hazards and to bring this information to the attention of the flight crew in a suitable form.
However, like paper charts, the airport moving map is currently limited to quasi-static airport information, because the underlying aerodrome database is envisaged to be updated only every 28 days with the regular AIRAC cycle [ARI06]. This is a significant limitation when it comes to short-term and/or temporary changes typically conveyed by NOTAM.

[61] Short-term changes are alterations that occur between AIRAC effective dates; the changes may be either of temporary or permanent nature. A runway, for example, could be closed for several months due to pavement refurbishment, while a permanent taxiway closure might be published on short notice.

In this context, it has been argued that the advent of AMM technology might represent a further challenge to the conventional PIB/NOTAM system: particularly when integrated with flight deck displays, an airport moving map provides information at a quality and level that is far more compelling than a paper chart. Employing disparate media for aerodrome mapping and PIB/NOTAM information could thus lead to a strong difference in its respective conspicuousness to the flight crew. Consequently, a runway displayed on the airport moving map without any indication of closure might be perceived as open even if contrary NOTAM information exists elsewhere in the cockpit. As a result, the absence of integrated operational status information, particularly when pertaining to runway closures or restrictions, is believed to be an even more severe limitation than for paper charts [Ver08].

Accordingly, to enhance the flight crew's situational awareness, a graphical overlay of ATIS and NOTAM information on an electronic display has already been outlined as a potential application of AMDBs [RTC01, RTC05], and SAE ARP 5364 specifically mentions a NOTAM overlay as a potential add-on to an airport moving map display [SAE03]. Nevertheless, neither of these references contains material beyond initial ideas and artists' impressions. Concerning symbology, a first proposal for the visualisation of construction areas on airport moving maps was presented in [Kub99].

Consequently, in contrast to airport moving map and CDTI, there is very little existing material to build on, and the required functionality must be studied from scratch. Therefore, a key research issue is an analysis of the prerequisites for an onboard visualisation of short-term/temporary information on an aerodrome's operational status and configuration. Evidently, this results in an intrinsic focus on the HMI, particularly the required level of integration with the airport moving map. In this context, the issue of whether an overlay or an integral representation is preferable must be resolved before adequate symbology can be derived.

4.3.3.2 Considerations on data handling and operational concept

Nevertheless, as outlined previously, PIB/NOTAM and ATIS data have their origins on the ground and need to be transferred to the aircraft avionics in a suitable form to enable an onboard solution. Consequently, a crucial step towards a flight-deck based visualisation of NOTAM, ATIS and other aerodrome status/configuration information is the availability of an underlying data handling and operational concept.

For ATIS, this is comparatively straightforward and encompasses decoding and presentation of the successively received D-ATIS transmissions. By contrast, with respect to PIB/NOTAM information, a suitable operational concept for the onboard functionality, which subsequently determines the necessary data handling, remains to be established. The fundamental issue in this context is whether the transmission of NOTAM to the flight deck systems is merely to be considered as part of routine flight preparation and data-loading on the ground, or whether in-flight updates - and thus full air-ground cooperativity - are required.
While it is doubtlessly important that flight crews have access to the most recent NOTAM information available, there is no evidence from the incident & accident

analysis in Section 2.2 that unavailability of NOTAM emerging **during the flight** was causal in one of the occurrences. This finding needs to be reassessed, though, in view of emerging ultra long-haul flights with a duration of 16 hours and more. Nonetheless, the operational necessity of in-flight NOTAM updates remains to be established.

With respect to potential in-flight NOTAM transmission, one of the possibilities outlined by the references above is that dedicated xNOTAM or FIS-B services are available via a specialized aeronautical data link, such as ACARS, VDL or SATCOM, provided either by the Air Navigation Service Provider (ANSP) or the AIS unit in charge of supplying this data.
However, the availability of such services does not eliminate the need for adequate flight preparation and the Pre-Flight Information Bulletin, irrespective of its current limitations. Besides, it is neither intended nor desirable to shift the dispatcher role to the flight deck. Additionally, there are, at least in a U.S. scheduled airline operations environment, important regulatory constraints regarding the in-flight update or addition of NOTAM. Dispatchers are responsible for issuing information necessary for the safety of the flight in the USA, according to FAR §121.533 and §121.535 [FAR07]. Since dispatchers are involved in decision making, for which NOTAM might contain important relevant information, a direct NOTAM transmission from the AIS/ANSP provider to the flight deck is only possible if the dispatcher is simultaneously provided with the same information, i.e. if information is shared system-wide. Consequently, a fundamental requirement for NOTAM upload, including but not limited to in-flight updates, is that this process must be handled via the airline's Airline Operational Control (AOC) to ensure that the dispatcher is involved in decision-making where necessary. Data handling via AOC or with AOC in the loop also ensures that an airline keeps track of the database configuration of its aircraft.

4.3.3.3 Conclusion

In conclusion, pre-processing and combining PIB/NOTAM information with the airport moving map to aid the flight crew in creating an adequate mental picture of the aerodrome, including all short-term and temporary changes as well as other operationally relevant information, emerges as the most promising solution to address both the previously discussed shortcomings of conveying PIB/NOTAM conventionally and the additional concern associated with airport moving map technology itself. In the frame of this thesis, the focus is on closures or restrictions of runways, taxiways and apron areas. In principle, fixed obstacles could also be visualised on the airport moving map, employing the initial symbology defined by the author for the project described in [TUD06]. However, fixed obstacles on or in the vicinity of the aerodrome are of virtually no importance for Runway Incursion prevention according to the definition in Section 1.2, and thus not further discussed.
Any data handling and operational concept for NOTAM and other relevant short-term or temporary information will have to address both the issue of dispatching aircraft with information consistent with the conventional PIB, as well as the handling of potential updates or additions of NOTAM while the aircraft is in flight. Eventually, the overall onboard functionality (including data-handling) must be validated against ***High-Level Requirement III*** in a representative environment.

4.3.4 Taxi Route Assignments and Other Clearances

The worst accident in aviation history, the Tenerife disaster, was essentially caused by a misunderstanding concerning the take-off clearance. In many other incidents and several accidents, a breakdown of communication between flight crew and controller was also causal. To aid flight crews in dispelling any potential doubts about the controller's intentions, therefore, both taxi route assignments and clearances related to surface movement or other runway operations must be conveyed to flight crews in a suitable form. Additionally, ***High-Level Requirement IV*** demands that route and clearance information has to be continuously accessible and robust against phraseology or language proficiency issues, and that conditional clearances must unambiguously identify the aircraft they refer to. Essentially, therefore, ***High-Level Requirement IV*** calls for improved awareness of taxi route assignments and runway-related clearances.

4.3.4.1 Taxi route

Several current SMGCS and most emerging A-SMGCS installations heavily rely on ground-based aids, mainly sophisticated ground guidance using advanced lighting functions which are controller-selectable or even automated, to enhance pilot awareness of taxi route assignments and applicable (intermediate) holding positions, as discussed in Sections 3.5.2 and 3.5.3.

However, particularly with respect to the assigned taxi route, it is important to note that ground-based systems are in principle **not** capable of providing complete situational awareness of the route to be followed. Any 'follow-the-greens' approach can only provide segment-wise guidance, but not a general overview of the assigned route, because the presence of other aircraft usually prohibits that the complete intended route can be lighted up. Even without this constraint, flight crews would typically not be able to see the entire intended route or route segment at a glance in perfect visibility conditions due to airport geometry and the presence of other airport lights.

In this context, it is essential to take into account that effective guidance, which can doubtlessly be provided by airport lights, does not necessarily create (and is not equivalent to) an adequate level of situational awareness. In fact, a strong focus of attention on the guidance provided may even be detrimental to situational awareness through effects such as cognitive tunnelling. Anybody who has ever 'blindly' followed another car to an unfamiliar location and tried to find the way back independently afterwards will be able to confirm this effect. Besides, dense fog, snow and slush can easily jeopardise the efficiency of ground-based guidance systems.

Consequently, a visualisation of the assigned taxi route on the flight deck, i.e. an on-board solution, appears as the most promising way of fulfilling all aspects of ***High-Level Requirement IV*** with respect to situational awareness, and has previously been suggested, cf. [Kub99, RTC01, RTC05, SAE03]. Again, considerations on the practical realisation in these references typically end at the level of stating that the taxi route will be up-linked to the flight deck via data link.

While Controller-Pilot Data Link Communication (CPDLC) appears to be the preferred variant of obtaining the data required for an onboard taxi route visualisation, both the technical details, such as machine-readable encoding of the corresponding data, and potential alternative solutions need to be investigated in detail. Indeed, a fundamental question to be assessed is whether, in absence of CPDLC service for taxi routes, flight crews should be provided with tools enabling them to manually create the taxi route to be displayed based on R/T controller instructions, or whether this only creates additional hazards to surface movement. Further important aspects to be researched encompass a consistent graphical and textual representation of the assigned taxi route, applicable holding positions and conditional clearances involving other aircraft throughout the flight deck, with focus on the associated HMI issues.

In conclusion, it is expected that an onboard a taxi route visualisation should help to prevent Runway Incursions due to flight crew disorientation and runway confusion. Nonetheless, a representation of only the taxi route might not be sufficient to create the clearance awareness required to avoid all types of Runway Incursions. Therefore, making the crew aware of runway-related clearances using e.g. the airport moving map display has to be considered as well.

4.3.4.2 Runway-related clearances

For Runway Incursion prevention, it is essential that flight crews correctly understand and comply with approval to line-up, cross or back-track on a runway, as well as take-off or landing clearances. In low visibility conditions, stop bars currently provide effective safe-guarding against inadvertent runway entry by indicating that approval to enter the runway has not (yet) been given. Switching off a lighted stop bar constitutes an extremely powerful ground-based means of conveying approval to line-up or to cross a runway by visually reinforcing the verbal ATC instruction. In principle, this concept can be extended to all-weather operations and other types of holding instructions.

By contrast, standardized operational means of conveying take-off clearances by ground-based lighting are currently not available, but feasible in principle. A corresponding solution was evaluated in the wake of the Tenerife accident, but not pursued further because it could not be demonstrated that it enhanced safety [FAA81]. Besides, the effectiveness of similar ground-based visual means in conveying a landing clearance must be questioned at least for low visibility operations, since the minimum required RVR for CAT III B approaches is 75 m, and the decision height (if specified) may be as low as 15 m. Enhanced awareness of landing clearances therefore requires an onboard solution, and it is also highly desirable to have an onboard presentation of take-off clearances, particularly in view of the ease with that colours may be confused in foggy conditions, as discussed in Section 4.3.2.

It is imperative that any runway-related ATC instruction or clearance intended for presentation on the flight deck originates from a CPDLC service. In contrast to taxi routes, therefore, a solution permitting pilots to manually enter such instructions or clearances based on information received via R/T can be excluded a priori. Otherwise, in view of the Tenerife accident, there is an unacceptable risk that a crew member under the erroneous impression that approval to enter the runway or a take-off/landing clearance has been received, feeds this false information into the aircraft systems. Once visualised, this may not only reinforce the erroneous impression of the crew member entering the information, but will also result in a presentation of hazardously misleading information to fellow crew members. This, in turn, could make it even more difficult for pilots to challenge their mental model of the situation[62].

The main problem in this context is that runway-related clearances and instructions provide a last line of defence against Runway Incursions, leaving virtually no margin to trap and correct the errors resulting from a faulty manual clearance entry. By contrast, both flight crew and controller have ample time and opportunity to detect the inevitable discrepancies resulting from erroneously entered taxi instructions aboard the aircraft before a hazardous situation emerges, if at all.

Consequently, from a flight safety perspective, CPDLC service for runway-related ATC instructions and clearances emerges as the by far most important exchange of data between aircraft and ground-based ATM installations. Its potential value can hardly be overestimated, because it might enable not only a visualisation of runway-related clearances in the cockpit, but is also prerequisite for system-based monitoring of adherence to ATC instructions. With information on clearances available to both ATC and aircraft systems, it becomes possible to generate preventive advisories or alerts if the crew is in danger of disregarding them.

However, there are various operational, several technical and Human Factors issues with respect to the use of CPDLC for runway-related ATC instructions and clearances. First of all, runway-related clearances are tactical and thus highly time-critical clearances, especially in an airport environment with high traffic density. Consequently, this results in rigorous performance requirements for the CPDLC infrastructure, as there must be virtually no delay in exchanging clearance and read-back. Potential delays of CPDLC messages could otherwise decrease runway throughput and create confusion for air traffic controllers and flight crews if messages are delayed or lost. Likewise, the acknowledgement process in the cockpit, i.e. the time the crew needs to receive and acknowledge the clearance, must be such that it does not increase workload or induce delays compared to current R/T.

Apart from these performance issues, a fundamental problem is that using CPDLC for runway-related clearances would deprive the crew of the so-called party line effect, which is particularly important in this situation. Since all runway-related manoeuvres (including runway crossings) are typically coordinated on a single frequency today, flight crews can listen to the R/T communication of the controller with other traffic and employ this information in building a mental picture of traffic in the runway environment.

62 If flight crews exchange clearance information verbally, as today, it may be possible for both pilots to detect whether the other is sure of the information he or she is conveying, mainly from subtle cues in the voice, and it is easy to voice concerns.

Nevertheless, the party line effect goes beyond mere traffic awareness, because it enables pilots to anticipate the intent of other aircraft and vehicles, based on the ATC instructions and clearances that have been issued to this traffic, which makes it the sole means of detecting controller errors today. To date, there is no conclusive concept how this crucial party line information could be compensated for in a CPDLC scenario. Concerning the location of the surrounding traffic, it is believed that a CDTI as proposed in Section 4.3.2 would provide more than adequate compensation in a CPDLC environment, whereas this solution is obviously not sufficient to address the missing intent information.
Last but not least, an operationally viable scenario for a transition period from conventional R/T clearances to CPDLC must be developed. While this is not an issue for taxi instructions, there is a clear need to address the related transition and obsolescence/legacy issues for runway-related clearances. This transition might be achieved e.g. by segregating CPDLC and legacy operations at airports with multiple runways. In addition, it should be taken into account that R/T is foreseen as both for emergency use and as fallback solution in case of CPDLC failure.

Nevertheless, to gain more insight in the operational and human factors issues related to the use of CPDLC for runway-related ATC instructions and clearances, it is assumed that these issues can – at least in principle – be resolved. In parallel, the impact of not having a corresponding CPDLC service any time in the foreseeable future has been studied as well. The main research issue concerning the presentation of runway-related ATC instructions and clearances on the airport moving map was to validate its operational necessity and perceived relevance for Runway Incursion prevention. Apart from this, another key interest was to determine an adequate and consistent visualisation of runway-related clearances.

4.3.4.3 Assumptions on CPDLC

The key challenge with respect to CPDLC and surface movement is how the corresponding clearances[63] can be obtained a suitable machine-readable format that permits bringing them to the attention of flight crews as required. This section discusses the assumptions and the resulting conceptual or technical issues related to the transmission and processing of CPDLC clearances for taxi routing and runway operations.

For the purposes of this thesis, it is assumed that the existing Future Air Navigation System (FANS) CPDLC communication protocol, avionics equipment and interfaces (see Section 3.4.1) are also used for CPDLC clearances related to aerodrome operations. Consequently, this thesis employs, extends or adapts the associated HMI and interaction principles and does not strive to determine an optimum solution. In particular, this means that the Datalink Control and Display Unit (DCDU) and the Multipurpose Control Display Unit (MCDU) are used for interaction with clearances, i.e. to display and acknowledge CPDLC clearances, or to initialize crew requests [FAN06]. With this technology, which is currently available as option, clearances are

[63] For simplicity, 'CPDLC clearance' is used as a generic term for CPDLC ATC instructions and clearances in this section.

therefore generally transmitted in textual format, with the possibility to define certain items as variables that can subsequently be used by other aircraft systems.

This choice has the important implication that the textual part of any received CPDLC clearance will always be presented on the DCDU, irrespective of other means of visualisation on the flight deck. Since FANS mimics the conventional read-back process, this raises the issue whether only clearances already acknowledged by the crew should be displayed on other flight deck displays, or whether clearances assigned by ATC should be represented as well.
However, since pilots might find themselves unable to comply with an ATC instruction, it can be assumed that they would therefore potentially want to review a clearance before acknowledging or rejecting it, and will – particularly in the case of a taxi route – benefit from the graphical representation of clearances on the airport moving map in this process. Consequently, it is presumed that the distinction between a clearance assigned by ATC and a clearance already acknowledged by the crew must be visualised. Therefore, the concept pursued was to represent read-back status on the airport moving map in a CPDLC environment at minimum for all clearances that would require a read-back in a conventional R/T environment.

At large airports, aerodrome control is usually shared between tower controllers responsible for the runways and ground controllers responsible for the remainder of the manoeuvring area [ICA01a]. It is assumed that this separation will be maintained in a CPDLC environment. Consequently, all runway-related manoeuvres will still be coordinated by the tower controller, which means that all pilots, irrespective of whether they only want to cross a runway or intend to take off, will have to change to the tower when reaching the holding position or stop bar. Therefore, all runway-related clearances will typically be addressed by a separate CPDLC clearance/approval and acknowledgement process. With the exception of crossing non-active runways in a U.S. operational environment, runway-related clearances will therefore **not** be implicitly contained in the assigned CPDLC taxi route. It should be noted, though, that this concerns CPDLC data handling and interaction only, and is independent of the way clearances are eventually presented on the airport moving map.

4.3.5 Safeguarding Against ATC Errors

At a conceptual level, it is straightforward that both controllers and pilots should be provided with tools providing better situational awareness, advising or alerting them if they are at risk of causing a hazardous situation, or if a dangerous situation has evolved otherwise. Of course, this does by no means preclude providing flight crews with means of detecting controller errors and vice versa, but in principle any problems should first be addressed in the domain in which they occur. Nonetheless, in view of the role that controller errors played in some of the Runway Incursion incidents and accidents studied, a means of enabling pilots to anticipate and mitigate potential ATC errors is required according to ***High-Level Requirement V***.

Since a controller error leading to a Runway Incursion will most likely result in a traffic conflict of some form, it appears that the most powerful tool for the detection of controller errors from a flight crew perspective is the traffic conflict detection functionality. As outlined previously, the issue whether a mere visualisation of traffic as with a CDTI is sufficient to detect potential conflicts remains to be studied in this and the following sections.

For illustration, consider the case that a take-off clearance is issued to an aircraft while other traffic is erroneously still on the runway. A representation of traffic on an airport moving map could give the flight crew the opportunity to detect the problem even in reduced visibility and to check back with ATC, or if the other traffic is just vacating, delay take-off for a few seconds. In case of visual acquisition of an intruder, this is precisely what a crew would do today, thus this proactive conflict detection does not imply a change of the overall procedures, let alone a shift of responsibilities.

By contrast, it is straightforward that a visualisation of ATC instructions and clearances for ownship alone will not reveal controller errors. However, a combined visualisation of traffic and clearances might enable intuitive consistency checks. As a further example, approval to cross a runway is inconsistent with traffic taking off or landing on that same runway. While this does not point to the source of error and cannot distinguish controller errors or flight crew mistakes, which is irrelevant at this stage from a flight safety perspective, any visualisation or alerting based on consistency checks between traffic and clearance data, where available, is implicitly also capable of safeguarding against ATC errors.

In conclusion, it is therefore presumed that there is no need for an onboard functionality specifically aimed at the detection of controller errors. Rather, the considerations above suggest that integrating traffic and CPDLC information might be a viable approach to detect ATC errors through visual or automated consistency checks. The expected benefit compared to an approach purely based on traffic surveillance is that this consistency analysis might enable the identification of ATC errors before they result in an acute collision hazard.

From an ATM perspective, a solution solely based on runway-related CPDLC service could be used to support controller decision making, and to advise or alert controllers if they attempt to assign incompatible clearances or instructions. As an example, with a take-off clearance assigned to an aircraft on a given runway, the controller interface could prevent assigning a crossing approval to other aircraft for the same runway while the aircraft taking off is still on the runway. However, such support would then also require the presence of A-SMGCS or ASDE-X traffic surveillance.

4.4 Considerations on Alerting

4.4.1 The Need for Alerting

The main purpose of the envisaged integrated Runway Incursion avoidance functionality is to enable the flight crew, by means of improved situational awareness, to avoid potential Runway Incursions proactively at a strategic or pre-tactical level, and not necessarily the addition of new alerts to the flight deck. By nature, to minimize any undesirable interference with flight crew tasks in normal operations, cf. [SAE88], alerts have to occur comparatively late, which in turn means that the level of safety is already very close to unacceptable when they are triggered. Consequently, alerts are typically associated with recovery procedures, which may raise crew workload dramatically. Last but not least, alerts create awareness of a specific problem rather than of the global situation.

However, the ***High-Level Requirements*** were deliberately worded in a neutral fashion. Bringing a certain aspect to the attention of the flight crew merely means that information must be conveyed; this does not dictate whether information is visualized only or whether alerting is additionally required. Nonetheless, from a flight deck perspective, according to the standardized categorization of information presented in Table 5, any information requiring immediate flight crew awareness or reaction necessitates a caution (Level 2) or warning (Level 3) alert. By contrast, Levels 0 and 1 are typically referred to as advisories [SAE88a].

Alert Level	A/C condition	Criteria	Attention-Getter (AG)	
			Visual AG	Aural AG
3	EMERGENCY Situation	Emergency operational or aircraft system conditions which require immediate corrective or compensatory action by the flight crew	Red	Voice or sound
2	ABNORMAL Situation	Abnormal operational or aircraft system conditions which require immediate flight crew awareness and subsequent corrective or compensatory flight crew action	Amber	Voice or sound
1	RECOGNITION Situation	Operational or aircraft system conditions which require flight crew awareness and may require flight crew action	Highlighted symbology (e.g. pulsing)	None
0	INFORMATION Situation	Operational or aircraft system conditions which require flight deck indication	None	None

Table 5: Alert classification scheme (after [SAE88a])

In line with these considerations, the NTSB specifically requires a technical solution providing *"immediate warnings"* of potential Runway Incursion or runway collision hazards directly to the flight crew [NTS07a] in its 'Most Wanted' list, without specifying the source of alerts. Likewise, current Air Traffic Management (ATM) procedures require controllers to alert the flight crews concerned whenever they detect a Runway Incursion involving conflicting traffic [ICA01a].

Indeed, an important argument in favour of alerting is that monitoring the onboard visualisation of information provided for enhanced situational awareness is not the only flight crew task, and that attentional resources are limited. Consequently, even in case the information presented is in principle sufficient for intuitive and pro-active conflict detection, system design should take into account the possibility that the flight crew is busy with other crew duties or otherwise momentarily distracted.

Additionally, as particularly the Paris accident (Appendix I-8) and the Munich incident (Appendix I-16) show, conflicting traffic must in principle be expected to enter the runway at any time during take-off or landing, causing a highly dynamic situation that may be difficult to perceive even if the corresponding cockpit display is appropriately configured and in the flight crew's routine scanning pattern. Besides, if the onboard solution chosen encompasses a configurable multifunctional display, the selected range or zoom level, mode and display options may not always be appropriate for a visual detection of an emerging hazard; conflicting traffic could be hidden due to range settings.

Furthermore, due to limited display resolution, particularly emerging Runway Incursions due to traffic entering the runway may be virtually impossible to detect at an early stage solely based on the visualisation, even if the display is suitably configured. For a display resolution of 768 x 768 pixels, which is quite typical for current-generation aircraft, a range selection showing a 4,000 m runway in its entity means that one pixel will correspond to a distance of at least 5 m. Consequently, an aircraft or vehicle moving at a speed of 5 kts (2.5 m/s) will, on average, only move by one pixel every two seconds. With ownship moving at high speeds, as in the case of take-off, final approach or landing, this difference will be impossible to perceive for the flight crew, and they will consequently most likely fail to note that the other traffic is **not** stopped. In case this particular traffic was expected to hold short of a runway used for take-off or landing by ownship, valuable margin for conflict resolution will be lost without alerting.

In conclusion, it is therefore presumed that efficient Runway Incursion avoidance requires tactical onboard alerting for last resort conflict avoidance, and to attract the attention of the flight crew whenever a mere presentation of information is not sufficient to prevent a hazardous situation and to ensure flight safety. In analogy to the tactical alerts triggered by existing surveillance systems such as the Airborne Collision Avoidance System (ACAS) or the Terrain Awareness and Warning System (TAWS), the alerting part of the onboard system can therefore be regarded as a backup or safety net function.
Nevertheless, alerts could also originate from the ASDE enhancement AMASS, ASDE-X or an A-SMGCS installation, which encompass functionality to alert controllers, as discussed in Sections 3.5.1 and 3.5.3. However, conveying Runway Incursion alerts to pilots via controllers is highly inefficient, because valuable time for conflict resolution is lost due to the fact that controllers have to alert pilots verbally via R/T. Apart from the issue that pilot and controller reaction times are additive in this communication chain, the need to include aircraft callsigns in the corresponding transmission results in an added time penalty of ~ 2 seconds[64] until the essentials of

[64] This assumes that, even under the strain of the conflict situation, the controller manages to recall the correct callsign immediately, and that the aural communication of the alert is efficient at first attempt, i.e. neither garbled, otherwise unintelligible nor truncated.

the alert can be related. Since pilots (and vehicle drivers) are literally at the controls and thus capable of taking immediate remedial action, there is a clear need to alert flight crews (and vehicle drivers) directly[65], irrespective of the source of the alert.

4.4.2 Preventive and Reactive Runway Incursion Alerting

Based on the fundamental considerations on Runway Incursion avoidance in Section 4.2, alerts can be subdivided in two classes, because the scope of alerting encompasses not only the detection and potential mitigation of Runway Incursion traffic conflicts, but also the prevention of inadvertent or unauthorised runway operations.

Accordingly, Runway Incursion prevention focuses on rigorous ownship surveillance and enhancing situational awareness. However, provided that this fails to prevent erroneous surface movement for one of the above reasons, a timely and adequate alerting concept consistent with today's flight warning principles is intended to catch the crew's attention if they are at risk of causing a Runway Incursion, with the goal of preventing them from entering the runway protection zone. These alerts can therefore be categorized as preventive Runway Incursion alerting.

Nonetheless, as discussed above, situations in which a Runway Incursion has already occurred and resulted in a potentially hazardous traffic conflict must be covered by alerting as well. If a potential Runway Incursion caused by conflicting traffic is detected, appropriate alerts and, in a second step, potential conflict resolutions, could be given to flight crew, enabling them to react to this dangerous situation. This is therefore referred to as reactive Runway Incursion alerting.
From a flight deck perspective, assuming that the preventive measures are efficient for ownship, reactive alerting will typically address dangerous situations caused by others. Irrespective of whether a traffic conflict is caused by another aircraft, vehicle or the controller – pilots are confronted with a Runway Incursion they have not caused.

In principle, the concept of preventive and reactive alerts could be generalised to all kinds of aerodrome incursions. Nonetheless, the runway is a special case of surface movement where, due to the procedures employed, virtually no collision can occur that is not preceded by an incursion. After all, access to and usage of the runway is usually limited to one aircraft at a time, except for runway crossing, back-tracking and line-up. While the concept of protection zones can be extended to all airport areas, a risk of collision might exist independently of an incursion within these areas, especially on the apron or when aircraft are queuing for take-off on a taxiway.
Nevertheless, since alerting might not be limited to the immediate runway environment, but at least cover the manoeuvring are, the generic term 'Surface Movement Alerting' seems more appropriate to include also alerts triggered while ownship is operating on taxiways or the aprons.

[65] Considerations on systems for airport vehicles are beyond the scope of this thesis, but this subject has already been addressed exhaustively, cf. [Kra04].

4.4.3 Ground-generated vs. Onboard Alerting

With the hypothesis that onboard alerting in case of potential Runway Incursions is necessary established, a key subsequent issue requiring further research concerns the source of alerts. While the considerations on worldwide availability in Section 4.1 suggest an independent avionics solution for Runway Incursion alerting to ensure that the functionality is available everywhere, the source of alerts could also be a ground-based surveillance system, as for the Honeywell/Sensis technology demonstrator described in Section 3.3.3.

Consequently, with a full-scope A-SMGCS or comparable ATM installation in place, the issue whether the generation of Runway Incursion alerts **for the flight crew** should be left to a ground-based system, or if an onboard solution is superior in this case must be addressed. As a preamble to these considerations, it should be mentioned that only tactical safety-net type alerts are discussed here. Strategic advisories pertaining to conflicts several minutes or longer ahead are most likely best generated by a ground-based system if available, because it has access to all the relevant planning information, e.g. in the form of electronic flight strips. Likewise, it is not in the least questioned that a ground-based system should generate alerts to bring a potentially hazardous situation to the **attention of the controller**.

However, when it comes to sharing this ground-generated tactical alert information with the flight deck, there are some important safety and certification implications. From a liability perspective, the Pilot-in-Command, representing the airline, is ultimately responsible for the safe conduct of the flight, not the controller [ICA90]. As mentioned before, controllers have to alert the flight crew via conventional radiotelephony (R/T) if they detect a Runway Incursion after a take-off or landing clearance has been issued [ICA01a]. The flight crew will then consider this information in decision-making. If a ground-based system detects a Runway Incursion, and alerts the controller only, the same procedure can be maintained in principle. In both cases, the flight crew can unambiguously identify the source of the alert information, and include this knowledge in their decision-making; hence there is no issue in this case.

Nonetheless, as discussed previously, conveying system-generated alerts to the flight deck via the controller might lead to the loss of valuable seconds required for conflict resolution. Therefore, directly up-linking alert information from the ground to the flight deck is currently under consideration, cf. Section 3.3.3. However, this would constitute a paradigm shift, since all caution and warning alerts on the flight deck are currently generated by rigorously certified onboard systems, which have to fulfil very high standards with respect to nuisance, false, and undetected or missed alerts [SAE88a]. From this perspective, up-linking alert information from the ground, derived from a system with potentially unknown and site-specific system design or configuration, to the aircraft avionics constitutes a major certification issue[66].

[66] Furthermore, regulations require that, depending on the criticality of the onboard function performed, the probability of failure and subsequent unavailability must be very low, both from a hardware and software point of view. However, numerous ATM applications, especially for ground and apron, are based on conventional desktop computers and workstations today. These can mostly neither fulfil the hardware nor the software requirements, particularly when Microsoft Windows is used as operating system.

While a potential solution could be to certify the ground-based alerting system according to aircraft industry standards, this will only address only part of the problem. One of the unresolved fundamental questions is the presentation of ground-generated alerts on the flight deck. If, in analogy to the current way these alerts are transmitted, the CPDLC uplink strand and associated crew interfaces are used, the alerting character might be lost. Conversely, once ground-generated alerts are seamlessly integrated in the flight-deck alerting philosophy of an aircraft – which seems necessary from a certification perspective to ensure that, e.g. while landing, ground-generated Runway Incursion alerts do not interfere with higher-priority windshear or stall warnings, cf. [SAE88a] – it will be virtually impossible for the flight crew to determine the source of the alert.

Nevertheless, this discernibility might be essential, because standalone onboard and uplinked ground-generated alerting could be available simultaneously in principle, which, in turn, raises the issue of prioritisation of potentially contradictory onboard and ground-generated alerts. In view of the catastrophe of Überlingen [BFU04a], unambiguous guidance on the precedence of onboard or ground-based systems is required in this case.

Another issue with ground-generated alerts are scope, latency and update rate of the available traffic surveillance data. A ground-based system will have to use surveillance and/or ADS-B data for the prediction of future positions of two or more conflicting aircraft or vehicles in the runway environment solely based on velocities and track angles. However, accelerations, which are additionally required for accurate predictions of aircraft positions and the determination of a potential conflict, can neither be determined accurately via secondary surveillance radar, nor are they currently part of ADS-B messages, and can consequently only be estimated on average.

By contrast, an onboard system will have access to the complete aircraft state vector with update rates, compared to ADS-B, higher by roughly one order of magnitude or more [ARI06] and negligible latency, which allows accurate and continuously updated predictions at least for ownship. Furthermore, determining the intention of a flight crew to take off is straightforward and instantaneous for an onboard system. Take-off Configuration Warning Systems, which are mandatory for transport category aircraft according to §25.703 [FAR07], alert flight crews whenever the airplane is not in a safe configuration for take-off. These systems typically use parameters such as thrust lever position, Engine Pressure Ratio (EPR), the number of engine revolutions N1 or a combination thereof to establish that take-off is intended or has commenced [FAA93]. Besides, most aircraft types currently employed by airlines feature an internal flight phase logic. The triggering of the TAKE-OFF flight phase may therefore serve as a further means of determining pilot intent. In both cases, the precise logic, which may involve additional sensor inputs, varies between aircraft types.

In conclusion, current aircraft systems are capable of determining the intent to take off – which is crucial for detecting conflicts reliably – even before the aircraft starts moving or immediately after. By contrast, it is very difficult for a ground system to detect whether an aircraft is still lining up on a runway, or whether it is already in the initial seconds of take-off, and thus a speed threshold etc. must be employed for an unambiguous prediction, which might lead to a loss of valuable time and margin for resolution in case of conflict.

To achieve the same precision with a ground-based system, scope, latency and update rate of e.g. ADS-B would have to be improved significantly, which is possible in principle, but would result in a substantial increase of the data volume to be transmitted and processed by the ground system.
Moreover, V_1, V_R and V_2 of the aircraft taking off are currently not available to ATC and thus ground-based systems, which has two implications: First, these speeds mainly depend on available runway length and actual aircraft performance, which, in turn, is influenced by airfield elevation and temperature. Consequently, knowledge of these speeds may be crucial to determine, e.g. by comparison to actual speed, whether an alert is required. As an example, a nearly empty single-aisle aircraft or regional jet might reach v_R after less than two thirds of the runway length and thus be capable of climbing over another aircraft intruding near the end of the runway without problems, while the same situation could be extremely dangerous for a fully loaded wide-body cargo aircraft. Likewise, a ground-based system can only very roughly estimate the actual braking capabilities of an aircraft, whereas in the majority of cases onboard information is already accurate enough to determine whether a certain runway exit can be taken or not, at least within a given margin of runway contamination [Vil09].
The second implication relates to the suppression of alerts in the high-speed regime. Like virtually any other alert on the flight deck, all ground-generated alerts – at least when seamlessly integrated with the flight deck – would have to be suppressed when entering the high-speed regime (usually beyond 80 or 100 kts) or at V_1 the very latest, cf. [SAE88a], depending on the threat level. Otherwise, there is a substantial risk that the ground-based system, ignorant of the V_1 speed(s) of the aircraft concerned, issues an alert after V_1, and that the flight crew might feel compelled to reject take-off nonetheless, with a likely runway overrun as result.

Apart from these theoretical considerations, there is a wealth of evidence that ground-based Runway Incursion alerting systems currently do not feature the reliability that would be required to up-link their alerts directly to the flight deck. Unfortunately, there is insufficient information to assess to what extent the issues identified above were causal for the problems reported below.
At both Munich and Frankfurt airport, existing ground-based Runway Incursion alerting functionality had been de-activated due to an unacceptable number of false and spurious alerts when the incidents discussed in Appendix I-16 occurred.
Likewise, AMASS, which is based on Ku-Band ASDE-3 radar, has been observed to malfunction due to precipitation interference in bad weather, i.e. in situations when it would be needed most. At Denver International Airport, AMASS failed to detect a Runway Incursion involving a landing United Airlines Boeing 737-500 and a snowplough [NTS07b]. In a second Runway Incursion incident at the same airport, AMASS activated only several seconds after an approaching aircraft had visually acquired the conflicting traffic and initiated a go-around. Given that both aircraft eventually missed each other by only 15 m, it is somewhat questionable whether AMASS would have prevented an accident in this particular situation [NTS07e].
Apart from delays in deployment, a major concern with the AMASS successor, the ASDE-X Safety Logic, is that controllers may manually remove targets they consider false from the system to limit nuisance alerts in precipitation. Furthermore, pilots

expect alerts in a consistent fashion, a feature essential to build confidence in a system, cf. [Bil96, SAE88a]. However, since particularly the 'precipitation mode' of the ASDE-X Safety Logic, intended to limit nuisance alerts, requires site-specific tailoring and adaptation [FAA07c], which may result in airport-dependent variations in conditions triggering alerts.

In view of these numerous and highly complex issues concerning both reliability and uplink of ground-generated alerts to the flight deck, which are clearly beyond the scope of this thesis, it was decided to focus on alerts generated by the aircraft avionics. The above considerations suggest that this approach is superior when using current and near-future technologies.
Therefore, instead of uplinking ground-generated alerts to the flight deck, future research should consider sharing Runway Incursion alerts generated by the onboard system with controllers, in analogy to present studies concerning the down-link of TCAS Resolution Advisories for presentation on controller working positions, cf. [Eur06a]. This way of achieving a common situational awareness with respect to Runway Incursion hazards, where each suitably equipped aircraft acts as independent alert sensor, also seems to be advantageous in terms of redundancy and availability. Last but not least, it appears worthwhile to recall that the primary research objective with respect to alerting is a validation of its operational relevance and its potential to prevent Runway Incursion accidents.

4.4.4 Considerations on Conflict Resolution Guidance

By nature, any aircraft-based Runway Incursion avoidance functionality capable of providing alerts, be it preventive or reactive, can be considered as an onboard surveillance system like the Terrain Awareness and Warning System (TAWS), ACAS or a windshear warning system, because it addresses threats or unsafe conditions external to the aircraft.

Regarding onboard surveillance systems, pilots typically expect instructions on how to react in case of a warning (Level 3) alert. As an example, current TAWS implementations like the EGPWS urge the pilot aurally and textually to "PULL-UP" [FAA02c] or, if a vertical manoeuvre alone is not sufficient, to "AVOID TERRAIN" [Tha04]. Likewise, ACAS provides the crew with resolution advisories in case of a traffic conflict and might, depending on the situation, advise a climb or a descent, supplemented by an indication of safe vertical speed ranges, as presented in Section 3.2.1.

By contrast, the reactive windshear warning may consist of a mere "WINDSHEAR" indication accompanied by a triple callout [FAA96a][67]. In this case, conflict resolution is entirely procedural: on alert, the flight crew's expected reaction is to perform a windshear escape manoeuvre, which consists of applying full thrust and minimizing altitude loss by raising the aircraft's nose. Training for the windshear escape manoeuvre, which is designed "*to keep the airplane flying as long as possible in the hope of exiting the windshear*", is mandatory for all flight crews [FAA96].

These considerations lead to the important question whether the warnings provided by Runway Incursion avoidance functionality should merely alert flight crews to the existence of potential Runway Incursions hazards, or whether guidance for conflict mitigation or resolution might be provided as well.

Concerning this issue, the example of the reactive windshear warning illustrates two essential points. First of all, it is generally permissible from a regulatory point of view to have an aircraft alerting system that merely detects conflicts, even at warning level, with an entirely procedural recovery manoeuvre. Furthermore, the statement above confirms that regulators acknowledge the existence of situations in which an external threat can be detected, but not necessarily be mitigated. In this context, the discussion on the mitigation of runway incursion traffic conflicts in Section 4.2.3 suggests that similar restrictions may also apply to certain Runway Incursion scenarios.

From a flight crew perspective, it can be assumed that conflict resolution guidance as for TAWS and ACAS would also be desirable for Runway Incursion alerts. Particularly the decision on how to react to conflicting runway traffic is time-critical and must be taken in a highly dynamic environment, as discussed in Section 4.2.3; it is therefore expected that pilots will appreciate any support in decision-making they can get in this situation. However, the crucial question to be answered is whether such conflict resolution guidance is technically feasible with sufficient integrity. This section addresses some of the challenges and constraints that will have to be dealt with when attempting to demonstrate the feasibility of conflict resolution guidance for Runway Incursions.

[67] However, according to TSO-C117a, so-called 'Airborne Windshear Warning and Escape Guidance Systems' may additionally provide the flight crew with flight guidance commands to perform a recovery manoeuvre, and even automatic recovery autopilot/auto-throttle modes are permissible, provided that they are sufficiently independent from the core alerting system [FAA96a].

4.4.4.1 Regulatory prerequisites for conflict resolution guidance

For any alerting system, regulations require that the conflict resolutions it provides do not lead to hazardous (severe-major) or catastrophic situations. Additionally, even in the rare event that the system creates false or nuisance alerts, it has to be warranted that the crew's obedience to these erroneous alerts does not cause hazardous or catastrophic failures, either [FAA88].

This has two significant implications. First of all, these criteria must individually be fulfilled by all of the potentially dissimilar conflict resolutions an alerting system is capable of providing, i.e. it has to be proven that the manoeuvres which can be instructed by the system are not hazardous by themselves. Trivially, this will then also address the issue of false and nuisance alerts.

Secondly, the criteria above also apply to the capability of the alerting system to make an appropriate choice from the available options for conflict resolution. Accordingly, system design must ensure that the probability of providing a hazardously or catastrophically wrong conflict resolution is less than 10^{-9} per flight hour, respectively. Consequently, the worst case scenario to be avoided is that an alerting system provides a wrong conflict resolution, which subsequently causes an accident that could have been prevented by another evasive manoeuvre, or by not performing a recovery procedure at all.

4.4.4.2 Implications for Runway Incursion alerting

4.4.4.2.1 Manoeuvres eligible for conflict resolution

In terms of potential manoeuvres that can safely be instructed by an onboard alerting system, the above regulations constrain the options available for runway traffic conflict resolution, as discussed in Section 4.2.3, to a go-around, continuing take-off as planned (or with full thrust applied), and to rejecting take-off in the low speed regime. In either case, the adverse impact of a nuisance or false positive alert would merely be of economical nature, such as higher fuel burn or increased wear on engines, brakes and tyres; apparently, none of these manoeuvres degrades the safety of flight.
However, all of the other manoeuvres mentioned in Section 4.2.3 – particularly the unconventional ones – are associated with the risk of aircraft damage and potential injuries to passengers and flight crew. It is therefore questionable whether a system proposing such conflict resolutions will be accepted by regulators, operators and pilots, even if these manoeuvres might be the only remaining option to avoid a collision. By contrast, the pilot-in command may deviate from the rules of the air if absolutely necessary in the interest of flight safety [ICA90], and can thus attempt an unconventional conflict resolution at his or her own discretion (and responsibility) if a runway traffic conflict cannot be resolved otherwise.

Consequently, even without the added complication of conflicting runway traffic, certifying an avionics system to the design assurance level required to instruct e.g. rejected take-offs for the full spectrum of take-off speeds up to V_1 constitutes a formidable challenge. It would have to be demonstrated that the prediction of deceleration distance is sufficiently robust against uncertainties and potential sudden variations in the parameters critical for its calculation, thus permitting to control the risk of a runway excursion inherent in such a manoeuvre within the high-speed regime. Additionally, the almost inevitable damage to aircraft brakes and tyres would have to be assessed in the light of potential false and spurious alerts, possibly building on the analogy with windshear warning systems in terms of the achievable reliability[68].

4.4.4.2.2 Determination of the correct evasive manoeuvre

For Runway Incursions involving conflicting traffic on the runway, an alerting system providing conflict resolution guidance will only have to determine the correct evasive manoeuvre for take-off scenarios. In view of the considerations above, the required recovery procedure is straightforward and essentially without alternative for all other scenarios, irrespective of whether it is explicitly instructed or triggered by a warning that merely indicates the conflict.

The need for the alerting system to calculate which evasive manoeuvre is best suited to resolve or mitigate the conflict is therefore limited to take-off scenarios. However, in contrast to ACAS resolution advisories, which may be reversed or amended based on continuously reiterated predictions at any time, there will be virtually no possibility to revise the decision to abort or to continue take-off once the corresponding actions have been initiated by the flight crew.

In consequence, the worst case scenario that must be avoided is that an aircraft taking off would routinely be capable of climbing free of an intruder on the runway, but the alerting system erroneously instructs to abort take-off. If the flight crew complies and cannot stop their aircraft before impacting the conflicting traffic, the outcome might be catastrophic and effectively worse than without alerting.

Therefore, the fundamental technological question is whether it is possible to predict both take-off and braking performance with the precision and integrity required to ensure that this worst case scenario does not occur. It is presumed that real-time onboard take-off performance functionality, which is currently not available, will be required to achieve this. In addition, the associated key issue from an operational point of view is whether, given the constraints on evasive manoeuvres and the safety margins that will inevitably have to be added to address virtually unpredictable meteorological variations such as gusts, changing wind direction or runway contamination level, the resulting system will eventually be capable of providing more than conflict resolutions for a number of straightforward cases, such as large distances to conflicting traffic, and low ownship speeds. Furthermore, additional uncertainties caused by inaccuracies and latencies in intruder data have to be considered.
Performing the extensive numerical simulations and error analysis required to address these issues is, however, clearly beyond the scope of this thesis. Nevertheless,

[68] The use of 'firewall' thrust in the windshear escape manoeuvre may result in the need to replace or overhaul the engines; therefore, the required robustness against nuisance alerts might serve as a guideline for an onboard system instructing a rejected take-off in the high speed regime in view of likely brake/tyre damage.

the number of high-profile take-off and landing runway excursion accidents in recent years, such as the overrun of an Air France Airbus A340 in Toronto in 2005 [TSB07] or a Kalitta Air Boeing 747-200 at Brussels airport in 2008 [AAU09], may illustrate the sensitivity of current performance calculations to variations in operational conditions, meteorological conditions and crew response, and thus the magnitude of the challenge.

Besides, the prospect that even a highly sophisticated alerting system capable of calculating conflict resolutions might eventually not be able to provide mitigation for all imaginable conflict scenarios raises additional questions from a human factors perspective. One is how an operationally meaningful blend of instructions for evasive manoeuvres and merely indicative warnings can be achieved, given the risk that the latter might be perceived as announcing imminent doom, when the alerting system determines that neither aborting nor continuing take-off will resolve the conflict.

4.4.4.3 Conclusion

Concerning Runway Incursions alerts, the focus of this thesis is on validating whether they are desirable in principle, not on the precise wording or nature of warnings. In view of the numerous and complex certification issues outlined above, it was therefore decided that the alerts for conflicting runway traffic devised and assessed in the following chapters should not contain any guidance on conflict mitigation or resolution.

Rather, as with windshear alerts, the flight crew response to the warnings will be entirely procedural. While this indicative warning approach eventually leaves the difficult and complex decision on how to react to a detected Runway Incursion traffic conflict to the crew, it might also give them more margin for a prudent reaction based on good airmanship and the enhanced situational awareness an onboard solution is expected to provide. As an example, if traffic visually acquired by the crew is almost off the runway, but still triggers an alert due to a slight latency in the traffic data, the crew can more easily continue than in a situation where the system calls for a go-around. Likewise, this approach leaves room for creative solutions, such as the decision of a flight crew to delay rotation when facing conflicting traffic on intersecting runways at Boston Logan International airport in 2005 (cf. Appendix I-16.2).

4.5 Allocation of Functionality to Onboard and Ground Segment

The analysis on the compensation of current deficiencies and limitations concerning surface operations in Section 4.3, which is at the heart of the preventive Runway Incursion avoidance strategy, clearly demonstrates that the requirements for improved flight crew situational awareness outlined in Chapter 2 can hardly be met by ground-based systems alone, but rather necessitate an onboard solution as core Runway Incursion avoidance functionality, thus confirming the onboard-centric approach pursued by this thesis.

A major benefit expected from an onboard solution is that the situational awareness it provides with respect to ownship position (***High-Level Requirement I***) and other traffic (***High-Level Requirement II***) may enable the crew to detect potential threats and conflicts proactively, including those resulting from potential controller errors (***High-Level Requirement V***). The same applies to up-to-date information on the aerodrome's operational status, configuration and present limitations (***High-Level Requirement III***), which requires a data handling and operational concept for NOTAM and other short-term or temporary information. Nevertheless, it is assumed that alerting is required in addition to this mere presentation of information to ensure that information on potentially hazardous situations, in particular conflicting runway traffic, is not missed accidentally. For the reasons discussed in Section 4.4.3, this alerting functionality should be hosted onboard the aircraft.
Provided that ADS-B traffic data are used, and that digital NOTAM information is uploaded prior to flight, this solution is independent of ATM ground infrastructure, and thus forms a core standalone onboard functionality. Indeed, the main limitation to the autonomy or independence of an onboard solution is the availability of complete data on traffic in the airport environment in sufficient quality. However, first steps in legislation are under way to make ADS-B out mandatory for certain airspaces in Australia and the United States, where ADS-B is planned to be used in lieu of secondary surveillance radars in some areas, e.g. in so-called Non-Radar Airspace. There are similar plans in Canada and Europe.

At the same time, full interoperability with ground-based ATM systems must be ensured, particularly with respect to traffic data services (TIS-B, ADS-R) and CPDLC (***High-Level Requirement IV***), but also concerning the exchange and update of short-term and temporary information with the ground. In the transition period towards an ADS-B mandate, and potentially beyond, it is expected that TIS-B and ADS-R act as gap fillers completing the traffic surveillance picture available to flight crew and aircraft systems, based on information derived from ground-based surveillance.
From a flight safety perspective, however, runway-related CPDLC service is expected to be the by far most important air-ground cooperative service, and thus a strong driver for air-ground interoperability. It provides the additional advantage that it does not require sophisticated ground-based infrastructure. In particular, there is no need for an A-SMGCS installation to support this service. It could be realised as an extension of the existing FANS controller HMI interfaces since there is generally no need for an enhanced visualisation, whereas creating taxi-routes will most likely require advanced controller HMI.

Nonetheless, it seems reasonable to design the onboard components for Runway Incursion avoidance to be capable of operating in a standalone mode. If the aircraft's avionics supports air-ground cooperative services not available for the system on the ground, or if the corresponding airport installation is unavailable or inoperative altogether, this should only have minimum impact on the core onboard functionality. In particular, crew procedures should be essentially the same, irrespective of whether the system is used in an air-ground cooperative or standalone configuration. However, it must be assessed how each functionality will be reduced compared to the full air-ground cooperative setup.

Given the distribution of functionality outlined in this section, the absence of ground-based services mainly impacts the visualisation of CPDLC clearances for surface movement, and potential alerts based on the underlying information, an aspect to be investigated by this thesis. Essential elements such as alerting for conflicting traffic will always be available, but the impact of an incomplete traffic surveillance picture on the usability of alerting is one of the central aspects that needs to be studied.

4.6 Constraints

4.6.1 Flight Deck Integration Aspects

The additional onboard functionality proposed for Runway Incursion avoidance must be operated in the context of existing aircraft systems and functions. Design choices are therefore constrained and limited by the fact that integration with an existing flight deck has to be achieved.

It is therefore essential that the commonly accepted principles of flight deck design are followed in designing the associated Human-Machine Interface (HMI). In particular, the integration of the additional functions should be consistent with the principles and philosophy applied on the overall flight deck design of the host aircraft, particularly in terms of display formats (e.g. colour coding or symbology) and flight warning system. From a flight deck integration perspective, there is consequently an intrinsic focus on the HMI and alerting. Particularly in those two domains, however, a rigorous differentiation between functional and HMI requirements is not always possible.

For the proposed onboard Runway Incursion avoidance system, an aspect deserving particular attention in this context is that both traffic presentation and traffic conflict alerting should be integrated seamlessly with ACAS, because ACAS is a mandatory function. Besides, ACAS has shaped pilot expectations with respect to the functionality to be expected from a traffic surveillance system, and can therefore be regarded as an important guideline for functional requirements.

Another important aspect is that the number of additional controls required for any new system must be kept at a minimum; employing available cockpit hardware is favourable over new controls. Apart from easier retrofit and line-fit into current production aircraft types, this has the additional advantage that crews are already familiar with existing control panels, which would minimize the additional training effort. Furthermore, additional controls or control panels result in additional development, integration and certification costs, and may interfere with the original flight deck interaction concept, particularly when they are located, due to a lack of available space, at sub-optimum locations from an ergonomics point of view. This may significantly alter scanning patterns when interacting with the new onboard system, with potential impact on the efficiency of existing systems.

From the considerations above, one can also deduce that it will be necessary to choose a specific aircraft type or family as baseline for a prototype implementation to address these integration aspects properly. Whenever a model or straw man aircraft was required in this thesis, the Airbus single aisle/long range family was used. It is representative of current-generation aircraft with electronic displays ('glass cockpit') and well proven in millions of flight hours, with thousands of aircraft on the market and on order. As an added benefit, this enables both a retrofit and line-fit perspective on system integration. Furthermore, in contrast to the more advanced Airbus A380, sufficiently detailed technical information on this aircraft family is readily available.

4.6.2 Limitations of a Technology Approach

In the runway environment and on taxiways, the onboard system approach outlined in this chapter is expected to solve many of the current safety issues associated with surface movement. In this context, an important question is whether this approach is only valid for the manoeuvring area, or whether it can be extended to the whole movement area, i.e. including aprons.

A closer look, however, reveals that traffic awareness and alerting has a fundamentally different quality on the apron because of the significantly different scenarios. From a technical perspective, all vehicles on the movement area could be equipped with ADS-B transponders and GPS at reasonable costs, which means that it would be technically possible to display them on a cockpit CDTI with reasonable accuracy. But unless the HMI is very carefully designed, this will most likely result in a cluttered display due to the large number of service vehicles typically operating on the apron and at the aircraft stands. Besides, it must be expected that there will be intrinsic sources of display clutter around the ownship symbol. First of all, many vehicles, including e.g. refuelling cars or baggage loaders, operate in close proximity to or directly attached to the aircraft, leading to traffic symbols overlapping with the ownship symbol. In addition to this, the layout of the apron and, potentially, the vehicle roads may add to the resulting overlap clutter around the ownship symbol.

Figure 28: Apron scenario at Frankfurt Airport (EDDF), Spring 2005

All of these issues can be nicely demonstrated using the photo of an apron scene at Frankfurt Airport (EDDF) depicted in Figure 28: Several vehicle roads are designed such that they run beneath the tails of parked aircraft, as can be seen from the vehicle in the yellow circle. The tail of the parked Boeing 747-400 thus protrudes into the vehicle road in the photo. The same is true for the small bus in the green circle, which is, in addition, a bit off the vehicle road painted on the tarmac. Likewise, the Airbus A300-600 entering the stand will move over the holding catering truck with its right wing (red circle). And depending on the number of baggage carts attached, the little train pulled by the tractor in the blue circle has a variable length. Last but not least, positional inaccuracies of GPS/D-GPS will, together with the effects described above, lead to further overlap of the own-ship symbol with vehicle symbols.

As these examples illustrate, any useful traffic alerting function on the apron would require that the correct vehicle dimensions (including height) are broadcast via ADS-B, which is currently not the case, because it is highly relevant whether the vehicle in question is a passenger car used by a marshaller or a 20 m bus used to transport passengers to airplanes at remote parking positions. In the absence of vehicle height information, it will be very difficult to judge for both crew and alerting system whether a vehicle below the aircraft's tail or wing is a hazard or not.
When it comes to a flight deck alerting system, the requirements on the content and quality of traffic data become even higher, because nuisance alerts have to be avoided, and no real alerts should remain undetected. Especially for the case where parts of the aircraft extend over vehicles, as shown in the figure, it will be very difficult to accomplish this, as even typical GPS accuracies of ~5 m will lead to a maximum additive error of ~10 m for the system vehicle – aircraft, and alerting and protection zones would have to be dimensioned accordingly. Taking this into account, it is very likely that the situation shown in the red circle would lead to a nuisance alert.

In view of these facts, a reasonable and operationally meaningful presentation in the aircraft cockpit is very difficult to achieve for **all** airport vehicles; the same applies to traffic alerting. Therefore, the following solution could be envisaged:

- ADS-B equipage should only be mandatory for manoeuvring area vehicle traffic (cf. Section 4.3.2.2), thus enabling its visualisation on a moving map.
- Apron vehicle traffic hazards near the parking stand should be tackled procedurally or by vehicle-based applications, except for follow-me cars or other vehicles operating outside the dedicated vehicle roads on the apron or on taxiways (excluding the immediate stand area).
- Vehicles required for safe and efficient airport operations, such as follow-me cars and fire engines, may additionally be equipped with an airport moving map display with traffic representation, and potentially basic other Runway Incursion avoidance functions, cf. [Kra04].

Even with ADS-B technology, parked and thus unpowered vehicles are not detectable. Furthermore, equipment, containers and other objects in the vicinity of the parking stand cannot be detected with this technique, either, and it would be very costly to survey them accurately in real-time and to transmit the corresponding information to the flight deck subsequently. This is a further indicator that object and vehicle collision avoidance at the ramp and on the apron should be tackled procedurally and not by a technological solution.

5 Experimental Surface Movement Awareness and Alerting System

Since deficiencies in flight crew situational awareness are virtually always a causal factor in Runway Incursions and other surface movement incidents or accidents (cf. Section 2.3)[69], it is of paramount importance to ensure that the flight crew maintains an adequate level of situational awareness at all times.
From the considerations in Chapter 4, it is evident that this might be achieved by an integrated onboard-centric solution compensating the deficiencies and limitations of current flight deck instrumentation concerning surface movement.

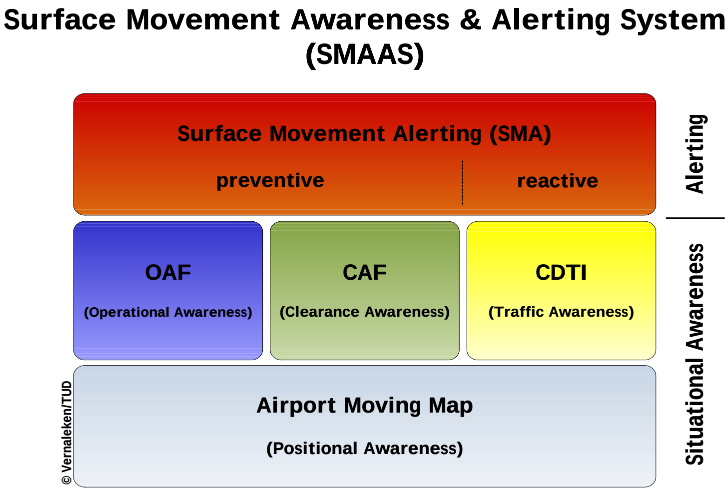

Figure 29: Elements of the experimental Surface Movement Awareness & Alerting System (SMAAS)

To investigate the research issues identified in the previous chapter, and to validate whether an approach focussing on onboard functionality is capable of providing pilots with the required support during ground operations, an experimental Surface Movement Awareness and Alerting System (SMAAS) prototype was developed as a scientific research tool in the frame of this thesis. It consists of two complementary parts (see Figure 29), one aimed at maximizing crew situational awareness in the domains identified in Section 2.3, and the other dedicated to alerting in case this is not sufficient to prevent a hazardous situation. Due to the fact that Runway Incursions constitute a hazard external to the aircraft, there is a deliberate analogy to existing onboard surveillance systems such as ACAS and TAWS, which is also mirrored by the safety net character of the envisaged alerting functionality.

In view of the holistic approach proposed in Chapter 4, there appears to be a clear need for presenting all the required information in an integrated fashion to facilitate its assimilation by pilots. Consequently, an airport moving map based on a DO-272A/ED-99A compliant Aerodrome Mapping Database (AMDB) [RTC05] was chosen as the core element of SMAAS. Apart from providing the crew with enhanced position awareness to avoid disorientation on the airfield, thus addressing ***High-Level Requirement I***, the Airport Moving Map (AMM) is also intended to serve as a basis for the visualisation of all other information relevant in an aerodrome operations context, resulting in a second layer of three further situational awareness elements in Figure 29:
By displaying relevant surrounding traffic on the ground and in the take-off or landing phases in relation to the airport moving map, Cockpit Display of Traffic Informa-

[69] While there are numerous cases where ATC errors (often also due to a lack of controller situational awareness) have led to Runway Incursions as well, the focus of this thesis is on flight deck causal factors.

tion (CDTI)[70] functionality can be added to the basic airport moving map to increase traffic awareness, in response to ***High-Level Requirement II*** and in line with the considerations in Section 4.3.2. As outlined previously, the necessity of traffic visualisation in the airport environment can be regarded as further rationale for an airport moving map, which was therefore selected to form the backbone of the SMAAS and the basis of all additional awareness and alerting functionality.

In addition, the Operational Awareness Function (OAF) is envisaged to process and present relevant information on the operational configuration of the airport, such as runways in use, runway closures, whether Low Visibility Procedures (LVP) are in force and other information typically contained in Automatic Terminal Information Service (ATIS) transmissions (voice or digital) or Notices to Airmen (NOTAM). Furthermore, the take-off or landing runway selected in the Flight Management System (FMS) flight plan (referred to as 'FMS-selected runway' in the remainder of this thesis) is highlighted on the airport moving map to remind the crew of the FMS settings, which is intended as another measure to prevent take-off and landing operations on the wrong runway, hence addressing ***High-Level Requirement III***.

Last but not least, the Clearance Awareness Function (CAF) was conceived to raise the crew's awareness of ATC clearances and instructions relating to surface operations, such as the assigned taxi route, in response to ***High-Level Requirement IV***.

Only if the display of all this information fails to prevent a hazardous situation, the second part, the Surface Movement Alerting subsystem, which builds on the same information as the awareness part, comes into play. It can be subdivided into two integral parts, a preventive and a reactive one. The first goal of the Surface Movement Alerting system is to ensure that ownship does not cause a Runway Incursion, i.e. preventive Surface Movement Alerting. To achieve this, the alerting part is armed using the same airport, operational and clearance data as the awareness part of the SMAAS. In contrast to systems such as the RAAS (cf. Section 3.3.1), this is believed to enable specific alerting tailored to the particular operational situation, which is seen as a prerequisite for preventive alerts up to Master Warning level (Level 3). Without operational and clearance information, it would, for example, be impossible to alert the flight crew specifically when they enter a runway that is completely closed, or when they enter or try to take off from a runway without the appropriate clearances.

In parallel to this rigorous ownship surveillance, relevant surrounding traffic will continuously be monitored to alert the crew if a Runway Incursion caused by others poses a significant hazard (Reactive Surface Movement Alerting) during take-off, final approach and landing, thus answering to ***High-Level Requirement V***. Likewise, alerts are provided if other aircraft are taking off or landing on a runway that is about to be entered by ownship. In an environment where runway-related clearances are not provided via data link, this function can also be employed to prevent the crew from erroneously entering a runway.

The following sections are dedicated to a detailed description of the individual elements of the SMAAS and the implementation chosen for this thesis.

[70] The term CDTI is used here for an enhanced display of traffic information in the cockpit beyond current ACAS. While this may include an additional, separate cockpit display, the preferred solution is an ND-integrated traffic display.

5.1 Airport Moving Map Display

The analysis of selected incidents and accidents in Section 2.2.2 identified disorientation on the aerodrome surface due to inadequate position awareness as a common precursor of Runway Incursions. Therefore, flight crews need better support to maintain awareness of their position on an airfield at all times, especially in adverse weather conditions. An independent source of airport navigation information that can help to overcome visibility limitations and potential airport signage/marking issues (e.g. presence, conformity with regulations and conspicuousness) is consequently required (***High-Level Requirement I***).
As the analysis in Sections 2.3.1 and 4.3.1 has shown, this requirement cannot be met by ground-based systems. Consequently, a moving map display of the aerodrome emerges as the onboard solution of choice. While there is still some dissent about the optimum format (see Section 3.1 and the following pages), the Airport Moving Map (AMM) has been widely accepted by both research, industry and operations as the core technology to increase the flight crew's situational awareness in terms of position on the airport surface. Accordingly, while most of the other SMAAS elements have to be conceived from scratch or based on initial research, certified AMM products are already available (cf. Section 3.1), Therefore, this sub-chapter focuses on the integration and Human Factors aspects of AMM design resulting from its application to Runway Incursion avoidance, including the additional information layers and alerts provided by SMAAS.

5.1.1 Concept & Research Issues

5.1.1.1 Operational concept and procedures

The operational concept for the basic airport moving map is to support both crew members during taxi operations to facilitate surface navigation, to increase situational awareness and to prevent errors. Generally, it is envisaged that the normal crew task sharing between flight crew members will be maintained, in that one pilot is in control while the other attends to communication with ATC and aids in operating and navigating the aircraft[71]. Today, the pilot not taxiing the aircraft uses paper charts to accomplish this, and it is foreseen that instead of referring to paper charts or their electronic equivalent, the airport moving map display will be used instead.

Airport navigation encompasses several sub-tasks, such as obtaining an overview of the location of ownship on the airport (or the taxi route), monitoring progress along the assigned route and required turns, or finding a certain parking position or gate. Additionally, in the frame of Runway Incursion Avoidance, the usage of the AMM is extended to take-off, final approach and landing, because there is a clear need for traffic and runway status surveillance in these phases. To support these navigation and surveillance tasks, different ranges and levels of detail are required.
However, unless take-off performance monitoring or brake-to-vacate functions are available, the added value of using an airport moving map during take-off and land-

[71] While taxi procedures are globally similar, the division of crew duties may differ in detail from airline to airline, and thus this section can only give generic information as guideline.

ing is probably limited if no traffic is displayed. An operational concept and the procedures associated with airport moving map usage during take-off and landing are therefore described in conjunction with the display of surface traffic in Section 5.2.
At any rate, procedures cannot require crew members to have the airport moving map visible at all times while taxiing to departure, since a recapitulation of the take-off briefing or a scan of the weather or terrain environment may require the usage of other modes and ranges if the airport moving map is part of a multifunction display or the EFIS. However, the crew should be advised to limit, if possible, such activity to taxi route segments not requiring a turn or runway crossing. In view of the considerations in Section 4.3.1, crew procedures must also emphasise the necessity that at least one crew member has to focus on the outside environment irrespective of visibility conditions.

5.1.1.2 Separate vs. EFIS-integrated airport moving map

As outlined in Section 4.3.1, the main research interest in terms of airport moving map design concerns the repercussions and implications of a holistic Runway Incursion avoidance functionality on display formats and flight deck integration. Consequently, since commercial airport moving maps are available both on separate Electronic Flight Bag (EFB) type displays and as EFIS-integrated solutions (cf. Section 3.1), one of the fundamental choices to be made in setting up the experimental SMAAS was between these two options. This section provides the rationale for the approach pursued by this thesis.

Separate displays like EFBs are usually installed at sub-optimum locations in the cockpit, as illustrated e.g. by Figure 18 on p. 65. Furthermore, EFBs are typically side displays not aligned with the aircraft axis, which might become problematic if an ownship symbol indicating heading or track information is displayed. In this context, it also seems worthwhile recalling that having aerodrome mapping information on the side panel has been deemed sub-optimum even for conventional paper charts in the context of the Detroit accident [NTS91], cf. Appendix I-5. Last but not least, a separate display means that the pilot's scanning pattern must be extended, which could be associated with additional workload.

Nevertheless, there is no reason to question the suitability of an EFB as a retrofit airport moving map display. However, several issues from both a cockpit design philosophy and consistency perspective will need to be addressed when considering the integration of traffic information and preventive or reactive alerting functionality.
With respect to the traffic displayed, consistency issues might arise especially in case of retrofit. For illustration, consider any classic glass cockpit aircraft featuring a Navigation Display (ND) limited to ACAS traffic retrofitted with a side display featuring ADS-B and TIS-B traffic. In normal operations, this will result in two potentially different traffic surveillance pictures in the cockpit, which is clearly undesirable.
This consistency issue is aggravated when taking into account alerts for conflicting traffic as well. In case of an alert exclusively based on ADS-B/TIS-B traffic data, such as a Runway Incursion alert, the particular traffic target causing the alert might either

not be visible on the ND at all (such as ground traffic not present in the ACAS surveillance picture), or be displayed as non-threatening traffic (e.g. conflicting traffic on approach that is obviously not identified as threat by the ACAS logic).
This problem cannot be solved fully even if a new avionics traffic computer feeding both the EFIS and the side display is retrofitted, since the conventional EFIS currently lacks the range selections required for an uncluttered representation of airport surface traffic.

From a cockpit design philosophy point of view, having different and possibly inconsistent traffic alerts on two separate displays seems highly questionable, since the crew would have to be trained to look primarily at the side display on the ground, at the EFIS displays in the air, and potentially at both during final approach when an aural alert is triggered.
In view of these considerations, it is probably not desirable to display Runway Incursion and other surface movement alerts on a separate display. Besides, due to its criticality, Runway Incursion alerting is expected to use both Level 2 (Caution) and Level 3 (Warning) alerts like ACAS, which necessitates a connection to the aircraft's Flight Warning System to ensure an appropriate presentation and prioritisation of alerts, and also requires certification of both the display hardware and software employed to Level C or higher, cf. [SAE88a]. This might eventually diminish the cost benefits of an EFB solution compared to an EFIS-integrated approach.

In conclusion, therefore, it appears favourable to present both airport information, traffic information and alerts on the EFIS displays. Consequently, in view of the fact that the airport moving map forms the basis for the visualisation of further SMAAS functionality, the cockpit concept selected for this thesis consists of extending the standard Navigation Display (ND) by additional ranges dedicated to aerodrome operations, which are available in all usual modes, ARC, ROSE and PLAN. The use of the ND has the additional advantage that the airport moving map can be operated intuitively without additional controls, provided that the range selector is enhanced to lower ranges, accordingly. Only more advanced interaction, such as a panning function, would require additional controls. However, if the Cockpit Display System (CDS) of the target airframe provides advanced interactivity as with ARINC 661 [ARI02a], the corresponding provisions could be implemented as soft controls. Along with the greater variety and configurability of airport views enabled by range and mode selections, the improved position awareness provided by airport moving map displays is believed to be a huge advantage over conventional paper charts.

5.1.1.3 2D vs. 3D airport moving map

For an airport moving map integrated in the EFIS as proposed in the previous section, the envisaged use for traffic surveillance during take-off and landing raises the question of how an intuitive transition to the conventional Navigation Display ranges can be achieved. A straightforward approach is to require consistency between the airport moving map and the ND, which means that scales and symbology should be identical or at least similar wherever possible. This is a constraint that limits the usability of 3D exocentric airport moving map formats proposed and studied e.g. by NASA [FAH05], since none of the current or near-future transport category aircraft have 3D exocentric ND modes. With respect to these formats, which have shown advantages compared to the purely two-dimensional airport moving maps, the potential added value compared to 2D displays also has to be seen in the light of cost-benefit considerations. 3D does not only require a significantly higher hardware performance, it also results in dramatically more complex data requirements for the Aerodrome Mapping Databases (AMDB), which must be fully three-dimensional to reflect, among others, runway slopes and building heights accurately. An assignment of generic heights for buildings and missing runway or taxiway slopes are probably prone to lead to confusion. Last but not least, and this is an aspect overlooked by most of the studies pushing for 3D exocentric airport representations, the classic 2D moving map and exocentric formats are not mutually exclusive, but rather complementary, i.e. they could easily co-exist as different modes of a future EFIS display.

Furthermore, it should be noted that the choice of a 2D, ND-integrated airport moving map as the basis of SMAAS does not preclude the additional display of aerodrome mapping data on other display formats such as Primary Flight Display (PFD) or Head-up Display (HUD). A dedicated SVS-PFD taxi mode, including the presentation of an assigned taxi route and applicable stop bars, has already been developed and evaluated successfully in a research flight simulator in conjunction with an airport moving map on the ND [Ver05]. In fact, such a display or a HUD might be required to provide guidance for taxiing an aircraft when visibility is extremely low; a basic moving map will most likely not be sufficient in this case.

5.1.2 Design of Airport Moving Map Prototype

5.1.2.1 General approach

The existing airport moving map prototype available at the Institute of Flight Systems and Automatic Control (see Figure 30) was used as a starting point for the development in this thesis. It had been conceived as a demonstrator based on the pioneering work of the Institute in the field, cf. [Kub99]. From a Runway Incursion avoidance perspective, however, the crucial drawback of this design is the absence of taxiway holding positions and stop bars. Furthermore, there is a lack of contrast between apron areas and the runways. Its main technical limitation was that AMDBs could only be visualised after offline processing into a single Open Inventor file with pre-defined content and colours, which resulted in two major disadvantages. The first was that any runtime changes of airport moving map design and features in

Figure 30: The Institute's AMM prototype at the beginning of SMAAS development

terms of content or colour scheme could only be realised in a very cumbersome and performance-consuming manner, since any such modification required searching the whole Open Inventor tree for every instance of the respective airport element. More importantly, though, the choice of airports that could be used for testing and prototyping was limited to those few for which the time-consuming AMDB offline processing had already been accomplished. However, to ensure that the AMM design devised by this thesis would be sufficiently generic and not optimized to a particular airfield layout, different airports[72] were eventually used during the development. Therefore, the existing AMM prototype was extended by the capability to directly load ED-99 or ED-99A compliant AMDBs using ESRI Shape Files as exchange format, which gave the application direct control over the individual airport features to be displayed, as well as the respective colours, line widths and layering used.

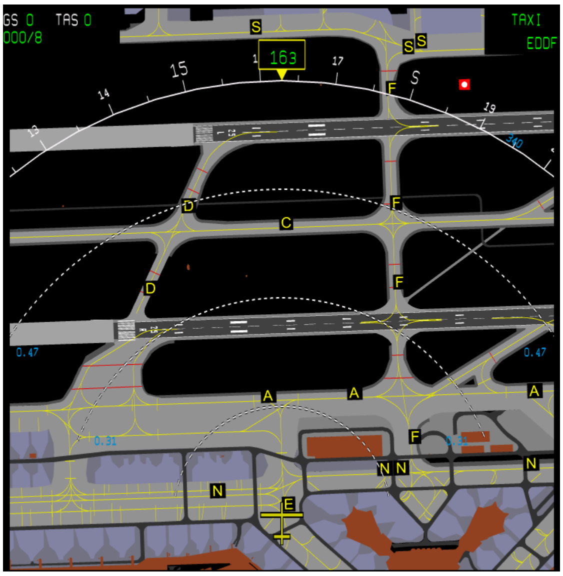

Figure 31: Initial airport moving map design before prototyping

Taking into account the general Human Factors engineering guidelines for electronic cockpit displays laid down in standards such as SAE Aerospace Recommended Practices ARP5364 [SAE03] and based on the analytical considerations in the following sections, an initial refined airport moving map design (Figure 31) was then drafted and subsequently refined in several prototyping sessions with test and technical pilots. Prototyping was aimed at a fine-tuning of the human-machine interface prior to the simulator assessment with airline pilots described in Chapter 8. The underlying objective of this iterative validation approach and subsequent refinements was to enable an assessment focussing on the actual validation objectives by preventing disturbances resulting from an immature Human-Machine Interface (HMI) design as far as possible.

The prototyping core team consisted of two male experimental flight test pilots from different manufacturers. Both of these pilots additionally had a significant background as captains in airline operations. They were joined by a third pilot who was a former air traffic controller now responsible for performing Navaid calibration flights for a major European ANSP. In one of the final prototyping sessions, two further male airline captains active in the International Federation of Airline Pilots' Associations (IFALPA) Aircraft Design and Operation Committee reinforced the above assessment team. Prototyping sessions consisted of free-play surface movement scenarios at Frankfurt and Paris Charles-de-Gaulle airport in the Institute's fixed-based flight simulator (see Section 8.3 for a detailed description). Pilots were given the opportunity to evaluate and explore the airport moving map and its functionalities at their own discretion; their comments during the runs were taken down and subsequently consolidated in a debriefing session with all participants.

[72] The airports routinely used to assess the design were e.g. Frankfurt (EDDF), Paris Charles-de-Gaulle (LFPG), Prague (LKPR), Newark (KEWR), Atlanta (KATL), Dallas-Fort Worth (KDFW), Denver (KDEN), Sydney (YSSY), Boston (KBOS) and Cleveland (KCLE).

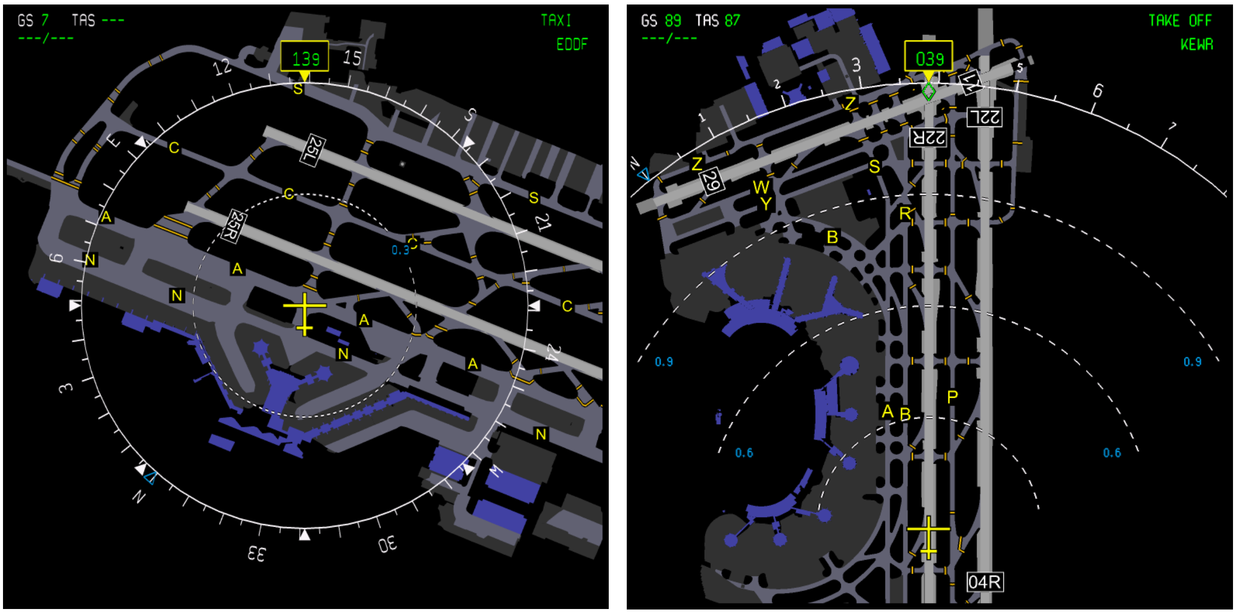

Figure 32: Airport moving map in ROSE mode (left) and ARC mode (right) at 1.25 NM

Figure 32 shows the resulting airport moving map design eventually realised and assessed for two different range selections. In view of the flight deck integration concept derived in Section 5.1.1.2, ownship symbol, display layout and compass rose are virtually identical to the ND of the current Airbus single aisle aircraft family, cf. [Air05]. In the background of the display, there is a 2D representation of the airport derived from airport elements contained in an DO-272A/ED-99A compliant AMDB [RTC05], see Section 5.1.2.2 below for details.

5.1.2.2 Identification of airport features to be displayed

Unlike for Cockpit Displays of Traffic Information (CDTI), there is no guidance material exclusively dedicated to airport moving map displays. Still, there appears to be consensus in the applicable literature and guidance material, such as DO-257A on the depiction of navigation information on electronic maps, that all runways and taxiways, along with their respective identifiers, are the minimum required content, cf. [RTC03a, Yeh04]. Given the multitude of features and information available in Aerodrome Mapping Databases (AMDBs), the need for a de-cluttering concept is also outlined, and benefits and shortfalls of automatic vs. manual de-cluttering are discussed [Yeh04].

Nonetheless, a number of important design considerations and key design guidelines are missing in the above references. When considering an airport moving map as part of the Synthetic Vision concept [Ver05, Ver06], it emerges that airport features should be presented in such fashion that there is sufficient resemblance between reality and the cockpit depiction, because flight crews need to be able to establish a correspondence between the electronic cockpit display and the outside world as seen from the cockpit windows. Another conceptual approach towards airport moving maps is considering them as animated airport charts, or an extension of the Navigation Display, in that existing navigation information (waypoints, Navaids, SIDs, STARs, etc.) is supplemented by information relevant for airport navigation.

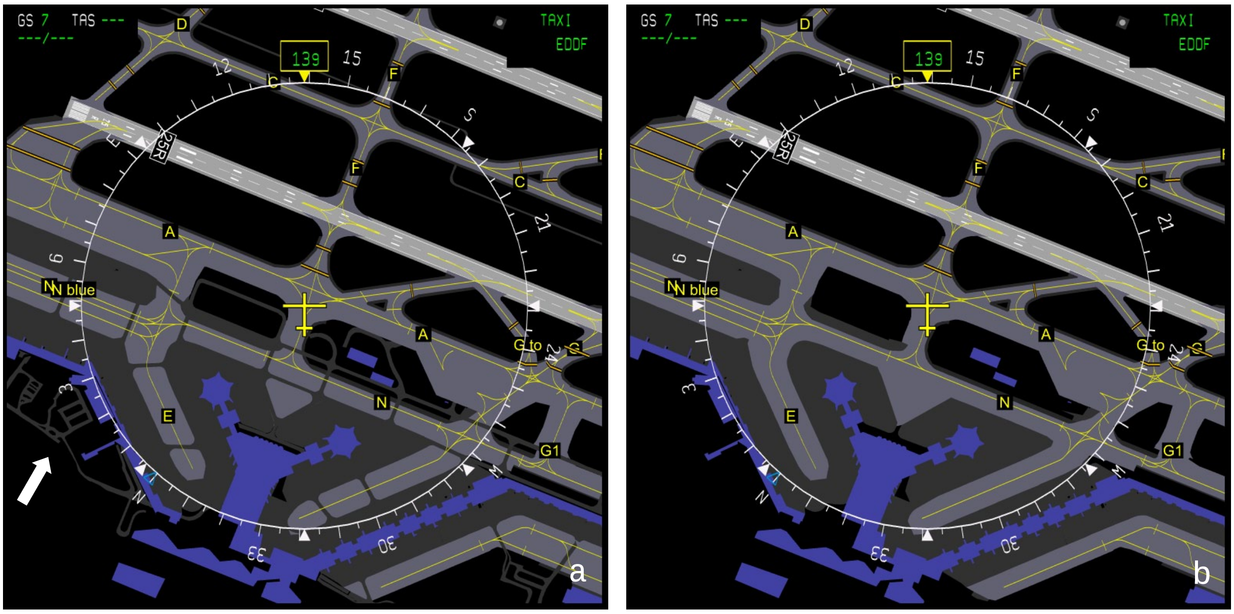

Figure 33: Airport moving map with (a) and without (b) visualisation of vehicle roads

At any rate, since the airport moving map is intended to replace paper charts for the surface navigation task, it must provide at minimum the same navigation information as paper charts, cf. Section 2.1.3.2. Accordingly, all runways and taxiways need to be displayed. Furthermore, all aprons with aircraft stands, aircraft servicing areas and buildings of operational significance have to be presented. Consequently, as a general principle, all paved surfaces relevant for aircraft operations, including runway and taxiway shoulders, must always be visualised.

By contrast, a comparison of Figure 33a and b confirms that a representation of vehicle roads on an airport moving map intended for aircraft use creates display clutter and is of little use for the airport navigation task. Furthermore, as the white arrow in Figure 33a indicates, a significant fraction of vehicle roads may be situated behind buildings or otherwise obscured from the airside, thus creating exclusively display clutter. Due to these considerations, prototyping results and the right-of-way rules for aircraft and vehicles (see Section 5.2), it was eventually decided not to visualise vehicle roads on the AMM.

The AMM overview of Paris Charles-de-Gaulle Airport (LFPG) in Figure 34a also illustrates the necessity of limiting the number of buildings displayed, because an indiscriminate representation of all buildings contained in the AMDB creates significant display clutter. In determining a method to limit the buildings displayed to those of operational significance, it was found that the most promising approach is utilizing the building name attribute defined in ED-99A [RTC05]. By selecting appropriate keywords (such as terminal, concourse, hangar, tower, and fire etc.) and displaying only the buildings featuring these keywords in their name attribute, the airport moving map can be de-cluttered effectively, as shown in Figure 34b. Compared to alternative de-cluttering methods using e.g. the spatial proximity or adjacency of buildings to runways, taxiways and aprons, this ensures that all functionally relevant and, depending on keyword selection, all landmark buildings can be represented. As an example, the aerodrome control tower is both an operationally relevant building and an important landmark, but not necessarily spatially close to the paved airport surfaces used for aircraft operations.

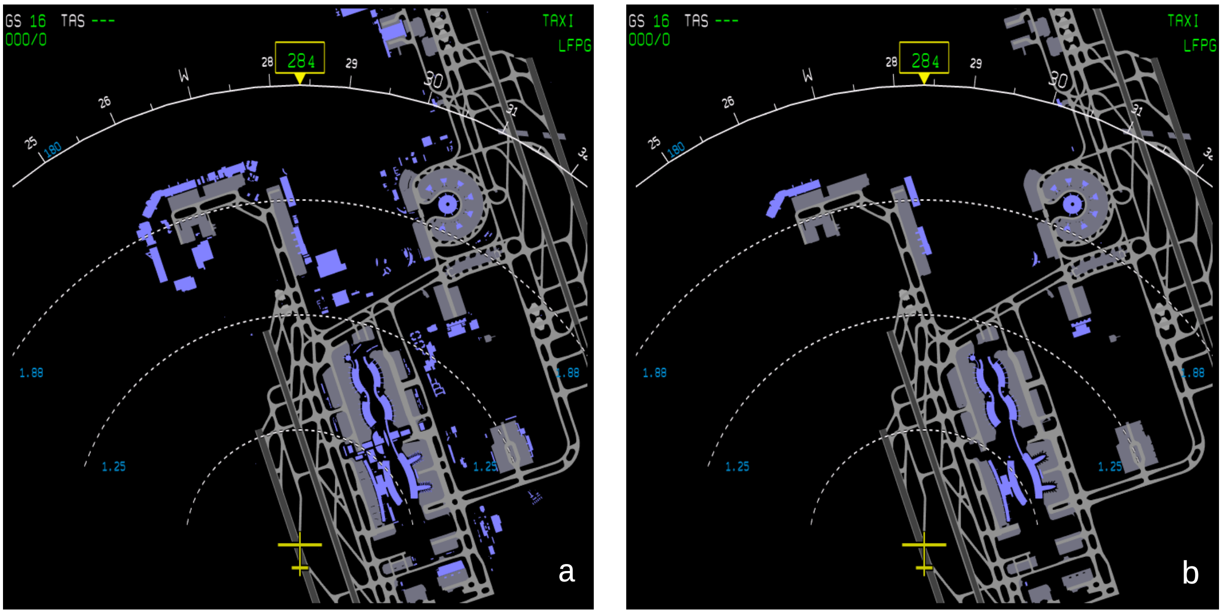

Figure 34: Airport moving map with all buildings displayed (a) and de-cluttered solution (b)

While the need to display paved airport surfaces and buildings of operational relevance can be clearly traced back to the airport charting heritage of the AMM (cf. Section 2.1.3.2) and DO-257A [RTC03a], it is not immediately apparent whether airport markings need to be visualised as well.
According to the analysis of current procedures in Section 2.1, holding positions and stop bars play an essential role in surface navigation and Runway Incursion avoidance, since they delineate the runway protection zone and are used as limits in taxi instructions. Consequently, there is a clearly established need for provisions to display them on the AMM.
By contrast, for runway markings and taxiway guidance lines, the potential benefit of presenting them on an airport moving map remains to be established. Taking into account the Synthetic Vision heritage of the AMM, however, it is believed that runway markings, which serve as an unambiguous identification of runways, visually reinforce the runway presentation in certain AMM ranges. Likewise, taxiway guidance lines not only indicate valid turns and routes on the taxiway surface, but may also support the recognition and disambiguation of visualised airport pavements as taxiways. Consequently, it is generally relevant to display airport markings on an AMM, but in contrast to runways, taxiways, aprons and buildings, the need for visualisation must be carefully balanced against display clutter aspects for each envisaged AMM range setting; this is discussed in Section 5.1.2.4 below.

5.1.2.3 Labelling of airport features

A mere visualisation of airport features as in Figure 34 is not sufficient to create an operationally usable AMM display. As a minimum, runways, taxiways and gates/parking positions have to be unambiguously identified to the flight crew, who will otherwise not be able to perform surface navigation according ATC instructions. Consequently, as on conventional paper charts, this identification is achieved by adding labels to the corresponding airport elements. Additionally, it seems appropriate to label airport functional zones, such as de-icing areas, and terminal buildings.

Labelling of different airport features raises several issues, such as overlapping/masking effects, priorities and the integration of dynamic elements, particularly the surrounding aircraft. Traffic symbols may also be accompanied by a label and additional situation-dependent information (e.g. relative altitude, climb/sink arrow). Although seemingly fixed except for PLAN mode, even the ownship symbol adds dynamics and can thus virtually always cover any label displayed at a fixed position. This could only be avoided by a fully dynamic labelling that would also have to consider intruder symbols and labels as part of the optimization process. Since this might eventually result in high processor loads and detrimental effects on performance, an intermediate solution might consist of linear label ranges and predefined evasive strategies, i.e. sliding/jumping labels in case of overlap.
However, since labelling algorithms for both paper charts generated from AMDBs and AMM displays were the subject of a further PhD thesis at the Institute in parallel to this study [Psc08], these issues were not pursued further in the frame of this thesis, and only a coarse makeshift algorithm for labelling was devised. Whenever a new AMDB was loaded, it would generate a set of labels according to a simple predefined rule set with the aim of marking all taxiway guidance lines with sufficient length. Likewise, all parking positions and runways are labelled.

5.1.2.4 Available ranges and range-dependent display of airport features

One of the key issues in airport moving map design is finding a balanced representation of airport features providing all of the information required for surface navigation without creating a cluttered display. This is closely related to the question of display range selections available for the airport moving map and their respective content and level of detail.
In fact, from a flight deck integration perspective, the main challenge is that an airport moving map needs both smaller ranges and a finer range gradation than a standard ND to be of operational use. Since the existing ND range controls on the FCU should be re-used as far as possible to achieve a logical and consistent solution, the AMM ranges must be defined using the 'classic' ND ranges of 10 NM, 20 NM, 40 NM, 80 NM, 160 NM, 320 NM (and sometimes 640 NM) as starting point. The straightforward approach eventually taken by this thesis was to continue dividing the previous range by two below 10 NM by, leading to additional ND ranges of 5 NM, 2.5 NM, 1.25 NM and so forth for the AMM, because this is the logical continuation of the conventional ND range series[73].

To address de-cluttering and the need for different levels of detail, only runways, taxiways, apron areas and selected buildings are always displayed, whereas most other airport features and their corresponding labels are displayed only in certain ranges. Table 6 summarizes the range-dependent airport feature visualisation concept implemented for de-cluttering and more efficient information access, which was established and validated in the course of the prototyping sessions.

[73] An equivalent approach would be to use 1/100 of the original ND ranges, i.e. 0.1 NM to 3.2/6.4 NM for the AMM. From an integration perspective, the apparent advantage is that the original range selector does not need to be modified; the only additional control required for this solution is a switch between the two range domains. The corresponding values could be added to the conventional FCU range selector scale in a smaller and/or differently coloured font.

Due to their importance for runway safety, stop bars, as the only airport markings, are maintained in most AMM ranges. By contrast, runway markings, taxiway guidance lines and markings associated with parking stands/gates are successively activated with decreasing display range, thus increasing the level of detail presented. As Table 6 indicates, airport labels are part of the range-dependent de-cluttering concept. For ranges larger than 1.25 NM, only major taxiways, i.e. taxiways beyond a length threshold (1000 m), are still labelled. By contrast, runway labelling is maintained in all relevant AMM ranges, and parking positions and gates are always labelled when displayed.

Feature	> 10 NM	10 NM	5 NM	2.5 NM	1.25 NM	0.725 NM	≤ 0.5 NM
Runways	x	x	x	x	x	x	x
Taxiways	x	x	x	x	x	x	x
Apron Elements	x	x	x	x	x	x	x
Airport Buildings	x	x	x	x	x	x	x
Runway Labels			x	x	x	x	x
Taxiway Labels				major TWYs	x	x	x
Stop Bars					x	x	x
Runway Markings						x	x
Taxiway Guidance Lines						x	x
Parking Stand Guidance Lines							x
Gate and Parking Position Labels							x

Table 6: Overview of range-dependent de-cluttering of AMDB features

5.1.2.5 Symbology for ownship representation

To fulfil ***High-Level Requirement I***, the ownship position must be displayed on the airport moving map, and provide both position and heading/track information. For reasons of consistency, the same ownship symbol as for the airborne mode, which is always drawn with fixed size, should be used. This symbol is usually significantly larger than a representation of the aircraft to scale (cf. in Figure 35a). However, when this relation reverses in low ranges, as shown in Figure 35b for an Airbus A380[74], there might be a risk that the crew will overestimate distances, spacing and e.g. wingtip clearance.

A more realistic symbol displaying the aircraft to scale is therefore envisaged for the lowest ranges, because there appears to be the need to display the aircraft in its correct proportions to the environment to prevent misleading cues resulting from the symbolic ownship representation. A concern with this realistic representation is, however, that it might indulge head-down taxi operations, with the crew attempting to control precision movement of the aircraft just based on the display, which is not intended. Nonetheless, this to-scale representation could, in combination with a traffic display, support intuitive conflict detection in high traffic density areas, such as the apron, on stand areas or when queuing for take-off.

[74] The range at which the reversal occurs is dependent on aircraft type. To improve contrast, the fixed-size symbolic ownship representation has been coloured in magenta in Figure 35 b.

The key issues associated with the display of the position of the own aircraft are navigational precision and integrity. Therefore, provisions for degraded navigational capabilities have to be made. A first step could consist of blocking the lowest taxi mode ranges with the realistic symol ($R_C > 5$ m), and further measures might be to display a positional error margin ($R_C > 10$ m) or to limit the display to PLAN mode centred around ownship, but without displaying the symbol ($R_C > 15$ m).

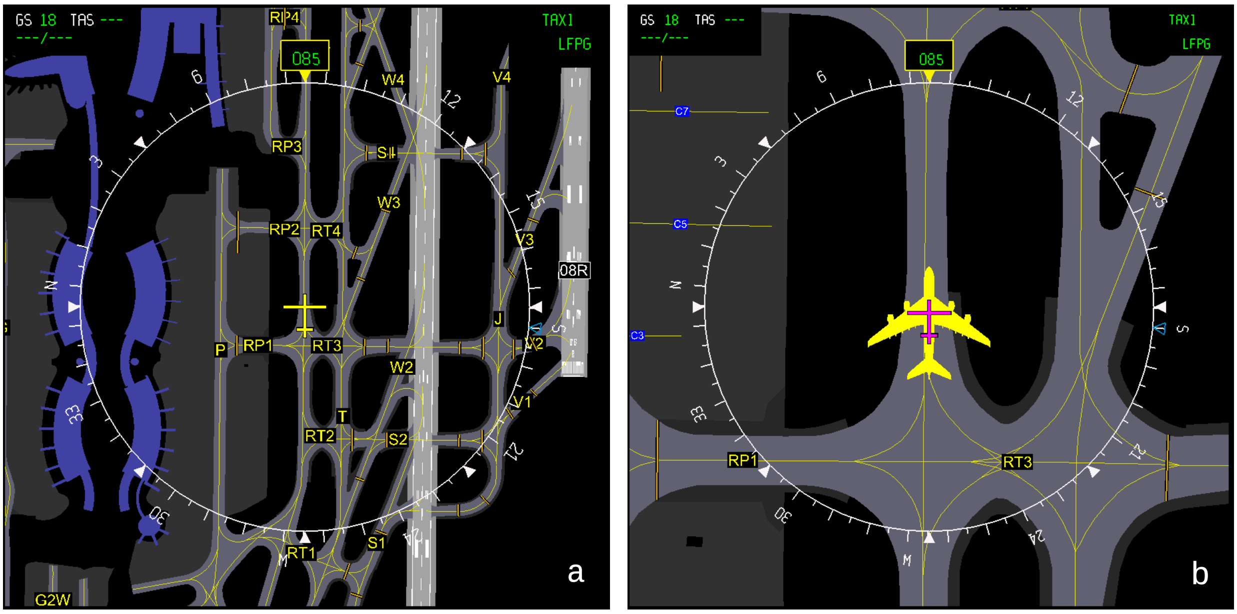

Figure 35: Comparison of fixed-size symbolic and ownship representation drawn to scale

5.1.2.6 <u>Colour and colour concept</u>

As outlined above, the airport moving map mixes elements of Synthetic Vision and conventional flight guidance display design. This dual heritage is epitomised by the colour concept. To represent paved airport surfaces, including the runways, different shades of grey are used, resembling the colour of actual pavement used at most airports. Likewise, runway markings and taxiway guidance lines use white and yellow, respectively, and thus precisely the colours required by ICAO Annex 14 [ICA04b] for the real markings. By contrast, taxiway holding positions and stop bars are displayed by a single line instead of the actual combination of lines to reduce clutter, and coloured in amber by default to achieve a better distinction from the surrounding taxiway guidance lines.

Furthermore, distinct functional parts of the movement area, such as aprons or taxiways, are assigned different shades of grey irrespective of whether the actual pavement features this distinction or not. After all, the concept behind Synthetic Vision is to create a sufficient resemblance for an intuitive perception of information, not to mimic reality exactly. For a more detailed discussion refer to [Ver05].
Generally, the presence of labels for runways, taxiways and parking positions is a derivate of conventional display and map design. However, the colour coding of the taxiway labels, yellow letters on a black square, is an adaptation of the actual taxiway signs used. Likewise, white text on blue background for parking position and gate labels is inspired by the colouring of the actual signs at Frankfurt Airport (EDDF).

For the runway labels, by contrast, white on black is used instead of white on red, since the usage of the colour red for normal indications violates the accepted principles of colour coding on flight deck displays (cf. [SAE88]). Finally, the use of the colour blue for buildings is an 'artificial' colour coding, which on the one hand allows a clear distinction of three-dimensional structures and two-dimensional pavements at a glance, but also avoids confusion with the colours used to visualize terrain (brown, and, to a certain extent, green) on NDs on the other hand.

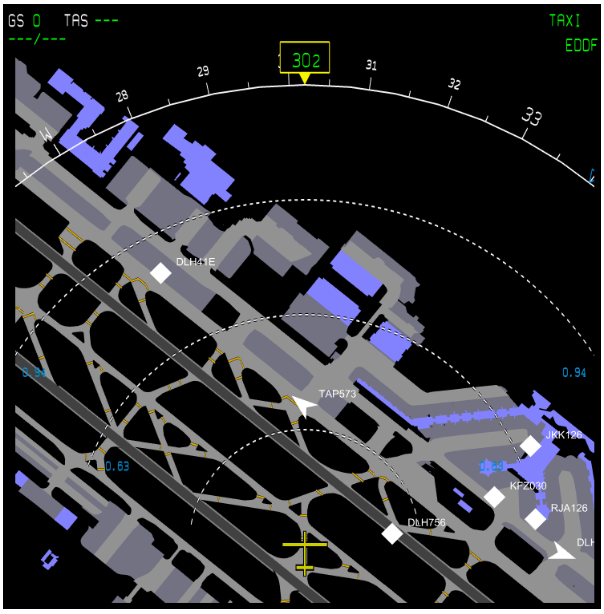

Figure 36: Preliminary colour concept

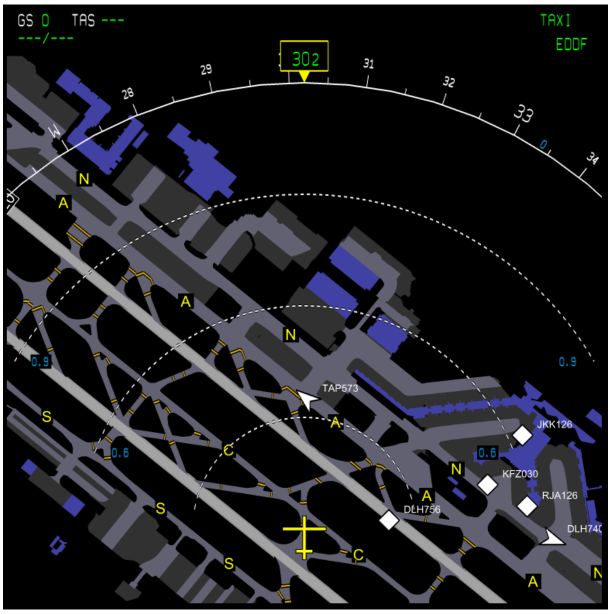

Figure 37: Final colour concept

Figure 36 shows the preliminary colour concept proposed for the AMM, using various shades of slightly bluish grey to reflect the difference between runways, taxiways and apron areas. Furthermore, an initially envisaged distinction of parking stand areas and apron areas (shown only in Figure 31) had been found to increase display clutter in a first design review with project test pilots, and thus been discarded.

During the prototyping sessions in the Institute's flight simulator, this preliminary colour concept was rejected by the participating pilots, who criticised that the runways were not displayed with sufficient conspicuousness and that the contrast of the display was not acceptable. Therefore, the colour concept was changed, using the principle of brightness to reflect the different relative importance of runways, taxiways and apron areas. The resulting final colour concept, which was retained throughout the evaluation on the Institute's Research Flight Simulator described in Chapter 8, is shown in Figure 37. Compared to the preliminary colour concept, there is a partial inversion. Apron areas are now the darkest airport feature shown, taxiways are displayed slightly lighter, but still darker than before, and runways are visualized in the lightest shade of grey. The colour of buildings was just slightly darkened.

5.2 Cockpit Display of Traffic Information (CDTI)

Awareness of other traffic in the aerodrome environment, which consists of aircraft, vehicles and aircraft under tow, is crucial to understand the traffic situation and to anticipate potential conflicts. Accordingly, the main goal of any traffic awareness functionality in the cockpit is to provide the crew with adequate, sufficient and unambiguous information on operationally relevant surrounding traffic in an intuitive way. This is intended to supplement and simplify the generation of the crew's mental picture of the surrounding traffic, particularly for traffic which is beyond the effective or convenient line of sight, thus fulfilling the traffic information part of ***High-Level Requirement II***. Besides, a traffic presentation might also enable a verification of ATC instructions, thus addressing ***High-Level Requirement IV***.

As discussed in Section 4.3, the only viable basis for an aerodrome traffic presentation is an airport moving map, because this provides the unique opportunity to display traffic both in relation to ownship and the aerodrome. Consequently, existing guidance material requires an airport moving map in conjunction with a surface traffic CDTI, cf. [RTC02].

5.2.1 Concept & Research Issues

The need of having a single consistent traffic surveillance picture in the cockpit, as discussed in Section 5.1.1.2, is one of the main reasons for using an EFIS-integrated airport moving map as basis for SMAAS. While this is certainly the most prominent repercussion of the traffic presentation on airport moving map design, it also significantly constrains the design choices to be made for the Cockpit Display of Traffic Information (CDTI). At the same time, EFIS integration ensures that basic CDTI requirements set forth in RTCA DO-243 [RTC98], such as the capability of presenting the position of traffic relative to own aircraft within a range of at least 10 NM or an indication of range via range rings, are automatically fulfilled.

Nevertheless, from a flight deck integration perspective, the key challenge associated with achieving a single traffic surveillance picture in the cockpit is how the enhanced traffic information provided by ADS-B and TIS-B can be utilised while maintaining consistency with existing ACAS installations. The envisaged usage of a CDTI based on an airport moving map for traffic surveillance during take-off and landing also raises the issue of transitioning from the small display ranges typically used for the airport moving map to the larger ranges of the 'airborne' ND modes remains an issue. Apparently, this has not been studied systematically so far, and demonstrates that the need for consistency also encompasses the visualisation of airborne and ground traffic, irrespective of available sources of traffic data.

There are two further key research issues concerning the display of traffic information on the airport moving map. First of all, this functionality is dependent on the availability, accuracy and integrity of the corresponding traffic data. However, since a survey of potential traffic data sources has already been conducted within the scope of Chapter 3 and Chapter 4, the discussion below focuses on considerations on

the operational aspects of traffic data availability. In this context, the main aspect to be investigated is the influence of an incomplete traffic surveillance picture resulting from less than 100% equipage on the usability of a CDTI. Research on this matter, which should be largely independent of a particular CDTI design, was conducted during on-airport trials with TUD's Navigation Test Vehicle at Frankfurt and Prague using ADS-B live traffic, see Chapter 7.
In view of the large number of aircraft and vehicles simultaneously operating in high density traffic environments such as large hub airports, the second key issue is determining what constitutes operationally relevant surrounding traffic, since a down-selection might become necessary to limit display clutter.

In conclusion, the common core of both issues concerns the impact that the scope of traffic visualisation has on the operational usability of a CDTI. A largely theoretical analysis on this aspect is presented below.

5.2.1.1 Operational concept and procedures

During surface operations, a crew-selectable CDTI traffic representation is envisaged to aid flight crews in maintaining appropriate awareness of the surrounding traffic irrespective of pertinent meteorological or geometrical visibility restrictions. It is therefore expected that pilots will routinely use the airport moving map with the display of traffic activated while taxiing. Outside the runways, however, the surface navigation task should drive airport moving map configuration in terms of range and modes used.

By contrast, when approaching active runways for crossing or line-up, the airport moving map is expected to be configured for surveillance of potentially conflicting runway traffic, in support of the current visual check that the approach ends of the runway are clear. Likewise, during the take-off roll, the focus of AMM/CDTI usage is monitoring the display for potential Runway Incursions. In line with pilot roles proposed in Section 5.1.1.1, it is expected that airlines will mainly allocate this task to the Pilot Not Flying (PNF), whose role is currently focussed on monitoring engine parameters and speeds during take-off.

Consequently, in order not to extend his or her scanning pattern, it could become necessary to duplicate critical engine parameters on the airport moving map[75]. Thus, the PNF could monitor both take-off performance and traffic situation at one glance; besides, additional performance cues could be added to the airport moving map itself[76]. In the first design iteration in the frame of this thesis, however, these take-off performance monitoring aspects were not addressed.

[75] As an example, on an A380, the N1 indications of could be duplicated in the rectangular area below the AMM during take-off, cf. Figure 14.

[76] The take-off speeds v_1 and v_R correspond to a certain geometric location from the runway threshold or the intersection chosen for take-off. For a very basic form of take-off performance monitoring, the tolerance bands corresponding to v_1 and v_R with nominal engine performance could be added to the runway representation on the airport moving map. If the actual engine performance falls significantly short of the expectations, the crew could determine this when the aircraft crosses v_1 (or v_R) band with the indicated speed is still significantly lower.

5.2.1.2 Scope of traffic visualisation

Especially at large airports with high traffic density, a general indiscriminate display of all traffic in the aerodrome environment will most likely result in tremendous display clutter. Since the resulting information overflow will probably increase crew workload and might subsequently decrease CDTI usability, it is feared that this could jeopardise the intended function. Even in present-day airborne traffic surveillance, the display of ACAS intruders is therefore limited to the most threatening eight [Air05]. Consequently, control and minimization of display clutter is an important CDTI design goal in DO-243. Traffic information is required to be partially or completely crew-selectable, and reducible to a minimum set of information by a simple crew action, such as pressing a de-clutter button [RTC98]. Additionally, reducing range is mentioned as valid method of limiting display clutter, specifically for surface traffic [RTC00a]. All of these references illustrate the necessity to limit the presentation of traffic in the airport environment to operationally relevant targets.

5.2.1.2.1 Considerations on operationally relevant traffic

Information needs regarding the surrounding traffic during the different phases of surface operations may vary. As an example, a presentation of airborne traffic approaching or departing the runways is operationally most likely irrelevant while taxiing on the apron, but will become more important on the manoeuvring area in the vicinity of runways, and is essential within the runway protection zone, e.g. during runway crossing or when lined up for take-off. Likewise, with ownship in the runway environment, aircraft waiting for line-up on a different runway only a few hundred metres away or local traffic on parallel taxiways are most likely fairly irrelevant from an operational and safety perspective, whereas aircraft on final approach to the runway at a distance of several km may potentially cause conflicts. When lined up for take-off, all traffic on final approach, on the runway surface and immediately adjacent taxiways, including vehicle roads intersecting the runway, is relevant due to the potential Runway Incursion hazards.

These examples illustrate that using distance as a simple metrics for the identification of relevant traffic is not possible due to the large bandwidth of traffic speeds involved. The same applies to closure rates, since traffic stopped at a runway holding position and then erroneously starting to cross it might initially have a very low closure rate. However, a classification according to type of movement by assigning all aircraft and vehicles operating in the airport environment to one of the following major categories might prove helpful in the identification of relevant traffic:

- **Aircraft operating under their own power.** This category encompasses all airborne aircraft, aircraft taking off or landing, and aircraft taxiing with running engines.
- **Aircraft under tow or during pushback.** Aircraft can also be moved by tugs, with engines off or being started. The main distinction to be made between towing and pushback is that aircraft being towed to/from maintenance, or aircraft being relocated between remote parking positions and gates by tugs are often moved with the majority of the electrical system off.

- **Vehicles with special functions operating on the manoeuvring area.** Some airport vehicles perform functions that routinely require them to use the manoeuvring area, such as tugs, marshaller or airport authority cars, snow clearing equipment, runway service cars and emergency response vehicles, such as fire fighting units.
- **General service vehicles.** This group encompasses all vehicles that do not have functions performed on the manoeuvring area. Typically, this includes all vehicles required to service aircraft, to handle cargo and to transport passengers to parking positions outside the terminals, such as refuelling trucks, passenger busses, transporters for the cleaning personnel and baggage cart tractors.

Since airport vehicles account for a significant share of airport surface traffic, cf. Figure 28, the display policy for vehicles appears to be a key element of controlling display clutter.

5.2.1.2.2 Principles for the visualisation of other aircraft

All other aircraft operating under their own engine power, might constitute relevant traffic, since they can potentially cause conflicts on the runways or the movement area. Additionally, aircraft under tow or being pushed back may be relevant, especially in view of a serious incident at Schiphol, where a B767 had to abort a take-off when a Boeing 747 was towed across the runway by accident, cf. Appendix I-14.3. Of special concern from a human factors point of view is whether parked aircraft should be displayed, since they might be relevant as obstacles if adjacent taxiways do not provide sufficient clearance for all aircraft types to pass by. Therefore, information on aircraft parked on or immediately adjacent to taxiways has to be made available via the AIS per ICAO recommendation already today [ICA04]. From an operational, but not from a safety perspective, a visualisation of parked aircraft might, after landing, support flight crews in verifying whether the assigned parking position or gate is already available.

5.2.1.2.3 Display policy for vehicles

Vehicles operating on the manoeuvring area have been involved in Runway Incursions, and although this has not resulted in fatalities aboard aircraft so far, it nevertheless constitutes a high threat to flight safety. Consequently, all vehicles with special functions operating on the manoeuvring area must be incorporated in the onboard traffic visualisation and alerting concept.
By contrast, as discussed in Chapter 4, mobiles do not pose any threat while driving on dedicated vehicle roads, and the hazards associated with aircraft-vehicle collisions on the apron, during pushback or at the intersection of vehicle roads and taxiways are low, at least for persons aboard the aircraft. Since vehicles have to give way to aircraft on the airport surface at all times, according to current rules laid down in ICAO Annex 14 [ICA04b], the main responsibility for collision avoidance and the installation of appropriate traffic awareness functions, such as the ETNA system [Kra04], resides with airport authorities and vehicle operators, at least for service vehicles.

Consequently, a representation of general service vehicles, which would cause significant display clutter especially for large AMM range settings, is most likely not adding any safety benefits for aircraft operations and therefore probably not required for the default airport traffic awareness display. This exclusion might help to avoid cluttering the display with operationally insignificant vehicle traffic. However, this does not preclude that the display of service vehicles may be activated on explicit crew selection, e.g. in the vicinity of parking positions and gates, when the lowest available airport moving map ranges are envisaged to be used. Likewise, any vehicle traffic identified as conflicting by the alerting part of SMAAS should be displayed irrespective of its type, provided that accuracy and integrity issues as well as the concerns for the pushback phase (see below) are addressed appropriately.

The main underlying reason, as discussed in Section 4.6.2, is the absence of a useful operational concept for a function providing awareness of general service vehicles. Even if the enhanced awareness of service vehicles on the apron might enable pilots to detect potential traffic conflicts during parking and pushback intuitively, the flight crew's possibilities to react are limited, particularly during pushback, when they are not in control of the aircraft. Alerting the ramp agent via voice communication when perceiving a potential conflict on the traffic display is the only possibility, which, given typical reaction times, might be inefficient. Other pilot reactions, such as braking, could even be detrimental in this situation, since damage to the tug, pushbar or the nosewheel might result. In a worst case scenario, the aircraft may end up resting on its tail, which constitutes a higher hazard to the safety of passengers and crew than the actual collision with a service vehicle.

5.2.1.3 Considerations on automatic display and de-cluttering of traffic

In line with present ACAS implementations (cf. Section 3.2.1) and the CDTI design criteria discussed above, the display of traffic has to be crew-selectable, to allow pilots to de-clutter the display manually in case they feel the need to do so. However, with the traffic presentation switched off, the flight crew might eventually miss safety-critical traffic alerts, and could be confused or react with delay if there is a mere aural alert (e.g. callout) without a corresponding indication on the display. Therefore, in case of a conflict, i.e. in the presence of traffic-related SMAAS alerts, conflicting traffic is displayed automatically, irrespective of display settings, consistent with current ACAS implementation.

Beyond the straightforward de-cluttering options, such as reducing display range or changing the mode, three different approaches of limiting the number of targets to be displayed can be envisaged:

- **Configurable traffic awareness display:** The flight crew is provided with additional controls to configure the traffic awareness display, e.g. controls to select or de-select the display of airport vehicles. The drawback of this solution is that the responsibility (and thus the workload) for configuring the display to show only the traffic relevant for a given situation remains with the flight crew, who might potentially miss relevant traffic in case of display misconfiguration.

- **Static de-cluttering:** The traffic awareness display could be limited to certain airport areas, or traffic within a certain boundary around ownship, both with a potential dependency on flight phase.
- **Situation-based automatic 'intelligent' de-cluttering:** The visualisation of the surrounding traffic adapts dynamically and automatically to the operational context. As an example, while on the manoeuvring area, the traffic display function may filter any traffic not located on own, parallel, neighbouring, adjacent or intersecting taxiways in order to reduce clutter.

Each of the options above, which can be combined in principle, has its disadvantages when applied individually. While display configuration options are generally desirable, they should not impose additional workload on the crew. For an interactive CDS, a much wider range of additional features for configuring the traffic display and information shown for individual traffic can be implemented, but any additional functionality should be strictly driven by operational needs.

However, both static de-cluttering and any crew-configurable solution will only partially succeed in achieving a limitation of the traffic displayed. Situation-based automatic de-cluttering, in turn, might require expensive additional onboard processing capacity, apart from the fact that it might be very difficult to find a suitable algorithm that can be validated for the myriads of different airport traffic constellations. Furthermore, special care is required with respect to traffic de-cluttering for the runways, because all potentially conflicting traffic within the runway protection zone(s) must always be visualised, irrespective of its type or nature, applicable filter rules and traffic display settings.

Nevertheless, intelligent de-cluttering algorithms linked to AMDB topology are required to fully implement 'single-button' automatic de-cluttering put forward by DO-243. However, since the Institute lacked a powerful traffic simulation capable of creating realistic hub airport traffic densities, the development of these algorithms was postponed beyond the scope of this thesis, since there would have been no way of validating the results.

5.2.2 Traffic Symbology

5.2.2.1 Design considerations on basic traffic symbology

For reasons of HMI consistency, the envisaged EFIS integration of SMAAS constrains the design choices on traffic symbology, as outlined above. Besides, the traffic parameters listed as mandatory for a CDTI by DO-243 are essentially the same as for ACAS[77] [RTC98]. Consequently, to be compatible with current ACAS implementations (cf. Section 3.2.1.2) and to ensure display consistency over both airport moving map and airborne ND ranges, the following requirements apply:

- Traffic symbols must be presented in either white or blue, provided that no alert or additional information applies.
- Traffic symbology used for the representation of aircraft on the ground and in the airport environment must be identical, or at least visually and functionally similar, to the symbology used for airborne CDTI applications.
- To achieve a harmonized and consistent air/ground traffic presentation, filled traffic symbols must be used, since relevant airport traffic is typically within a horizontal range of 6 NM and a vertical range of +/– 1200 ft, thus fulfilling the criteria for so-called ACAS 'proximate traffic', cf. Section 3.2.1

In contrast to ACAS, both ADS-B and TIS-B traffic data typically contain heading/track information. However, supplementing conventional ACAS symbols with additional heading or track vectors has previously been identified as not desirable, because this leads to complex symbols and display clutter. One of the main reasons given was that ACAS traffic symbols are supplemented by altitude data and, if applicable, an arrow for climb and sink rates in excess of 500 ft/min [RM01]. By contrast, a chevron-like traffic symbol with unambiguous directionality, which intuitively reflects heading/track, received very positive flight crew ratings in extensive flight trials in the United States [BAO00], and can therefore be regarded as the most mature CDTI symbology available at present.

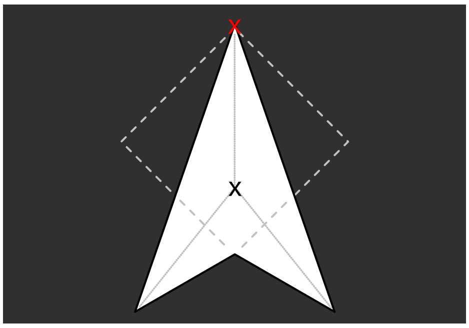

Figure 38: Traffic symbol with integrated heading/track and directionality indication

Consequently, it was adopted for this thesis with very minor modifications necessary to ensure compatibility with ACAS traffic symbols. Figure 38 details the original construction idea behind this directional traffic symbol and its size interrelation with the conventional ACAS diamond. When not within the 'proximate traffic' range, it is shown as an unfilled outline, e.g. to visualise airborne ADS-B traffic. This symbol contains two natural position anchors, the centre of gravity, marked by a black cross, and the tip of the symbol, indicated by a red 'x'. This second anchor was initially considered due an issue resulting from the fixed traffic symbol size: when an aircraft is stopped well in front of a runway holding position, the tip of the symbol might protrude across the holding position for larger AMM range settings although the aircraft has not crossed it in reality. However, this

[77] As an example, explicit reference to TCAS altitude data tags (cf. Section 3.2.1.2 and Figure 20) is made.

solution was eventually considered as counter-intuitive during prototyping sessions and abandoned. Consequently, the aircraft CG, which is usually used and transmitted as position reference, serves as the symbol reference and rotation axis. As an additional benefit, the directional traffic symbol in Figure 38 is clearly distinguishable from the standard ownship symbol in terms of shape, which is believed to avoid potential confusion, especially in difficult lighting conditions, when the display is viewed from an unusual perspective or when the pilot scan is perturbed.

A prerequisite for using this directional symbol, however, is the availability of heading/track data from the traffic source data, because directional symbols with a default heading have been proven to be misleading, irritating and thus unacceptable for pilots during the evaluation with the Navigation Test Vehicle in Frankfurt and Prague (see Chapter 7). Consequently, in case traffic data do not contain valid heading or track information, there is a reversion to the omni-directional standard ACAS symbology[78].

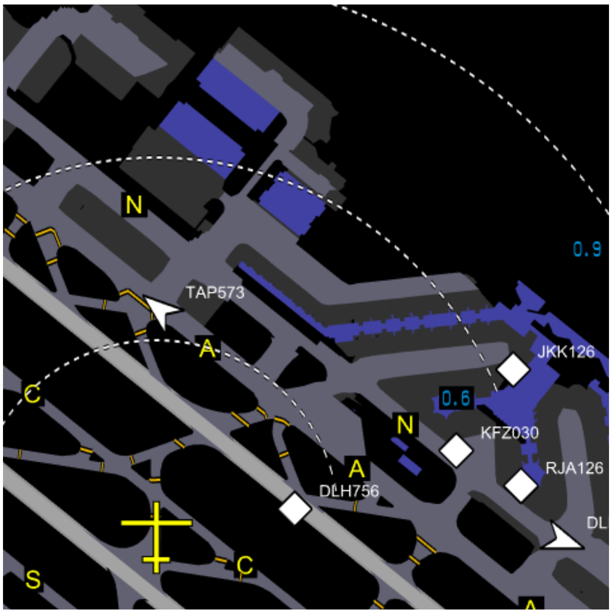

Figure 39: Airport moving map display with display of ADS-B ground traffic (detail)

Figure 39 shows this solution based on real ADS-B traffic data recorded during an evaluation session at Frankfurt Airport (EDDF). The screenshot features both types of traffic symbols, which are accompanied by a very simple label, consisting by default only of the callsign of the corresponding traffic, if available, or the aircraft registration. Otherwise, there will be no label (see next section). Unless the operational context requires highlighting in advisory or alerting colours, traffic is displayed in white. All aircraft supplying valid track or heading information are displayed using the chevron-shaped directional symbol introduced in Figure 38, such as the TAP Air Portugal flight TAP573. For all other traffic, the omni-directional standard ACAS proximate traffic symbol is used, in line with the considerations above. Both symbols have a fixed size throughout all ranges in which they are used, i.e. they are not re-scaled with range, identical to current ACAS implementations. The figure also clearly demonstrates that both types of traffic symbol have distinctly different shapes from the yellow standard Airbus ownship symbol.

As for the ownship symbol, the issue of a symbolic versus a 2D scale representation (cf. Section 5.1.2.5) also exists for traffic symbols. At first glance, it appears that a traffic representation to scale might be helpful in establishing the precise location of other aircraft in relation to a holding position, and allow a more intuitive traffic conflict avoidance while taxiing or queuing for line-up.

[78] The directional symbol is only presented if the heading/track information supplied via ADS-B or TIS-B is consistent with the direction of motion calculated from the last two reported positions. If heading/track information is lost while traffic is stopped, the last known value is retained for display until it starts moving again.

A closer look, however, reveals that this issue is significantly more complex than for the ownship symbol. First of all, since ADS-B transmits only the wake vortex category of aircraft and dimensions [RTC00], data on aircraft type - essential for a representation to scale – are not directly accessible. However, this information can in principle be retrieved based on the unique ICAO 24-bit Mode S transponder address of each aircraft (e.g. 383E7A for the first A380, F-WWOW), provided that additional onboard aircraft registry database containing data on the precise aircraft type for each Mode S address is created to enable this correlation[79].
Nevertheless, a 2D scale representation of the surrounding aircraft is operationally meaningful only if accuracy and integrity of traffic data are sufficient, and additionally requires valid heading/track data to be supplied. Otherwise, there is a high risk that a scale representation leads to false cues and misleading information. Further complexity originates from the fact that these criteria would have to be fulfilled by all traffic within the selected display range and mode, unless it can be proven that a mix of scale and abstract symbols might be acceptable to pilots. Last but not least, care must be exerted when defining the changeover between symbolic and scale representation due to the variations in aircraft sizes. In view of the multitude of unsolved issues and the substantial effort required for their systematic study, it was eventually hypothesized that a symbolic representation of the surrounding traffic is sufficient for the purposes of Runway Incursion avoidance.

5.2.2.2 Distinction between airborne and ground traffic

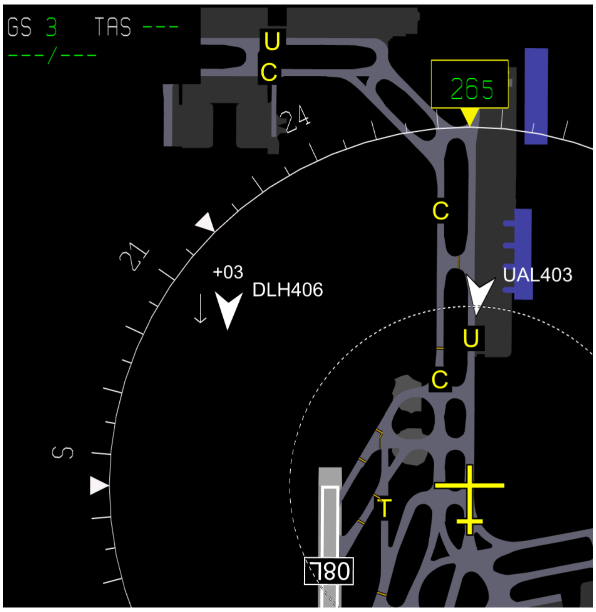

Figure 40: Visualisation of airborne traffic on Airport moving map (detail)

For consistency reasons, airborne traffic has to be represented like conventional ACAS traffic, irrespective of whether the directional or the standard ACAS symbology is used. As shown in Figure 40, the only significant difference to ACAS is that the airborne flight DLH406 is represented by the directional symbol and features a label consisting of the flight plan call-sign. Relative altitude is indicated numerically above or below the traffic symbol. In the example in Figure 40, DLH406 is on short final to RWY 08R and approximately 300 ft above ownship, which is why the numerical value is displayed above the symbol. In good approximation, this is also the altitude above the runway threshold. Likewise, climb or sink rates in excess of 500 ft/min are visualised by an arrow pointing upward or downward next to the traffic symbol, cf. Section 3.2.1.2.

[79] There is no need to sacrifice valuable airborne data link bandwidth for these data, which essentially remain the same as long as an aircraft is not re-registered. This traffic registry database could be updated along with FMS and aerodrome mapping databases within the AIRAC cycle.

Nonetheless, an intuitive distinction between airborne and ground traffic seems appropriate, and has already been identified as desirable in previous research [BAO00], whereas the particular design chosen by this reference, the use of symbol colour to distinguish airborne and ground traffic, was criticised by participants. Besides, a corresponding solution is incompatible with the symbol colour change in case of TCAS alerts. Likewise, the introduction of dedicated symbology for traffic on the ground does not seem favourable, because it increases the complexity of the HMI.
Therefore, in view of the need to limit HMI complexity and information density, a different approach consisting of the reduction of information compared to airborne traffic was taken. To limit display clutter, it seems imperative to suppress the operationally irrelevant altitude indication for ground traffic, such as UAL403 in Figure 40. To ensure that this suppression does not erroneously filter airborne traffic flying at the same altitude, the altitude indication is only removed when at least one of the following conditions is satisfied[80]:

- The relative difference between ownship and traffic altitude is less than 100 ft, traffic is moving at a speed of less than 100 kts, and the weight-on-wheels switch or other means determine that ownship is on ground;
- ADS-B/TIS-B surface type messages are received from traffic;
- ADS-B/TIS-B messages indicate that traffic is a vehicle.

By default, while ownship is airborne, the display of ground traffic is activated at and below 1,000 ft Radio Altitude (RA) in descent. To avoid flickering due to the terrain profile and resulting oscillations of RA, there is a hysteresis: ground traffic is only removed when climbing through 1,500 ft RA again. After take-off, this ensures that ground traffic is removed at 1,500 ft RA and only brought back when descending through 1,000 ft RA. While ownship is on ground, the visualisation of ground traffic also encompasses aircraft on final approach. All airborne aircraft up to 1,000 ft above the runway threshold or Aerodrome Reference Point (ARP) are displayed[81].

5.2.2.3 Symbology for vehicles and aircraft/vehicle combinations

Figure 39 implicitly illustrates a further issue that needs to be addressed. The traffic on taxiway November ('N') labelled 'KFZ030' is actually an aircraft tug. This raises the issue of whether a dedicated symbol for vehicles is necessary. Accordingly, during the evaluation with the Navigation Test Vehicle in Frankfurt and Prague, several pilots expressed the desire to be able to distinguish aircraft and vehicles in the traffic presentation, cf. Chapter 7. In fact, information on the nature of traffic might be helpful or even essential for establishing a visual correspondence or predicting its future behaviour. Likewise, for the same reasons, it seems that aircraft moving under their own power and aircraft being towed or pushed should be discernible. Consequently, a dedicated symbology for vehicles was developed.

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[80] This combination of conditions takes into account that airports are not fully planar and also filters erroneous altimeter settings/readings for ground traffic.

[81] Neither ACAS nor ADS-B data contain radio altitude, but the altitude above the airport can be determined using barometric altitude (from ACAS or ADS-B traffic data) and the runway threshold or Aerodrome Reference Point (ARP) elevation stored in the AMDB. Since there is no logic to determine whether aircraft are landing or taking off, all airborne traffic up to 1,000 ft above the airport is always shown by default.

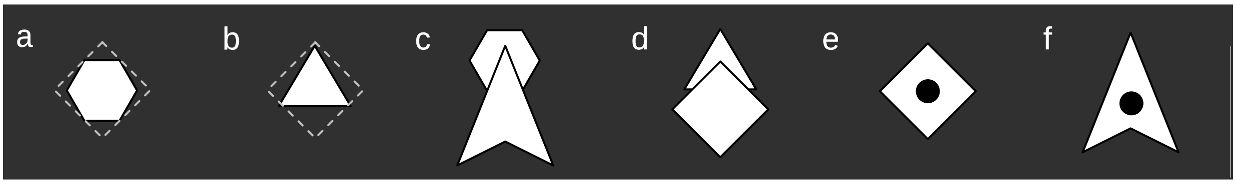

Figure 41: Symbol alternatives to present vehicles and aircraft during pushback/tow

Since circle and square are already in use for ACAS alerts, the number of geometric primitives left to choose from is very limited. To represent vehicles, it was therefore conceived to use either a hexagonal or triangular omni-directional symbol, fitting inside the default ACAS symbol (see Figure 41 a and b). To limit complexity, it was decided not to use a directional symbol for an implicit presentation of heading or track, because this would have an additional second vehicle symbol for traffic without valid heading/track, as for the aircraft case.
The main issue in this context, however, is the representation of aircraft-vehicle combinations that occur during pushback or while aircraft are under tow. The trivial solution, shown in Figure 41 c & d, consists of presenting both aircraft and vehicle symbols, with drawing priority assigned to aircraft. When both tug and aircraft are ADS-B equipped, this is the 'natural' picture resulting during pushback or tow, with relative position and overlap between symbols determined largely by the positional accuracy of the navigation solution used. In the worst case, the vehicle might either be fully covered by the aircraft symbol, or displayed separately next to the aircraft. For aircraft being towed, the main issue is an appropriate procedure to ensure that ADS-B out is activated during tow; otherwise, only the vehicle symbol would be shown.

There are two issues with the symbol combination shown in Figure 41 c & d. First of all, the overlapping symbols might be perceived as clutter. Secondly, the combination of two omni-directional symbols as shown in Figure 41 d may provide false directional cues. In view of these issues, it is worthwhile to consider a more abstract representation of aircraft being pushed back or under tow. In Figure 41 e/f, the standard aircraft symbols are supplemented by a simple black dot centred around the position reference of the symbol to indicate that they are being moved by a tug.

Technically, this latter solution would necessitate an extension of the current ADS-B surface position message by a status flag indicating that an aircraft is being pushed back or towed. Apart from a means of activating this flag aboard the aircraft, this approach would also require that the ADS-B out transmission of the tug is inhibited in parallel. Consider the following scenario for illustration: As soon as an aircraft tug is connected to an aircraft by the push bar, the tug's own ADS-B transmission will be inhibited. At the same time, the status flag in the ADS-B transmission of the aircraft would change to 'pushback', causing its symbol to change to the representation shown in Figure 41 e/f on the CDTIs of other aircraft, whereas the tug symbol would vanish. For aircraft under tow, the same solution can be realised. However, this might result in the potential inconvenience that the callsign of the tow combination would have to be entered into the aircraft's FMS, and the aircraft would have to be towed with ADS-B out activated.

Nevertheless, the precise technical realisation of this ADS-B out inhibition and status change mentioned above is clearly beyond the scope of this work. In the simplest case, it could be achieved by procedurally operated manual switches[82], but a more automated solution can be envisaged as well. As an example, the suppression of vehicle ADS-B signals and the status change of the message aboard the aircraft might be mechanised by sensors in the landing gear of the aircraft and the tow bar connector of the tug.

Since neither the traffic surveillance equipment used in the Prague trials nor the traffic simulation used in the simulator provided a possibility to distinguish or include, respectively, vehicle traffic, the dedicated vehicle symbol could not prototyped or assessed. However, this section has identified some of the key issues that need to be taken into account for a further investigation of this matter.

5.2.3 Traffic Identification & Labelling

ADS-B and TIS-B messages contain additional traffic parameters beyond those required for a mere visualisation, such as traffic identification, cf. Section 3.2.2. Since availability of data is decidedly not a criterion for its visualisation, this section is dedicated to an analysis of the operational requirements regarding traffic identification and required additional information.

According to DO-243, further desirable features in addition to the mandatory elements of the traffic symbol include

- an alpha-numerical indication of the **callsign** (up to 7 characters),
- an alpha-numerical (up to 3 digits) or graphical depiction of **ground speed**,
- a graphical visualisation of the predicted **ground track**,
- an alpha-numerical presentation of the **closure rate** (up to 4 characters),
- an indication of a **vertical rate** exceeding a certain pre-defined threshold, and
- the visualisation of pertinent **traffic alerts**.

Additionally, the flight crew should be able to select aircraft targets on the CDTI in an intuitive fashion; selected targets should then be highlighted, e.g. by boxing or circling the corresponding symbol [RTC98].

As traffic identification information beyond the ICAO 24-bit Mode S address, ADS-B and TIS-B messages contain the flight plan callsign, where available. In view of the guidance material above, it seems at first glance appropriate to display this callsign in conjunction with the traffic symbol. However, in contrast to controllers, pilots are currently not formally trained to interpret the three-letter airline codes used in this callsign, which may be different from the radio callsign used in R/T transmissions. As an example, British Airways Flight 123 will appear on controller screens and in ADS-B/TIS-B messages as “BAW123”, but be addressed as “Speedbird 123” by air traffic control. Furthermore, if other aircrews use either of these callsigns in R/T

[82] Since the nosewheel steering is typically de-selected prior to pushback, the position of the switch might be a candidate to trigger the transmission of ‘pushback’ status aboard the aircraft.

transmissions, this might create confusion with current procedures. Last but not least, this introduction of ATM information on the flight deck could even provide an undesirable distraction, particularly if pilots attempt to look up exotic three-letter-codes or inquire with ATC.
In many cases, though, the correlation between the flight plan callsign and the radio callsign is either straightforward, common knowledge or at least easily deducible. In principle, it is therefore considered useful to have provisions to display the flight plan call sign as label for traffic identification, because it might provide pilots with additional cues to establish a correspondence between traffic shown on the display and traffic acquired visually, which may add to the awareness on the intent of other aircraft gained from the so-called 'party line effect' in a radiotelephony environment.

Nonetheless, particularly at the hub airports of certain airlines, where many flights consequently have flight plan callsigns with the same airline prefix, other information may additionally be required to achieve this correlation between display and outside world. Labels could be supplemented by information that can be confirmed visually, i.e. the aircraft type – which can usually be deduced from the silhouettes even at large distance – and aircraft registration, which is visually accessible at least over short distances.

However, in view of the multitude of additional information already presented adjacent to the symbol of DHL406 in Figure 40, it becomes evident that, contrary to the recommendations of DO-243 [RTC98], it is most likely not desirable to add alphanumerical closure rate, ground speed, ground track or aircraft type information by default. Rather, if the flight crew can select individual traffic targets on the display, using e.g. a Cursor Control Device (CCD), this additional information on other traffic could be displayed on explicit pilot request. Unfortunately, the CDTI implementation used for this thesis lacked such interactivity. After prototyping, it was therefore decided to limit the default traffic label to the callsign, because the basic question related to traffic labelling was more the general necessity than the precise content.

5.2.4 Control of Displayed Traffic

As outlined in Section 5.2.1.3, the flight crew must at minimum be provided with controls to select and de-select the presentation of traffic on the airport moving map. For the experiments concerning the CDTI, the Institute's flight simulator was therefore fitted with buttons on the overhead touchscreen that allowed a separate activation of the traffic display on the NDs of captain and first officer. Additionally, there was a second button for each crew member to select and de-select the display of traffic labels. Irrespective of these settings, however, conflicting traffic causing a Level 1 alert or higher was always displayed.

5.3 Operational Awareness Function (OAF)

Awareness of the operational status and configuration of an airport and its installations is crucial for safe and efficient surface movement operations, as identified by ***High-Level Requirement III***. In particular, it is essential that the crew is aware of the runways in use and potential runway closures or restrictions; this information must be brought to the attention of flight crews in a suitable form.

Consequently, the goal of the Operational Awareness Function (OAF) is to aid the flight crew in creating an adequate mental picture of the airport including all short-term changes and other operationally relevant information. With just textual information available in sources such NOTAM and D-ATIS, the crew has to merge this information with their mental picture of the airport. Based on the considerations in Section 4.3.3, it is presumed that pilots can be greatly aided in this process by a corresponding representation on the flight deck, which is achieved by pre-processing and combining this information with the airport moving map, thus answering to ***High-Level Requirement III***. Due to the lack of existing research and guidance material in this field, the entire functionality has to be studied from scratch.

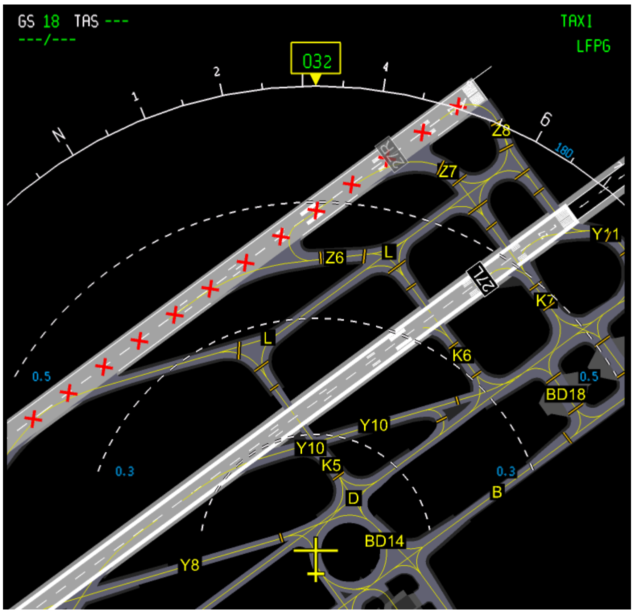

Figure 42: Airport moving map with representation of closed runway

The OAF is therefore expected to reduce the risk of error and confusion as well as pilot workload, because the crew does not have to look for information in various places to build a mental model of the situation any more. In terms of flight safety, this particularly addresses take-off and landing operations on closed or otherwise unsuitable runways.

Since attentional resources are limited, this is believed to be particularly important for airports that the crew is not very familiar with, i.e. airports they visit only once every few months[83], where they have to devote a larger share of their attention to orientation and navigation. Significant benefits are also expected if the crew has to deviate to one of the alternate airports, for which they have most likely not memorized NOTAM information for the reasons above. While there will be usually some time left to access and review the relevant material for an en-route or destination alternate, depending on the nature of the events triggering the deviation, this will hardly be the case for a take-off alternate.

[83] Crews usually operate less than 50% of the time at their home base. Depending on the type of operation and the particular scheduling policies of airlines, this might drop to values as low as 10%. Besides, even pilots' home bases are subject to change, mainly due to construction work for airport extensions, maintenance or improvement.

5.3.1 Concept & Research Issues

From the analysis of incidents and accidents in Section 2.2, it is evident that runway closures and restrictions are the most significant short-term and temporary changes from a safety perspective. Consequently, in line with ***High-Level Requirement III***, it is essential that the crew is aware of these. In other words, a visualisation of runway closures and restrictions on the airport moving map provides information on the runways **not** to be used and limitations to be taken into account.

However, from a Runway Incursion prevention perspective, this raises the question whether it might not be equally important to supply the flight crew with positive confirmation of the runways available or assigned for take-off and landing. As e.g. the Taipei Singapore Airlines SQ006 (see Appendix I-6) and Lexington Comair (see Appendix I-12) accidents show, there is a non-negligible risk of confusing runways. It must therefore be studied whether presenting information on active runways and a reminder of the runway envisaged for ownship use can provide additional support in preventing disorientation or erroneous runway choices. Consequently, to address the above issues, the visualisation of the following additional information on the airport moving map was therefore analysed, conceived and evaluated by this thesis:

- Indication of the take-off or landing runway selected in the FMS (Section 5.3.2)
- Presentation of active runway information (Section 5.3.3)
- Display of short-term and temporary changes, NOTAM (Section 5.3.4)

Regarding the visualisation of short-term and temporary changes on an AMM, a limitation to runway-related NOTAMs may seem a good starting point, but in view of the discussion in Section 4.3.3, it is clearly not desirable to retain paper-based NOTAMs for the remainder of the airport in the long run. As a result, the prerequisites for an onboard visualisation of short-term or temporary information must be studied from a broader perspective to enable a holistic overall concept for a simultaneous representation of NOTAM and aerodrome mapping information. This is one of the key research issues, and addressed in Section 5.3.4. Another fundamental aspect is how a sufficiently modular data handling and operational concept enabling both NOTAM upload on the ground (as part of routine flight preparation) and in-flight updates can be realised, see Section 5.3.5.

Eventually, the prototypic OAF encompassed provisions to supply the flight crew with information on the FMS-selected runway, the runways in use, closed runways, closed taxiways, and restrictions of either runways or taxiways in an integrated fashion. While there is more information on the operational environment that might be relevant for presentation on the flight deck, the limitation of the initial OAF implementation to the items above was deemed sufficient for assessing the concept.

Additionally, however, displaying information of meteorological nature, such as RVR or runway braking action, and derived information on whether LVP are in use, could be envisaged. Concerning the RVR, which may be different for individual runway segments, one of the main challenges is how the corresponding values can be linked intuitively to the runway segments they relate to. Likewise, for the braking action, there is a similar issue, and it should be analysed whether the corresponding ECAM (or EICAS) pages of the braking system are potentially a more appropriate location to display this information than the airport moving map.

5.3.2 FMS-selected Runway Representation

5.3.2.1 Operational background & relevance

In current generation Flight Management Systems (FMS), flight crews define take-off and landing runways as part of the FMS flight plan, and may then select Standard Instrument Departures (SID) or Standard Arrival Routes (STAR) for the respective runways. All take-off performance calculations, including configuration used, engine ratings applied, the speeds V_1, V_R, V_2, initial departure speed, are also made for the specific runway chosen.

The FMS-selected runways are, in virtually all cases, the runways actually used for take-off and landing. If runway changes occur prior to take-off, it is mandatory to update take-off performance calculations for the new runway, and therefore aircraft should never take off from a runway other than the one selected in the FMS. Likewise, the departure procedure should also be adapted to prevent unexpected autopilot commands after take-off, when the FMS tries to align the aircraft with the originally planned departure route. For the landing runway, the situation is completely different. Sometimes, there are last minute runway changes during approach on such short notice that changing the FMS data is not possible or procedurally allowed any more. Another example is the so-called sidestep manoeuvre, in which the pilot uses the Navaids of the FMS-selected runway (e.g. an ILS) for the initial approach before side-stepping, after transition to the visual segment, to land on a parallel runway, e.g. if ATC assigns the other runway for operational reasons (traffic still on the runway, Navaids unserviceable, …), or in case the parallel runway is a non-precision runway.
On Airbus aircraft, an oriented white runway outline is presented on the ND in conjunction with the FMS flight plan as the sole airport element, provided that a runway has been specified in the flight plan. If the selected range is 10, 20 or 40 NM, the FMS-selected runway is drawn to scale in terms of paved length[84] [Air05].

5.3.2.2 Rationale

Since an EFIS-integrated airport moving map should not provide less information than a conventional ND, a representation of the FMS-selected runway on the airport moving map could solely be motivated from an ND integration and consistency perspective.
Nevertheless, a visualisation of this information as the basic stand-alone element of the OAF was chosen for an entirely different reason. Particularly when taxiing out for take-off, this feature is intended to provide the crew with an intuitive, positive confirmation of the runway to be used for take-off. This is envisaged to prevent inadvertent runway entries or transgressions beyond basic disorientation, which should already be addressed by the AMM. In short, this feature is presumed to provide protection against erroneous runway operations, including also line-up, take-off and landing, whenever the reasons for runway confusion are more subtle.

[84] Generally, the runway representation is supplemented with the airport's ICAO identifier and the runway name, also in white. If no runway is selected, the airport is represented by a white star, and only the ICAO identifier is displayed. If the ARPT pushbutton is pressed on the EFIS control panel, all airports in the database that are not part of the flight plan are displayed as magenta stars along with their ICAO identifiers [Air05].

Besides, displaying the FMS-selected runway is expected to enable improved situational awareness especially in the absence of a simultaneous taxi route presentation on the airport moving map. In this situation, it should help the flight crew to detect inconsistencies between FMS settings and actual operation; this also applies to final approach and landing.

At Taipei Chiang Kai-Shek International Airport in October 2000, with Runway 05L correctly set in the FMS and displayed on an airport moving map, the crew of SQ006 might potentially have noticed an inconsistency when entering Runway 05R, which could then have led them to re-confirm the situation with ATC. Likewise, the Comair Flight 5191 crew at Lexington might also have had a chance to notice that they were at the threshold of RWY 26 instead of RWY 22. Consequently, the perhaps most important justification for the presentation of the FMS-selected runway is that it might enable pro-active error detection by the flight crew. It seems that the only other possibility of preventing take-off or landing on a wrong and potentially unsuitable runway consists of alerts if the flight crew commences take-off from or approaches a runway not selected in the FMS (see Section 5.5).

5.3.2.3 Prototypic realisation

5.3.2.3.1 Symbology

For reasons of consistency, the highlighted runway outline as indication of the FMS-selected runway on the airport moving map was adapted from the standard ND. As additional benefit, this solution does not interfere with the displayed runway markings or any other airport moving map elements, i.e. it does not cover them or reduce their conspicuousness. It is also compatible with using a change of the runway surface colour for runway-related alerts (see Section 5.5). With this choice of symbology made, the main remaining issue is colour.

5.3.2.3.2 Initial colour concept

Due to its brightness, white is generally a good choice to highlight information on electronic displays. However, since the colour white is already widely used on the industrial airport moving map prototype shown in Figure 43, the initial hypothesis was that retaining a white outline for the FMS-selected runway by might not be conspicuous enough.
Furthermore, on Airbus aircraft, magenta is the colour typically associated with displaying values calculated by or stored in the FMS. All navigation data, such as airports, waypoints and navigational aids are consequently displayed in magenta on the ND. Therefore, the FMS-selected runway was visualized by adding a magenta outline to the corresponding basic runway representation in the first implementation of the feature. Only for ranges larger than 1 NM, the entire runway was coloured in magenta, because it was initially anticipated that solely presenting the outline would not be conspicuous enough. However, since this does not (yet) specify a unique runway, the threshold label indicating the magnetic runway heading (QFU) as runway identifier was coloured in magenta as well.

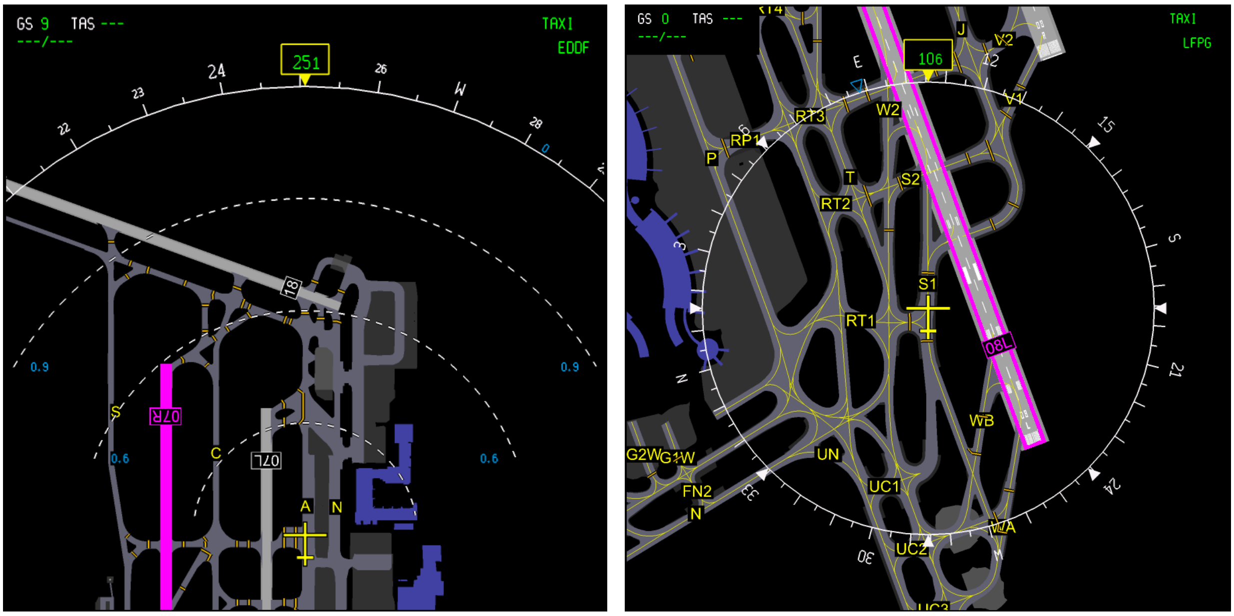

Figure 43: Initial FMS-selected runway representation evaluated in the EMMA project

Figure 43 shows this initial solution, which was also implemented in a prototypic Airbus airport moving map display, called 'Taxi Driver System' (TDS), in the framework of the European research project EMMA. This HMI was used during the field trials with the Navigation Test Vehicle at Frankfurt and Prague airport described in Chapter 7. On the left side, the solution for ranges of 1 NM and larger with the whole runway surface coloured in magenta is shown. For ranges of 0.5 NM and less (right side), the FMS-selected runway is indicated by a magenta outline. The runway identifier, visible only in the left screenshot, is generally displayed at all ranges, but may be cropped due to the particular range and mode settings made by the flight crew.

With a magenta instead of a white runway outline, there is a minor consistency issue concerning the transition from the display ranges typically used for the airport moving map to the ranges associated with the 'airborne' modes of the ND, i.e. 10 NM and larger. The colour of the FMS-selected runway would have to be changed to magenta in these ranges as well to avoid a sudden unmotivated colour change. Besides, to maintain the distinction between airports which are part of the FMS flight plan and other airports, the white ICAO identifier for airports in the FMS flight plan would have to be retained, resulting in a magenta runway with a white label.

5.3.2.3.3 Revised colour concept

The initial evaluation of the FMS-selected runway presentation described in Chapter 7 revealed that although magenta was found to be compatible with the overall cockpit colour philosophy (cf. Figure 121), several of the participants recommended to study an alternative colour coding. Furthermore, in the subsequent preparation for the second evaluation campaign (see Chapter 8), several of the pilots involved in HMI design reviews and prototyping sessions voiced concerns about magenta, because they feared it could be confused with red too easily. Additionally, there are a number of special cases that need to be taken into account where a single colour, and particularly magenta, fails.

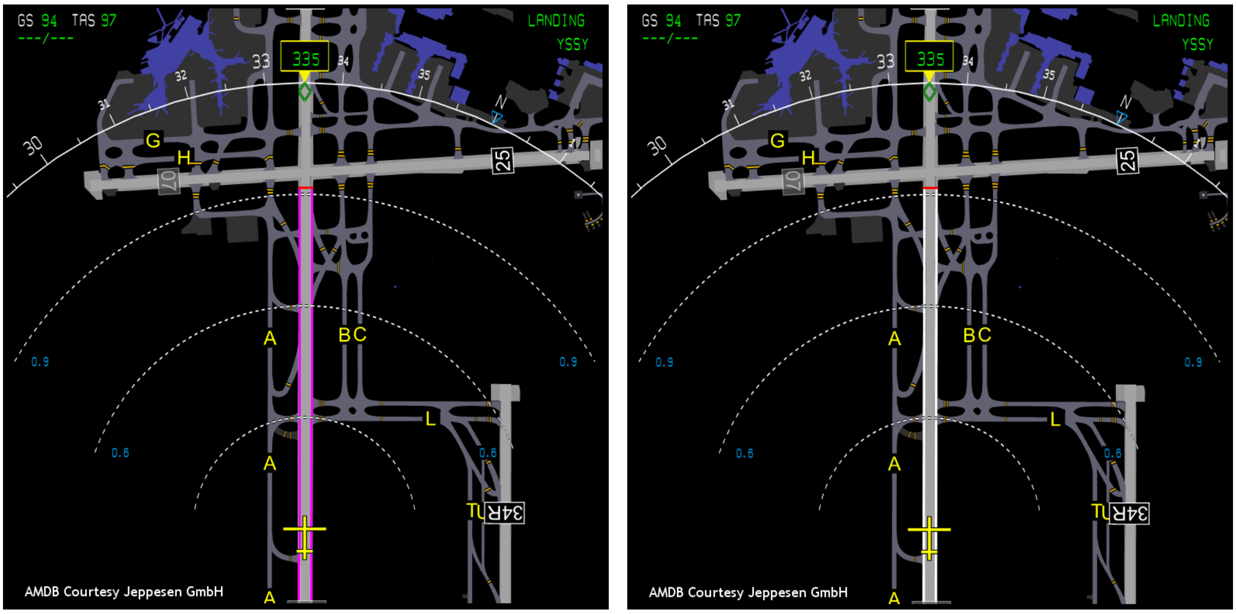

Figure 44: Comparison of magenta (left) and white (right) FMS-selected runway outline for LAHSO operations

The first special case to be considered are LAHSO operations, cf. Section 2.1.2. When LAHSO operations are in force, landing aircraft have only a reduced landing distance from the corresponding threshold to a pre-defined LAHSO location available, which is typically located in front of an intersecting runway. LAHSO locations, which are established permanently, are contained in the AMDB [RTC01, RTC05]. The fact that LAHSO operations are in force is typically conveyed together with active runway information. In certain countries, airlines and flight crews must be specially certified to perform LAHSO operations. Thus, runway length limitations imposed by LAHSO operations must be considered individual rather than general limitations.

In case of LAHSO operations, highlighting the complete runway outline might give the crews misleading visual cues about the available runway length, since the LAHSO location and thus the intersecting runway must not be crossed in this situation. Furthermore, with the full outline, there might be insufficient emphasis on the hold-short location. Consequently, if LAHSO operations are effective, the FMS-selected runway presentation on the airport moving map should be limited to the part from the runway threshold to the LAHSO location. Since the LAHSO location itself represents a clearance limit rather than a physical restriction, it is visualized as a red line across the runway to emphasize the clearance limit, in accordance with the principles derived in Section 5.4.

A comparison of the two options presented in Figure 44 immediately explains why magenta is not a suitable colour choice for the runway outline in this case: the red LAHSO location and the magenta outline are virtually indiscriminable. By contrast, a white outline provides sufficient contrast. Consequently, in the LAHSO case, the FMS-selected runway is probably best represented by three white lines and one red line (the LAHSO location). The second special case rendering white the better choice of colour concerns the physical runway length restrictions addressed in Section 5.3.4.3 on ‘Symbology for runway status, closures and restrictions’ below.

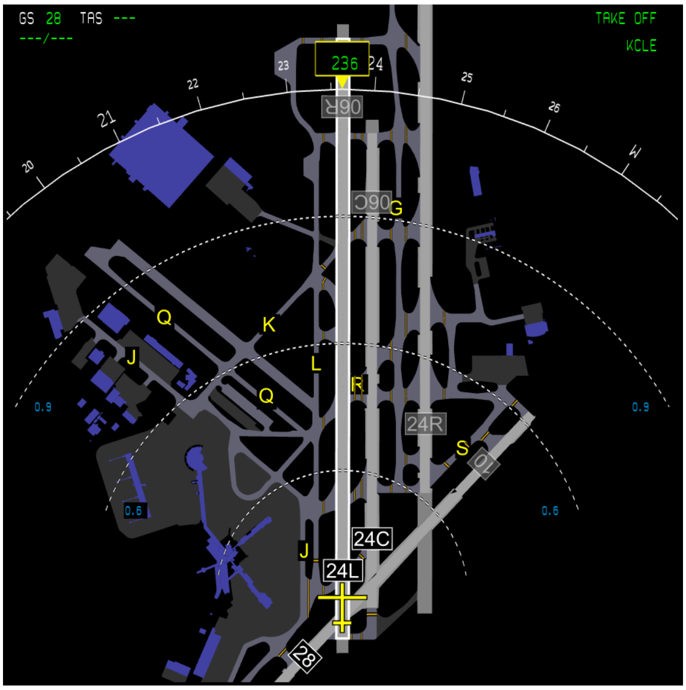

Figure 45: Symbology for FMS-selected runway visualisation as evaluated on the flight simulator

If the available runway length is reduced compared to the original value stored in the FMS or AMDB database or otherwise restricted, the FMS-selected runway is displayed by a yellow outline to attract the crews attention to the limitation. The change from white to yellow is consistent with common flight deck colour usage, whereas a suitable change from magenta still remains to be found.
In conclusion, therefore, the colour of the FMS-selected runway was changed to white for the second evaluation campaign on the Research Flight Simulator described in Chapter 8. As the airport moving map of Cleveland-Hopkins International Airport (KLCE) in Figure 45 shows, the FMS-selected runway is also automatically displayed as active runway by dimming the runway label of the threshold not in use; a detailed description of this feature is provided in Section 5.3.3.

5.3.2.4 <u>Safety considerations</u>

This section discusses the impact of erroneous runway selections in the FMS on the FMS-selected runway visualisation and potentially associated safety issues. First of all, it should be noted that erroneously entering a wrong departure or landing runway in the FMS is a risk that already exists today. Secondly, the proposed visualisation of the FMS-selected runway on the airport moving map merely represents a crew selection and does not, neither explicitly or implicitly, endorse operations on the corresponding runway in any way. Consequently, as a mere reminder of crew settings, the FMS-selected runway information displayed can never become invalid. As a result, the additional visualisation does not worsen the situation in case of an erroneous selection. On the contrary, an explicit representation of the FMS-selected runway on the airport moving map display might actually help the crew to notice the inevitable inconsistencies with ATC instructions when an incorrect runway has been entered in the FMS, even in the absence of a simultaneous visualisation of the uplinked taxi route. With a conventional ND, noting these inconsistencies requires far more subtle observation. At a system level, SMAAS can only detect inconsistencies or crew errors in setting runways in the FMS if there are other independent sources such as clearances via data link, D-ATIS or NOTAM information available for cross-check. As an example, if active runway information is available via D-ATIS, potential inconsistencies between the active runway and the crew selection in the FMS can be addressed by a warning message on the ECAM and/or the MCDU (see Section 5.5).

5.3.3 Runways in Use (Active Runways)

5.3.3.1 Operational background & relevance

Most runways feature two opposite thresholds[85], of which only one may become runway-in-use at a time, depending on the prevailing conditions, cf. Section 2.1.1. Moreover, not all runways may be simultaneously in use, particularly for aerodrome configurations with intersecting runways.

Active runway information is included in ATIS broadcasts (voice or digital), because it is essential from an operational perspective that flight crews are aware of the runways-in-use. For decision-making and preparations, such as the take-off or approach briefing, pilots need to know the take-off or landing procedures to be expected, including specific operational procedures such as LAHSO. A visualisation of active runways is also important to understand the prevailing traffic patterns, and enables the fine-grain distinction between runways not actively used for take-off/landing and temporarily closed runways (see Section 5.3.4).

Last but not least, especially in the United States, it is essential to know the active runways to interpret taxi clearances correctly: in contrast to active runways, all runways that are presently not used for take-off or landing may still be crossed without explicit ATC approval (cf. 14 CFR §91.129) [FAR07], although the NTSB has recently recommended a change to this procedure as a result of the Comair accident [NTS07].

5.3.3.2 Rationale

A visualisation of the runways in use, or active runways, in conjunction with the airport moving map has already been proposed as an exemplary application of AMDBs by ED-99 [RTC01]. Furthermore, the necessity of displaying active runways in this manner has been acknowledged by previous research projects, cf. [RM01, Ver05].
Presenting active runways is envisaged to increase flight crew situational awareness with respect to the current aerodrome operational configuration in an intuitive manner. A potential benefit expected is a reduced likelihood of misreading D-ATIS text or misunderstanding the recorded ATIS issued via radio. Besides, since the download of D-ATIS information could be performed automatically at certain intervals without crew interaction, this might ensure that the crew always has access to the most recent ATIS data, and can additionally be notified of significant operational changes immediately. This is also believed to prevent erroneous crossing of active runways and take-off or landing attempts in the wrong direction – a risk considered non-negligible, especially in case the operating direction is changed on short notice.

5.3.3.3 Prototypic realisation

The previous research projects mentioned above have also conceived proposals for a human-machine interface, which are briefly surveyed and analysed below.

[85] RWY 18 at Frankfurt Airport (EDDF) is a famous counter-example of a runway with only one threshold.

5.3.3.3.1 *Survey of previous active runway visualisations*

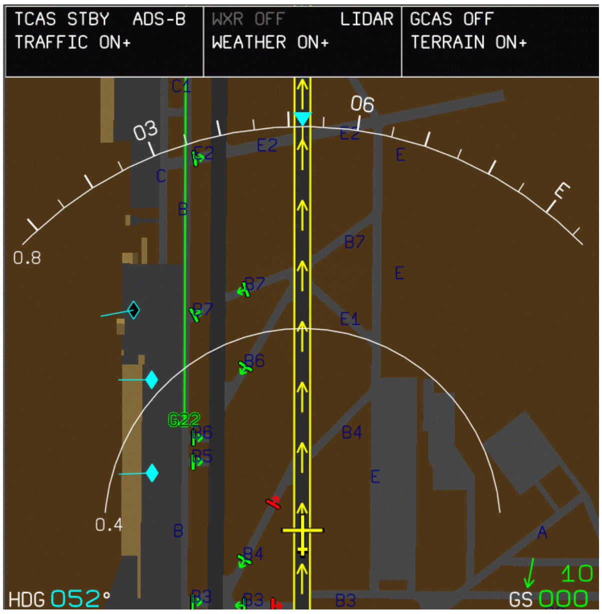

Figure 46: Active runway representation in ISAWARE [RM01]

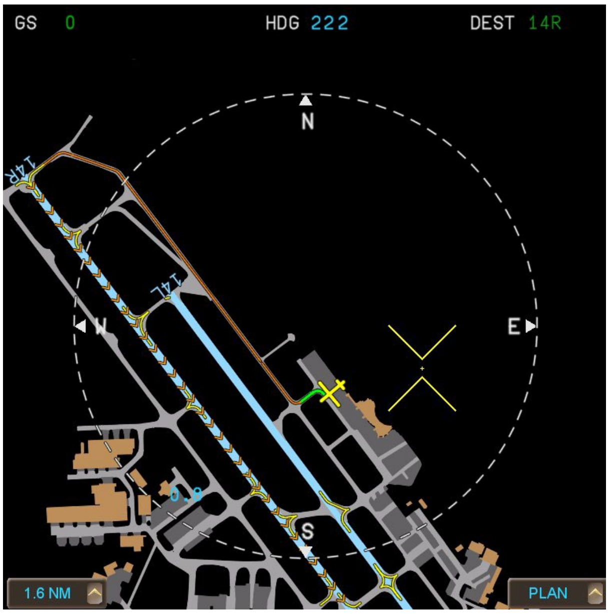

Figure 47: Taxi route & active runway visualisation in VICTORIA/ISAWARE II [Ver05]

Figure 46 shows the active runway representation chosen for the European research project ISAWARE. On the display, the runway centreline marking is replaced by equidistant yellow arrows, and the runway outline is highlighted in yellow as well [RM01]. However, an issue with this representation is that this type of marking has, according to ICAO Annex 14, already an entirely different and contrary meaning: white arrows instead of the normal centreline markings are used to indicate a displaced runway threshold [ICA04b]. Despite the fact that the ISAWARE symbology uses yellow instead of white, it might give pilots the hazardously misleading impression that the threshold is displaced and still ahead of them. This risk is particularly high if the symbology is applied without any other runway markings, as shown in the figure, or when only part of the runway is visible on the airport moving map during landing. Apart from this, when superposed over the normal runway markings, the ISAWARE symbology will most likely lead to display clutter. Last but not least, the exclusive use of yellow, a colour associated with taxiway markings, has to be criticised.

The European research projects VICTORIA and ISAWARE II used an alternate active runway representation with the arrows reduced to chevrons, cf. [Ver05]. Depending on the clearance, these chevrons would be either displayed in amber (no take-off clearance yet) or green (clearance available). Again, the problem is that chevrons already have a different meaning when employed as runway markings. According to ICAO Annex 14, any paved surface before a runway threshold longer than 60 m and not suitable for normal use by aircraft should be marked with chevrons of a conspicuous colour, preferably in yellow [ICA04b]. In view of this international standard and the fact that the colours amber and yellow are easily confused, particularly in difficult lighting conditions, cf. [SAE88], the VICTORIA/ISAWARE II solution has to be rejected as well. Of course, the way these chevrons are applied also raises the same issues regarding misleading information, compatibility with existing markings and display clutter as the ISAWARE solution (see Figure 47).

5.3.3.3.2 Development of active runway symbology

Developing an appropriate active runway symbology for this thesis proved to be difficult for two reasons. First of all, both arrows and chevrons along the runway centreline are already used as airport markings with entirely different meanings, as discussed in the previous subsection. Secondly, adding arrows as additional elements in any other fashion is prone to cause display clutter, and can also be ruled out as appropriate symbology. This causes the dilemma of having to indicate a direction without the universal symbol of directionality, the arrow.

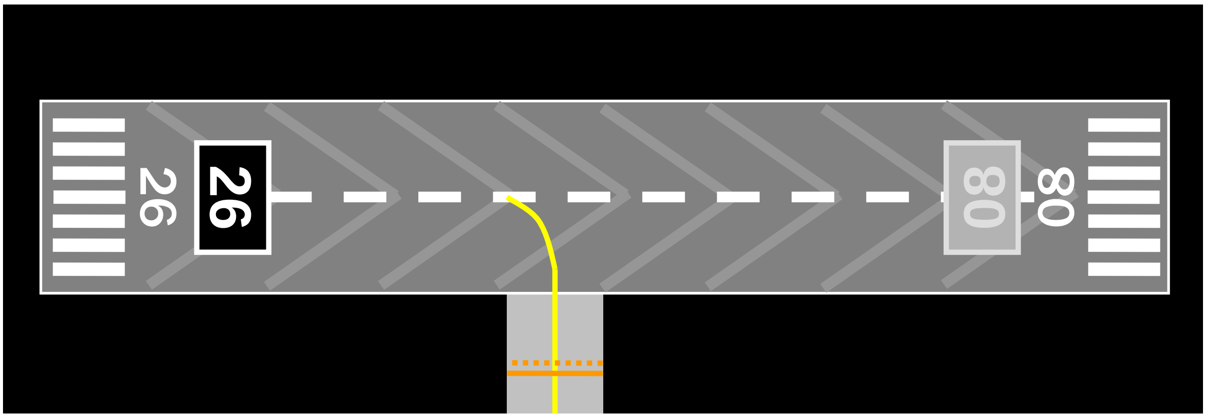

Figure 48: Schematic standard runway representation with indication of active runway

In a first approach, the chevron solution was revisited and adapted. It was assumed that the problem of symbol misinterpretation discussed above is limited to situations where the chevrons are the only runway markings displayed. Consequently, it was expected that using equidistant chevrons as additional layer below all other runway markings, i.e. with less priority, would eliminate the risk of confusion with unusable runway areas. Furthermore, to reduce the visual dominance of the chevrons compared to the VICTORIA/ISAWARE II solution, i.e. to make them less intrusive, they were drawn in a shade of grey slightly lighter, but nonetheless close to that of the runway surface. Figure 48 as schematically illustrates this approach. In all ranges below 5 NM, chevrons were displayed in a fashion such that the on-screen distance appeared equal in all ranges. With increasing display range, the distance between chevrons became larger, i.e. there seemed to be fewer chevrons at larger ranges. For 5 NM and beyond, nothing was displayed for reasons of display clutter. To visually reinforce this chevron-based active runway indication, the labels of the thresholds not active were dimmed by representing them in grey instead of black and white.

A clear benefit of this modified chevron solution is that it is visible when only part of the runway is in view. Additionally, both colour and priority of the chevrons can be changed, e.g. to inform the crew that they are approaching the runway opposite to the active direction, either on ground or in the air, or that a take-off clearance has been given. In a design reviews and prototyping with pilots, however, this HMI proposal was nonetheless rejected for potential confusion with unusable pavement (see above) and a tendency to clutter the display. Thus, both the ISAWARE, the VICTORIA/ISAWARE II solution and the dimmed chevron approach had to be abandoned for a lack of compatibility with existing runway markings, aggravated by display clutter concerns.

Symbol	Directionality	De-Clutter	Compatibility	Conspicuousness	Conclusion
Arrow	+	-	-	+	reject
Chevron	+	-	-	+	reject
Dimmed Chevron	+	o	-	+	reject
Runway Label	o	+	+	o	assess

Table 7: Comparative rating of symbology alternatives for active runway representation

Advantages and disadvantages of the different symbology variants are summarized in Table 7. Although it is only of average conspicuousness and not very strong in indicating directionality, only the dimmed runway label concept remains, because all other variants do not comply with the essential compatibility criterion.

Eventually, therefore, a design exclusively based on the dimmed label, which is used in all ranges and modes, was down-selected for simulator evaluation, as illustrated by Figure 49. Whenever information on active runways is available, the label of any non-active QFU is dimmed. In the exemplary AMM screenshot of Newark Liberty International Airport (KEWR) in the USA shown in the figure, RWY 11 and RWY 04L are active.

Figure 49 also anticipates the use of the dimmed label concept in the visualisation of closed runways discussed in the following section. If a runway is closed, it can obviously not be active, and thus both runway labels are presented in a dimmed state to reinforce the presentation of the closed runway.

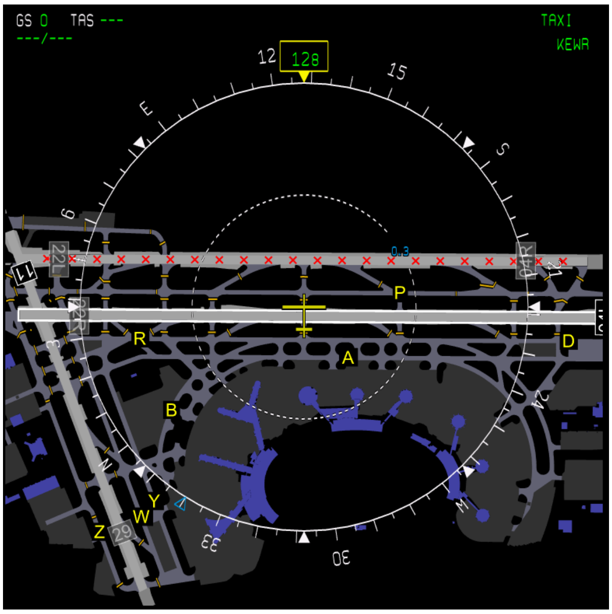

Figure 49: Active runway representation via dimmed runway labels

An expected major advantage of this representation compared to solutions requiring additional symbology is that it intrinsically indicates the availability of information, instead of potentially creating confusion in those cases where the display of this information fails, e.g. because the underlying information is not available.

If no active runway information is available, both QFU labels will retain their normal representation, and the flight crew can, at least in principle, determine that information is unavailable. By contrast, if additional symbology is employed as with the rejected alternatives, it may not immediately obvious to the pilots whether information is missing or whether a runway is actually not active, which will consequently necessitates an additional indication of information status elsewhere on the flight deck.

The only apparent drawback of using the runway labels for an indication of active runways is that the label is not visible in all range/mode combinations. Nevertheless, the crew is always free to choose an appropriate range or mode to access this information when needed. Furthermore, for the FMS-selected runway, which always indicates the QFU chosen in the same fashion, a consistency check with active runway data, where available, could ensure that the runway chosen is in fact active. This is realised in the frame of Surface Movement Alerting (see Section 5.5).

5.3.4 Representation of Short-term and Temporary Changes

5.3.4.1 Prerequisites for an integral NOTAM visualisation

5.3.4.1.1 Availability of machine-readable NOTAM data

To enable an integral visualisation of NOTAM and other relevant temporary data on an airport moving map, the corresponding data must be provided to the aircraft systems. However, making the manual entry of this data a routine crew task would constitute an additional step in flight preparation, and thus most probably raise workload in a phase already crammed with activity. Since a shift of the dispatcher role to the flight deck is neither intended nor desirable, any manual NOTAM entry would start from a conventional PIB, resulting in a highly mechanized task under time pressure[86], which must therefore also be regarded as a potential source of error. Furthermore, making manual entries during flight preparation is likely to have an adverse impact on turnaround times, since it requires the aircraft to be at the gate or parking position. Consequently, it is essential that NOTAM data are made available onboard in a machine-readable format via data loading or data link, thus enabling the automatic display of this information without routine crew interaction.

An integrated NOTAM presentation on a flight guidance display, however, has a totally different quality than a paper printout, even if it originates from an aircraft system (such as METAR or D-ATIS printouts) with significant impact on the data quality and integrity requirements. As discussed in Section 4.3.3, this insight leads to the conclusion that the crucial step towards a combined representation of airport moving map and NOTAM, including other relevant short-term or temporary information, is the integration of the underlying data through an adequate handling and operational concept. Today, airlines as the end-users are ultimately responsible for ensuring that the databases carried aboard their aircraft meet the quality requirements of the intended applications. In most cases, airlines meet this responsibility by obtaining databases from an accredited supplier. Consequently, the key issue associated with displaying airport-related NOTAM data integrated with the airport moving map is the availability of the required data in a machine-readable format with sufficient integrity. Since the data do not only serve as a basis for a display of information on flight deck displays, but also as input for an alerting system, any erroneous information might have severe consequences. Therefore, the accuracy, integrity and traceability of these data must be ensured at all times. In particular, this means that the corresponding data will have to fulfil at least the basic criteria for aeronautical data processing and quality management set forth in DO-200A.

In line with the considerations in Section 4.3.3, the initial focus is clearly on dispatching aircraft with all NOTAM contained in the conventional PIB also available to the avionics. Subsequently, the necessity of periodic or event-driven in-flight updates has to be evaluated. Consequently, the data handling and operational concept has to be scalable and extensible, from supporting initial, basic implementations at individ-

[86] One could argue that, in principle, a manual entry of NOTAM data through an adequate interface would force the crew to a detailed review PIB information and might thus have a positive impact on situational awareness and the accuracy of their mental model of the airport. However, the time pressure/mechanization issue may potentially annihilate this effect. Besides, a well-designed airport briefing procedure can achieve the same.

ual airlines or their sub-fleets to a future Aeronautical Information Services (AIS) environment supporting real-time in-flight updates via avionics data link. In this context, the variety in the time horizon of the required data due to their short-term and temporary character constitutes a major challenge.

5.3.4.1.2 Possibility of crew interaction with NOTAM data

Even in case the NOTAM data is provided via data link and updated during the flight when required, weather, incidents/accidents or other operational demands might necessitate short-term changes at a tactical level, thus eluding coverage by NOTAM or related means. Consequently, the short-term and temporary character of NOTAM data will most probably require a possibility to review, enter or amend the corresponding information on the flight deck – where necessary – as a back-up.

As an example, a runway closed for maintenance work might be temporarily reopened for take-off or landing of a large widebody aircraft, provided that the maintenance work can easily be discontinued (e.g. if only light bulbs of the lighting system are changed). Likewise, a runway that is, according to a NOTAM, closed daily from 11:30 p.m. to 6:30 a.m. over a certain period, might become available again at 5:50 a.m. on one particular day, and ATC could ask a crew to use it. The corresponding NOTAM would obviously not be impacted in their overall validity by these individual exceptions.

Due to the compelling nature of the airport moving map display, however, particularly the display of incorrect runway closure or restriction information is believed to be unacceptable from a human factors perspective, because it is likely to confuse the flight crew. This becomes an even more important concern if machine-readable NOTAM data is simultaneously used to generate safety-net type alerts, e.g. if the flight crew attempts to take off from a runway closed for take-off and landing, as in the frame of Surface Movement Alerting (see Section 5.5), because both missed and false alerts constitute a certification issue.

Consequently, the necessity of providing flight crews with a possibility to interact with NOTAM information must be evaluated. This includes means of cancelling individual NOTAM and entering new or updated information, especially on runway status. Since the instances where such manual crew entries would be required are isolated events rather than routine, the previously stated concerns (workload, possibility of error) might be addressed at a similar level as e.g. the entry of additional waypoints into the Flight Management System (FMS) due to a flight plan change.

5.3.4.1.3 Adequate, intuitive symbology and presentation concept

An integral representation of NOTAM and other operationally relevant short-term or temporary information on an airport moving map depends on an adequate, intuitive symbology set and presentation concept. The number of distinct new symbols for NOTAM visualisation should be kept at an absolute minimum, because a symbology set with the extent of a hieroglyphic alphabet does not appear to be desirable for usability, crew training and proficiency reasons. Additionally, the content of some NOTAM information might even completely elude an intuitive graphic representation. Consequently, the cases where a graphical representation is useful must be identified, because plain text can be superior to symbology once a certain degree of complexity has been reached. To limit the complexity of the symbology employed, therefore, a suitable transition from a graphic to a textual or hybrid representation must be defined. In combination with a generic attention-getting symbol, context-specific textual information might still have significant advantages over the conventional PIB/NOTAM system. Clearly, therefore, machine-readable NOTAMs must retain the currently used descriptive textual information[87].

To illustrate the symbology issue discussed above, a real-life example seems appropriate. At Toulouse Airport (LFBO), the use of the runway adjacent to the main Airbus facilities is sometimes restricted to flights carried out by the aircraft manufacturer, as is evident from Figure 50.

```
A2674/06 NOTAMR A2564/06
Q) LFBB/QMRLT/IV/NBO/A
A) LFBO B) 0607201330 C) 0607291700
E) RWY 14R/32L : LENGTH LIMITED, EXCEPT FOR
   ACFT BUILDER :
   - QFU 32L, TAKING-OFF ON 2700M FROM TWY
     M4 (POSSIBLE TAKE-OFF ON 3500M O/R AT
     START-UP)
   - QFU 14R : WHEN LANDING, RWY MUST BE
     CLEARED VIA TWY M4
   - WHEN LANDING AT QFU 32L, RWY MUST BE
     CLEARED VIA TWY M10 EXCEPT ACFT
     BUILDER
```

Figure 50: Toulouse NOTAM example

Representing the limited portion of the runway as closed to all other aircraft does not seem appropriate, because pilots might then be confused to see traffic taking off or landing on a runway marked as closed. In this case, a hybrid solution could consist of a generic 'runway restricted' symbol for any situation where the runway is neither closed nor restricted in length, along with the descriptive NOTAM text detailing the restriction. As another example, pilots could be required to obtain permission prior to using a particular runway.

5.3.4.1.4 *Temporal constraint visualisation and notification concept*

In many cases, relevant NOTAM are effective for the entire duration of the planned flight. However, if short-term or temporary changes become effective or expire during the flight, there are several issues that need to be addressed.

First of all, it must be ensured that only current and valid information is presented, and that important changes requiring immediate crew awareness are properly identified and brought to the attention of the pilots using an adequate notification concept. At or in the vicinity of an airport, runway status changes are potential candidates for such an advisory. Conversely, while airborne, a limitation to relevant landing runways at the destination or alternate airports seems reasonable, since changes at other airports are hardly relevant unless a diversion is considered.

Irrespective of whether a dedicated notification is deemed necessary or not, an indication of imminent or recent changes of operational relevance changes is probably required, since a sudden, unannounced change of the information displayed is prone to oversight or creating confusion. Further complexity is added by the fact that NOTAMs often use estimates for the time of expiry. At least in this case, an advisory to the crew to validate information with other sources such as ATIS or ATC is required.

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[87] Other reasons for this requirement are that the conventional PIB shall be in plain language [ICA04], and that a possibility of reviewing the original PIB/NOTAM information might be required depending on the interaction concept chosen, and to address contingency (e.g. in case of display failure) or retrofit.

Last but not least, in view of emerging ultra long-haul flight services with durations of 16 hours and more, the time reference to be used for the presentation of NOTAM information and the triggering of notifications deserves special attention.
If ownship is in the vicinity or within the area of interest, such as an airport, using current time as reference emerges as the only possibility. However, this is non-trivial for areas several flight hours ahead: When considering destination or alternate airports, information on e.g. runway closures and other pertinent restrictions is essential for decision making, such as the decision to divert and a suitable choice of an alternate airport. Nevertheless, only the conditions at the time of arrival are critical, whereas the situation at the time of departure or in cruise flight is most likely irrelevant. Consequently, a predictive component might be required, and the Estimated Time of Arrival (ETA), which is calculated by the FMS, could be used as time reference for visualizing the situation at any destination or alternate airport. When the aircraft approaches the destination or alternate airport, however, a transition back to current time will have to take place at some stage, because otherwise inconsistencies with simultaneously displayed real-time data, such as traffic, might result.

5.3.4.2 Closure and restriction cases to be covered

Runway closures and other applicable runway or airport restrictions are used as an example to demonstrate the principles of integral NOTAM representation on an airport moving map in this thesis; taxiway closures are addressed as a by-product.
Before defining the corresponding human-machine interface, a thorough survey of the different cases to be covered and the challenges associated with these must be performed. Generally, an important distinction to be made is whether closures or limitations apply to all aircraft operating at an airport, or whether they result from type-specific characteristics such as wingspan or mass.

It quickly emerges that a binary distinction between 'open' and 'closed' runways is not sufficient to address all operationally relevant situations, since different levels of runway closure must be taken into account. As an example, a runway could be closed for the desired type of operation (e.g. landing) but still be in use for another (e.g. take-off), and this must be clearly distinguished from a situation where no aircraft may use the runway for take-off and landing, or enter the runway.
To achieve this, the concept of runway status, which allows reflecting various operational conditions from complete closure of the whole runway to availability for all operations, is introduced. In contrast to ATC instructions, runway status information is applicable to **all** aircraft operating at or in the vicinity of an airport. The following high-level cases can be identified:

1. The runway is **completely closed**. Due to ongoing construction work etc., the runway cannot be used for any type of operation and may not be entered by any aircraft.
2. The runway is closed for take-off and landing, but **open for taxi** operations.
3. The runway is **open for landing** only.
4. The runway is **open for take-off** only.
5. The runway is **open for take-off and landing**.

Runway status thus covers the type of permissible operation, which commonly has to be provided per threshold, as discussed in Section 5.3.3. Closures form an exception. In this context, the fine-grain distinction between non-active runways and temporarily closed runways is generally as follows: in case the runway is officially closed, take-off and landing operations are forbidden, whereas a non-active runway may become active any time, depending on the wind direction, or on explicit crew request [ICA01a]. Obviously, runway status and active runway are not fully independent, since a closed runway cannot be active, and vice versa.

It is important to note that the above status concept does not allow any distinction of temporary and permanent closure[88]. However, from an operational point of view, this is of secondary importance: a permanently closed runway such as RWY 04/22 at Prague Airport (LKPR) – currently used to park aircraft – might create an equally serious hazard in case of an erroneous take-off or landing attempt as a runway that is closed temporarily due to construction work with heavy machinery.

5.3.4.2.1 Partial closure and length restrictions

Runway status and active runway information as defined above always refer to the complete runway surface. This has the advantage of consistency with the current DO-272A/ED-99A implementation of runways, which allows segmentation only for the case of intersecting runways [RTC05]. As a result, status and active runway could be handled very easily as additional 'pseudo-attributes' of the runway as stored in the AMDB. Although adequate to address many situations, this is still not sufficient to characterize the operational status of a runway exhaustively; reality is somewhat more complex. The main issue is segmentation: in many cases, only a certain segment of a runway, e.g. between certain taxiways or high-speed exits, is completely closed.

Consequently, completely closed parts and sections that may still be used for taxiing might coexist on a single runway, and not necessarily be separated by an intersecting runway. As an example, it could still be permissible to cross a completely closed runway via certain taxiway intersections. This principal discernibility of complete runway closure and closure still permitting taxi operations can be important when flight crews need to decide whether to accept a certain taxi route or not, and to understand the traffic patterns observed[89].

Depending on the location of a closed segment, the remainder of the runway can sometimes still be used for take off and/or landing, provided that sufficient runway length and obstacle clearance remain, although only one of the thresholds might remain usable if runway length is thus restricted. In conclusion, if a certain status does not apply to the whole runway, the crucial issue is an identification of runway seg-

[88] Technically, however, a distinction of permanently and temporarily closed runways is no problem, because a permanent closure would be included in the AMDB by setting the 'status' flag of the corresponding runway threshold to 'closed' [RTC01, RTC05].

[89] It is irrelevant in this context whether traffic is presented on the airport moving map or just acquired visually – observing aircraft taxiing on runways displayed as closed is prone to create confusion, if no distinction of closure cases is provided.

ments with differing status and their impact on the usability of the overall runway[90]. Consequently, runway status information must be provided per segment in these cases, which raises the question of how segmentation information should be coded and transmitted. In current NOTAM, the identification of the runway segments concerned is usually accomplished by specifying the identifiers of the intersecting taxiways, or, if the runway remains usable, the reduced available accelerate-stop distance. Indeed, since the runway geometry is already available in the AMDB, all segments can be unambiguously identified by specifying two distance values from a given threshold. Compared to the transmission of the complete segment geometry as proposed e.g. by [TUD06], this has several advantages:

- adverse effects of differing accuracies in the geodetic survey of the runway stored in the AMDB and the data in the NOTAM are minimized. A potentially irritating shift between runway segment data and the original runway representation based on the AMDB can be excluded;
- the volume of data to be transmitted is significantly lower; and
- a manual entry of segmented runway closure/restriction data is more convenient via distances
- information is also usable in case an AMDB is not available for a given (alternate) airport, and can also be applied by legacy systems relying solely on ARINC 424 for runway data, cf. [ARI02].

5.3.4.2.2 Further types of restrictions

Runway or taxiway restrictions other than closures or length restrictions (runways only) can be divided into two general categories. The first comprises restrictions that can be parameterized, such as aircraft type, wingspan or mass restrictions. Conversely, the second category consists of restrictions that cannot be evaluated by the system due to a lack of parameters.

Closures and restrictions of taxiways are less safety-critical, and the same applies to apron areas and parking positions. For taxiways and the movement area outside the runways, a fine-grain distinction of closure states is not necessary, since an administrative closure is either effective or not. With respect to taxiway restrictions, the only relevant differentiation is whether they apply to all traffic or only to aircraft with specific characteristics. Displaying taxiways that cannot be used by ownship due to a type-specific restriction as closed might be confusing, because the crew will then probably not expect other traffic on these taxiways. Usage limitations originating from airplane characteristics have to be indicated by other means.

[90] If the effect of completely closing a segment in the centre of the runway is that the whole runway becomes unusable for take-off and landing, this could still be reasonably well be modelled by setting the status of the whole runway to 'open for taxi' – the crew would then just not know where exactly the completely closed part is. With speed in the range typically used for taxiing, this information can be obtained visually (barricades and markings). But this approach fails if the runway remains usable for take-off and landing.

5.3.4.3 Symbology for runway status, closures and restrictions

This section addresses the human factors issues that need to be taken into account when designing symbology for a representation of runway status, closures and restrictions. In addition, the symbology eventually used during the evaluation campaigns is described.

5.3.4.3.1 Considerations on symbology for closed runways

In virtually all implementations, the airport moving map resembles the real airport in terms of the elements displayed and, to a certain extent, the colours used, cf. Sections 3.1 and 5.1. Therefore, the ICAO and FAA standards for marking closed runways described in Appendix II-2.1 should also serve as a guideline for visualizing closed runways and taxiways on an airport moving map. From a Synthetic Vision perspective, the main objective is to achieve sufficient resemblance for an intuitive perception of information, cf. [Ver05]. Consequently, while the corresponding symbology should be similar to the real markings, it is neither required nor intended to mimic these exactly. Additionally, due to the slight differences in colour concepts and marking philosophies employed in the USA and elsewhere, the presentation of closed runways on the airport moving map might intrinsically require some abstraction.

In this context, the consistency of closure markings physically applied on the runway surface and those displayed in the cockpit is one of the key issues, since the physical closure markings might not be according to standards, obscured or entirely missing. In fact, due to operational constraints, the application of real markings is deliberately kept minimalist and – in accordance with ICAO recommendations – even facultative for temporary runway closures. Therefore, a one-to-one correspondence of physically applied and electronically displayed closure markings would **not** fulfil the basic requirement of safeguarding the crew against inadvertent oversight of runway closures, and thus leave another advantage of Synthetic Vision unused: the possibility to augment the synthetic view by artificial cues conveying information relevant for the crew task, but not present in reality. In conclusion, the cockpit display must provide an indication of the closure status to the crew irrespective of whether and how runway closure markings are physically applied.

Likewise, since isolated crosses on runway thresholds or taxiway entrances – as envisaged by ICAO and FAA standards for airport markings – might not be visible in all possible AMM range and mode combinations, the corresponding symbology on an airport moving map should always cover the whole length of the runway or taxiway concerned. Furthermore, if a closed segment renders the entire runway unusable for take-off and landing, it is consequently probably not sufficient to display merely the corresponding part of the runway as closed, either. Rather, the whole runway surface will have to be marked, with the remainder presented as closed, but still usable for taxi operations.
Otherwise, the closure might be hidden from the crew: In analogy to the Taipei accident scenario, with a closed runway segment further down the runway not in view on the display, leaving runway parts that can still be used for taxiing without dedicated marking could tempt flight crews into believing that the runway can still be

used for take-off or landing. Although alerts when attempting take-off or landing on a closed runway might still prevent an accident in this case (see Section 5.5 for details), presenting potentially misleading information is clearly not desirable and might thus be considered a certification issue.
By contrast, if the runway remains usable in spite of closed segments, displaying the closed sections only, irrespective of their character, seems to be sufficient. Unless the flight crew intends to use this particular runway, there does not appear to be a need for a specific representation of the resulting length restriction, either.

Figure 51 gives a schematic summary of the HMI design for the representation of closed runways eventually down-selected for this thesis. In view of the considerations above, there appears to be no need to apply the closure crosses defined by ICAO using shape, dimensions and location to scale. Consequently, only one type of cross resembling more the ICAO taxiway closure cross is used to designate closed runways and taxiways. Likewise, the distinct cross shapes for runway and taxiway closures, respectively, do not have to be modelled exactly, because the difference in the shape of the crosses may be difficult to perceive at large range settings. Rather, to ensure visibility in larger display ranges, it was therefore chosen that closure crosses should extend virtually over the whole width of the runway or taxiway on the airport moving map. Colour and size of the crosses, however, are different for runways and taxiways (see below).

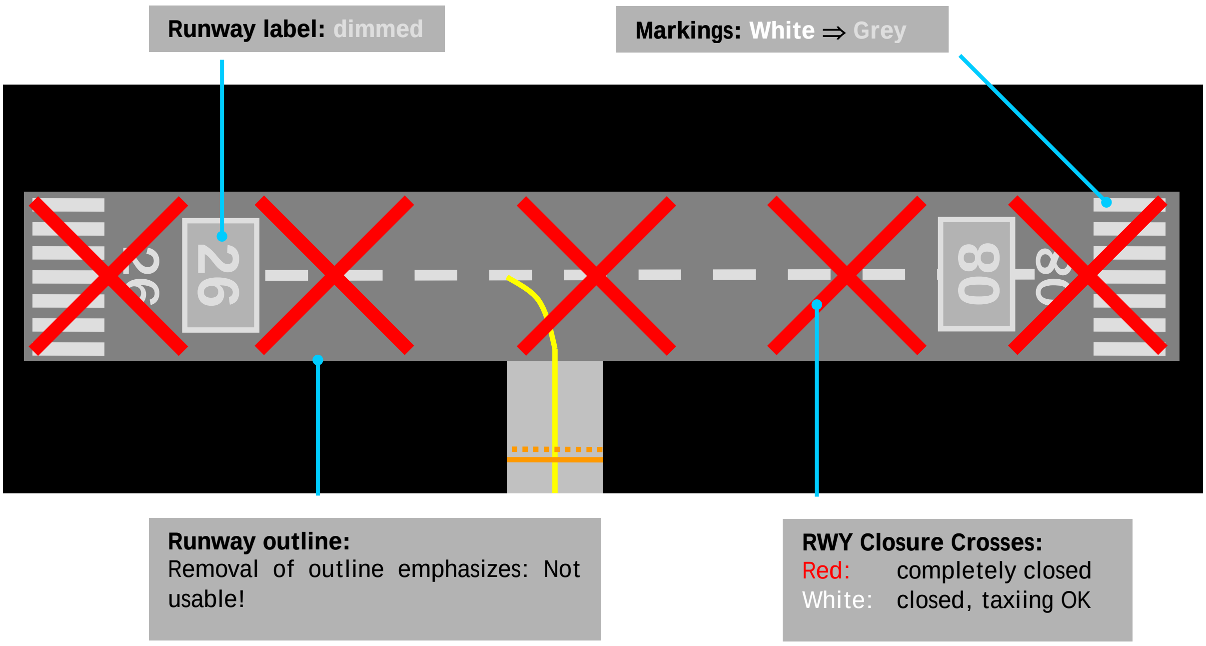

Figure 51: Schematic HMI definition for the display of closed runways

A closed runway or runway section is marked with equidistant crosses on the runway surface, covering all other runway elements or markings where displayed, with the exception of the runway label identifying the threshold. At larger range settings, there are fewer crosses, but – in analogy to the ICAO mandate – they are never separated by more than the equivalent of 300 m in the respective scale (i.e. range setting).

For the smaller ranges, there are more crosses to ensure that even runway segments that are only partially visible due to range or mode settings can be clearly identified as closed by the crew. With respect to intersecting runways, if only one of them is closed, the open runway is displayed normally, and closure markings are only placed on the segments of the closed runway on both sides of the open runway[91].

Closed taxiways or taxiway segments are also represented by equidistant crosses on the taxiway surface, and for the distance of the crosses and the intersection with open taxiways, the same criteria as for the runway are applied accordingly. The same applies to other airport areas closed for traffic. Clearly, the flight crew should also be able to distinguish closed runways (irrespective of closure level) and closed taxiways at a glance. The reason for this is not only different criticality for flight safety, but also the human factors consideration that it is essential to main sufficient contrast between the visualisation of runways and taxiways, whatever their state.

5.3.4.3.2 Colour concept

Due to these constraints and the need for differentiation, any solution with a unique closure symbol as shown in Figure 53 can only employ colour coding to distinguish the different cases of runway closure on one side and closed taxiways on the other side. As a result, different symbol colours must be used to discern closed taxiways from closed runways (or segments thereof) that may still be used for taxiing.

Using the same colour for closed taxiways and runway parts that are still available for taxiing might be prone to create confusion, because pilots would then be able enter one aerodrome area with a closure marking in a given colour, but not the other. Consequently, the colour of the crosses used to indicate closed taxiways should be different from the two cases of runway closure. Conversely, employing the colour for complete runway closure for closed taxiways as well would help to prevent these inconsistencies, but might not reflect the different criticalities appropriately and could make closed runways and taxiways look too similar.

In conclusion, therefore, a partially redundant coding is used, with the essential information that a runway, taxiway or corresponding segment is closed coded by the cross symbol, and the precise nature and criticality of the closure represented by the colour of the symbol[92]. The number of distinct closure categories is sufficiently small for colour coding to be applicable, cf. [SAE88].

[91] ICAO Annex 14 does not explicitly treat this case; the solution proposed here is, however, in line with FAA recommendations in [FAA05a].

[92] Redundant coding ensures the accurate transmission of information in high ambient lighting conditions or other situations where colours alone may be difficult to distinguish for persons with normal colour vision. Furthermore, although vision requirements on flight crews are strict, there is still some variation in colour vision performance even for pilots classified as having normal colour vision. In December 1998, there were approximately 2300 flight crew members in the USA with deficient colour vision who nonetheless held first class medicals. Therefore, redundant coding is also important for pilots with (albeit minimal) colour vision deficiencies. Furthermore, the ability to discern colours deteriorates with age. For these reasons, several of the newer FAA TSOs require a minimum of two coding techniques, which may include colour, shape, and location. In addition, this redundancy minimizes the effect of hardware failures resulting in a loss of colour [SAE88, FAA02b].

In accordance with common practice, the choice of symbol colour for a completely closed runway or runway segment is, in view of the criticality, consequently between amber and red as the two "*traditional warning and cautionary colors*" [SAE88]. An issue in this context is that the use of the colour red on the flight deck is usually reserved for emergency situations that require immediate flight crew action, since any inappropriate use may desensitize pilots and thus reduce the effectiveness of flight deck alerts [SAE88a, FAA02b]. According to DO-257A, however, the guidance in §25.1322 concerning amber and red should be understood to preclude only the excessive use of these colours on an airport moving map; thus amber and red still remain permissible for coding surface signs, lights and markings [RTC03a]. However, since this would justify the use of red for a nominal indication on a display[93], DO-257A is probably not specific enough in this matter.

The visualisation of closed runways with coloured crosses could potentially be reinforced by additional colour changes to the other runway elements displayed. For a runway closed for take-off and landing, therefore, both threshold labels are dimmed from the usual white-on-black representation to grey (as for the inactive QFU), since obviously neither threshold can be active.
Given the ICAO recommendation to obliterate the markings of permanently closed runways (as outlined in Appendix II-2.1), it was also considered to further emphasize the presentation of a closed runway by changing all standard runway markings from white to grey, as shown in Figure 51. This feature was, however, eventually not retained for assessment, because both airport moving map display prototypes used in the two evaluation campaigns feature light grey runway surfaces, and prototyping sessions revealed that any grey tones between white and the runway surface tone either obscured the markings entirely or did not prove sufficiently conspicuous in comparison with white markings. Nevertheless, it can be expected that the obliterated markings of permanently closed runways will eventually be removed from the corresponding AMDB in subsequent revisions. Intrinsically, therefore, there will be no runway markings for a permanently closed runway in this case.

In the frame of this thesis, two different colour concepts consistent with the SAE recommendations were devised and eventually assessed during the two evaluation campaigns. Both concepts use white crosses for runways or runway segments closed for take-off and landing only, but still usable for taxiing or crossing, because this colour seemed the least alerting and intrusive. Since flight crews will routinely perceive the ownship symbol on top of these closure crosses, it seemed important not to create the impression that there is an abnormal situation. Additionally, white is the predominant colour of runway markings.

The initial colour concept consisted of amber crosses for completely closed runways or runway segments (to avoid using red), and yellow crosses for closed taxiways (as the dominant colour of taxiway markings). To reinforce the representation of runway and taxiway closure, the corresponding surfaces were darkened. The associated implementation, which corresponds to a subset of the concept above, is shown in Figure

[93] In line with DO-257 guidance, the runway holding positions (stop bars) are displayed as red lines on some airport moving map implementations (see Section 3.1.1).

43. It was evaluated in the frame of the EMMA project; the results are described in Chapter 7. For technical reasons, the dimming of the runway surface was realised by an overlay, resulting in a complete removal of all runway markings. Due to the limited choice of colours, closed runways had the same colour as aprons. This concept was eventually revised for the second evaluation campaign due to the following reasons:

- Pilots participating in the first evaluation campaign found amber not strong enough (cf. Chapter 7), especially since the similar colour yellow is ubiquitous on the display due to a naturalistic representation of taxiway guidance lines.
- The simultaneous use of amber and yellow should be limited, since they may be difficult to distinguish due to their similar appearance on electronic displays, particularly under conditions of high ambient light [SAE88][94].
- Regardless of closure state, it was eventually considered more important to retain a consistent colour coding for the different airport surfaces, alongside the principle that a closed runway is still a runway and must be recognisable as such.

Consequently, an alternative set of colours was implemented for the simulator evaluation campaign described in Chapter 8, which comprised red for complete closure and amber for closed taxiways (see Figure 52). In spite of the SAE recommendations quoted above, amber crosses on top of yellow taxiway markings were eventually presumed provide a better contrast than yellow crosses on yellow markings.

Likewise, red is believed to provide a stronger distinction of completely closed runways, as requested by pilots. The use of red seems justified in this case, because it is used only for completely closed runways or runway segments, which definitely constitute a non-nominal condition and significant operational limitation.
Therefore, this second approach is even more restrictive than DO-257 and consistent with a certified solution on the Primary Flight Display (PFD) of Airbus A320 family aircraft, where the ground reference is indicated by a red tape [Air05]. In this case, red is also used to indicate a hard operational limit, rather than the necessity of immediate corrective action, since the tape may be in view while the altitude is still perfectly normal[95]. Therefore, with the argument of a hard operational constraint, red crosses for completely closed runways seem to be justifiable, all the more since pilots will probably not see this every day, thus lowering the risk that pilots will get comfortable and complacent with red indications on their display.

Figure 52 and Figure 53 illustrate the revised solution implemented on the basis of the Institute's airport moving map software. The figures also show a segment-wise distinction of the closure level; RWY 25R is completely closed between taxiways F and G, but the remainder of the runway may still be used for taxi operations. For completeness, Figure 52 also demonstrates the implementation of displaying closed taxiways.

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[94] In fact, according to [SAE88b], amber and yellow are to be used interchangeably for cautions and abnormal sources.

[95] In addition, the overspeed domain – which by comparison with the ground reference constitutes only a "soft" operational limit – is also indicated by a dashed red line on an Airbus family PFD [Air05].

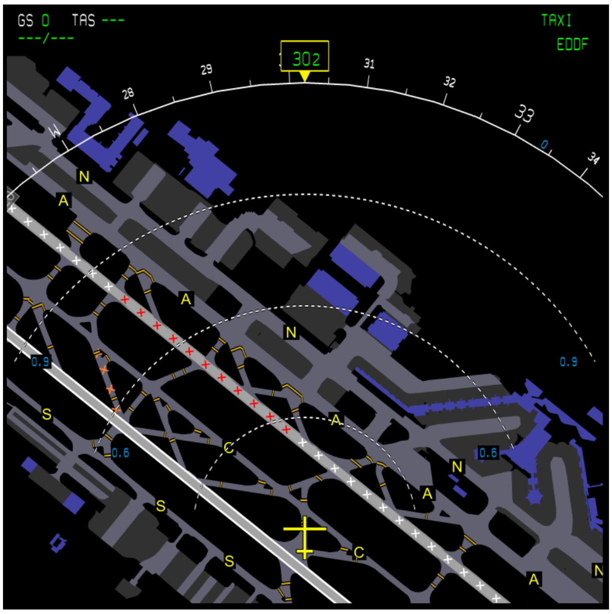

Figure 52: Display of closed runways and taxiways on the airport moving map

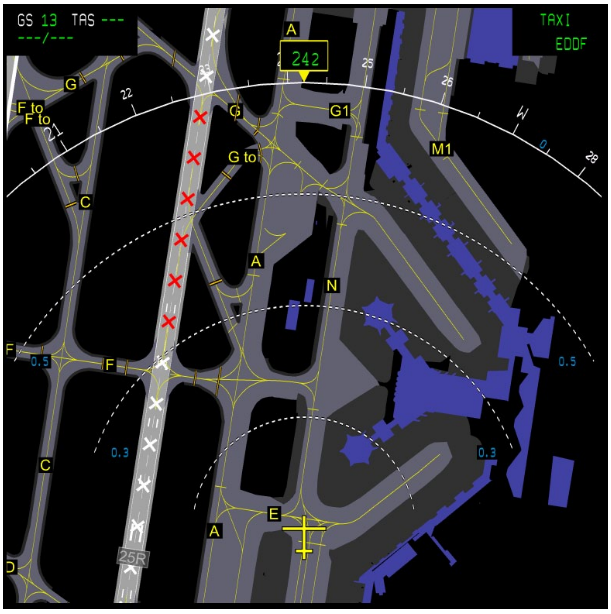

Figure 53: Runway closure symbology (low range)

5.3.4.3.3 Visualisation of runway restrictions

Restrictions to the runway length available for take-off or landing are quite common, and often the result of a partial closure at one runway end. A distinct representation of this situation is believed to be required only if the flight crew intends to use the runway in question for take-off or landing. Otherwise, displaying only closed runway segments – if applicable – appears sufficient. Consequently, the representation of length restrictions should be coupled to the display of the FMS-selected runway; see Section 5.3.2 for details.

In case there is a temporary length restriction of the FMS-selected runway, e.g. due to a partial closure as shown in Figure 54, this approach results in the definition of a new temporary runway, which by definition always accurately models the interdependency of closed segments and the remaining runway. Accordingly, the outline of the FMS-selected runway consequently only encompasses the temporary runway created by the restriction.
The fact that the runway is restricted in length is further emphasized by displaying the corresponding temporary runway outline – excluding the closed or unusable part – in yellow instead of the usual white to indicate the non-standard situation. Likewise, the active threshold is indicated by a yellow (instead of a white) runway threshold label.

For this design approach, the absence of a threshold label within the temporary outline signifies that the corresponding runway threshold is not available. In the example shown in Figure 54, only RWY 25R is available, though restricted in length, whereas the RWY 07L direction would be unavailable.

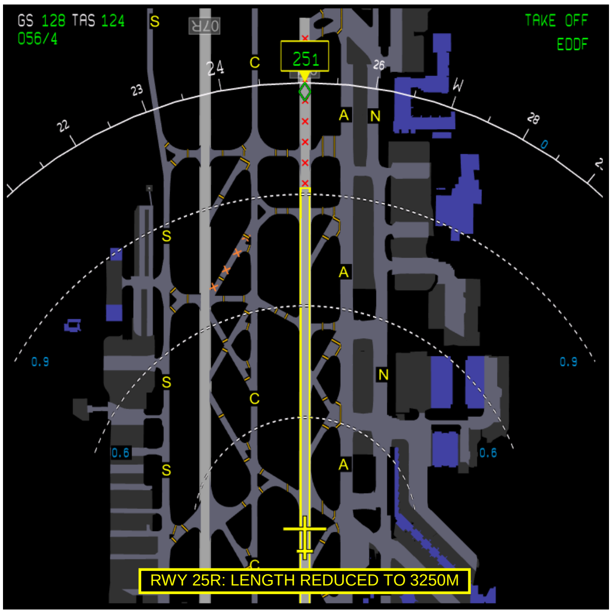

Figure 54: Runway length restriction due to partial closure

Since it may be difficult to estimate the length of the remaining runway just from the outline displayed on the airport moving map, this information should be visualised at a prominent location on the display. Provided that sufficient display space is available, the text of the NOTAM detailing the runway restriction (or a brief summary thereof) could be displayed automatically (see Figure 54) as soon as the flight crew enters a restricted runway that has been selected for take-off, or arms the approach mode for this runway, respectively. In addition, this is intended to reinforce the visualisation of the runway restriction; text and frame colour correspond to the runway status.

Depending on the level of integration with the aircraft's Electronic Centralized Aircraft Monitoring (ECAM) or similar systems, NOTAM messages requiring crew notification could additionally be forwarded to the Engine/Warning display, which already features a list of operational constraints resulting from system failures. Consequently, the ECAM could ensure that the crew is notified of emerging runway closures or restrictions at the destination in an appropriate fashion when in cruise flight.

Not all of the runway restrictions conveyed by NOTAM are related to runway length. Restrictions may apply to ownship due to certain aircraft characteristics, such as wingspan or weight; sometimes certain aircraft types are specified as well. If restrictions contained in NOTAM are relevant for ownship, the corresponding runway or runway section could be marked with a series of 'R' in lieu of the closure crosses, with the colour concept accordingly; restriction information not applicable is not shown. This could ensure that flight crews can differentiate closure, which is applicable to all traffic, from restriction, which may only concern certain aircraft.

However, runway-related NOTAM do not necessarily fall into either the length or usage restriction category, and it might not always be possible for the system to process restriction information, e.g. due to a lack of parameters, if it consists of text only or is very complex, such as in the Toulouse example (cf. Figure 50). In these cases, if restrictions cannot be translated directly into marking a certain runway as unusable for ownship or depicting the constraints in a direct way, a generic attention-getting symbol, supplemented by the identifier of the corresponding NOTAM, is envisaged. It could always be placed in the centre of the visible part of the runway concerned. As for length restrictions, the corresponding NOTAM text might be visualized automatically as detailed above if the runway is to be used for take-off or landing.

Closure crosses, the restriction symbol and the attention-getting symbol notifying the crew of the existence of a NOTAM are the only additional symbols used by the OAF. Operational conditions that are neither closure nor restriction are thus mainly covered by text, rather than by a complex symbol set, to limit the complexity of symbology. After all, this is the main reason why most early iconic alphabets were eventually superseded by the alphabets we know today.

The principles for visualizing restrictions and the presence of NOTAM information that cannot be decoded into a restriction could be applied to taxiways and other airport areas as well. Taxiways that are not usable by ownship due to restrictions are marked by amber 'R' instead of crosses. Wherever possible, NOTAM should be processed using relevant ownship data and then be presented as usability criteria for the airport element that the restrictions refer to. If this cannot be achieved, the attention-getting symbol can be applied accordingly, see Figure 55. To prevent display clutter, the attention-getting symbol could be coupled to the presentation of labels for the respective airport areas. For smaller taxiways and parking positions, the symbol would consequently only be shown in ranges where labels for these airport features are shown. Additionally, on an interactive ND, if the crew selects the attention-getting symbol (irrespective of whether it pertains to a runway or other airport area), the textual NOTAM information is directly displayed in an overlay window.

As for runway restrictions, NOTAM information is shown only if it is applicable to ownship. For example, if a taxiway is temporarily restricted for A380-size aircraft, but there are no limitations for A320 family aircraft, the A380 crew would see the taxiway marked as unusable – optionally with a reference to the corresponding NOTAM if they request additional information on the element – while the A320 crew would not be bothered with information not relevant for them; nothing would be displayed.

The human-machine interface discussed in this section applies to closures, restrictions and limitations resulting from short-term and temporary changes. The symbology developed is consequently intended for isolated, attention-getting application to highlight non-standard situations. However, there might also be permanent and more fundamental type-specific restrictions at airports, particularly for large aircraft such as the A340-600 or the A380, originating from basic airport characteristics. In principle, the symbology developed in this section could be applied as well, but this is an issue that should be addressed by future research.

Likewise, length restrictions imposed by LAHSO are handled differently, as shown in Figure 44, because they are established permanently and constitute a clearance limit rather than a physical limit.

Due to time constraints, the human-machine interface derived in this section could neither be prototyped nor formally be evaluated during the flight simulator campaign, but was briefly reviewed in a post-hoc meeting with one of the flight test pilots from the prototyping team.

5.3.4.4 Notification and indication of operational changes during flight

The human factors requirements with respect to the indication of imminent changes on the airport moving map are still subject to further research, and they were not addressed by this thesis beyond the level of some basic analytical considerations.

Consider the case that a runway closure, according to NOTAM information, ends at 22:00. It seems straightforward that, at 21:59, the runway should still be displayed as closed. Likewise, more than 12 hours later, it could be presented as open again based on the assumption that a new or changed NOTAM will have been issued by then if the closure persists. The critical time period encompasses the minutes and hours immediately following the scheduled end of the closure.

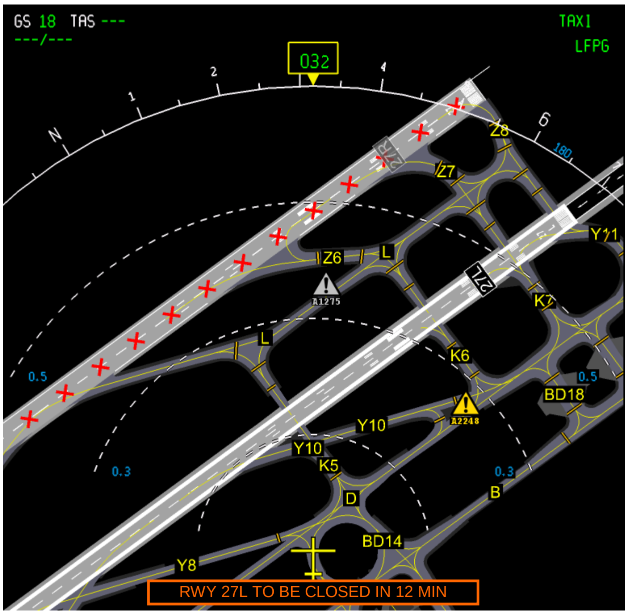

Figure 55: Active and expired attention-getting symbol for non-decodable NOTAM

A way of avoiding this problem would be an automatic data consolidation, e.g. with D-ATIS or ATC, to verify that the runway status has indeed changed as planned. But if such consolidation cannot be achieved due to failure or unavailability, the two essential indications from a human factors perspective seem to be that

a) a closure/restriction existed for a given runway until recently, and
b) the flight crew should be advised to initiate suitable measures to check the current runway status.

This is particularly important in case the end dates specified in a NOTAM are given as estimates only, and once more illustrates the necessity that the crew should have the ability to modify any operational awareness information manually.

To visualize expired closures and restrictions, the method of choice appears to be obliterating the corresponding markings themselves, e.g. by reducing them to an outline, making them transparent, dithered, darkened or dashed from e.g. one minute after the specified end of the closure until the end of the transition period. Reducing closure and restriction symbology to a dashed outline retaining the initial colour seems favourable, because it would allow to preserve information on the nature of the closure on the display. Unless contrary D-ATIS or NOTAM information is received, an initial guess is that for runways, this transition period should last until 30 minutes to 2 hours for a fixed and 2 to 6 hours for an estimated end time. For all other airport areas, it is most likely sufficient to remove the corresponding information much earlier, e.g. after 1 or 2 hours, respectively, due to the lower criticality.

Upon perceiving the expired closure symbol, flight crews would then procedurally be instructed to clarify the status of the runway or taxiway with ATC; the necessity of a brief advisory or reminder to initiate such clarification remains to be established.

For short-term and temporary restrictions conveyed via the generic attention-getting symbol, the proposed symbol accompanied by the NOTAM number could be changed from a yellow-coloured active representation to a grey expired representation, as shown in Figure 55.

To give pilots a better indication that a change is imminent, the active attention-getting symbol could additionally be added, potentially flashing or blinking, to the normal closure or restriction symbology a couple of minutes before expiration, and might remain as inactive attention-getting symbol afterwards, because the change of symbology to the 'expired' state itself (as described above) does not contain any information on whether the expiration time was an estimate or potential other details. Consequently, the symbol and the NOTAM identifier might help flight crews to retrieve the corresponding NOTAM more easily, particularly on an interactive CDS, where the NOTAM text could be invoked by applying the cursor to the attention-getting symbol.
Conversely, an indication that closures or restrictions are imminent appears to be required as well, and future runway taxiway closures could be indicated by applying blinking crosses to the corresponding taxiway with a lead time of e.g. two minutes. For runways, the same concept can be applied accordingly, with the difference that the general lead time would be increased, e.g. to five minutes, and that an additional text message, for example "RWY 18 TO BE CLOSED IN 7 MIN", could be displayed with ten or fifteen minutes lead time for FMS-selected runways, and, depending on the level of integration with the airframe, on the ECAM as well for any runway selected as part of the FMS flight plan[96]. For all other short-term and temporary changes visualised through an attention-getting symbol only, it is most likely sufficient to flash the symbol a couple of times when it is added to the display.

5.3.4.5 Safety considerations

A risk associated with manual modification of runway closure data is that the crew enters incorrect information. In contrast to the FMS-selected runway, which merely reflects a crew selection, this would lead to a display of misleading safety-critical operational information, because at least one potentially usable runway will be displayed as closed, while a closed runway will be marked as usable in the worst case. However, in combination with the FMS-selected runway, there are intrinsic safeguards, for example when the FMS-selected runway is also marked as closed, a situation that is additionally covered by an alert (see Section 5.5).
The combined risk of entering both an incorrect runway in the FMS and wrong runway closure data, however, can be regarded as low. Nonetheless, if the crew systematically confuses 'R' and 'L' for a given set of parallel runways, if one runway is the FMS-selected runway and the other one is closed, there might be an unsafe situation potentially resulting in a certification issue. Due to the compelling nature of the displays, certification authorities are likely to rate a wrong runway closure displayed on the airport moving map display as a more significant safety risk than an incorrect runway closure marking scribbled on a conventional paper chart.

[96] Since the landing runway at the destination airport is initially often left undefined in the FMS flight plan and specified later, the precise notification logic will require detailed analysis and evaluation.

5.3.5 Data Handling and Operational Concept

Since the envisaged Operational Awareness Function (OAF) is entirely data-driven, the availability of a data handling and operational concept making the required information accessible to aircraft systems is a crucial prerequisite for a sufficiently up-to-date flight-deck based visualisation of aerodrome operational status and configuration (cf. ***High-Level Requirement III***), as discussed in Section 4.3.3. At minimum, it must therefore be ensured (as part of routine flight preparation) that aircraft are always dispatched and operated with data consistent with the conventional PIB, since this is essential for safe and efficient operations. Nevertheless, the handling of potential updates or additions of NOTAM while the aircraft is in flight, which will most likely be transmitted via AOC due to regulatory constraints (cf. Section 4.3.3), has to be considered as well. Consequently, the data handling and operational concept must be sufficiently scalable and extensible to cover in-flight NOTAM updates.

Processes for the integration and transfer of the necessary data to the aircraft are, in turn, dependent on machine-readable formats for NOTAM, D-ATIS and other relevant sources of short-term or temporary information (cf. Section 5.3.4.1). In an increasingly data driven environment, with many airlines gradually transitioning from paper charts to Electronic Flight Bag applications, the role of future machine-readable NOTAM formats in these processes is therefore a key issue.

Furthermore, since the PIB encompasses all phases of flight, the limitations of the current NOTAM system identified in Section 2.3 are applicable beyond the domain of airport surface operations. This has two implications. First of all, it appears that storage and handling of digital PIB data aboard the aircraft should be centralised to prevent that each future onboard system making use of electronic NOTAM data offers a custom-tailored, isolated solution, because this is inefficient and prone to yield inconsistencies. At the same time, the data handling and operational concept must be sufficiently generic to ensure that the needs of onboard systems other than SMAAS can be taken into account. Nevertheless, this section focuses on issues endemic to NOTAM concerning airport surface operations, such as modifications to airport geometry.

5.3.5.1 Modified geometries: overlay vs. integral representation

```
A0443/08 NOTAMN
Q)EDGG/QMPCS/IV/BO/A/000/999/5002N00834E005
A) EDDF B) 0802181457 C) PERM
E) NEW PARKING PSN LOCATED AT TERMINAL 1
NORTH OF TWY E.
C13 PSN 5003N 00834.8E
C14 PSN 5003N 00834.8E
C15 PSN 5003N 00834.9E.
CREATED: 18 Feb 2008 14:59:00
```

Figure 56: Sample NOTAM announcing new parking positions

From a Runway Incursion prevention perspective, the NOTAM information of predominant interest concerns runway status, mainly in terms of closures and restrictions. Indeed, an unparalleled strength of NOTAM is their capability to convey information on the operational status of air traffic system installations, irrespective of whether they are runways or navigation aids. Nevertheless, relevant short-term and temporary changes in the aerodrome environment may also encompass modifications to the airport layout.

While simple additional non-AMDB geometries, e.g. point-like structures such as obstacles or navigation facilities, can easily be transmitted via machine-readable NOTAM, there are significant issues when changes to complex airport geometries such as taxiways are concerned, i.e. if the topology of an airport is modified. Even when disregarding potential certification issues for the moment, NOTAM containing geometrical changes may be hard to merge with existing AMDB information from a technical perspective.

To illustrate these issues, consider the – at first glance simple – case that permanent new parking positions at Frankfurt Airport (EDDF) are announced by NOTAM, as in the real-life example shown in Figure 56. Apparently, labels to identify these new parking positions can easily be placed on the airport moving map, using the coordinates supplied via NOTAM. The fact that positions C13 and C14 apparently coincide is of minor importance, since it is essentially a matter of accuracy and can be resolved with relative ease, unless both positions overlap and their use is mutually exclusive.

There are, however, two key issues. First, the content of the above NOTAM is not sufficient to create an airport moving map representation of the new parking positions, because it does not contain any information on the geometries defining these, such as the extent of the pavements hosting the parking position or the associated markings, such as parking stand guidance lines. Consequently, for a full representation of this change on an airport moving map, considerably more information of geometrical nature, would have to be transmitted. Technically, the definition of a machine-readable NOTAM format capable of conveying geometry information is not an issue – an initial xNOTAM format based on the Aeronautical Information Exchange Model (AIXM) for NOTAM relating to airports has been demonstrated to show-case the extended possibilities of AIXM 5.0 [TUD06].
However, the second and more important issue is that the exemplary NOTAM in Figure 56 does not contain any information about the interrelation of the new parking positions with the existing airport facilities or with each other (e.g. mutually exclusive use, see above). It does not give any indication concerning the fate of airport infrastructure that might previously have existed at these locations. Consequently, it remains unclear whether it has been removed (e.g. in case of buildings) or whether it is just re-used and re-designated (e.g. in case there were already parking positions). Likewise, information on the state of completion is missing. Flight crews have no way of inferring whether these new positions are already fully marked and equipped with the appropriate signage.

These two issues have significant implications regarding the onboard handling and utilization of NOTAM data involving changes to airport geometry. Evidently, it must be ensured that the new information matches existing information in terms of content, accuracy and integrity. Furthermore, just displaying changed geometries as an overlay to the original AMDB might eventually lead to a cluttered or even illegible display in the areas concerned. Additionally, onboard applications other than the airport moving map, e.g. a function displaying an assigned taxi route on the basis of data stored in the AMDB, might rely on connectivity and would thus require merging of the original AMDB data with the NOTAM information.

Consequently, for an operationally meaningful integration of the new information with AMDB data already available aboard the aircraft, the NOTAM would also have to contain instructions on which part of the existing data to remove. In an operational context where airlines may choose between AMDBs from several suppliers, however, this is non-trivial, since the originator of the NOTAM does not necessarily have access to all commercially available AMDBs for a given airport. Furthermore, since the validity dates of NOTAM are apparently not synchronised with the dates of the AIRAC cycle, the onboard system would also have to perform a check whether a change is already included in the AMDB currently available aboard or not.

In conclusion, pursuing the approach of merging temporary or permanent geometry changes and existing AMDB information onboard the aircraft seems somewhat unrealistic in view of the tremendous development effort required to realise a certifiable onboard application capable of the required processing. Apart from this, a corresponding solution is inefficient in view of the fact that the associated merging and validation processes would have to be performed individually aboard each aircraft.
Besides, one may righteously ask whether there might not be a more adequate solution from an operations point of view, because the introduction of new parking positions, taxiways or even buildings and runways is hardly ever a spontaneous overnight activity by the airport authorities, but rather planned carefully several weeks, months or longer in advance. Thus, construction plans detailing the future geometry (including markings) are in principle available with sufficient lead time to permit sharing them with database vendors and airlines well in advance, using e.g. AIP Supplements in AIXM or equivalent other digital formats.

Therefore, rather than submitting geometrical information via machine-readable, digital NOTAM and trying to develop a certifiable onboard processing application capable of merging these changes with existing AMDB information, planned amendments to the airport geometry should better be released sufficiently early to enable AMDB suppliers to provide an updated database to users. This could be achieved e.g. by regulations requiring that changes affecting the airport infrastructure or layout should be announced 72 h in advance and must be notified no later than 36 h before they become effective[97]. These time values are initial estimates which assume that efficient and partially automated update processes at database providers ensure, together with 24/7 operations, that an updated AMDB can be made available within 12 h of change notification, such that airlines would routinely have sufficient time to deploy aircraft even on ultra-long-haul flights with AMDBs containing up-to-date airport geometries.
Generally, these changes could then be automatically activated at the effective dates or, where necessary, by trigger-type digital NOTAM. A potential method of activation might e.g. be an AMDB database swap (as currently implemented for the FMS navigation database)[98]. It must only be ensured that any airport structures predefined as obsolete once the changes become effective are suitably invalidated.

[97] These comparatively short periods have been chosen to have a chance take into account temporary geometry changes as well, e.g. a provisional taxiway if a major taxiway is closed for reconstruction on short notice.

[98] Alternatively, in case of an airport expansion, the corresponding new airport elements could represented as closed prior to activation, i.e. while they are still under construction.

In case no updated AMDB versions containing NOTAM-ed geometry changes are available for some reason, or if the activation process fails, NOTAM with geometrical content not yet integrated in the AMDB could, as a back-up, still be handled as any other non-decodable NOTAM and visualised via the attention-getting symbol[99], as described in Section 5.3.4.3.3.

In conclusion, a conceptual separation of NOTAM and other relevant short-term information into status and geometry changes seems reasonable: a status change reflects the operational condition of an airport element, e.g. whether a runway is open, restricted or closed, whereas a geometry change consists of modifications to existing airport geometries, e.g. a broadened taxiway, or altogether new airport elements such as new runways, taxiways or buildings. Consequently, the machine-readable NOTAM information to be processed directly by the onboard system would routinely be limited to status information. From a human factors perspective, this approach has the additional advantage that it could significantly reduce the number of NOTAM to be considered for inclusion in the briefing material (PIB), since it would eliminate the need to include NOTAM related to geometry changes already effective and included in the AMDB when the flight commences.

5.3.5.2 Concept for an electronic PIB (ePIB)

The data handling and operational concept proposed by this thesis was conceived as an electronic, machine-readable extension of the conventional Pre-Flight Information Bulletin, taking into account the following fundamental considerations and basic requirements:

- The availability of onboard means of visualising short-term and temporary changes does not eliminate the necessity of making this information available to the crew as part of their briefing, as required by ICAO Annex 15 [ICA04].
- There is a clear need for consistency between the PIB and the NOTAM information uploaded to the aircraft's avionics (see above).
- Flight crews should be able to interact with NOTAM and other short-term or temporary information uploaded to the aircraft's avionics to address last-minute changes and exceptions, cf. Section 5.3.4.1.
- The availability of electronic, machine-readable NOTAM information should not depend on a large-scale introduction of the corresponding AIS aeronautical data link services, but be capable of using them. Conversely, any reliance on an airborne data link to obtain basic NOTAM information would require appropriate safe-guarding against data link failure or unavailability.
- There should not be a need to retransmit the complete NOTAM package following modifications or changes to take into account limited data link or data loader bandwidth during in-flight or on-ground updates.

[99] As for any other NOTAM not presentable in an intuitive form, the key issue is the positioning of the attention-getting symbol. By default, the position anchor from the NOTAM Q-line could be used. The accuracy requirements for this position reference would have to be increased to prevent a 'stacking' of attention-getting symbols on the ARP – initially, the augmentation of accuracy could be performed by AOC.

Therefore, from an operational perspective, a transition from the conventional plain-language PIB to a digital, machine-readable electronic PIB (ePIB) is a logic and straightforward step. As detailed in the previous section, onboard handling and processing of ePIB/NOTAM data will leave the original AMDB or any other onboard database untouched by limitation to status and simple geometry information. Consequently, AMDB and NOTAM information will be stored separately and can be combined at application level, which enables different handling policies depending on individual certification and data integrity requirements. As a basic example, if pilots question the integrity or validity of NOTAM data, they can simply switch them off[100].

The main advantage expected of an ePIB solution is that it can be aligned with the existing airline workflow, since the computer tools dispatchers currently use to compile conventional PIBs could be upgraded to produce an ePIB instead, which would then be supplied both to the crew for briefing – in the most simple scenario as a plain-text compilation virtually indiscernible from today's PIB[101] – and simultaneously uploaded to the aircraft avionics prior to flight. This intrinsically ensures consistency between the briefing material and the flight deck displays. Furthermore, the crew must be able to review all NOTAM contained in the electronic PIB in plain text, as this is an ICAO requirement on the PIB in general [ICA04].

Like the conventional PIB, the envisaged ePIB is made up of individual NOTAM messages. Since ICAO Annex 15 requires that each NOTAM shall be transmitted as a single telecommunication message [ICA04], this was translated into a policy that there should be a single, dedicated file for each digital NOTAM, with the file name containing the serial number of the corresponding NOTAM, preceded by the identifier of the originator for unambiguous identification (cf. Figure 57). This is necessary because NOTAM serial numbers are not unique. Rather, each AIS provider starts a new count every January 1st [ICA04]. The use of separate files has the advantage that NOTAM files already available on an aircraft could in principle be re-used for other future flights from the same airport, provided they are still valid and relevant, thus minimizing the volume of the data to be up-linked before each flight. Moreover, it facilitates the removal of outdated NOTAM from both ground and airborne systems, and provides dispatchers with an easy way of excluding irrelevant NOTAM when composing the ePIB, such as NOTAM relating to changes already contained in the most recent AMDB version. Most importantly, however, it allows a separation of the ePIB itself from the individual NOTAM data, in the same way the FMS flight plan is separate from the underlying navigation database – a change does not affect the waypoint data stored in the ARINC 424 database (cf. [ARI02]), either.

While the precise exchange format for NOTAM files remains to be chosen, binary XML seems a likely candidate, because this format is already used for AMDBs encoded in the ARINC 816 standard [ARI06]. In analogy to the Airport Database configuration file in ARINC 816, which lists the individual airport databases available, the ePIB can therefore be envisaged as an index referencing individual NOTAM files.

[100] By contrast, a solution processing complex AMDB geometry data aboard the aircraft would most likely have to drive applications from the merged 'working copy', necessitating a re-load of the original AMDB if the crew opts to discontinue NOTAM use.

[101] This does not preclude the generation of advanced graphical representations on any EFB-type or other electronic charting devices the crew might use during the briefing, but this is beyond the scope of this thesis.

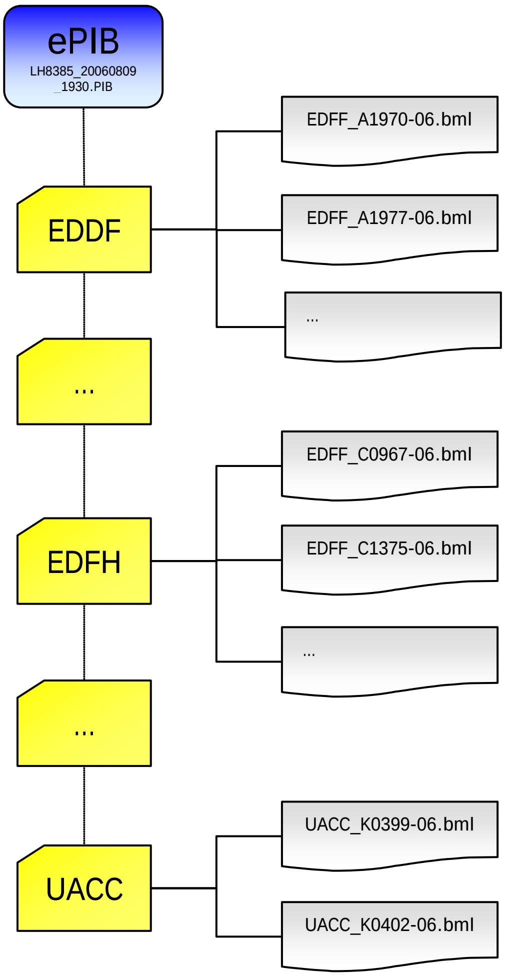

Figure 57: Sample ePIB onboard directory structure

The proposed ePIB directory and file structure is illustrated in Figure 57, which uses an adaptation of the conventional PIB presented in Figure 11 as example. Individual NOTAM files are placed in folders with the ICAO identifier of respective airport or Flight Information Region (FIR) as name, while the ePIB index file (cf. Figure 58) resides in the main directory.

To ensure that the ePIB index file is only usable for the intended flight on a given day, an index file naming convention containing the flight identification, date and creation time could be applied, e.g. `LH8385_20060809_1930.PIB` for Lufthansa flight LH 8385 on August 9, 2006, with the PIB created at 19:30 UTC. This way, the onboard systems can double-check whether the received ePIB file is valid for the current flight or not. For additional safeguarding, it is envisaged that this information is duplicated inside the ePIB index file, see Figure 58.

The separation of ePIB index and individual NOTAM files allows incremental changes and updates of the ePIB with minimal risk of corrupting the data already available on board. In particular, the cancellation of individual NOTAM can be realised in a fully reversible fashion by removing the associated NOTAM file references from the ePIB index only, while leaving the NOTAM file itself in storage. In addition, the need for file deletion operations, which could in the worst case result in file system corruption, e.g. if a bus failure occurs during the process, is eliminated.

Likewise, this approach also ensures the reversibility of any subsequent updates: the required additional or replacement NOTAM files are uploaded to the aircraft, accompanied by an updated ePIB index file substituting the current one. In case obviously corrupted or erroneous new NOTAM or ePIB index files are received, the flight crew may switch back to a previous version of the ePIB at any time.

In conclusion, any changes to the ePIB will also result in a new index file with a different time stamp in both file body and file name. This ensures that only NOTAM and potential AIP supplements contained in the currently applicable ePIB index file are eventually processed by the Operational Awareness Function (OAF) and displayed on the airport moving map. Furthermore, in case slow data links or data loaders are used for uploading and the ePIB upload time thus becomes a factor for turnaround time, aircraft could be supplied with preliminary ePIB indices and all referenced NOTAM files for the scheduled aircraft rotation during routine daily maintenance activities, since the file naming convention outlined above permits the coexistence of ePIB index files for several flights.

From a systems perspective, the ePIB processing system aboard the aircraft should be closely linked to the FMS and the ECAM as the central mission management systems aboard civil aircraft. This would also satisfy the aspect of centralised NOTAM data handling. Furthermore, the FMS provides the time predictions required for the notification service and presentation of NOTAM information not valid for the whole duration of the flight. Besides, the mentioned data link to AOC for the flight plan upload might be extended to handle the ePIB upload as well.

```
<?xml version="1.0" standalone="yes" ?>
<!-- XSD,XMI References here... -->

<ePIB>
<FlightNumber>LH3220</FlightNumber>
<CallSign>DLH47Y</CallSign>
<FlightDate>2006-08-09</FlightDate>
<CreationDate>2006-08-09</CreationDate>
<CreationTime>14:30:00Z</CreationTime>

<Origin>
   <ICAO>EDDF</ICAO>
   <Runway>
         <NOTAM bmlfile="EDFF_A1747-06.bml">A1747/06</NOTAM>
         <NOTAM bmlfile="EDFF_A1767-06.bml">A1767/06</NOTAM>
         <!-- ... -->
   </Runway>
   <MovementArea>
         <NOTAM bmlfile="EDFF_A1769-06.bml">A1769/06</NOTAM>
         <!-- ... -->
   </MovementArea>
</Origin>

<Destination>
   <ICAO>ULLI</ICAO>
   <Runway>
         <NOTAM bmlfile="ULLL_A3828-06.bml">A3828/06</NOTAM>
         <NOTAM bmlfile="ULLL_A3836-06.bml">A3836/06</NOTAM>
         <!-- ... -->
   </Runway>
   <ApproachProcedure>
   </ApproachProcedure>
   <MovementArea>
         <NOTAM bmlfile="ULLL_A3826-06.bml">A3826/06</NOTAM>
         <!-- ... -->
   </MovementArea>
</Destination>

<AlternateAirports>
   <Airport icao="LKPR">
   <Runway>
   </Runway>
   <ApproachProcedure>
   </ApproachProcedure>
   <MovementArea>
         <NOTAM bmlfile="LKAA_A0848-06.bml">A0848/06</NOTAM>
         <NOTAM bmlfile="LKAA_A0855-06.bml">A0855/06</NOTAM>
         <!-- ... -->
   </MovementArea>
   </Airport>

   <Airport icao="EDDT">
   <!-- ... -->
   </Airport>

<!-- ... -->


</AlternateAirports>

<Enroute>
<!-- ... -->
</Enroute>

</ePIB>
```

Figure 58: Sample ePIB index file

5.3.5.3 Core operational concept

As mentioned above, the baseline operational concept encompasses that the ePIB is created at AOC by the responsible dispatcher and subsequently transmitted to the aircraft prior to flight, using either the available data loaders, or data links such as Gate Link/WLAN, ACARS. Alternatively, a suitable interface with EFB or crew laptops could be employed.

This approach has the huge advantage that it is completely embedded in the airline workflow, independent of any advanced AIS functions or formats. In this sense, it can be regarded as an autonomous onboard function, since it could in principle be realised and introduced by an individual manufacturer or airline for a particular subfleet, provided that NOTAM can be made available in (or converted into) a machine-readable format. While it is apparently preferable that the AIS-C already provides NOTAM in machine-readable format, this conversion could also be performed by the airline itself, or the provider of the AMDBs in the beginning. Likewise, such conversion might initially be limited to status changes (i.e. closures, restrictions or renaming) relating to runways. Successively, an extension to taxiways and further AMDB elements could be introduced. Intrinsically, therefore, the ePIB is a perfectly scalable and extensible solution.

A further example of scalability is the correlation of NOTAM containing changes to the airport geometry and available AMDB revisions proposed in Section 5.3.5.1. As a first enhancement of the basic ePIB process, the dispatcher could identify, most likely aided by software tools, NOTAM containing modifications of airport geometry while compiling the electronic PIB. Subsequently, if the currently used AMDB does not yet incorporate these changes, a check on the availability of further AMDB revisions with the corresponding database provider would follow. Alternatively, database providers might submit changed AMDBs to subscribing aircraft operators as soon as they become available. If applicable, the corresponding updated AMDB would be acquired and uploaded to the aircraft as an off-cycle update together with the electronic PIB.

In terms of extensibility, the application of the ePIB concept is by no means limited to the immediate aerodrome environment and the airport moving map. It is sufficiently generic to support e.g. NOTAM on navigational facilities as well. As an example, for an ILS that is not working or in maintenance mode, machine-readable NOTAM could be used by the FMS e.g. to block the entry/tuning of that particular Navaid and related procedures in the aircraft's FMS or any other part of the autoflight system, provided that the flight crew is kept in the loop.

5.3.5.4 In-flight NOTAM updates

At least for domestic or continental flights of short duration (typically less than 2-3 hours), the majority of applicable NOTAM is already available prior to the flight, which, given the typical lead times for the release of a NOTAM following significant short-term changes, virtually eliminates the need for in-flight updates[102].

For initial ePIB implementations, the flight crew would be advised in a conventional fashion (i.e. via R/T or ACARS text messages) in case important NOTAM are amended or cancelled while the aircraft is airborne. To prevent that aircraft systems continue to use this then outdated information, pilots must consequently have a possibility to review and amend the respective data, cf. Section 5.3.4.1. Considerations on a corresponding human-machine interface for flight crew interaction with short-term and temporary information can be found in Section 5.3.6.

However, in line with the considerations in Sections 4.3.3 and 5.3.4.1, the data handling and operational concept must be capable of supporting the transmission of additional or updated machine-readable NOTAM information while in flight, at least as an option. Nevertheless, there are several open research issues concerning in-flight NOTAM updates which need to be addressed, and the number of feasible scenarios is considerably limited by the shared responsibility of dispatchers and flight crews in some countries, which necessitates that all in-flight NOTAM updates are handled via AOC or at least with AOC in the loop in this case, as discussed in Section 4.3.3.

[102] Following a runway excursion of a Continental Airlines Boeing B-737 at Denver International Airport on December 20, 2008 (local date), NOTAM announcing the closure of the affected runway RWY 16R/34L (A6517/08) and RWY 16L/34R (A6518/08) were released at 2:20 and 2:23 UTC on Dec. 21st, 2008, i.e. approximately one hour after the accident. Further NOTAM detailing taxiway closures and restrictions in the vicinity of these runways and the accident site were created four hours later.

One of the central issues is how the completeness, consistency and integrity of in-flight NOTAM updates can be guaranteed without shifting tasks from the dispatcher to the flight crew, which must be avoided at all cost in order not to increase pilot workload. In a scenario where AOC with the dispatcher as single point of contact prepares all in-flight NOTAM updates, a copy of the initial ePIB index file created for the briefing is always available and can simultaneously serve as an inventory of NOTAM already available on board. This facilitates the preparation of subsequent updates, because the latest available ePIB index file can be used to determine which additional NOTAM have to be transferred to the aircraft or whether any NOTAM cancellations are necessary. This helps to ensure that all relevant information is uploaded during an update[103], whereas e.g. the time filtering window concept proposed by the CASCADE OSED [BT05] cannot fulfil this requirement with certainty.
For scenarios where NOTAM updates can be received directly from the ANSP/AIS providers in addition, therefore, the NOTAM configuration of an aircraft must be shared with these prior to any in-flight update. However, it remains to be studied whether the corresponding data should be transmitted directly via the aircraft, e.g. by down-linking the ePIB index file to the corresponding provider, or whether the NOTAM configuration could be distributed prior to flight in the same fashion flight plan data are exchanged to save airborne data link bandwidth[104]. At any rate, for any in-flight NOTAM update, a direct, simultaneous transmission of relevant NOTAM files and an updated ePIB index directly from the ANSP/AIS provider to both aircraft **and** AOC will be required to ensure that the dispatcher remains in the loop where required, and that the latest NOTAM configuration is always used as baseline for subsequent updates. Nevertheless, inconsistencies between AOC and aircraft, which might result if information is correctly transmitted from the ANSP/AIS provider to the aircraft, but not the dispatcher (or vice versa) are a concern. Consequently, in this update scenario, neither the dispatcher nor the flight crew might eventually be aware that the other missed information, which could result in confusion if dispatcher and flight crew subsequently discuss an operational situation and try to conclude on the decisions to be made based on dissimilar information. By contrast, such transmission failures are more likely to be detected if **all** updates are handled exclusively via AOC, because the dispatcher is then aware that updated information has been supplied, and can double-check whether it was correctly received by the crew in subsequent communications.

The second significant problem domain encompasses the required flight crew interaction during the in-flight NOTAM update process and the associated workload. At first glance, this does not seem to be an issue at all, since fully automatic updates in the background could ensure that the latest NOTAM information is always available for the flight crew to review. However, a closer look reveals that this might not be appropriate, since flight crews would then be totally unaware of changes compared to the original briefing material and might be confused at first confrontation with updated, modified information, or miss relevant changes altogether.

103 Even if in-flight updates are not possible or unavailable, the use of the ePIB copy at AOC ensures that only relevant additional or cancellation information is communicated to the flight crew in another way (e.g. R/T).

104 In this case, however, modifications to the NOTAM configuration would have to be transmitted whenever AOC or the AIS/ANSP of another FIR have completed an in-flight NOTAM update.

Likewise, it is highly undesirable that pilots are required to collect updated short-term and temporary information from various ANSP/AIS provider sources, particularly since such updates would most likely occur while ownship is spatially close to the respective FIR. Conversely, if NOTAM updates are initiated by the ANSP/AIS providers, information would have to be sent every time the aircraft enters the respective domain, without warranty that this would remain the only update while in the service area of that particular ANSP/AIS provider.
Since not all of the updates received in either scenario might be operationally relevant for the immediate flight task at hand, the associated risk is that pilots are distracted by handling minor and potentially irrelevant updates, with probably detrimental impact on workload. Besides, it is unlikely that pilots can keep track of all updates received during the flight. Consequently, to ensure that neither critical information is missed nor workload increases, any updates initiated by an ANSP/AIS provider would require a very sophisticated flight crew notification concept, as an extension of the functionality discussed in Section 5.3.4.1. The same applies to occurring automatically in the background.

By contrast, if NOTAM updates are handled exclusively via AOC, the dispatcher could collect new, amended and cancelled NOTAM and send a consolidated update package whenever deemed appropriate or if significant changes occur. Additionally, the flight crew might request NOTAM updates at their discretion, either for the complete route, or for specific areas of interest, such as the destination airport or destination alternates. This might enable them to access relevant information when actually needed, without the constraint of having to be in the vicinity of the respective area of interest. Furthermore, routing NOTAM updates via AOC has the additional advantage that potential bandwidth limitations of typical airborne data links could be circumnavigated by using broadband onboard Internet connections where available. In this case, a fraction of the bandwidth of Internet services for passengers might be reserved for the transfer of operational information via an encrypted connection.
In conclusion, therefore, a centralised handling of in-flight NOTAM updates via AOC appears to be preferable, since the complexity of update scenarios and failure modes is much lower than for scenarios involving ANSP or AIS providers. Of course, this should not preclude the direct, immediate exchange of critical information between aircraft and ANSP or AIS providers when abnormal situations require this.

In principle, the availability of broadband data link connections aboard aircraft could also be used to upload entire AMDBs to aircraft. This seems appropriate for easier maintenance or faster flight preparation. However, in view of the considerations in Section 5.3.5.1, there is no credible operational concept for a corresponding in-flight functionality: neither airports nor airline route networks are spontaneously modified from one day to another without prior notification. Since it is assumed that aircraft will be deployed with AMDBs for the envisaged route network and the most likely alternate airports, the only valid use case for uploading a complete AMDB would be a diversion to an airport previously not considered as alternate airport and therefore not available onboard the aircraft. However, particularly in case of emergencies, the flight crew should not be distracted from the primary tasks in such abnormal operations by requesting AMDB downloads.

5.3.6 Crew Interaction with Short-term and Temporary Information

Even the short-term and temporary information on the aerodrome environment contained in NOTAM or conveyed via ATIS broadcasts may be subject to change or cancellation. Since this can occur on such short notice that a timely update of the respective information via these sources might be precluded due to the lead times typically required (cf. Footnote 102 on p. 198 and Section 3.4.2), it is assumed that flight crews need a means of interacting with NOTAM and other short-term or temporary information, as outlined in Section 5.3.4.1. In particular, the display of incorrect runway closure or restriction information seems unacceptable from a human factors and certification perspective. Therefore, provisions for cancelling individual NOTAM as well as possibilities to review, amend or enter new and updated information, especially concerning runway status, must be evaluated.

On most current-generation transport category aircraft, the Multipurpose Control Display Unit (MCDU, Figure 59), which is chiefly used to operate the Flight Management System (FMS)[105], still constitutes the only cockpit interface enabling complex interaction processes and alphanumeric data entry. It consequently also serves as interface to various other aircraft systems, such as Airline Operations Control (AOC) and ATC communication functions via the Air Traffic Services Unit (ATSU). On the ground, it is additionally used by maintenance personnel to access the aircraft's Central Maintenance System (CMS)[106] [Air05].

Figure 59: Multipurpose Control Display Unit (MCDU) currently used on Airbus A330/A340 [Tha05]

Nevertheless, with its text-based menu structure, the MCDU is quite far from a modern, human-centred ergonomic design, but rather reflects the technical possibilities at the beginning of the 1980s. It has consequently been replaced by a cursor- and keyboard-operated graphical user interface using a standard size cockpit display on the latest Airbus and Boeing aircraft developments.

In spite of this, the MCDU remains a likely candidate for flight crew interaction with short-term and temporary information, since the prime research focus in this context is not on the optimisation of the interface between flight crew and aircraft systems, but rather on validating the need for pilot interaction with NOTAM information in a representative environment. Besides, providing pilots with a way of interaction they

[105] This includes flight plan entry and modifications as well as the handling of aircraft performance data and the underlying ARINC 424 navigation databases.

[106] For simplicity, this section uses the Airbus names of the respective systems, some of which may be customer options not available on each airframe. Other aircraft manufacturers may use a slightly different terminology.

are familiar with will help to eliminate potential confounders resulting from an entirely new flight crew interface, which might unintentionally shift the focus of feedback towards the interaction concept. Therefore, a conventional MCDU-based interaction was selected for this thesis, which also addresses the flight deck integration aspects outlined in Section 4.6.1 appropriately, because the still MCDU-equipped A320 and A330/A340 aircraft families were chosen as reference aircraft.

On these aircraft, the MCDUs for the two flight crew member are located slightly forward and sideways of the thrust levers on the centre pedestal, as shown in Figure 24 on p. 82. A typical MCDU display screen contains 14 lines; the last is referred to as 'scratchpad' and used either to insert and modify data, or to display FMS messages, such as 'A/C POSITION INVALID' in Figure 59. Six Line Select Keys (LSK) each on the right and left side of the display screen, identified as 1L through 6L and 1R to 6R, respectively, can be used to transfer data typed in the scratchpad to data fields adjacent to the LSKs, to access sub-menus indicated by the symbols < and >, or to activate a specific function identified by the prompts *, ← and → [Tha05]. An example of MCDU data entry is given in Appendix III.

Based on the concept for an electronic PIB outlined in the previous section, an 'ePIB Main' menu page accessible from the MCDU root menu was created as central flight crew means of reviewing the ePIB and interacting with its content. To ensure consistency with current applications, all the MCDU page designs presented below were drafted taking into account the guidelines laid down in ref. [Tha05].

The proposed ePIB Main menu (see Figure 60) contains fundamental PIB information, such as applicable flight number, creation date and -time. Below, a typical MCDU menu enables a structured review of ePIB information based on the grouping of NOTAM information in a conventional PIB [DLH06a]. It is envisaged that flight crews can use this menu structure to obtain an overview of the NOTAM available for origin and departure airport, en-route segments or alternate airports and eventually access individual NOTAM, as shown in Figure 61. This would also give pilots the possibility to manually de-activate NOTAM that have been cancelled or to highlight the aerodrome elements concerned by a certain NOTAM on the airport moving map. A more detailed description of the ePIB MCDU pages and the underlying design considerations can be found in Appendix III-1.

Figure 60: ePIB Main Page displayed on the MCDU in the TUD simulator cockpit

Figure 61: ePIB NOTAM review page with highlight & de-activation function

However, it became quickly apparent during design reviews with pilots that it might be too cumbersome and slow to access specific runway-related NOTAM through this ePIB MCDU page structure in case of last-minute changes, because several interaction steps will typically be required. Furthermore, by definition, the ePIB MCDU page concept only allows the de-activation of existing NOTAM, but not the entry of new or additional information on runway status, and does not take into account D-ATIS information, e.g. on active runways, at all.
To address these shortcomings, and to ensure that any runway status update made available on very short notice by means other than data link (e.g. via R/T) can be entered conveniently, the idea of a synoptic Airport Menu presenting a combined NOTAM and ATIS status for all runways available at a specific aerodrome was born.

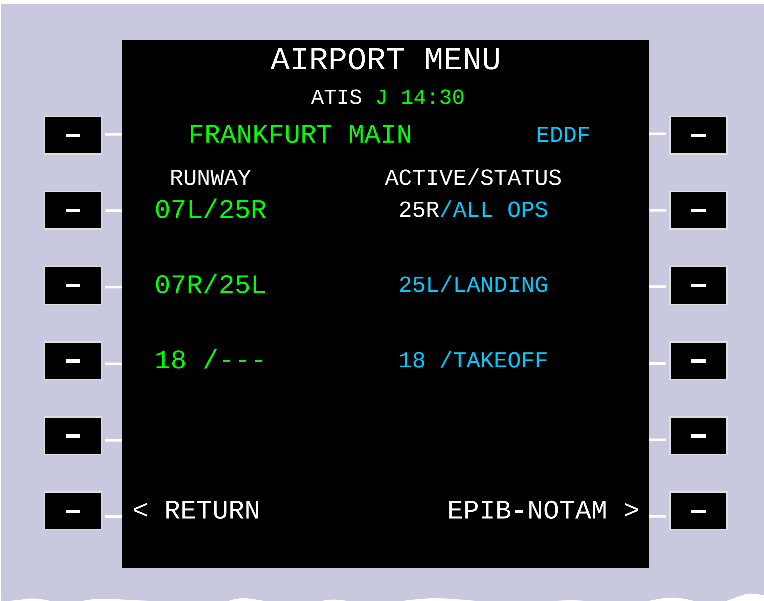

Figure 62: SMAAS Main Page (MCDU)

Figure 62 illustrates the solution evaluated in the frame of this thesis. The Airport Menu presents both official name and ICAO identifier of the currently selected airport. Besides, an ATIS code letter and the associated release time are indicated to emphasise on which ATIS transmission the information presented is based. In contract mode, the system would automatically receive the latest D-ATIS information on the runways in use and closed runways, if applicable.

By default, the Airport Menu will show data for the origin airport specified in the FMS whenever the aircraft is at the origin airport. Once the aircraft has taken off, the data for the FMS destination airport will be displayed. Using LSK 1R, however, the crew can alter the airport for which data should be displayed by typing in the ICAO identifier, e.g. if they want to review, enter or amend information for an alternate or the destination airport at any time during the flight.

The main feature of the MCDU Airport Menu is a list of the runways available at the currently selected airport. For each runway, information on the applicable active runway and general runway status is given. Titles and menu items are presented in white, and fixed data is visualised in green font, while information that may be altered by the pilots and functions that may be activated are displayed in blue. The only exception from this rule is the runway selected in the FMS flight plan (if applicable), which is shown in white, in line with colour coding used on the airport moving map (cf. Section 5.3.2).

Flight crews may change active runway and status information by typing the desired modification in the scratchpad and subsequently inserting it in the corresponding runway field with the appropriate LSK on the right. It is intentional that the alteration of data requires explicit typing and inserting, because this safeguards the system against inadvertent modifications, compared to a solution where flight crews can simply toggle active runway and status information with the LSKs. An issue that remains, of course, is the entry of erroneous information. Nevertheless, this is essentially applicable to all MCDU inputs by the crew. Generally, however, flight crews have adapted to using the MCDU and been able to partially compensate its ergonomic deficiencies, such as the alphabetically ordered keyboard.

Since the MCDU Airport Menu is limited to reviewing and editing runway-related short-term and temporary information, the use of ePIB MCDU pages presented above is envisaged for interaction with NOTAM concerning the remainder of the aerodrome. Whether this is appropriate remains to be evaluated. Likewise, the ePIB MCDU pages, which are essentially a by-product of the ePIB, may have an added value for reviewing or recalling NOTAM in flight, which also needs to be established by future studies. Last but not least, for aircraft with a fully interactive Cockpit Display System (CDS), a modification of runway or taxiway status using direct pilot interaction with the corresponding airport moving map elements will have to be assessed.

For the simulator evaluation campaign described in Chapter 8, some of the proposed MCDU ePIB pages and the Airport Menu were integrated in the NLR Research Flight Management System (RFMS), as described in Section 8.3.2. In fact, Figure 60 shows this NLR realisation. More detailed design considerations and the handling of special cases are described in Appendix III-2.

5.4 Clearance Awareness Function (CAF)

The Clearance Awareness Function (CAF) enables a visualisation of airport-related ATC instructions and clearances, such as the assigned taxi route or take-off and landing clearances, on the flight deck. This is aimed at improving both safety and efficiency of aerodrome operations. As discussed in Section 4.3.4, an onboard solution emerges as the most promising approach to address the corresponding ***High-Level Requirement IV***.

A continuously accessible representation of taxi instructions on the airport moving map, as shown in Figure 63, is intended to enable the flight crew to review an assigned taxi route, to monitor taxi progress and to detect potential deviations intuitively. Presumably, this will also contribute to resolving potential ambiguities and uncertainties resulting from phraseology or language proficiency issues, and might thus help pilots to dispel any doubts about controller intentions.

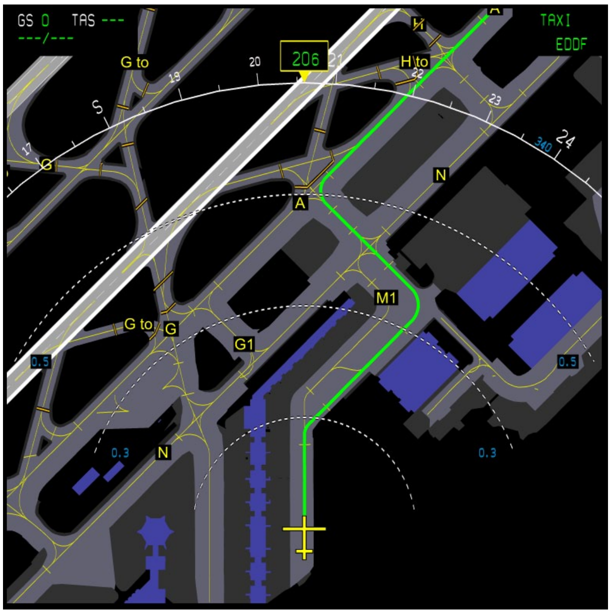

Figure 63: Airport moving map with representation of assigned taxi route

Consequently, a visualisation of the taxi route is expected to reduce the number of inadvertent deviations from ATC instructions, which may ultimately lead to Runway Incursions. This is believed to reduce the risk of Runway Incursions significantly, because it seems hardly possible to take a completely wrong taxiway or to confuse runways without noticing the inevitable discrepancies with the presented taxi route, which can therefore also be regarded as an additional layer of protection against disorientation. Furthermore, since ATC is obliged to provide conflict-free routing to aircraft [ICA01a], a stricter adherence to the assigned taxi route could also lower the risk of collisions with other traffic on the manoeuvring area outside the runways.

Apart from the expected increase in safety, there might be efficiency benefits as well. Particularly on complex airfields and if the crew is not too familiar with the airport environment, missing a turn or taking a wrong taxiway is hardly a rare exception, since there are presumably several occurrences around the world every day. In good visibility, chances are high that such navigation errors are detected, and see-and-avoid procedures can be employed to minimize the risk of colliding with other traffic. Nonetheless, such deviations nearly always lead to re-routing, increased taxi times and subsequently higher fuel burn. The inconveniences and delays that are likely to result in this situation may not be limited to the deviating aircraft itself, and thus cause an obvious reduction of efficiency. It is therefore believed that displaying the taxi route on the airport moving map is crucial for improving and maintaining safety and efficiency of ground operations.

However, Runway Incursions do not always result from a loss of position awareness on the aerodrome or a deviation from an assigned taxi route, but rather from a misinterpretation of an instruction to hold short of a runway, irrespective of whether this results from phraseology problems, call-sign confusion or a wrong mindset. Likewise, having the wrong impression of being cleared for take-off (or landing), or believing to have approval to cross a runway, to backtrack or to line up is hardly a problem of position awareness.
From a safety point of view, it is consequently essential that not only the taxi route, but also ATC instructions and clearances relating to the runway are brought to the attention of the crew in a suitable form, cf. Section 4.3.4. Therefore, displaying these on the airport moving map is believed to be crucial to avoid erroneous runway usage. Moreover, there is always a risk that a crew that has been instructed to line up on a runway gets the false impression that a take-off clearance has been issued as well, and takes off without clearance, as in the Tenerife disaster (cf. Appendix I-1).

5.4.1 Concept & Research Issues

It is assumed for the purposes for this thesis that interaction with ATC instructions and clearances in the aerodrome environment takes place via the existing optional FANS DCDU equipment, as discussed in Section 4.3.4. This has the important implication that the visualisation on the airport moving map will always be accompanied by a textual presentation, which is entirely equivalent to the phraseology presently used in conventional R/T communication, cf. [ICA01a, ICA01d, ICA06], in line with virtually all currently implemented FANS clearances [FAN06]. Figure 64 illustrates this concept for a standard taxi instruction. The fields containing variables (runway and route) are shown in cyan, since the flight crew has not yet acknowledged (cf. Section 3.4). The taxi route instructed in this example corresponds to the route presented in Figure 63.
Furthermore, it is presumed that having the DCDU installed at a prominent location in the cockpit will ensure that the pilots are always able to discern a CPDLC and a non-CPDLC environment.

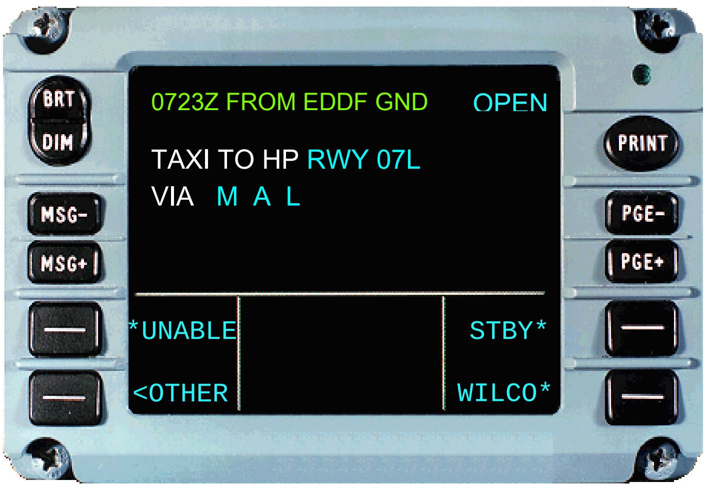

Figure 64: Airbus A320/A330 family DCDU with CPDLC taxi clearance

5.4.1.1 Taxi route and related instructions

There are several technical and conceptual issues regarding the encoding, transmission, processing and visualisation of taxi instructions that have to be assessed carefully. As discussed in Section 4.3.4, one of the key technical issues is how to obtain the taxi route in a suitable machine-readable format for display and, subsequently, the alerting part of the SMAAS. Receiving taxi instructions via CPDLC is apparently preferable, but requires that a corresponding CPDLC service supporting machine-readable taxi instructions is available. Therefore, an associated issue is whether it might be desirable (or required) to have provisions for manual entry as a back-up.

5.4.1.1.1 Manual entry of taxi instructions

There are no fundamental technical hurdles precluding the computation of a taxi route based on a manually entered series of taxiway identifiers and the geometrical information in an AMDB. Besides, many crews already use the scratchpad of the MCDU[107] to write down taxi instructions, which are typically issued as a sequence of taxiway identifiers by the controller. Consequently, a solution using a dedicated MCDU page to enable the flight crew to generate a taxi route for display in this fashion could be envisaged and would probably not create significant additional workload. As a further or alternative option, if standard taxi routes are used at an airport, pilots could retrieve a stored pre-processed standard taxi route in the same fashion SIDs and STARs are currently inserted in the FMS flight plan.

Nonetheless, workload aspects and the risk that the crew enters possibly incorrect data have to be considered versus the expected benefits. The variant of displaying pre-processed standard taxi routes appears to be a viable option for airports not equipped with CPDLC or as back-up in case of CPDLC failure, since the stored data can be validated beforehand by comparison to the published route, and will thus accurately reflect the controller’s intention. An apparent drawback of this approach, however, is its inflexibility: as soon as the dynamics of the situation necessitates a diversion from the standard taxi route, it would either have to be removed from the display to prevent showing potentially misleading information, or adapted manually. Nevertheless, the main risk associated with computing or adapting a route based on manually entered taxiway identifiers is that the resulting route might not exactly correspond to the controller’s intention for some reason, even if the crew enters everything correctly. As an example, verbal taxi instructions are sometimes simplified and may omit the identifiers of minor taxiways along the route, which might nonetheless be important for the system to obtain an unambiguous route. The situation can be complicated further by local rules, such as the usage of taxiway M for widebody aircraft and M1 for single aisle aircraft at Frankfurt Airport (EDDF), which would have to be captured sufficiently in the system.

In conclusion, due to the potentially compelling nature of displaying an assigned taxi route, the risk of potential ambiguities resulting in misleading information was considered unacceptable by the pilots during prototyping, and the approach of manual taxi route entry as a backup was therefore not pursued any further.

[107] All alphanumerical entries made on the MCDU keyboard are initially transferred to the bottom line of the MCDU, the so-called scratchpad. If the flight crew are satisfied with their entry, they can commit it into one of the data fields available on the current MCDU page by pressing the adjacent MFK.

5.4.1.1.2 Taxi route assignments

When flight crews receive taxi instructions in the current R/T environment, they can either acknowledge by reading back the route assignment, or declare themselves unable to comply, cf. Section 2.1.2. As discussed in Sections 3.4 and 4.3.4, this acknowledgment process is also retained in a CPDLC environment.

The main challenge associated with transitioning to CPDLC taxi instructions is accurately capturing the multitude of different route assignment scenarios that exist today. Typically, controllers will clear a flight up to a certain runway holding position or stop bar, either of the take-off runway or any other runway to be crossed on the way to the departure runway. Sometimes, however, additional intermediate holds may be required at taxiway intersections due to other traffic. Consequently, ATC usually does not assign the entire planned taxi route from the gate to the assigned runway (or vice versa) en block in a single step. Rather, most of the larger airports use progressive taxi instructions as described above, because this gives controllers more flexibility to react to changing situations. In fact, amendments to the instructed and acknowledged taxi route can occur any time.
During taxi operations, the aircraft will also frequently have to cross active runways, and occasionally use part of the runway itself to taxi or, less frequently, backtrack. Last but not least, the special case of conditional clearances needs to be addressed. ATC may instruct flight crews to follow a certain taxi route after another aircraft has passed, e.g. "Give way to company A320, then taxi…". Since the visualisation of conditional clearances involving other traffic might be dependent on the availability of traffic data for this particular aircraft (or vehicle), one of the main challenges is an adequate error handling in case this condition is not fulfilled.

It is evident from the above considerations that these different assignment stages and scenarios have to be accurately reflected when visualising taxi instructions. Clearly, displaying taxi instructions only after flight crew acknowledgment does not seem to be a desirable option, since this would deprive pilots of the possibility to review the route assignment in graphical format before acknowledging or rejecting.

First and foremost, therefore, pilots must be able to distinguish whether they have already acknowledged a taxi route presented on the airport moving map or not, also because a visualisation of read-back status is required for reasons of consistency with existing CPDLC implementations, cf. Section 4.3.4.
Besides, whenever an existing taxi route is amended or extended, a removal of the already acknowledged taxi route and a limitation of the display to the modified ATC route proposal does not seem to be appropriate, because a comparison of current and new or updated assignment might be relevant for an intuitive comprehension of changes and decision making. This scenario is illustrated in Figure 65, which makes exemplary use of different colours to allow a distinction of the currently assigned taxi route (green) and the changes and extensions proposed by ATC (cyan). It is immediately evident from the figure that an indiscriminate representation of taxi instructions irrespective of read-back status will almost inevitably create confusion, because the flight crew would have to refer to the textual instruction on the DCDU to distinguish the routes.

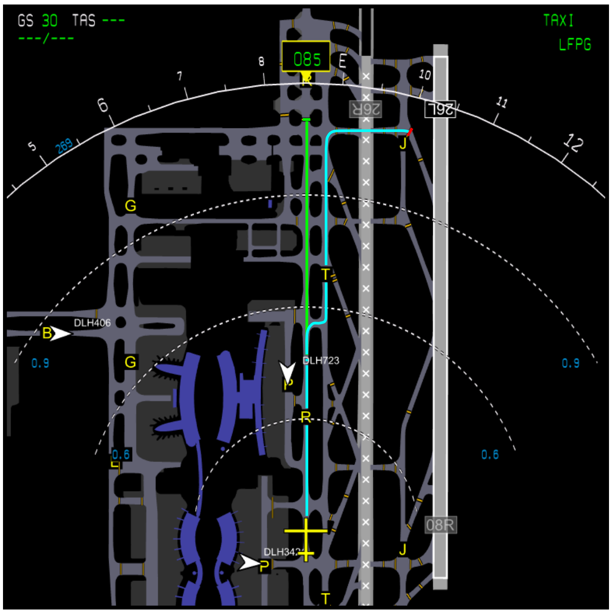

Figure 65: Simultaneous visualisation of current taxi route (green) and assigned, but not yet acknowledged amendment (cyan)

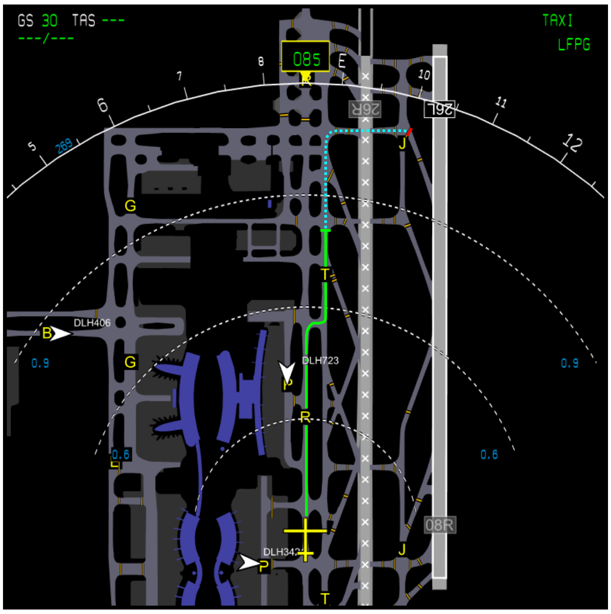

Figure 66: Taxi route with additional intermediate hold at a taxiway intersection, and full route (dashed line) given for information

When progressive taxi instructions are used, the intermediate holding position specified does not necessarily coincide with the end of the assigned taxi route segment, because the controller might sometimes want to provide the flight crew with an overall picture of ATC intentions for better planning. Consequently, to reflect this, there might be a need for different representations to distinguish the part of the route up to the intermediate hold, which is approved for immediate execution, and an assigned segment beyond subject to further ATC instructions or approval, as in Figure 66. However, particularly in complex traffic scenarios, there is an inherent risk that especially those parts of the taxi route that are given 'for information only' in this manner may subsequently change. Therefore, the added value of displaying this part of the route has to be assessed carefully. Likewise, it must be established whether flight crews always correctly understand what their acknowledgement relates to.

Additionally, another distinct representation might be required for conditional clearances as long as the specified condition is not fulfilled yet. For both conditional clearances and parts of the taxi route that are subject to further ATC approval, the underlying assumption is that the representation will change to the default assigned/acknowledged state as described above once the conditions are fulfilled or further approval has been obtained.
Last but not least, it must be studied how the taxiway intersection markings, taxiway holding positions or stop bars acting as clearance limits should be represented in all of the above cases to be sufficiently conspicuous to the flight crew.

5.4.1.1.3 Taxi route encoding

The main technical and conceptual issue related to the machine-readable encoding and transmission of taxi routes is whether the corresponding data should be transmitted as meta information in the form of taxiway identifiers, as a series of points, or

whether a combination of both approaches might be necessary. In either case, route information would have to be supplemented by a clearance limit (i.e. the applicable holding position) and data on conditional clearances, if applicable, which might contain the callsign of other traffic and a type code for the condition.
The obvious disadvantage of a purely geometric solution is that it is highly dependent on the aerodrome database used by ATC in generating the route. Imprecision of either the onboard or the ATC database might therefore lead to a taxi route that may routinely be slightly shifted from the taxiway centreline, and, in a worst case scenario, completely off the taxiway or extend beyond an intended holding position or stop bar. While the first case has merely human factors implications, the latter may eventually lead to the display of wrong or misleading information, with potential implications from a certification point of view.
Another issue concerns the bandwidth of the airborne data link envisaged for CPDLC. Especially for curves, several points or additional geometry information might be required for a sufficiently smooth and precise representation, and thus easily require the transmission of an array containing 20+ latitude and longitude values with high precision, which would potentially have to supplemented by geometry type codes (e.g. line, curve, spline, …).

In contrast to this, meta information for a taxi route will hardly exceed a series of 10 to 15 taxiway identifiers. Furthermore, a corresponding solution could potentially be realised on a smaller timescale, because it features better compatibility with the existing FANS CPDLC technology down-selected for this thesis, which will require taxiway identifiers at any rate to display the textual part of the clearance on the DCDU[108]. Subsequently, meta information would be used for onboard processing of the taxi route to be displayed on the AMM based on the taxiway guidance lines and other relevant features contained in the AMDB. An apparent advantage of this approach - apart from presumably lower data link load - is that the route thus calculated is intrinsically always perfectly aligned with the airport moving map. Nevertheless, this solution might require extensive onboard processing
Clearly, the meta information approach has the larger growth potential, because it enables direct cross-checking of the proposed route for potentially applicable taxiway closures and restrictions that are either directly stored in the AMDB (such as mass or wingspan limitations) or accessible via NOTAM (e.g. closures), and thus a detection of ATC errors. By contrast, with a purely geometric solution, an identification of the corresponding taxiways or taxiway segments will most likely necessitate extensive computations. Besides, this solution is not in accordance with the AMDB design philosophy of combining functional attributes and geometric data.

On the other hand, the risk associated with the meta solution is that ambiguities might occur if several possible routes can be constructed from a sequence of taxiway identifiers. Likewise, the connectivity of taxiway guidance lines in the AMDB is clearly an issue complicating the processing of a taxi route from meta information. A further problem is that the current AMDB standard DO-272A/ED-99A does presently not contain provisions for an unambiguous 'natural' identification of taxiway

[108] From a purely technical perspective, the changes required to the existing ATC controller working position FANS interface are less complex for this approach as well.

holding positions, cf. [RTC05], once a certain degree of complexity has been reached. For illustration, consider the example of the holding positions on taxiway K7 at the intersection with RWY 09R/27L at Paris Charles-de-Gaulle Airport (LFPG). In an AMDB, holding positions are primarily identified by the object identifier 'idlin', which always references the name of the taxiway segment the holding position is located on. For the LFPG example, this will result in four taxiway holding positions with 'idlin' set to K7. Since this is apparently not sufficient for characterisation, the two further attributes associated with the taxiway holding position feature in DO-272A/ED-99A are:

- idp (≡ idrwy) the runway the stop bar refers to
- catstop low visibility category for which the stop bar is applicable

Nevertheless, this still does not permit to fully eliminate the ambiguity, because there is a holding position corresponding to 'idlin.idp.catstop' on each side of the runway. Therefore, an extension of ED-99A might be envisaged to create a unique identifier for each holding position, which could consist of an additional attribute containing its relative location in relation to the runway, and would then indicate by a single character whether the holding position in question is rather north (N), south (S), east (E) or west (W) relative to the runway it refers to. Display and user applications could then access stop bars individually without comparison to geometrical reference positions.

In conclusion, neither approach currently fully satisfies all potential certification or human factors aspects. As a preliminary conclusion, a combination of both approaches, i.e. meta information supplemented by certain check point coordinates (e.g. one per taxiway), could integrate the advantages of both solutions while avoiding the potential pitfalls of each individual one. A more detailed discussion on this matter is beyond the scope of this thesis. In the long run, however, a meta solution seems preferable.

5.4.1.2 Runway-related clearances

While a taxi route ending at a runway holding position or stop bar might be suitable to emphasize a 'hold short of'-instruction and thus contribute to Runway Incursion prevention, the subsequent runway-related ATC instructions and clearances are even more essential from a runway safety point of view. As discussed in Section 4.3.4, they will therefore be addressed by a dedicated CPDLC clearance/approval and acknowledgement process and **not** be implicitly contained in the assigned CPDLC taxi route, which also reflects the organisation of ATC at airports. Only crossing or backtracking closed runways (where possible) and operation on non-active runways (in a U.S. operational environment only) may be handled as part of a taxi route assignment.

It should be noted, though, that this concerns CPDLC data handling and interaction only, and is completely independent of how these instructions and clearances are eventually presented on the airport moving map.

The following cases have to be covered:

- approval to cross a runway
- approval to taxi or back-track on a runway
- approval to line up and wait on a runway
- clearance to take off from a runway
- clearance to land on a runway

For all of the above CPDLC instructions and clearances, there is an additional conditional variant, for example “After landing KLM Fokker 100…” or “You are No. 2 after Lufthansa Airbus…” The availability of traffic and aerodrome mapping data on the display also provides fully new opportunities to visualize these conditional clearances involving other aircraft, which are particularly sensitive to misunderstanding, as the accident in Paris in 2000 (see Appendix I-8) and the Munich incident in 2004 (Appendix I-16) show. In contrast to taxi routes, neither assignment scenarios nor machine-readable encoding constitute any difficulty, and the considerations on read-back status and the availability of traffic data when conditional clearances are used apply accordingly. The key research issue is therefore an appropriate visualisation of these CPDLC instructions and clearances.
For an approval to cross or to back-track a runway, including using part of the runway for taxiing, one of the main decisions to be made is whether to represent these instructions implicitly in the fashion of a taxi route, or whether a dedicated, potentially entirely different explicit visualisation is necessary in this case. The same considerations apply to an approval to line up and wait on a runway as well. Here, the main concern with an implicit representation is that the difference between a situation where the aircraft has to hold short of a runway and a scenario where line-up is approved may not be as evident as desired particularly in the larger airport moving map ranges envisaged to be used for runway traffic surveillance.
Another aspect that needs to be studied is the timing of runway-related ATC instructions and clearances. This involves timeliness and time criticality as well as situations such as being lined up and waiting on a runway for an extended period of time without receiving a take-off clearance. In this situation, an advisory or alert of some kind might be required.

5.4.1.3 CPDLC implementation stages and scenarios

Since the transition scenario from the current R/T to CPDLC in the runway environment remains to be established, cf. Section 4.3.4, it is likely that CPDLC clearances in the airport environment will be introduced in two stages, beginning with CPDLC taxi route service. Therefore, two different scenarios have to be covered:

a) Taxi instructions are provided via CPDLC, but all runway-related clearances are still only transmitted via standard R/T.
b) All clearances are provided using CPDLC.

It is evident that the flight crew needs provisions to distinguish these two scenarios at a glance, because the transition may occur gradually on an airport-by-airport basis.

5.4.1.4 Compensation for the 'party line effect' in a CPDLC environment

One of the unresolved issues with a CPDLC environment is that the crew loses awareness of the ATC instructions and clearances issued to other traffic, which is obtained through the so-called 'party line effect' in a conventional R/T environment. While a detailed study of this aspect is beyond the scope of this thesis, a few general considerations are presented below.

In order to address the problem of the missing party line effect, broadcasting CPDLC clearances to all parties involved could be envisaged. The resulting CPDLC-B service might enable the visualisation of clearances assigned to other traffic, either on pilot request or in case of potentially conflicting clearances. Likewise, information of general interest to all parties, such as the take-off sequence for a given runway, could be shared in this fashion.
CPDLC-B information on what other traffic has been instructed to do might even improve the flight crew's situational awareness compared to the present situation and aid pilots in anticipating potential conflicts, because instructions or clearances to other traffic would be continuously available and accessible in graphical and textual form[109]. On the radio, if the flight crew misses part of the ATC communication with other traffic for some reason, the information is lost. On the system side, access to instructions issued to other traffic via CPDLC-B could help to make traffic alerting more specific and decrease the number of nuisance alerts.
Nevertheless, whether this is suitable to compensate for the party line effect remains to be studied. A possible drawback of the CPDLC-B approach apart from data link bandwidth is that it shifts the perception of further information from the audio channel to the visual channel. While the problem of frequency congestion, particularly at hub airports, should not be underestimated, the potential impact of concentrating information on the visual channel must not be neglected.

Another option could be the parallel use of CPDLC and voice communication for runway-related ATC instructions and clearances. However, this violates the recommendations of ICAO Doc. 4444, according to which either CPDLC or voice communication shall be used, except in case of emergency [ICA01a].
Nonetheless, the use of two different media to convey a runway-related clearance is already reality at many airports today. At airports equipped with stop bars, most airlines and several airports/ATM providers instruct pilots **not** to proceed across a lit stop bar even if line-up or crossing has been approved via R/T. In that sense, additional CPDLC clearances might add a third 'line of defence' to the runway for the case of entry on the ground and a second for take-off and landing, provided that the technology chosen to implement CPDLC can guarantee immediate delivery of these messages. Moreover, to avoid inconsistencies, the stop bar lighting could be coupled to the CPDLC process within the ground system.
At any rate, the concept of dual CPDLC/voice clearances for the runway environment needs further studies at conceptual level and extensive validation. Initial steps in this direction were conducted in the frame of the simulator experiment described in Chapter 8.

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[109] This could help to reduce problems due to language proficiency, as the crew could choose their preferred ICAO or even local language to display clearances.

5.4.2 Visualisation of Taxi Route Assignments

The most common solution to represent a route is a continuous line in a conspicuous colour. This applies to the FMS flight plan as well as to domains outside aviation, such as automotive navigation systems. While earlier studies experimented with a follow-me car like alternating pattern of black and yellow segments [Kub99], there is little dispute that a taxi route that has been assigned by ATC and acknowledged by the crew should be represented by a continuous green line, in analogy to FANS colour coding and the 'follow the greens' logic employed at some A-SMGCS equipped airfields. Another analogy is the representation of the active FMS flight plan also in green on Airbus aircraft.

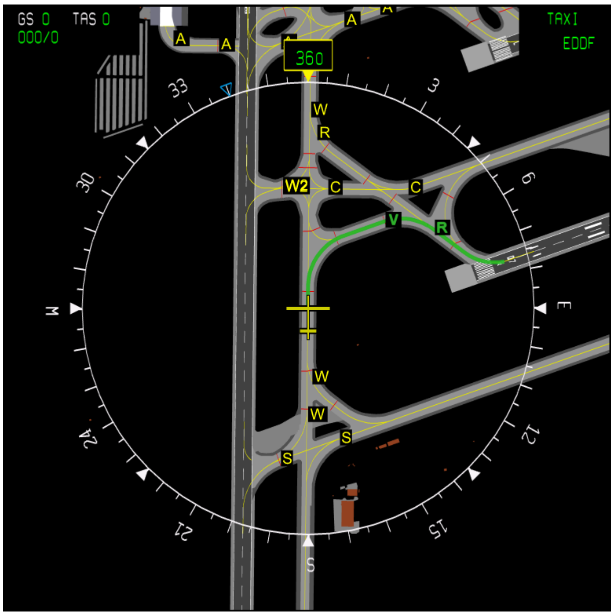

Figure 67: Display of the taxi route with highlighted taxiway labels

As discussed in the previous section, however, the read-back status of the instruction needs to be reflected as well in a CPDLC environment. If ATC assigns a new taxi route, the first step consists of displaying the taxi instructions on the Datalink Control and Display Unit (DCDU) or any other interface used for CPDLC in textual form, as for any other CPDLC clearance. Simultaneously or immediately afterwards, the proposed taxi route is also displayed on the airport moving map. In order not to confuse the crew by presenting an assigned route without the associated read-back or confirmation dialogue, it seems to be important to achieve either a simultaneous presentation of route and textual clearance, or to maintain the sequence above. The route assigned by ATC is presented in cyan, which is in line with the current use of this colour for ATC assignments on the DCDU. When the crew acknowledges the route using the DCDU, the representation is changed to green. To emphasize the representation of the taxi route, the text of taxiway labels along the taxi route could also be changed from the default yellow to cyan or green, respectively, as shown in Figure 67. Due to time constraints, however, the label highlight function was eventually not implemented for simulator evaluation.

Those parts of a taxi route beyond an intermediate hold subject to further ATC approval are always presented as a dashed cyan line. Only the part up to the up to the specified holding position or other applicable limit changes to solid green, based on the consideration that the flight crew's acknowledgement can only refer to the part of the taxi route assigned for immediate execution. Besides, from a human factors perspective, the acknowledgment process is more consistent if the dashed cyan route changes to solid cyan when ATC subsequently assigns the next part of the route for acknowledgment when the aircraft approaches (or is at) the intermediate holding position, compared to a solution where a dashed green route reverts to solid cyan.

For planning purposes, flight crews may also desire to have information on the taxi route to be expected while still at the gate. In line with the discussion above, an expected taxi route could therefore also be visualized by a dashed cyan line.
Route modifications and extensions are handled as follows: When ATC sends a route extension or amendment for acknowledgement, it is always drawn in addition to and on to of the already acknowledged (part of the) taxi route. If the change impacts the part of the route prior to the current clearance limit, the whole route assignment from ownship to the new holding position is drawn in cyan, as illustrated by Figure 65. Otherwise, only the part beyond the current clearance limit is presented in cyan. In either case, any 'for information only' part of the route is replaced if applicable, in an attempt to limit complexity.
An explicit result of the prototyping sessions was that those parts of the assigned taxi route that the aircraft has already traversed should be removed from the airport moving map, since they provide no added value.

5.4.2.1 Visualisation of clearance limits

From the considerations in the previous section, it is evident that the currently applicable holding position or other clearance limit needs to be visualised in conjunction with the taxi route. This is confirmed by design reviews and prototyping sessions with pilots, which revealed that an explicit visualisation of the clearance limit is desired that needs to be more conspicuous than merely an ending route.
Consequently, intermediate holding positions on a taxiway are always represented by highlighting the corresponding taxiway intersection marking in the colour of the route, or an equivalent line perpendicular to the end of the taxi route, cf. Figure 65. Likewise, if a taxi route contains a runway holding position, this holding position is displayed in red to emphasize the hold-short-of instruction (see Figure 68). Apparently, this is only useful in a scenario where at least CPDLC line-up clearances are employed.

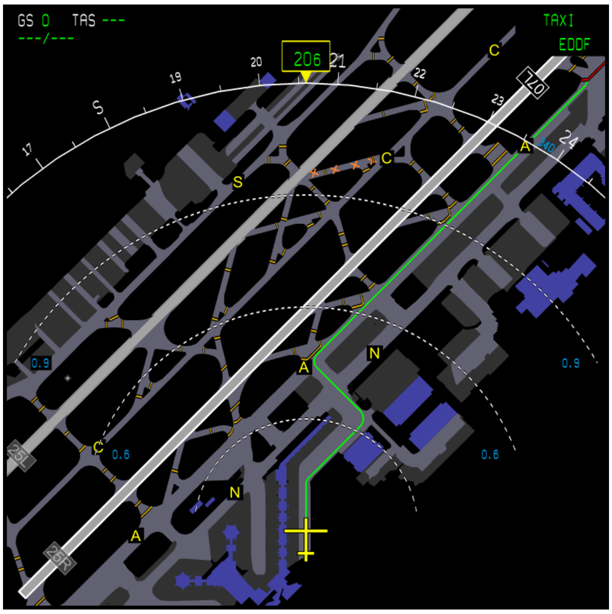

Figure 68: Taxi route with clearance limit (runway holding position)

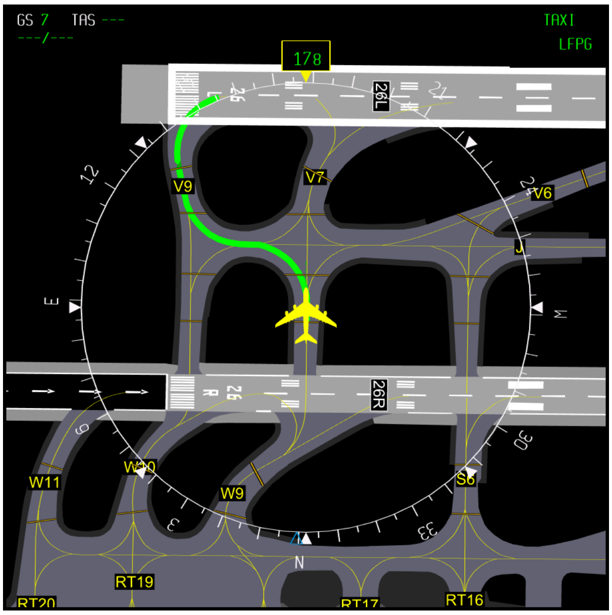

Figure 69: Taxi route with additional approval to line up and wait on RWY 26L

Otherwise, it seems virtually impossible to determine a useful triggering event for the ‘extinction’ of the red stop bar. As an example, switching the red stop bar back to normal a couple of seconds after the aircraft has come to a stop near the holding position might easily give the flight crew the misleading impression that line-up has been approved. Therefore, to emphasize the route-only CPDLC scenario to pilots, the clearance limit is indicated by a filled green circle, positioned slightly in front of the corresponding holding position, in this scenario, which ensures that the flight crew will not have to cross a ‘virtual red stop bar’ on the airport moving map.

5.4.2.2 Conditional clearances

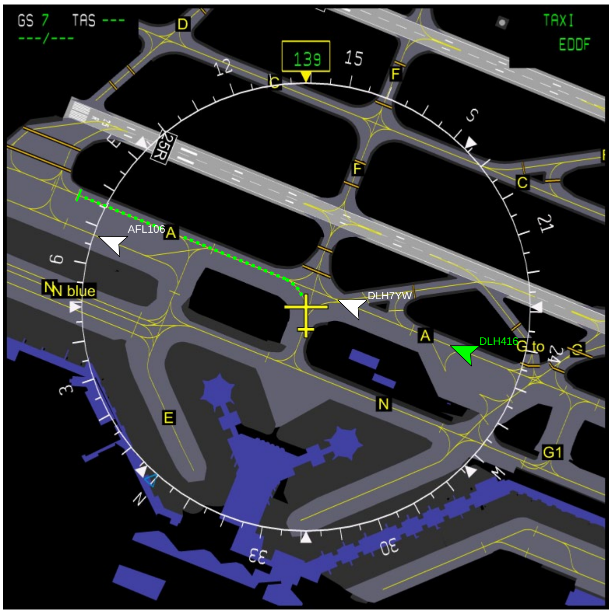

Figure 70: Acknowledged conditional taxi route assignment before condition fulfilment

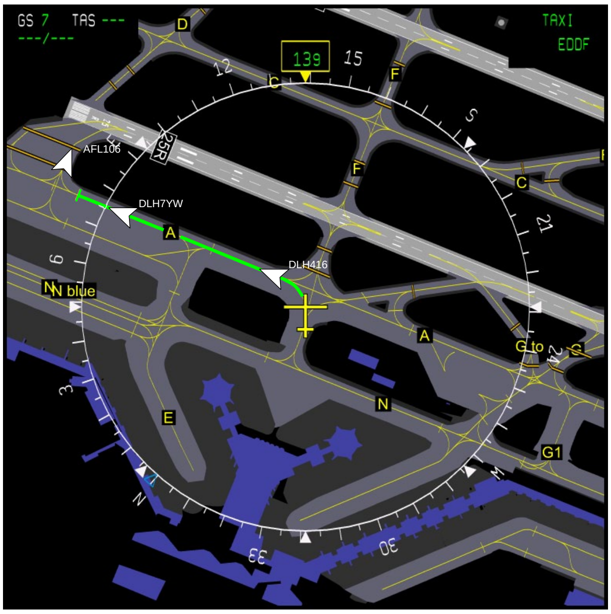

Figure 71: Conditional taxi route assignment after condition has been fulfilled

When a conditional taxi instruction involving other traffic is assigned, the part which is still subject to the constraint that the crew gives way to the other aircraft is represented as a dashed cyan line. Likewise, the aircraft or vehicle constituting the constraint, including its label, is displayed in cyan. When the crew acknowledges the clearance, the colour of both the traffic symbol and the dashed taxi route changes to green, in analogy to the non-active flight plan (see Section 5.4.3.4 below). This situation is illustrated by Figure 70: the flight crew will have to give way to flight DLH 416, which is the second to pass its present position. It is believed that highlighting the constraining aircraft in this fashion will help to prevent confusion as to which traffic the controller is referring to. Once the other aircraft has joined the taxi route (and achieved a certain safety distance from ownship), the taxi route representation changes to solid green, and the symbol of the aircraft ownship had to give way to changes back to the normal white representation, as shown in Figure 71 – once the condition of the route assignment has been fulfilled, there does not seem to be any need to deviate from the standard taxi route representation

Table 8 gives a concluding overview of the different taxi route representations conceived to reflect the various cases for the assigned and the acknowledged stage.

Taxi Route Representations	assigned	acknowledged	Remark
Default taxi route or route segment *for immediate execution*	cyan	green	FANS standard colour coding
Route segment beyond clearance limit *subject to further progressive clearance*	dashed cyan	dashed cyan	
Route segment subject to conditional clearance *condition not fulfilled*	dashed cyan	dashed green	Reverts to solid green as soon as condition is fulfilled

Table 8: Summary of different taxi route representations

5.4.2.3 Taxi instructions to other traffic

In connection with the loss of the party line effect in a CPDLC environment, a compensatory broadcast of taxi instructions to all parties concerned has been proposed (see Section 5.4.1.4). However, it is evident that an indiscriminate visualisation of all taxi instructions issued to the surrounding traffic will result in tremendous display clutter. Consequently, the amount of information to be displayed will have to be restricted to arrive at an operationally meaningful presentation. This section contains some initial considerations as a suggested starting point for further research on this matter. The central idea is that the taxi routes assigned to other aircraft should generally be displayed only on explicit pilot request or in case of conflicts:

- A taxi route assigned to another aircraft should only be displayed if the other crew has acknowledged.
- The crew may only select the representation of the taxi route for one other aircraft at a time.
- An automatic display of taxi instructions to other aircraft may only take place in case a conflicting route has been issued to the other aircraft, or if ownship violates the right of way of another aircraft.
- The routes issued to other aircraft could be represented in the same colour as the other traffic, which will typically be white. Only if the colour of the other aircraft, due to conditional clearances, is cyan or green, its associated clearances should still be displayed in white.

These principles are intended to ensure that the risk of confusing taxi instructions assigned to ownship and to other traffic is minimized, and that the taxi routes for other traffic do not clutter the display.

5.4.3 Design for Runway-related ATC Instructions & Clearances

Irrespective of the conceptual issues and technical challenges with runway-related CPDLC instructions and clearances previously discussed, this thesis conceived an option for their presentation on the airport moving map to assess the associated operational and human factors issues. As for taxi instructions, the visualisation on the airport moving map display is, as for taxi instructions, always accompanied by a corresponding textual message on the DCDU.

5.4.3.1 Take-off and landing clearances

In line with the dark and silent cockpit philosophy [Bil96][110], the fact that there is no take-off or landing clearance presumably does not need to be shown explicitly, because this is apparently the default pertaining to all runways[111]. Consequently, the concept proposed is that only 'positive' clearances should be displayed.
As outlined in Section 5.3.3, the runway outline is already used to reflect the FMS-selected take-off or landing runway. Conceptually, the runway outline is thus already used to emphasize that a runway has been selected for take-off or landing. It is therefore obvious to use the runway outline to reflect the clearance status as well.
Consequently, the same colour concept as for the taxi route is applied. In case a take-off or landing clearance has been issued by ATC, the outline of the FMS-selected runway changes from white to cyan, and then to green when confirmed by the crew. The display of the take-off or landing clearance thus supersedes the FMS-selected runway representation. The rationale for this choice is quite simple. First of all, the clearance information has higher priority, because it authorises runway usage, while the FMS-selected runway just represents a crew selection. Secondly, the change of the FMS-selected runway outline to green is envisaged to give a visual confirmation to the crew that this is indeed the runway used for take-off or landing operations. Along with the runway outline, the threshold label (QFU) of the corresponding runway also turns from white (via cyan) to green, as shown in Figure 72.

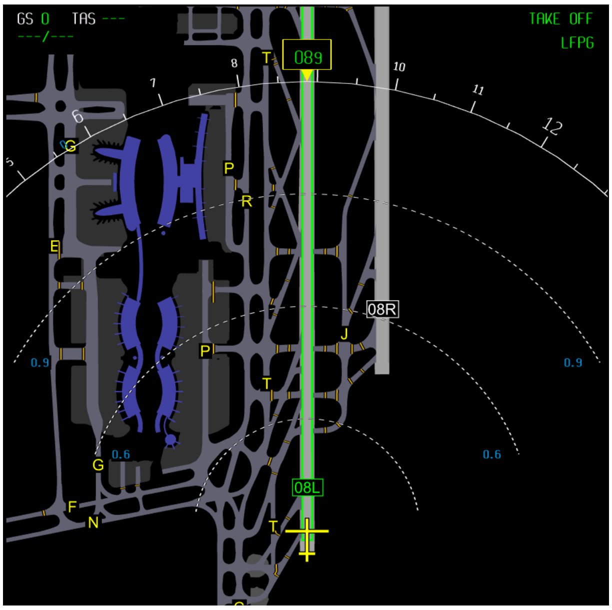

Figure 72: Visualisation of take-off/landing clearance on airport moving map

Of course, take-off and landing clearances are displayed via cyan/green runway outline and threshold labels irrespective of whether the corresponding runway has been selected in the FMS or not. Therefore, this representation is also envisaged to emphasize the special situation if a runway other than the FMS-selected is used for landing (e.g. in case of a sidestep manoeuvre or circling procedure).

[110] Information is only displayed if relevant for the current crew task, no information means everything is normal.

[111] As an example, using red outlines for all runways of an airfield that the flight crew is not cleared to take off or land on might only represent a distraction and not provide added operational value.

Whenever this is not intentional, i.e. for all take-off scenarios and other landing scenarios, the presence of a FMS-selected RWY outline on one runway and a clearance outline on a different runway is therefore intended to advise pilots of potential flight crew or ATC errors.

Two special cases deserve to be mentioned, although they are fairly straightforward. First of all, a LAHSO location as shown in Figure 44 will trivially remain red also in case a landing clearance is assigned. Accordingly, only the part used for the FMS-selected runway outline is changed to cyan or green, respectively. Likewise, the yellow temporary FMS-selected runway outline visualised in case of runway length restrictions (cf. Figure 54) will also change as specified above in case of a take-off or landing clearance.
For conditional clearances, the same HMI design principles as for taxi instructions are employed. The other traffic constituting the constraint is highlighted as described in Section 5.4.2.2. Since the difference between a dashed and a solid runway outline might not be sufficiently conspicuous, however, the cyan or green runway outline is only shown once the condition has been fulfilled.

In the initial implementation of this concept for the field trials with the Institute's Navigation Test Vehicle, there would be a switchover from the runway outline to the full runway area at ranges of 2 NM and beyond, since it was felt that a mere outline would not be sufficiently conspicuous and, consequently, efficient in these ranges. Since pilots had no difficulties with the mere outline even at slightly larger ranges during subsequent prototyping sessions in preparation of the simulator trials, the use of a modified runway surface colour was subsequently restricted exclusively to advisories and alerts, cf. Section 5.5.3 below.

5.4.3.2 Approval for other runway operations (line-up, crossing, backtracking)

The principle of displaying positive information only is also applied to ATC instructions for other runway-related operations. Therefore, in case of CPDLC availability, the absence of information means that approval for runway operations still has to be obtained.
For the case of crossing a runway or backtracking, an implicit representation of the corresponding approval via the taxi route was chosen, as shown in Figure 73, irrespective of the underlying technical implementation. A green taxi route segment extending across a runway therefore signifies approval to cross a runway in a presumably intuitive fashion; there are no other 'natural' transversal runway elements that could

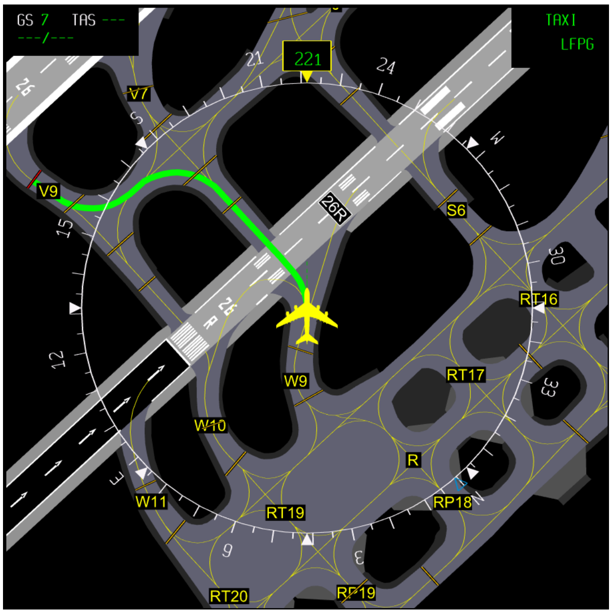

Figure 73: Visualisation of approval to cross a runway on the airport moving map

be employed. Since crossing runways is typically part of taxi operations, this consistency with the taxi route seems to be desirable. The same applies to backtracking or using a runway as taxiway, where approval is also is reflected by displaying corresponding taxi route segments on the runway. Additional symbology was deliberately avoided, because it is believed that this would only make the interpretation of the displayed ATC instructions more complicated.
The only exception from the above rule to display only positive information concerns the presentation of taxi route segments extending across or along a runway in case CPDLC services for runway-related ATC instructions and clearances are not available. In this scenario, the part of the taxi route across the runway between the applicable holding positions is always shown as a dashed amber line in order to remind the flight crew that this part is excluded from the taxi instruction and that approval to cross the runway has to be obtained via R/T.

For the visualisation of a line-up approval, several potential alternatives were considered. Initially, when the use of the chevron concept for an indication of active runway was still considered a viable alternative (cf. Section 5.3.3), using a cyan/green runway outline to represent an approval to line up and wait on a runway was envisaged. Take-off and landing clearance would then have been presented by highlighting the active runway chevrons in cyan/green. However, this solution had to be abandoned, since chevrons were rejected for a representation of the runway-in-use for the reasons given in Section 5.3.3. This eventually led to the solution for take-off and landing clearances described above.
Since a line-up approval may precede the take-off clearance, using a dashed, differently coloured or flashing runway outline was subsequently envisaged, thus representing the line-up approval as a precursor of the take-off clearance. Dashed or flashing outlines were not pursued further to avoid potential confusion with the visualisation of take-off clearances. Likewise, using a yellow runway outline was dropped, because this colour is already employed for runway restrictions associated with the FMS-selected runway, as described in Section 5.3.4.
Apart from defining additional symbology, the only remaining options are a visualisation of the line-up approval by a taxi route extending onto the runway surface, or via the colour of the associated taxiway holding positions/stop bars. Both options can obviously be combined, and this is the solution chosen for this thesis, as shown in Figure 69. A line leading towards the runway centreline is displayed as part of the taxi route, using the existing extension of taxiway centrelines onto the runway as required per ICAO Annex 14 [ICA04b]. Additionally, once an approval to line up on a runway has been acknowledged by the crew via CPDLC, the colour of the taxiway holding position changes from red back to the default representation. Simultaneously, the lead-on route changes from cyan to green. Conditional line-up approvals are visualised in exactly the same fashion as taxi instructions, with the addition that the colour of the holding position only changes when the condition has been fulfilled.
All of these solutions for visualizing approval to cross, backtrack or line up on a runway are deliberately very different from the representation of the take-off clearance, which is intended to ensure that there is no confusion. After all, in RT phraseology, the word 'clearance' is intentionally avoided for all cases except take-off and landing for the very same reasons.

5.4.3.3 Automatic revocation of runway-related CPDLC messages

If the aircraft has to cross the landing runway again while taxiing to the terminal, or if the runway is vacated after a rejected take-off, the flight crew will definitely need a new permission before re-entering the runway for crossing or another take-off attempt, respectively, because the authorisation for using the runway obvisously ceases upon leaving the runway. Consequently, all runway-related ATC instructions and clearances are revoked automatically by SMAAS and no longer visualised if the aircraft vacates the runway. After take-off, the automatic revocation takes place when crossing 400 ft radio altitude during climb. After landing or crossing, this occurs while physically leaving the runway surface on the ground.
Furthermore, this ensures that the runway will be treated like any other runway in the frame of Surface Movement Alerting once the aircraft has vacated it, which ensures that the appropriate alerts are not erroneously suppressed and can be triggered if required.

5.4.3.4 Transition to airborne ND modes and ranges

On the Navigation Display (ND), the FMS flight plan extends from the FMS-selected runway representation or airport symbol to the selected waypoints, or vice versa. Depending on MCDU selections and flight plan status, the various flight plans that can be displayed on the ND are as follows [Air05]:

- active flight plan, followed by the aircraft (green)
- primary flight plan, not active (dashed green)
- missed approach procedure (blue)
- alternate flight plan (dashed blue)
- temporary flight plan (dashed yellow)
- secondary flight plan (dimmed white)

As a consequence, if the FMS flight plan were to be shown in all available ND ranges and modes, including those introduced for the airport moving map, there might be a risk that the representation of the active, primary or alternate flight plan intersects or otherwise visually interferes with the simultaneously presented taxi route, which is also presented in cyan or green. In the worst case, the crew could confuse flight plan and taxi route, and thus get the false impression of being approved, via the taxi route, to proceed up to the runway threshold.

The only viable solution to avoid these issues appears to be displaying, depending on range, either the assigned taxi route or the various FMS flight plans. As it is the lowest range currently used for the ND, 10 NM, seems a suitable point for the switchover. By contrast, the cyan/green outline for a runway for which a take-off or landing clearance has been assigned can be retained for all ND ranges and replace the standard white outline, because it does not lead to any inconsistencies on the display.

5.5 Surface Movement Alerting (SMA)

Since attentional resources are limited, and monitoring the airport moving map display is not the only pilot task during taxi, take-off and landing operations, the SMAAS situational awareness functions intended to aid flight crews in building a more accurate mental model of their environment may easily become inefficient in preventing hazardous situations when the flight crew's cognitive resources are expended on a different task. As an example, weather along the departure route might be of concern to pilots, thus necessitating the use of the weather radar and associated ranges on the ND during taxi out. The same applies in case a recapitulation of the Standard Instrument Departure (SID) or a review of significant terrain features is needed. Besides, mistakes by other traffic in the aerodrome environment or erroneous ATC instructions may rapidly evolve into a hazardous situation that might be difficult to perceive due to its inherent dynamics. Therefore, as outlined in Section 4.4.1, alerting is considered necessary as last resort safety net function.

5.5.1 Concept & Research Issues

The preventive part of Surface Movement Alerting is, as discussed in Section 4.4.2, primarily intended to prevent ownship Runway Incursions by providing alerts to the flight crew whenever they are at risk of causing a Runway Incursion, both on ground or while airborne. Preventive alerts are solely based on ownship position, airport topology information from the AMDB, and the same machine-readable data on the aerodrome operational environment or CPDLC ATC instructions and clearances as used by the OAF and the CAF. By contrast, reactive Surface Movement Alerting utilizes surveillance data of the surrounding traffic and mainly aims at alerting pilots of any pertinent conflicting runway traffic. This will typically encompass Runway Incursions caused by other flight crews, vehicle drivers or air traffic controllers.

Surface Movement Alerting creates a new domain of alerts in the cockpit. Generally, the unambiguous **characterisation of situations necessitating an alert** and the **identification of suitable metrics** to detect these are among the greatest challenges in designing flight deck alerts**.** The aspect of detectability is intimately interwoven with the definition of suitable trigger conditions, which have to ensure that alerts occur in a timely, sufficiently specific and reliable fashion.

Flight deck alerts must be triggered with sufficient margin for the flight crew to take remedial action, assuming an immediate pilot response after a nominal reaction time. Conversely, if alerts are too unspecific or triggered prematurely, there is a high risk that they will be perceived as mere nuisance alerts by the flight crew, who might subsequently lose trust in the system. Indeed, it is a well-established fact in cognitive psychology that a loss of trust in an alerting system is accompanied by a reduction of responsiveness and increased reaction times. Conversely, highly reliable alerting systems induce a faster operator response [BB04]. Beyond the mere performance level, a loss of trust may have further and potentially far more severe consequences. Pilots might eventually entirely ignore a system prone to unspecific or nuisance alerts, with the result that its alerts in situations of actual danger are either missed or a priori treated as nuisance/false alerts by the flight crew, cf. [Bil96, HSL02].

Accordingly, the key research issues concerning Surface Movement Alerting are an analysis of situations requiring an alert, see Section 5.5.3, as well as the subsequent functional definition of preventive Surface Movement Alerting (Section 5.5.5) and its reactive counterpart (Section 5.5.6), including the identification of suitable trigger conditions, which may be common to both, as outlined in Section 5.5.4. However, in accomplishing this, further challenges resulting from the boundary conditions and constraints imposed by airworthiness requirements, commonly accepted industry standards or the integration in an existing cockpit environment, as detailed in Section 5.5.2, need to be addressed.

With respect to airworthiness, there is – apart from the directly applicable regulations – a substantial indirect impact originating from alerting systems that are currently mandatory for transport category aircraft, such as the Airborne Collision Avoidance System (ACAS, cf. Section 3.2.1), the Terrain Awareness and Warning System (TAWS, §121.354), the Windshear (§121.358) or the Take-off Configuration (§25.703) Warning System [EAS06, FAA87, FAA93a, FAA01a, FAR07]. Their presence will necessitate special emphasis on the prioritisation and general interrelation, e.g. in terms of the human-machine interface, of Surface Movement Alerting and the alerts generated by these mandatory systems. Last but not least, all of these aspects have to be taken into account in the design of a suitable human-machine interface for Surface Movement Alerting, which encompasses the visualisation of alerts and the associated callouts (Section 5.5.7).

5.5.2 Flight Deck Alerting System Philosophy & Design

The integration of Surface Movement Alerting in the cockpit has to be in line with the commonly accepted recommendations for flight deck alerting systems [SAE88a]. Accordingly, Surface Movement Alerting will make use of the alert levels defined by the SAE industry standard, as indicated by Table 5 in Section 4.4.1. In particular, this means that an appropriate criticality has to be assigned to all advisories and alerts, and that at least a distinction of caution (Level 2) and warning (Level 3) alerts must be provided. Besides, consistency with the cockpit design and alerting philosophy chosen for the particular aircraft type in question is required, cf. [SAE88].

On current and next generation transport category aircraft, the so-called ‘Dark and Silent Cockpit’ philosophy is applied for all information and alerts. Information is only displayed if relevant for the current task of the crew, and the absence of information or alerts essentially means that the situation is normal [Bil96]. Moreover, in order to avoid distraction of the crew in critical flight phases like take-off and landing, many alerts are inhibited during these phases, cf. [SAE88a]. The alerting philosophy applied to nearly all types of alerts is ‘Alert, Localize, Explain’ [Air05]. A major goal is to keep the overall number of alerts, especially the number of aural alerts, as low as possible [SAE88a]. For aural alerts, there is an inherent danger of interference with voice communication with ATC or procedural communication inside the cockpit. Consequently, the use of voice callouts is limited to Level 2 and Level 3 alerts. Last but not least, in line with the considerations in the previous section, eliminating the risk of nuisance alerts is a further important design goal for flight deck alerting systems, cf. [SAE88a].

Generally, flight deck alerts can be sub-divided in two major categories: alerts addressing the internal (system) state of the aircraft, and alerts linked to the external environment. Examples of alerts concerned with aircraft systems are e.g. the Take-off Configuration Warning, engine fire or brake overheating alerts, which convey information on abnormal or critical system states to the flight crew. So-called onboard surveillance systems such as the Airborne Collision Avoidance System (ACAS) and the Terrain Awareness and Warning System (TAWS) provide, in addition to basic situational awareness functions, alerts on external threats like traffic and terrain.

By nature, SMAAS is an onboard surveillance system like ACAS or TAWS, and should therefore strive for maximum consistency with these alerting systems in terms of behaviour and cockpit integration. Since Surface Movement Alerting addresses an everyday task, taxiing, alerts have to be designed with exceptional care in order to minimize any undesirable interference. This necessitates to limit the overall number of additional cockpit alerts for Surface Movement Alerting to the required minimum, in line with the previous considerations that the main purpose of an onboard system for Runway Incursion avoidance is enhanced situational awareness, and not the creation of additional alerts. Besides, limiting the number of distinct alerts minimizes the training effort, and allows for a more intuitive response to alerts by flight crews [Bil96]. Nevertheless, alerts must be sufficiently specific and tailored to the actual situation to avoid pilot confusion; finding an appropriate balance between these potentially conflicting requirements may prove to be a formidable challenge. In line with the 'Dark and Silent Cockpit' philosophy, there is clearly no need to indicate that a runway is used by other traffic, or that the flight crew is not authorized to enter, since both reflects the nominal condition.

In this context, the importance of providing the flight crew with unambiguous, consistent and sufficiently reliable alerts and an appropriate human-machine interface specifically indicating the cause of the alert condition cannot be overemphasized, particularly in view of the Helios Airways Boeing 737 (5B-DBY) accident near Athens in 2005 [AAI06]. Irrespective of the failure of the flight crew to detect the non-standard configuration of the pressurization system during the cockpit preparation and various checklists[112], their misinterpretation of the Cabin Altitude Warning horn as spurious Take-off Configuration Warning (which uses exactly the same horn/sound on the Boeing 737, albeit continuously) deprived them of taking remedial action[113]. During the accident investigation process, it turned out that a confusion of the Take-off Configuration Warning and the Cabin Altitude Warning on the Boeing 737 was by no means endemic to the Helios Airways accident[114] [AIU03,

[112] After unscheduled maintenance following pressurization problems during the previous flight, ground personnel had left the outflow valves in an open position [AAI06].

[113] The FDR record, in fact, revealed that the crew's initial reaction on the intermittent sounding of the warning horn was to disconnect the autopilot and to retard and subsequently advance the throttle, which suggests that they confused the alert with a Take-off Configuration Warning [AAI06].

[114] In 2003, a Ryanair Boeing 737 (EI-CJE) had performed a climb to FL250 with incorrect pressurisation configuration, but the crew, initially also mistaking the alert for a Take-off Configuration Warning, quickly found the true reason during a thorough scan of the overhead panel and solved the problem [AIU03]. Two years earlier, the crew of a Norwegian Boeing 737-700 (LN-TUD) had made the same mistake and silenced the Cabin Altitude Warning horn with the circuit breaker, realising the true nature of the situation only when the passenger oxygen masks were automatically deployed [HSL02].

HSL02]. Therefore, the official accident investigation report concluded, among others, that the use of the same aural warning for two completely different alert situations (Take-off Configuration and Cabin Altitude Warning) was "*not consistent with good Human Factors principles*" [AAI06]. Besides, the fact that a Norwegian flight crew used a circuit breaker to silence the Cabin Altitude Warning in a very similar incident – which can be regarded as strong evidence that they also mistook the alert for a false or spurious Take-off Configuration Warning, cf. [HSL02] – clearly demonstrates the attitude flight crews will develop towards systems they perceive as generating nuisance alerts.

Consequently, the philosophy pursued by this thesis is that Surface Movement Alerting, and particularly Runway Incursion avoidance alerts, have to be accompanied by an appropriate visualisation and dedicated voice callouts (where justified by the alert level) to avoid such ambiguity and potential flight crew confusion. Preferably, the alert visualisation should employ modifications of or additions to the airport moving map, supplemented by textual information where necessary. A key design goal in this context is to achieve commonality, consistency and recognition between the different alerts. Likewise, while chimes, bells and other unspecific aural alerts clearly have attention-getting capabilities, they eventually make the cockpit noisier without relating any specific information on the situation to the crew [SAE88a]. Therefore, Surface Movement Alerting is envisaged to use exclusively dedicated voice callouts to get pilots' attention and to present unambiguous information on the nature of the alert.

Since particularly Runway Incursion avoidance alerts are highly safety-critical and will have to be relied upon by pilots, a key requirement is that no alert situation must remain undetected, since this may have catastrophic consequences. A further design goal is to limit the number of nuisance and false positive alerts, in accordance with [SAE88a], although this may not always be strictly possible due to a trade-off between not missing an alert situation and limiting the amount of spurious alerts. Nonetheless, in the high-energy regime of take-off it is mandatory that no nuisance alerts occur, based on the considerations in Section 4.2.3. Consequently, the design goal is that no alert situation corresponding to a Level 2 alert or higher remains undetected, and no nuisance Level 2 or higher alerts occur beyond 80 kts, cf. [FAA93].

Last but not least, the new alerts defined for Surface Movement Alerting need to be properly prioritized in relation to existing cockpit alerts, cf. [SAE88a], which requires that the avionics hosting the Surface Movement Alerting function is either directly connected to the aircraft's flight warning system, or that Surface Movement Alerting functionality is part of an onboard Integrated Surveillance System (ISS), cf. [ARI05]. A suggested prioritisation of the alerts generated by Surface Movement Alerting and currently mandatory alerting systems will be presented in Section 5.5.9.

5.5.3 Analysis of Situations Requiring an Alert

This section is dedicated to a precise characterisation of situations with existing, impending or emerging surface movement hazards, mainly Runway Incursions, which will subsequently serve as basis for the definition of specific alerts. An approach frequently taken in determining the conditions requiring a Runway Incursion alert strives to define a set of conflict scenarios that need to be covered. Corresponding 'shopping lists' can be found e.g. in the ICAO Manual on A-SMGS, as discussed in Section 3.5.3. Nevertheless, the inherent danger associated with such a method based on use cases is that it is not exhaustive, as even those employing it have to admit, cf. [ICA04a]. In the worst case, potentially critical situations may thus accidentally be missed.

Consequently, this thesis attempts to pursue a more generic and comprehensive approach towards situations necessitating an alert, based on the extended definition of a Runway Incursion as an "*incorrect presence or manoeuvre of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take off of aircraft*" (cf. Section 1.2). Evidently, any incorrect presence or manoeuvre within the runway protection zone, irrespective of whether it is caused by ownship or other traffic, corresponds to a violation of the procedural safeguards associated with runway operations.
This leads to the fundamental insight that the procedures associated with runway operations, as discussed in Section 2.1.2, must be translated into a set of basic rules and conditions unambiguously characterising hazardous constellations, which enables a rule-based analysis of situations requiring an alert instead of a scenario-based approach. Due to the myriads of local variations in the way operations are handled, which may result in differences even between two airports in the same country, this constitutes a formidable task. However, a common framework is laid down in ICAO Annex 11 [ICA01], the PANS-ATM [ICA01a] and various other ICAO documents, cf. Section 2.1.2, which is taken as a baseline.

The corresponding analysis eventually yields that an incorrect presence or manoeuvre on a runway, and thus a Runway Incursion, can only occur as the result of runway operations

- without proper authorisation by ATC (Section 5.5.3.1);
- on a closed or otherwise unsuitable runway (Section 5.5.3.2); or
- in the presence of conflicting traffic (Section 5.5.3.3).

In this context, the term 'runway operations' encompasses take-off and landing as well as entering, crossing, back-tracking, lining up or holding on a runway. Additionally, the specific incident and accidents analysed in Section 2.2.2 and the subsequently derived ***High-Level Requirements*** (Section 2.3.8) suggest that any actual or attempted take-off and landing operations on a taxiway or other paved surface outside the runways have to be addressed by an alert as well (Section 5.5.3.4). Besides, an advisory when deviating from the assigned taxi route seems appropriate to attract pilots' attention (Section 5.5.3.5). A detailed discussion is provided in the following sections.

5.5.3.1 Runway operations without proper authorisation by ATC

Runway operations without proper authorisation can either be the result of disorientation, as evidenced e.g. by the 1983 Madrid, the 1990 Detroit or the 2006 Lexington accidents (see Section 2.3.1 for details), or a lack of situational awareness with respect to ATC instructions and clearances. The latter encompasses e.g. an erroneous interpretation or oblivion concerning an instruction to hold short of a runway, or misunderstanding regarding a take-off clearance, cf. Section 2.3.4, with the 1977 Tenerife disaster as most prominent example. Irrespective of the cause, two generic cases have to be distinguished:

- **Infringement of the runway protection zone during surface movement:** Alerts have to be provided whenever pilots are at risk of violating or actually crossing the currently applicable taxiway holding position or stop bar in the absence of

  a) ATC approval to cross, line up on or back-track the corresponding runway;

  b) a clearance to take off on that particular runway.

  For airports with non-parallel runways, infringement of the runway protection zone from an intersecting runway (including a violation of a LAHSO location if applicable) has to be covered by an alert as well.

- **Take-off or landing without clearance:** An alert is required whenever a flight crew initiates take-off on a runway without a corresponding clearance. The same applies if pilots attempt to land on a runway without being cleared to. An issue that has to be addressed in the light of potential nuisance alerts in the latter case, however, is the potential late arrival of a landing clearance, which may frequently be the case during final approach at hub airports with high traffic density.

To address the highly dynamic situation in the runway environment, any CPDLC assignment relating to runway operations not yet acknowledged by the flight crew, cf. Section 3.4.1, has to be considered as sufficient authorisation for the purposes of alerting. On the ground, this is intended to avoid spurious alerts if the flight crew member at the controls of the aircraft commences executing the instructed manoeuvre while the other is simultaneously sending the acknowledgement. Likewise, during final approach, this can be used as a measure to ensure that the late arrival of a landing clearance does not result in an unnecessary alert. Furthermore, to address situations in which a flight is already cleared for take-off while still outside the respective runway, cf. Section 2.1.2, a corresponding CPDLC clearance – which implies exclusive runway usage – must be considered as implicitly including approval to line up, since a dedicated CPDLC message to that extent might be omitted in this case.

Apparently, the above alerts can only be generated if runway-related ATC instructions and clearances are provided in a machine-readable format by a corresponding CPDLC service, since the possibility of having pilots enter the required information has been excluded due to the risks associated with potential errors, as discussed in Section 4.3.4. If CPDLC services are unavailable, fail or merely support the provision of taxi instructions via data link, it is consequently impossible to infer whether the flight crew is authorised to use a runway or not.

At first glance, this appears to preclude the generation of specific, operationally meaningful alerts in this situation. As an example, a general caution alert upon entering the runway protection zone is highly undesirable, since it would routinely be triggered even in perfectly normal conditions when appropriate authorisation to operate on the runway has been obtained via R/T. This would constitute a violation of the 'dark and silent' cockpit philosophy and is prone to induce flight crew complacency towards the alert, as discussed in Section 5.5.2.

Nevertheless, it will be shown in the following sections how information on the operational environment, the selections made in the Flight Management System and traffic surveillance data can be utilized to detect potentially hazardous procedural inconsistencies irrespective of the availability of CPDLC.

5.5.3.2 Runway operations on a closed or otherwise unsuitable runway

Based on the assumption that it should not be possible to obtain ATC authorisation for operations on a closed or otherwise unsuitable runway in the first place, one might argue that this case does not need to be treated separately. Nevertheless, relying exclusively on ATC instructions and clearances to address this situation would necessitate that controllers always work flawlessly. However, there is a wealth of evidence that this is not the case, see Section 2.3.5. In particular, the Denver incident in 2001 (cf. Appendix I-10) demonstrates that ATC may even erroneously clear an aircraft for take-off on a closed runway.

In view of these facts and given that CPDLC services encompassing runway-related clearances might not be available at all or fail, protection against Runway Incursions must not depend solely on ATC instructions. Instead, taking into account the 2000 Taipei accident and the 2001 Denver incident, cf. Section 2.3.3, runway closure and restriction information, as discussed in Section 5.3.4, has to be used as basis for alerting in the following situations:

- **Infringement of a completely closed runway or runway segment:** An alert is necessary whenever the flight crew is at risk of entering or actually intruding into a completely closed runway or corresponding runway segment, irrespective of whether the aircraft is approaching from the taxiway system or another runway segment. By contrast, there is no need for an alert when ownship is taxing on a closed runway or a part of the runway that is still usable as taxiway.

- **Attempted take-off or landing on a closed runway:** Pilots have to be alerted if they attempt to take off or land on a runway that is closed, irrespective of whether the runway in question may partially still be used for taxiing or not.

Particularly in view of the 2006 Lexington accident, it is unquestionable that alerts are also required when pilots attempt to use an unsuitable runway for take-off and landing, irrespective of whether short-term and temporary changes, such as length restrictions, render the runway in question unusable for ownship, or whether an a priori inappropriate runway has erroneously been chosen.

The key issue in this context is how the operational suitability of a runway can be determined. It quickly emerges that inconsistencies between the runway chosen by the flight crew and active runway information available via D-ATIS, as described in Section 5.3.3, do no justify an alert, because they neither yield any clues concerning runway suitability, nor do they conclusively hint at a procedural error, because the flight crew may always request (and be granted) using a different runway, as discussed in Section 2.1.1. Consequently, pilots can have a perfectly valid operational reason for using a runway not listed as active or as available for the desired operation (departure/arrival) in the current D-ATIS broadcast.
Therefore, especially when D-ATIS information is updated automatically as envisaged, this would only lead to nuisance alerts when a change of active runway is already announced via ATIS while ownship is, with ATC approval, still on final approach to the previous active runway. Besides, for the approach and landing case, the possibility that an aircraft is accidentally routed to the 'wrong' runway threshold or entirely unsuitable runway seems very remote due to the use of STARs.

In the absence of closed runway segments, the crucial criterion determining the suitability of runway for an intended take-off operation is the available accelerate-stop-distance, although requirements concerning width, pavement strength and runway lighting should not be neglected. At any rate, all of these aspects are taken into account when choosing a take-off runway during flight preparation, which eventually culminates in the entry of the selected runway and the take-off speeds resulting from performance calculations in the FMS. Assuming that unsuitable runways are thus already identified and excluded at this preparatory stage leads to the insight that the best and most simple available protection against take-off from an unsuitable runway might be alerting pilots whenever take-off is commenced on any runway other than the one selected as departure RWY in the FMS. As discussed in Section 5.3.2, this evidently constitutes a substantial violation of standard operating procedures, because it implies at the very least taking off with invalid take-off performance data, e.g. if the flight crew forgets to update data in an otherwise correctly executed last-minute runway change. In all other cases, this additionally means that take-off is initiated on the wrong and thus potentially unsuitable runway. Simultaneously, there is a significant probability that take-off is therefore not authorised by ATC, either, as the accidents involving runway confusion at Taipei and Lexington clearly show.
Conversely, for all landing scenarios, unsuitable runways cannot be identified as unambiguously based on FMS selections. Valid operational scenarios involving landing on a different runway – and thus situations in which an alert is undesirable – are last-minute runway changes precluding an entry of updated data in the FMS due to time or procedural constraints, or a sidestep manoeuvre, in which the pilot uses the Navaids of the FMS-selected runway for the initial approach before side-stepping to a parallel landing runway. Unless a revised FMS interface permits flight crews to specify that they intend to perform a sidestep, positively identifying this manoeuvre or a last minute runway change is therefore only possible in a CPDLC environment, in which this constellation would be characterised by a landing clearance for a runway other than the FMS-selected arrival runway. Consequently, a warning is only justified if the aircraft is neither approaching the FMS-selected runway **nor** cleared to land on this particular runway, which indicates something may be wrong.

5.5.3.3 Runway operations in the presence of conflicting traffic

The need to alert pilots whenever there is conflicting traffic in the runway environment to avert imminent collision hazards has already been established, cf. ***High-Level Requirement II***. In line with the considerations in Sections 4.2.2 and 4.4.2, this is mainly required to provide protection against Runway Incursions caused by other traffic and controller errors (***High-Level Requirement V***), both of which may manifest themselves in the form of traffic conflicts. Consequently, reactive Surface Movement Alerting must be completely independent of the availability of CPDLC.

The particular challenge concerning reactive Runway Incursion alerting is that all potentially hazardous traffic constellations must be covered adequately while simultaneously minimizing the risk of nuisance alerts, particularly in high density operations. Besides, if potential traffic conflicts are not detected sufficiently early, especially during take-off, it may not be possible to avoid an accident any more, as discussed in Section 4.2.3.

To identify situations involving conflicting runway traffic, the novel approach pursued by this thesis is to characterise the anomalies in the traffic pattern in the vicinity of the runway which unambiguously indicate a violation of the procedural safeguards associated with runway operations. A corresponding analysis of the 'Procedures for Aerodrome Control Service' as discussed in Section 2.1.2 yields that this characterisation can be achieved by a classification of runway-related manoeuvres according to whether they require exclusive runway usage or not, because the corresponding ATC instructions and clearances are assigned based on the compatibility of the intended runway manoeuvres.

The procedural safeguards for runway operations can therefore be translated into rules for exclusive and non-exclusive runway usage. This permits using traffic surveillance data to draw conclusions on whether it is safe for ownship to perform the currently intended runway manoeuvre or not. An identification of manoeuvres incompatible with the one ownship intends to perform can thus be used to directly identify situations necessitating an alert. Table 9 summarizes this approach.

Ownship ...	*Crossing RWY*	*Lining Up*	*Taking Off*	*Approach*	*Landing*
Runway Usage	non-exclusive	non-exclusive	**exclusive**	non-exclusive	**exclusive**
Other Traffic ...	➢ may cross as well ➢ may line up ➢ may back-track or stop ➢ ***must not*** take off or land	➢ may still cross ➢ may line up ➢ should not backtrack or stop on the runway ➢ ***must not*** take off or land	➢ ***must not*** cross ➢ ***must not*** line up ➢ ***must not*** backtrack or stop on the runway ***must not*** take off or land	➢ may still cross ➢ *should not* line up ➢ *should not* backtrack or stop on the runway ➢ *should not* take off or land	➢ ***must not*** cross ➢ ***must not*** line up ➢ ***must not*** back-track or stop on the run-way ***must not*** take off or land

Table 9: Classification of ownship runway manoeuvres according to exclusive/non-exclusive runway usage

As an example, if the flight crew is instructed to hold short of a runway, this implies that this particular runway is required for exclusive usage by (an)other aircraft. Likewise, a take-off clearance issued to ownship means that all other aircraft must be instructed to hold short of that particular runway, or remain behind the aircraft lined up for departure. Conversely, if ownship is lining up or crossing a runway, this does not require exclusive runway usage. In this case, ATC may still allow other aircraft to cross the runway simultaneously. In all of these cases, the surrounding traffic has to be surveyed for potential manoeuvres by other traffic incompatible with non-exclusive runway usage. An alert is therefore only required if another aircraft is taking off, on final approach below a certain altitude threshold or landing.

Evidently, exclusive runway usage in Table 9 always relates to the part of the runway ahead of the corresponding aircraft. In this way, only manoeuvres that can at least in principle result in an intersection of trajectories are considered. This ensures that there will be no nuisance alerts if another aircraft crosses the runway or commences line-up behind ownship during a manoeuvre requiring exclusive runway usage. In fact, at airports with high traffic density, aircraft sometimes line up simultaneously from adjacent taxiways to expedite traffic flow.
For configurations with intersecting runways, these principles can be generalised; with ownship taking off or landing, corresponding operations on intersecting runways are not permissible. For LAHSO operations, the respective limit is considered like a normal holding position; an impending or actual infringement is the criterion for an alert if traffic is taking off or landing on the intersecting runway.

Generally, when approaching the runway protection zone, an alert is necessary once an aircraft taking off or landing on the runway is detected, provided that the closure rate is positive. These reactive alerts therefore safeguard the flight crew against errors by other pilots or the controller, since they provide, based on traffic surveillance data, an indication when it is not safe to enter the runway, irrespective of whether clearance data are available. This ensures that runway safety is maintained even if no runway-related ATC instructions and clearances are available. Nevertheless, runway-related CPDLC services may help to make alerting more specific if available.

5.5.3.4 Take-off or landing on a taxiway or other surface outside the runways

In the past, there have been numerous attempts where aircraft attempted to take off from a taxiway. Fortunately, this was either realised early enough or accomplished successfully, as in the case of the China Airlines aircraft taking off from TWY K in Anchorage (cf. Section 2.2.2 and Appendix I-13). However, one should not be deceived by the lucky outcome of these incidents – this scenario is rather an accident waiting to happen. The same applies to the cases where aircraft erroneously but successfully landed on a taxiway.

Although the probability and frequency of occurrence are, based on Section 2.2.2, much lower than for a Runway Incursion, taking off from or landing on a taxiway has a much higher potential for fatalities, since the aircraft attempting to take off or land might – in the worst case – collide with multiple other aircraft, which is extremely improbable for a runway scenario. Consider, for example, long straight taxiways, like A and N at Frankfurt Airport (EDDF), on which aircraft are frequently queuing for line-up. A large widebody aircraft unsuccessfully attempting to take off or land on a corresponding taxiway and hitting such a queue with speeds in excess of 100 kts might easily destroy several other aircraft, with catastrophic consequences.

In conclusion, to mitigate this hazard, any attempt to take off or land outside a runway necessitates the immediate awareness and remedial action of the flight crew. Therefore, an alert is required as soon as the intention of the crew to commence take-off or to land outside the confines of the runway(s) available at a certain airport be detected unambiguously.

By contrast, a simple 'overspeed' warning is neither desirable nor suitable to detect an attempted take-off from a taxiway. First of all, there is no general speed limit for taxiways, although an 'unwritten law' and common sense usually mandate not to exceed a speed of 30 kts on taxiways. Nevertheless, as discussions with Airbus flight test pilots yielded, taxiing at as much as 40 kts does not significantly endanger aircraft, passengers and crew on a long, straight taxiway in dry and good visibility conditions. By contrast, even 10 kts may be extremely critical when turning on an icy taxiway with a very small radius. Consequently, the real challenge in taxiing is to adapt the speed to the surface state (dry/wet/icy) and the curvature of the taxiway.

5.5.3.5 Deviation from the assigned taxi route

Outside and in safe distance from the applicable runway protection zone, a deviation from the assigned taxi route is not immediately safety-critical. Nevertheless, such surface navigation errors may indicate pilot distraction, inattention or disorientation. If the flight crew deviates substantially from the assigned taxi route, this might subsequently lead to hazardous situations, such as the infringement of a runway protection zone, or a collision with other traffic. Although these situations will eventually be covered by the other alert conditions outlined in the previous subsections, it seems highly desirable to trap potential errors in surface movement as early as possible. It is therefore deemed necessary direct the flight crew's attention to the fact that there is a deviation from the assigned taxi route. A low-level alert (advisory) should be sufficient in this case.

At any rate, the situation becomes critical only in case the crew attempts to take off from a runway that they are only approved to use for taxi operations. This condition requires a safety-net type of alert, because there might be other traffic crossing or lining up on the runway. However, this scenario is already implicitly addressed by the alerts for take-off without authorisation and departure from the wrong runway, which once more demonstrates the benefits of the rule-based approach.

5.5.4 Common Functions and Alert Trigger Conditions

The analysis of situations necessitating an alert in the previous section reveals that two key criteria, an infringement of the runway protection zone and the (erroneous) initiation of take-off, repeatedly appear in the characterisation of hazardous surface movement constellations. Accordingly, Surface Movement Alerting must be capable of determining probable or actual intrusions into the runway protection zone, irrespective of whether they occur via the airport surface or from the air. Furthermore, the intention of flight crews to take off needs to be established unambiguously. Not surprisingly, these criteria correspond to the identification of an "*incorrect presence*" or an "*incorrect manoeuvre*", thus reflecting the definition of a Runway Incursion. Evidently, they have to be applied to ownship as well as to the surrounding traffic. Although the precise methods of detecting these situations may differ for ownship and traffic, two common core functions can be defined employing this abstraction:

- Runway Infringement Detection (Section 5.5.4.1)
- Take-Off Intent Detection (Section 5.5.4.2)

These functions yield global trigger conditions for several alerts, consequently forming the functional basis of both preventive and reactive Surface Movement Alerting.

5.5.4.1 Runway Infringement Detection

The detection of actual or impending ownship runway infringements is based on a continuous comparison of the aircraft state vector (and its extrapolation) to the airport topology stored in an ED-99/ED-99A compliant AMDB. Likewise, potentially conflicting traffic is also identified based on its position in relation to the runway protection zone thus extracted from the AMDB. As fallback solution in case of AMDB failure or unavailability, e.g. for a diversion airport, runway information can be retrieved from either the Navigation System (ARINC 424) or TAWS database instead.

5.5.4.1.1 Landside infringement of the runway protection zone

The applicable runway protection zone is dependent on the type of runway and the type of operation. For a meaningful assessment of the Runway Incursion risk, therefore, the system has to be capable of determining whether Low Visibility Procedures (LVP), cf. Section 2.1.2, are in force, because infringing the ILS critical area poses a hazard to approaching aircraft when automatic landings are performed. It is assumed for the purposes of this thesis that the applicability of LVP can automatically be inferred based on the RVR contained in D-ATIS transmissions[115], but that the result may subsequently be overruled by manual LVP mode (de-)selection[116]. In the absence of RVR information, the non-LVP scenario is used as default.
In principle, standardized rectangular runway protection zones according to the definitions in ICAO Annex 14 [ICA04b], as detailed in Appendix II-2, could be used.

[115] Since there is no LVP operations flag in D-ATIS, the LVP mode will be activated by default whenever the reported RVR for the FMS-selected departure runway, or else the lowest reported RVR, is below 550 m.

[116] This could be achieved as part of a SMAAS MCDU/MFD menu, or a pushbutton on a potential SMAAS hardware control panel.

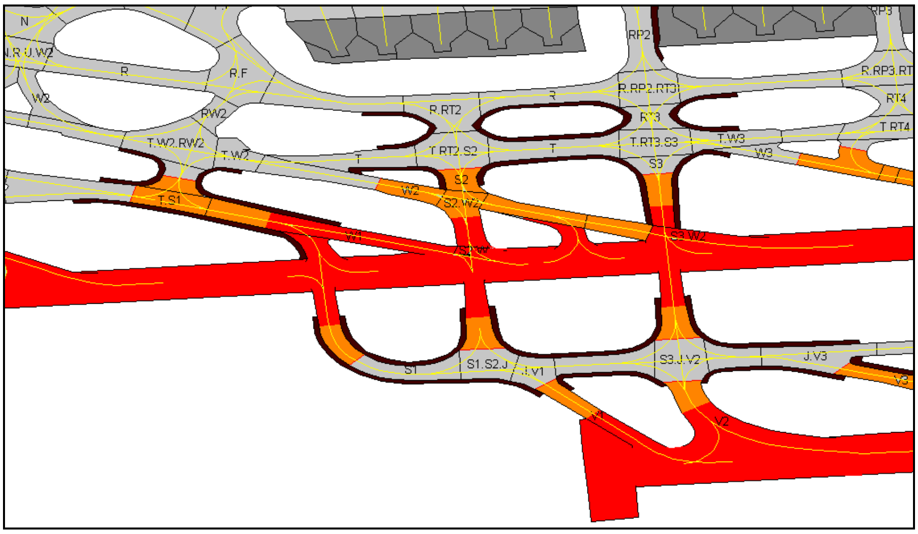

Figure 74: AMDB with highlighted runway protection zones for LVP (amber + red) and non-LVP operations (red) for RWY 08L/26R and RWY 08R/26L at Paris Charles-de-Gaulle airport

However, this bears the risk of perceivable inconsistencies in alerting whenever the actual holding positions or stop bars are not according to this standard, which gives minimum values only and specifies various corrective factors, e.g. for airfield elevation or altitude differences between holding position and runway threshold. Further discrepancies may result from the need to take into account curved taxiway geometries. Alerts might then be perceived as occurring either too early or too late, depending on whether the painted holding position is closer or farther away from the runway centreline.

Consequently, for the purpose of Surface Movement Alerting, the runway protection zone consists of the runway surface and any taxiway part beyond the currently applicable runway holding position (see Figure 74). Accordingly, crossing the currently applicable holding positions or stop bars is used to determine whether ownship or traffic has infringed the runway protection zone. In doing so, the direction in which the crossing occurs must be taken into account, i.e. the corresponding algorithm has to determine whether the runway to which the holding position/stop bar being crossed refers to is ahead of or behind an aircraft. For contingency, though, whenever SMAAS cannot determine the applicable holding position from the AMDB, the system uses a reduced core runway protection zone extending 55 m from the centreline, which corresponds to ~75% of the nominal distance for a CAT holding position, cf. Appendix II-2. This ensures proper infringement detection even in case a relevant taxiway/holding position is missing in an AMDB, or if the protection zone is approached from an intersecting runway. Likewise, the core protection zone is used in fallback mode (see above) when only runway data are available.

ILS critical areas on perimeter taxiways constitute a special case requiring particular attention. Figure 75 shows an excerpt from an AMDB of Frankfurt Airport (EDDF). While the blue arrows each mark a set of holding positions defining the ILS critical areas on taxiways Bravo and Bravo East pertinent to RWY 07L/25R, the green arrows delineate the corresponding area for RWY 07R/25L. Crossing the corresponding holding positions does not constitute a Runway Incursion hazard in the classical sense, since there is no risk of a physical runway surface infringement.

Nevertheless, entering the ILS critical area will jeopardise the integrity of the ILS signal. Besides, depending on the distance of the perimeter taxiway from the runway threshold, there might be insufficient vertical margin for aircraft to cross while take-off and landing operations are being conducted. Except for a closed runway, which may safely be circumnavigated on any perimeter taxiway, alerts are consequently required when entering the ILS critical on a perimeter taxiway.

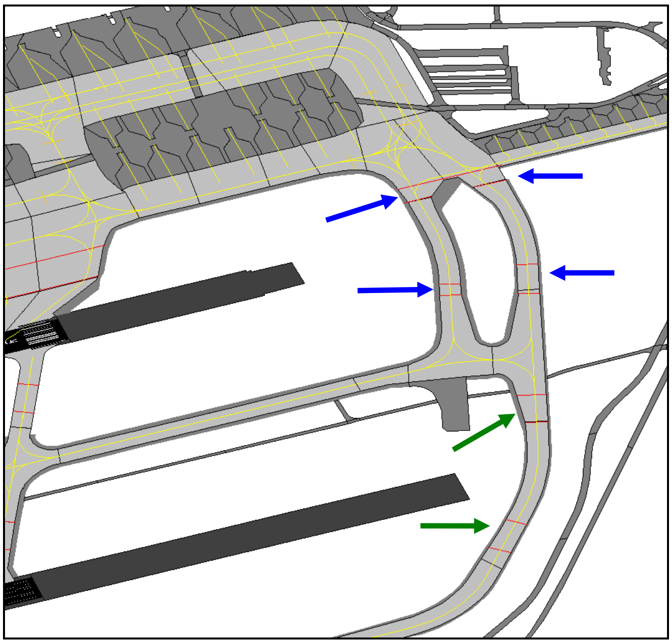

Figure 75: Excerpt from Frankfurt Airport AMDB with ILS critical areas on perimeter taxiways

Technically, the runway protection zone is infringed whenever an aircraft's nose protrudes across the applicable holding position. However, for large aircraft like the Airbus A340-600 or the A380, the nose is some 30…40 m ahead of the aircraft's navigation reference point, which typically coincides with either centre of gravity and/or the location of the yaw axis [Air09, Air10]. Consequently, to ensure that crossing the holding position is detected in a timely fashion, the aircraft nose position, which can be calculated based on the known aircraft geometry, has to be used instead to determine whether ownship has entered the runway protection zone. Nevertheless, the risk of nuisance alerts due to positional inaccuracies in the order of a few metres is comparatively low. Assuming that flight crews usually stop their aircraft with the corresponding holding position marking still in view, and given the visibility restrictions from the cockpit due to a typical cut-off angle of ~20° (see Figure 27), there will commonly be a margin of approximately 10…20 m[117].

By contrast, reliably detecting an intrusion of other traffic into the runway protection zone is more difficult. Obviously, the positions broadcast via ADS-B refer to the navigation reference point, and ADS-B data do not contain aircraft or vehicle type information, but only generic dimension information, cf. [RTC00]. The same applies to TIS-B traffic data. While aircraft type could in principle be retrieved based on each aircraft's unique ICAO 24-bit Mode S transponder address as discussed in Section 5.2.2, a corresponding registry database remains to be created. For the initial implementation, therefore, an extrapolation of received ADS-B or TIS-B aircraft positions to the respective aircraft nose or nose wheel positions could not be achieved, which means that an entry into the runway protection zone is detected comparatively late, approximately when the first half of the aircraft has already crossed the applicable holding position. Conversely, combined with potential latency effects, this virtually eliminates the risk of premature nuisance alerts, because only substantial infringements of the runway protection zone are considered.

[117] Typical values for the distance ahead of the aircraft's nose thus invisible from the cockpit are 12.5 m (Airbus A320 family), 13.75 m (A310), 14.00 m (A340-600) and 20.28 m (A380) [Air10].

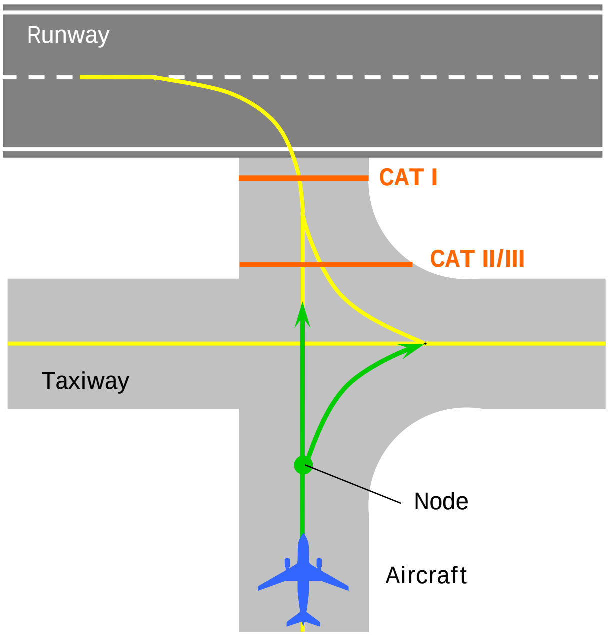

Figure 76: Determination of taxiway guidance line branching points ahead of ownship

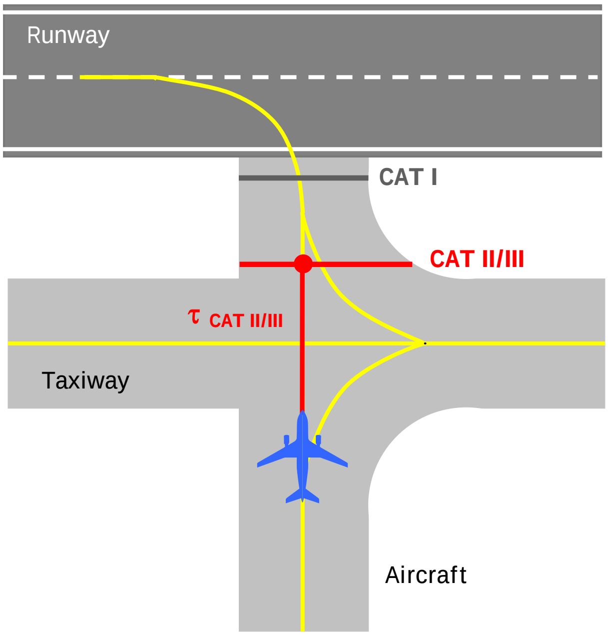

Figure 77: Calculation of time $\tau_{\text{CAT II/III}}$ until intersection with CAT II/III holding position

To establish the risk of ownship entering or infringing the runway protection zone, it is apparently required to predict its trajectory for a certain period of time, to assess whether there is an intersection with one of the currently applicable holding positions or the core protection zone, and to determine – in analogy to TCAS – the time τ until a potential intersection occurs, which can subsequently be compared to predefined alert thresholds that will be discussed in Section 5.5.5 and 5.5.6. In view of the comparatively low speeds during taxi operations, predicting ownship trajectory for the next 15 s appears to be sufficient: even when taxiing relatively fast at a ground speed of 20 kts, this corresponds to a distance of only slightly over 150 m.

Virtually all airports feature a system of taxiways parallel to the main runways, and frequently, particularly the corresponding CAT II/III holding positions are comparatively close to the edges of these taxiways, as illustrated by Figure 74 and Figure 75. In the frequently occurring constellation schematically presented in Figure 76, there is consequently a high probability of a spurious infringement risk detection, because it cannot be established at this stage whether ownship intends to turn right or plans to continue straight ahead, especially when the size of the aircraft or the narrowness of the turn, respectively, additionally require oversteering.
This clearly demonstrates the challenges associated with trajectory prediction and the subsequent need for sophistication. To eliminate premature infringement risk detections, it is therefore necessary to ascertain that ownship is indeed heading directly towards the runway and not intending to turn. Consequently, as a first measure for disambiguation, the algorithm devised for this thesis always follows the taxiway guidance line segments ahead of ownship for a fixed distance of 150 m to determine whether there is an intersection with either a runway or a corresponding holding position. In the latter case, the sweep distance is doubled to establish whether the holding position in question protects the runway itself or an ILS critical area. Simul-

taneously, the number of intersecting taxiway guidance lines ahead of the aircraft is calculated. In case at least one of the taxiway guidance lines emerging from these nodes does not yield an intersection with a runway protection zone, the calculation of τ is suppressed. This is illustrated by Figure 76, where a single node with diverging taxiway guidance lines, of which only one leads towards a runway, has been detected. The second measure to make predictions more precise consists of taking into account all available linear and angular velocities as well as accelerations in determining the future ownship trajectory.
Accordingly, when the aircraft advances further straight ahead, as shown in Figure 77, there are no remaining nodes, because the perpendicular taxiway guidance line directly in front of the aircraft is not considered as relevant, as turns with more than 80° are excluded. Since the predicted trajectory simultaneously intersects the CAT II/III holding position currently applicable in this example, it is now increasingly likely that ownship is indeed heading towards the runway protection zone, and the time $\tau_{\text{CAT II/III}}$ is calculated and evaluated against the alert thresholds.
Due to the missing accelerations and turn rates in the currently available traffic data, a sophisticated prediction of the infringement risk is not feasible for the surrounding traffic, and a simple linear extrapolation of traffic position with respect to the applicable holding position seems prone to create nuisance alerts. However, given the fact that the distance between the boundary of a 60 m wide runway and the CAT I holding position may be as low as 45 m, and thus approximately equal to the distance covered by traffic moving at a speed of 10 kts in less than 10 seconds, it appears to be necessary to increase the margin for the detection of hazardous situations. Consequently, the time τ_{RWY} until the runway surface is physically violated is used as additional criterion. Accordingly, the surrounding traffic is considered as infringing the protection zone whenever it is either determined to be located inside or predicted to physically infringe the runway surface within 10 s.

5.5.4.1.2 Airside infringement of the runway protection zone

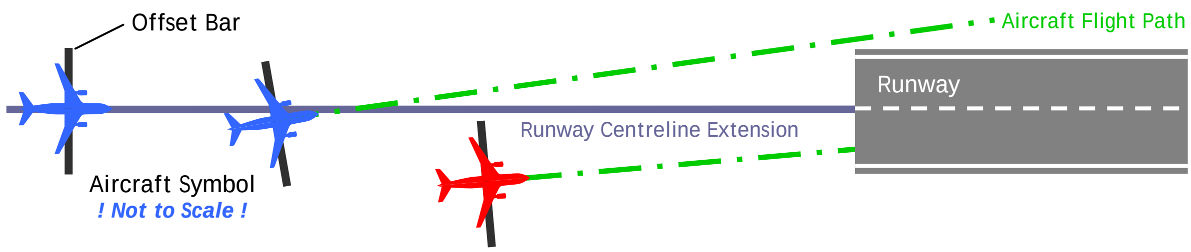

Figure 78: Determination of runway currently being approached

In order to establish whether there is an airside infringement of the runway protection zone, it is essential first to determine the runway currently being approached. Clearly, the intersection of the aircraft's projected lateral flight path with the runway surface is not a suitable criterion, because the aircraft is obviously not intending to land when flying perpendicular to the runway. At the same time, even when perfectly aligned with the runway centreline at 5 NM from the runway threshold, the projected flight path will miss a runway 60 m wide if an angular deviation from runway heading of more than 0.18° in either direction occurs.

Consequently, a different approach is necessary. As illustrated by Figure 78, the runway centreline is extended by 20 km from the runway threshold. Furthermore, a so-called Offset Bar perpendicular to the aircraft's longitudinal axis through the centre of gravity is introduced. Below 5000 ft above field elevation, whenever this 150 m wide[118] Offset Bar intersects with the Runway Centreline Extension and aircraft track does not differ by more than 10° from runway orientation, the aircraft is considered aligned with and approaching the runway. This ensures that the runway intended for landing is continuously and consistently detected even if the flight path predictor misses the runway surface, as shown in Figure 78 (blue aircraft). Conversely, if the Offset Bar is disconnected from the Runway Centreline extension, the aircraft is not considered to be approaching the runway in question even if the flight path intersects the runway surface (red aircraft). This method, which is deliberately not coupled to any particular landing system technology, works for all types of straight-in approaches, but the principle could be extended to curved approaches as well.
Moreover, the relatively small width of the Offset Bar, which corresponds to the typical extent of the runway protection zone for non-precision operations, ensures that erroneous approaches to taxiways parallel to the actually intended landing runway can be detected as well, the characteristic criterion being that the aircraft is not aligned with any runway below a certain altitude threshold.

Due to the need for sufficient vertical margin to initiate a go-around, e.g. in case of conflicting traffic, an airside infringement of the runway protection zone during approach already occurs when an aircraft descends below a certain altitude threshold. In consequence, the determination of suitable altitude thresholds for caution and warning alerts deserves particular attention. Surface Movement Alerting is intended to cover every type of approach operation, irrespective of whether it is precision or non-precision, in all visibility conditions. Therefore, a coupling of the trigger conditions to the decision height (DH) or decision altitude (DA) does not make sense for several reasons. First of all, certain operations are based on RVR only and do not specify a DH/DA at all. Besides, decision heights and altitudes exhibit a high variability, from several hundred feet for non-precision approaches down to 50 ft/0 ft for CAT III approaches. Consequently, pilots could perceive an incoherent behaviour of alerts when these are always triggered at different altitudes. More importantly, though, an alert at the DH might not be sufficient to prevent unsafe conditions in CAT II/III operations when taking into account the vertical dimensions of current long-range aircraft and typical reaction times. After all, the tail fin of the largest commercially used aircraft, the Airbus A380, towers approximately 80 ft (24.4 m) above the airport surface, cf. [Air09].
However, standardized glide slopes and defined type-specific approach speed ranges allow for a consistent behaviour of the infringement detection when coupling alerts directly to fixed radio altitude thresholds irrespective to the type of approach. During final approach, airliners lose approximately 500-800 ft per minute on a typical 3° ILS glide slope. In case a protection zone infringement necessitates an alert, it seems reasonable to provide an initial alert slightly less than half a minute before touchdown. Accordingly, a caution (Level 2) alert is triggered at 450 ft; this altitude was chosen to avoid interference with the automatic radio altitude callout at 500 ft

[118] This applies for zero crosswind only; obviously width has to be compensated for any side wind component.

installed on many aircraft. If the aircraft descends further, a warning (Level 3) is triggered at 250 ft, which should provide ample vertical margin to initiate a go-around even with an A380 size aircraft lined up or crossing at the runway threshold.
Furthermore, if there is no alignment with any landing runway at low altitude, which would be the case when attempting to land on a taxiway, the same altitude thresholds as for a runway protection zone infringement can be used to alert the flight crew. At the same time, these trigger conditions do not interfere with a potentially intended sidestep manoeuvre, because alignment with the landing runway should have been achieved at 450 ft. In conclusion, therefore, the 450 ft/ 250 ft RA criterion is applied for all ownship landing scenarios. To prevent spurious alert removal and re-triggering due to terrain undulations in the approach zone, there is a hysteresis allowing alert removal only if the radio altitude increases by more that 100 ft above the respective threshold. When using the pressure altitude above the airfield instead of radio altitude, the criteria for runway protection zone infringement derived in this section can also be applied to the surrounding traffic.

5.5.4.2 Take-off Intent Detection

Several of the hazardous situations identified as necessitating an alert in Section 5.5.3 may be detected when it can be established that the flight crew is attempting to take off. In this context, it should be noted that virtually all aircraft types currently employed in commercial air transport already feature a certified logic capable of detecting that take-off is intended or has commenced (cf. Section 4.4.3), because Take-off Configuration Warning Systems are mandatory for transport category aircraft according to §25.703 [FAR07]. On an Airbus A320 family aircraft, for example, the warning that the aircraft is not in take-off configuration[119] is triggered when the thrust levers are advanced to the FLEX/TOGA detent [Air05], i.e. if the crew commands take-off thrust. In this case, the Master Warning button illuminates, and a continuous repetitive chime is sounded.
Evidently, therefore, the interrelation of Surface Movement Alerting and the Take-off Configuration Warning deserves special attention, both in terms of consistent system design and alert prioritisation, as already mentioned in Section 5.5.1. In order to achieve a consistent behaviour of alerts, the trigger conditions of the Take-off Intent Detection employed by SMAAS have to be identical or at least very similar to those used for the Take-off Configuration Warning on a particular aircraft type, depending on the specific implementation used by the manufacturer. Nevertheless, in view of the issues identified in connection with the Helios airways accident [AAI06], cf. Section 5.5.2, dedicated aural alerts for SMAAS are required at any rate to allow for an unambiguous identification of the source of the alert. Therefore, while the trigger conditions may be the same as for the Take-Off Configuration Warning, a simultaneous re-use of the aural alert for the purposes of SMAAS would result in similar undesirable ambiguities as those discussed Section 5.5.2.
It quickly emerges that thrust lever position and thus commanded thrust constitutes a better trigger criterion than EPR or %N1, because there is clearly no need to let the

[119] An Airbus A320 family aircraft is considered not to be in take-off configuration whenever its flaps/slats are not set appropriately, if the speed brakes are not retracted, or when pitch and rudder trim are not within the range permissible for take-off [Air05].

engines run up before triggering the alert, since the procedure in case of a Take-Off Configuration Warning is to cancel take-off, and the corresponding SMAAS alerts are intended to induce the same reaction. Besides, the goal is to detect a potential alert condition as early as possible. Consequently, for the purposes of SMAAS, the flight crew's intention to take off is therefore also deduced from the fact that thrust levers are symmetrically advanced to the FLEX/TOGA position[120], with the additional constraint that the engines must be running. Requiring symmetric thrust lever positioning for all engines is intended to avoid nuisance alerts in case of engine test runs.
A potential alternative for Take-off Intent Detection considered by this thesis makes use of the aircraft's internal flight phase logic. For Airbus A320 family aircraft, the flight phase changes from PREFLIGHT to TAKEOFF whenever the so-called Speed Reference System (SRS) mode is activated and N1 is simultaneously 85% or more. Alternatively, the transition occurs whenever the speed exceeds 90 kts or EPR≥ 1.25. The SRS mode itself is also activated[121] when the thrust levers are moved to the FLEX/TOGA detent [Air05], but additionally requires Auto-Thrust and Flight Director (FD) to be armed or active. Besides, SRS is only available with a valid V_2 value entered. In view of these preconditions, which might not always be fulfilled, and the need to run up the engines to 85% N1, the changeover to TAKEOFF flight phase does not seem to be a favourable primary criterion to establish the intent to take off, at least on Airbus aircraft, but could constitute a viable back-up option. Nevertheless, since both the logic for flight phase changeover and Take-off Configuration Warning may be implemented differently by other manufacturers, the precise choice whether the SMAAS Take-off Intent Detection should be based on the Take-off Configuration Warning or a flight phase change has to be made individually for each aircraft type.
Irrespective of aircraft type and the precise implementation, however, there is the issue of prioritisation, i.e. whether the Take-Off Configuration Warning or the SMAAS alerts based on take-off intent should take precedence. In principle, the crew should never take off in the presence of either the Take-off Configuration Warning or the corresponding SMAAS alerts, i.e. the intended pilot reaction is identical for both.

Consequently, the sequence in which the underlying problems are addressed by the flight crew is irrelevant. Since the aircraft may not be flyable at all if configured inappropriately for take-off, the Take-Off Configuration Warning should take priority. Besides, the checks to resolve preventive SMAAS alerts could be somewhat more complex, because the crew might e.g. need to double-check for themselves and with ATC whether they actually ended up on the wrong runway or whether the alert is due to incorrect or outdated data in the system.

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[120] As a side note, the ECAM control panel on Airbus aircraft features a button permitting the flight crew to emulate the conditions that would trigger the take-off configuration warning. The crew can employ this button to check whether the aircraft is configured correctly for take-off [Air05]. With SMAAS simultaneously present, this raises the question if and how those alerts using the same trigger conditions should be integrated in this concept. Evidently, the envisaged SMAAS alerts when attempting to take off outside the runways must be inhibited when this T.O. button is pressed. Otherwise, the corresponding alert would be triggered as a nuisance each and every time the flight crew attempts to check the take-off configuration. On the intended take-of runway, however, triggering the corresponding runway-related SMAAS alerts as well might prove to be beneficial, since it allows the flight crew to perform an extended system configuration check.

[121] The SRS mode is a managed vertical speed mode used to maintain SRS speed (V_2, $V_2 + 10$, V_{APP}) at take-off and during a go-around. SRS is a control law which provides a pitch that allows maintaining at least V_2 +10 kts with the selected thrust.

5.5.5 Preventive Surface Movement Alerting

To ensure specific alerting tailored to the actual situation, detailed information on the operational environment and clearances is required. Consequently, the scope of the preventive Surface Movement Alerting functionality that can be provided to flight crews is strongly dependent on the availability of ATC instructions and clearances in machine-readable form via a corresponding CPDLC service. Essentially, three different scenarios have to be distinguished. The first scenario is characterised by either unavailability or complete failure of CPDLC. In the second scenario, taxi routing is available via CPLDC, while runway-related ATC instructions and clearances are still solely communicated via conventional R/T. For both of these scenarios, the preventive part of SMAAS can only generate specific alerts in case runways or taxiways are used in an inappropriate fashion, based on operational context information concerning closures or restrictions, thus addressing ***High-Level Requirement III***, and the take-off runway selected in the FMS. This leads to the important insight that alerting solely based on such operational environment data is not sufficient to prevent pilots from causing a Runway Incursion on the runway that has been assigned to them for take-off or landing. Even in the presence of a taxi route, a failure to hold short of a runway or taking off without clearance on the 'correct' runway cannot be addressed in this routine scenario.
This only changes fundamentally in the third scenario, which provides the complete spectrum of CPDLC services, and thus the complete range of alerts. Only if runway-related ATC instructions and clearances are available in machine-readable format, the system can detect if pilots fail to hold short of an active runway or take off without clearance, and generate a corresponding alert.

For the design of preventive Surface Movement Alerting, this means that flight crews must be able to discern the currently applicable scenario in an unambiguous fashion. A further prerequisite is that Surface Movement Alerting has to be capable of coping with all three scenarios in a way that is consistent and logical for the pilots, i.e. the absence of a CPDLC service should not result in an entirely different behaviour. Besides, for the system to work correctly, therefore, the currently available CPDLC environment must be accessible in a simple fashion, e.g. via a service level flag associated with each ATC data authority.

In other words, preventive Surface Movement Alerting can alert pilots whenever inconsistencies between the operational configuration of the aerodrome and the flight crew's actions arise, irrespective of whether the corresponding mismatch is due to a pilot error, controller error or any other reason. Consequently, in a full CPDLC environment, it provides protection against disorientation, as demanded by ***High-Level Requirement I***, and immediately alert pilots in case of non-adherence to ATC instructions or clearances, which addresses ***High-Level Requirement IV***.

5.5.5.1 General cross-functional consistency checks

The preventive Surface Movement Alerting functions conceived by this thesis provide several layers of protection. The first consists of continuously monitoring the airports and associated departure/landing runways selected as part of the FMS flight plan against potential inconsistencies with the available closure or restriction information and – where available – CPDLC messages related to runway operations.
Depending on the result of these consistency checks, which will typically permit the detection of potential procedural errors well before the conditions for a high-level alert are fulfilled, the following text messages may be displayed, accompanied by a single **atten**tion-getting **sou**nd, the so-called ATTENSON (cf. [SAE88a]), if applicable:

- ❖ CHECK FMS RWY is presented as text message on the ECAM in amber, accompanied by an ATTENSON, in case a line-up instruction or take-off clearance is received for a runway not selected as departure runway in the FMS. For a landing clearance, the same message is shown as mere reminder in white and without ATTENSON, because a potential last minute runway change or an intentional sidestep manoeuvre may be a valid reason for this discrepancy.
- ❖ RWY CLOSED appears in the scratchpad of the MCDU in amber as error message whenever a closed runway is selected for departure or landing. Usage of the corresponding runway for departure is blocked in the FMS; but it may be used for landing due to a potentially intended sidestep manoeuvre[122].
- ❖ RWY 27L TO BE CLOSED IN 18'25'' will be visualised as a text countdown on the ND if the FMS-selected take-off runway (RWY 27L in this example) is, based on NOTAM information, expected to be closed within 30 min. As shown in Figure 55, the font colour changes from white to amber if time remaining before closure decreases below 15 min. For a landing runway, the ETA at the airport must be within 45 min for this message to be displayed, which ensures that runway closures beginning during the flight, but ending well before the aircraft's arrival are filtered and do not distract the flight crew.
- ❖ CHECK RWY STATUS will be presented on the ECAM and in the MCDU scratchpad in amber, accompanied by an ATTENSON, if the FMS-selected runway
  - is within 15 min of closure or has already been closed;
  - has been re-opened within the last 10 min (defined end time of closure);
  - has re-opened within the last hour (estimated end time of closure); or
  - will be subject to a restriction that will be effective within less than 15 min;

  with ownship at the airport or arriving within 45 min.
- ❖ AIRPORT CLOSED will be shown as error message in the scratchpad of the MCDU upon blocking the flight crew's attempt to enter the identifier of an airport which is closed by NOTAM or has no remaining open runways at ETA ± 60 min.
- ❖ CHECK AIRPORT STATUS is presented as amber text message on the ECAM to advise pilots of an impending, effective or recently expired airport closure, with conditions completely analogous to the **"CHECK RWY STATUS"** message.
- ❖ CHECK ALTERNATE STATUS will appear on the ECAM in white font whenever one of the alternate airports currently specified in the FMS flight plan is closed and must be expected to remain closed beyond the ETA.

[122] Nevertheless, when using the Navaids of a closed runway, particular attention has to given to their operational status. If these are unserviceable, the selection of the corresponding approaches needs to be blocked.

5.5.5.2 Advisories and alerts in case of inadvertent runway infringement

The alerting envisaged in case of an inadvertent violation of the runway protection zone forms the core of the preventive Runway Incursion alerting functionality within the SMAAS; its purpose is the avoidance of Runway Incursions by preventing the aircraft from entering or crossing runways it is not authorised to operate on.

5.5.5.2.1 Runway Proximity Information

In a conventional R/T environment or with only taxi routes available via CPDLC, there is no possibility to detect deviations from an ATC instruction to hold short of a runway, and consequently no specific alert offering protection against inadvertent runway entry. Nevertheless, to provide at least a basic level of safeguarding against erroneous runway infringement even in the absence of CPDLC, a general reminder in the form of an unspecific advisory is generated to draw the flight crew's attention to that fact that they are about to enter a runway. Furthermore, a corresponding advisory is also envisaged as part of the OANS on the Airbus A380, cf. Section 3.1.1.

Therefore, a so-called Runway Proximity Information (RPI) is triggered systematically when the aircraft is approaching any runway during surface operations. Accordingly, the advisory, which mainly consists of highlighting the runway on the airport moving map (see Section 5.5.7 for details), is presented totally irrespective of whether there is, in a CPDLC environment, already approval to proceed further onto the runway or not.
Likewise, since the RPI serves as a general reminder and not as an alert, it is consequently not coupled to the time τ remaining until the runway protection zone will be entered, but always triggered at a fixed distance from the runway. In normal operations, the RPI is presented when the CAT II/III holding position or stop bar is crossed. In LVP, an additional margin of 50 m is added. This is intended to ensure that this advisory is always and consistently triggered before any other potentially applicable other Runway Incursion alerts, which always take priority over the RPI.

While on the ground, runways or runway sections which are completely closed form the only exception. The RPI advisory is suppressed in this case, because the closed runway alerting as described below takes priority. Besides, the advisory is also suppressed during final approach and landing, because there is obviously no need to inform pilots that they are about to land on a certain runway.

In conclusion, irrespective of the available CPDLC environment, the RPI will be the only functionality of Surface Movement Alerting which will always visible to pilots during each and every flight, and is thus a core means of ensuring a consistent perception of SMAAS by flight crews. In perfectly routine operations, it will simultaneously remain the only SMAAS advisory or alert encountered by pilots. At the same time, it can also be used as an intrinsic fidelity check for Surface Movement Alerting – if the RPI does not behave as expected, this points at system degradation.

5.5.5.2.2 *Principles for the distinction of caution and warning alerts*

The common functions for Runway Infringement and Take-off Intent Detection discussed in Section 5.5.4 form the basis for a consistent behaviour of Surface Movement Alerting across the full spectrum of alerts. However, to ensure that there is perceived consistency in alerting, common criteria for assigning the applicable alert levels are required in addition.

Evidently, any actual Runway Incursion due to erroneous runway entry justifies a warning (Level 3) alert. Nevertheless, in line with the considerations in Section 5.5.3, alerting the flight crew only when the runway protection zone has already been physically infringed does not seem desirable, particularly with respect to potential ILS disturbances. Consequently, all warnings concerning erroneous ownship runway entry always have to be preceded by a caution (Level 2) alert. Accordingly, the principle governing the distinction between caution and warning chosen for this thesis is that a risk of infringement will generally result in a caution, while the actual entry into the applicable protection zone will yield a warning. To minimize the actual infringement, an additional warning threshold was introduced for an infringement risk as supplementary trigger condition for a warning in some cases.

The underlying rationale behind this staged alerting is that the caution creates immediate awareness of the problem, which is expected to be sufficient in most cases to trigger remedial pilot action. Therefore, the warning mainly serves as contingency measure and indicator to the crew that their initial response to the alert may not have been sufficient.

Once the aircraft has physically entered the runway, all alerts concerning erroneous runway entry, irrespective of whether the underlying reason is a lack of authorisation or a closure, will persist only until the aircraft leaves the runway surface, because maintaining a warning while the aircraft is within the applicable protection zone appears to be exaggerated, since the problem is already being resolved.

5.5.5.2.3 *Unauthorised runway entry & operations*

In an environment where ATC instructions and clearances related to runway operations are available via CPDLC – and **<u>only in this case</u>** – Surface Movement Alerting is able to provide alerts protecting the flight crew against inadvertent infringement into the protection zone of a runway they are not authorised to enter, cross, or otherwise operate on. Consequently, unless there is CPDLC authorisation to proceed beyond the applicable holding position, a **"RUNWAY AHEAD"** caution alert is triggered whenever ownship is at risk of infringing the runway protection zone. Evidently, the main challenge consists of defining suitable τ values, because there is a clear need to minimize nuisance alerts while ownship, in expectance of a line-up clearance, slowly taxies towards the holding position of the departure runway. Accordingly, in normal operations, the caution alert is not issued until $\tau \leq 5$ s, which e.g. permits the aircraft to proceed within ~15 m of the holding position at a constant taxi speed of 6 kts without alert. This appears to be a reasonable value in view of the distance ahead of the aircraft typically obscured due to the cockpit cut-off angle, and fact that aircraft are typically taxiing slowly and decelerating when approaching a holding position.

Since it is, for obvious reasons, furthermore desirable to minimize the distance actually travelled beyond the holding position until the aircraft can be stopped, it seems appropriate to trigger the warning alert slightly before actually infringing the protection zone. Consequently, the **"RUNWAY INCURSION"** warning is activated either for $\tau \leq 2$ s (equivalent to ~5 m at 5 kts) or if the holding position is crossed.
By contrast, in Low Visibility Operations, there is no immediate collision hazard when entering the ILS critical area, and the corresponding holding positions are commonly very close to the edges of taxiways frequently used, which increases the risk of spurious alerts, as discussed in Section 5.5.4. Therefore, and in view of the fact that aircraft taxi very slowly when LVP are in effect, the margin for the **"RUNWAY AHEAD"** caution alert is reduced to $\tau \leq 3$ s, which corresponds to ~9 m at 6 kts, and the warning is only triggered when the aircraft actually infringes the holding position. Entering the ILS critical area on a perimeter taxiway without authorisation will by default be treated like any other protection zone infringement, based on the assumption that approval to cross on the protection zone via the perimeter taxiway is also given by the aerodrome controller due to the potentially hazardous interference with runway operations.

5.5.5.2.4 Infringement of closed runways

For alerts pertaining to the risk of erroneously entering closed runways, a distinction of normal operations and Low Visibility Procedures is not necessary, because the navigational facilities of a closed runway, such as the ILS, will only be used for sidestep manoeuvres (if at all), which are exclusively conducted in conditions permitting a visual transition to the parallel runway. Consequently, there is no extended ILS critical area to protect in case LVP are in force. Likewise, if runways are only partially closed and may still be used for taxi operations, there is no need to alert the flight crew upon runway entry, either. Only if pilots attempt to take off, a warning is required, as detailed in the next section.

In analogy to the alerts for unauthorised runway entry, a **"CLOSED RUNWAY"** caution alert will therefore only be presented in case the aircraft is approaching the holding position of a completely closed runway or runway segment and at risk of infringing it. If the flight crew continues in spite of this alert, it will be raised to warning level as soon as the time τ decreases below the warning threshold or whenever the holding position is actually crossed. Evidently, the alert will persist if the aircraft enters the runway surface or attempts to take off.
However, in view of the dead-end character of any taxiway leading up to a completely closed runway or respective segment, there is no need to permit pilots to advance almost up to the holding position before providing an alert. Besides, there is a wide variation in the placing of the physical barriers indicating closure, if available, between different airports. Consequently, to address this aspect, the applicable alert threshold τ is doubled to 10 s for a caution and 5 s for a warning alert in this case.
With ownship already on a closed runway still available for taxiing, the same alerting criteria are used when approaching the boundary of a completely closed runway segment. Likewise, a cautionary **"TAXIWAY CLOSED"** will be triggered if ownship is within 5 s of infringing a closed taxiway segment.

5.5.5.3 Protection against erroneous Take-off operations

In accordance with the analysis of situations necessitating an alert in Section 5.5.3 and the trigger criteria derived in Section 5.5.4, the following warnings are provided in case the flight crew erroneously initiates take-off by forwarding the thrust levers symmetrically to the FLEX/TOGA detent, if N1 exceeds 85% or if the TAKEOFF flight phase is entered[123] while ownship is within the confines of the respective runway surface:

- A **"WRONG RUNWAY[124]"** warning is activated if take-off is performed on any runway other than the FMS-selected one. It is triggered irrespective of and with priority over any potentially available CPDLC take-off clearance.
- A **"CLOSED RUNWAY"** warning will be issued if the flight crew attempts to take off from a runway which is either completely closed, available for taxiing only or rendered unusable for take-off and landing by completely closed runway segments. This alert has a higher priority than both the alert for taking off from a non-FMS runway and the CPDLC-based alert.
- A **"RUNWAY INCURSION"** warning is triggered immediately when the crew commences take-off without a corresponding clearance for the current runway, but **only in case** a CPDLC service capable of providing runway-related ATC instructions and clearances is available.

Outside the runway surface, but in otherwise identical conditions, the so-called Taxiway Take-off Prevention is triggered. A **"NOT ON RUNWAY"** warning is presented as soon as the intention of the flight crew to take off on a taxiway has been detected. This alert is not limited to the taxiway system, but generally triggered if the flight crew attempts to take off outside the known runway surfaces at an airport; it is consequently also available on aprons, at parking positions or de-icing areas.

Initially, a distinction of caution and warning level similar to the alerts in case of inadvertent runway infringement was also envisaged for the SMAAS alerts related to take-off operations. Once the flight crew's intention to commence take-off in an unsafe condition had been established by SMAAS as described above, a caution alert was triggered, which would subsequently be raised to a warning as soon as a speed threshold of 40 kts was exceeded in addition. However, in a first design review with Airbus test pilots, this two-stage concept was rejected, based on the argument that there is no need to let the aircraft accelerate to 40 kts before warning the flight crew that they are involved in an unsafe take-off operation.
Moreover, from an analytical perspective, there is no incremental safety margin for the take-off manoeuvre, since it is either safe to take off in a given situation or not. Consequently, there are no intermediate stages that would justify additional alert levels. This is particularly evident for the case of taking off from a taxiway, which is obviously never safe in routine operations[125]. Besides, the conventional Take-Off

[123] The primary trigger condition is the thrust lever advancement to FLEX/TOGA; the other two conditions merely serve as a back up and will result in a delayed activation of the alert.
[124] For better distinction from the remainder of the text, all callouts are given in "CAPITAL LETTERS".
[125] The use of a taxiway as temporary runway that sometimes occurs at airfields with just one runway forms the only exception, but requires dedicated authorisation, such as a NOTAM defining a temporary runway.

Configuration Warning exclusively uses Level 3, presumably for the same reason. In conclusion, therefore, a warning is immediately triggered without intermediate caution whenever SMAAS has detected that the pilots intend to take off in a situation necessitating an alert.
From a conceptual and operational perspective, this functionality can be seen as an extension of the existing Take-off Configuration Warning systems, which alert for an unsafe condition of the aircraft configuration, whereas the SMAAS alerts described above warn pilots if the external conditions are not safe due to the status and configuration of the aerodrome environment.

During the take-off roll, all preventive SMAAS alerts are suppressed as soon as the aircraft enters the high-speed regime at 100 kts. The visualisation of the alerts that have already been triggered is retained as long as the alert condition persists, but callouts will cease, and the Master Caution/Master Warning lights extinguish. The underlying rationale is that a flight crew, having been confronted with the preventive alert from the setting of take-off power, will have had ample opportunity to react to the alert by then. Additionally, in contrast to reactive surface movement alerting, no hazardous new situations can emerge between 100 kts and V_1. Even in the only remotely probable case that a runway closure becomes effective during the take-off run, a rejected take-off in the high-speed regime induced by this situation is not desirable. Therefore, any runway status changes and associated alerts are inhibited 10 s after take-off has commenced. Likewise, a potential cancellation of the take-off clearance in case of emergency is expected by voice via conventional R/T, in accordance with ICAO recommendations [ICA01a]. Conversely, the suppression beyond 100 kts trivially ensures that there will not be any nuisance or false positive alerts in the high-speed regime. In particular, a sudden failure or degradation of the navigation system, which might potentially resulting in a position shift, will not lead to the triggering of e.g. the Taxiway Take-off Prevention or a preventive Runway Incursion alert for a parallel runway.

5.5.5.4 Advisories and alerts during approach and landing

As outlined in Section 5.5.3, hazardous approach and landing scenarios are comparatively difficult to detect if there are no runway closures or restrictions, because landing on a runway other than the FMS-selected one is, in contrast to the take-off case, not necessarily associated with procedural error. Due to the fact that a last-minute runway change could have been advised by ATC on too short notice for the crew to enter the required changes into the FMS, or since a sidestep manoeuvre might be intended, there may be an operationally valid reason for doing so. Consequently, there will be no advisory or alert if the flight is approaching or landing on a runway not selected in the FMS in the absence of CPDLC landing clearances.

If landing clearances are available in machine-readable format via CPDLC, alerts can in principle be provided if the crew attempts to land on a runway without clearance. However, particularly at airports with high density operations, landing clearances are often issued very late during final approach for legal reasons even in a conventional R/T environment, although a landing clearance still missing below 250 ft is

rather exceptional. Nevertheless, in view of the fact the expected procedural flight crew reaction in case of a SMAAS warning during approach is the initiation of a go-around, issuing a Level 3 alert in case of a missing CPDLC landing clearance can be precluded. Otherwise, especially in view of potential data link latency effects, a late arrival of landing clearances might result in unnecessary go-arounds, which has to be avoided. Consequently, only a **"CLEARANCE MISSING"** caution alert is triggered when, during approach to the FMS-selected runway, there is still no landing clearance at or below 250 ft radio altitude (RA). Depending on the precise circumstances, the flight crew may then decide to continue the approach or to go around.
Conversely, if the aircraft is approaching a different runway than the one selected in the FMS and there is no landing clearance, either, there will be a **"WRONG RUNWAY"** caution at 450 ft RA, followed by the corresponding warning at 250 ft RA, see Table 10. Likewise, to prevent landing attempts on a taxiway or elsewhere outside the runways, these two alerts are also triggered if the system is unable to establish the runway intended for landing when crossing 450 ft or 250 ft RA, respectively, irrespective of whether CPDLC landing clearances are available or not.

For the reasons detailed in Section 5.5.3, the advisories and alerts provided in case ownship erroneously attempts to land on a closed or otherwise unsuitable runway are completely independent of the CPDLC environment and have priority over any alerts triggered based on CPDLC clearances. The general consistency checks described in Section 5.5.5.1 are believed to provide pilots with an opportunity to detect potentially hazardous situations with respect to current or emerging runway closures proactively. Nevertheless, the **"CHECK RWY STATUS"** Level 1 alert is additionally triggered whenever pilots arm the autoflight system with an approach to a closed runway. Apparently, a higher level alert is not desirable in this case, because there should be sufficient margin to resolve the situation. Besides, the approach mode might have been routinely selected as part of a sidestep manoeuvre or circling procedure to another runway. Safety-net type alerts are only required if the aircraft continues the approach[126]. Accordingly, on final approach to a runway that is either completely closed or may only be used for taxi operations, a **"CLOSED RUNWAY"** caution alert is presented whenever the aircraft descends through 450 ft RA, which is raised to warning level in case the flight crew proceeds below 250 ft RA.

For intersecting runways, SMAAS will always assume that ownship is always entitled to use the full available runway length during roll-out, i.e. there will be no advisories or alerts when approaching or crossing the intersecting runway. Only if explicit information that LAHSO operations are being conducted is received, e.g. as part of a CPDLC landing clearance, there will be a **"RUNWAY AHEAD"** caution alert if the predicted time τ until crossing the LAHSO location drops below 15 seconds, and a **"RUNWAY INCURSION"** warning if this clearance limit is actually crossed.

[126] When using the Navaids of a closed runway for a sidestep manoeuvre, particular attention has to be given to the operational status of the Navaid in question.

5.5.5.5 Surface Movement Alerting outside the runway environment

5.5.5.5.1 Taxi Route Conformance Monitoring

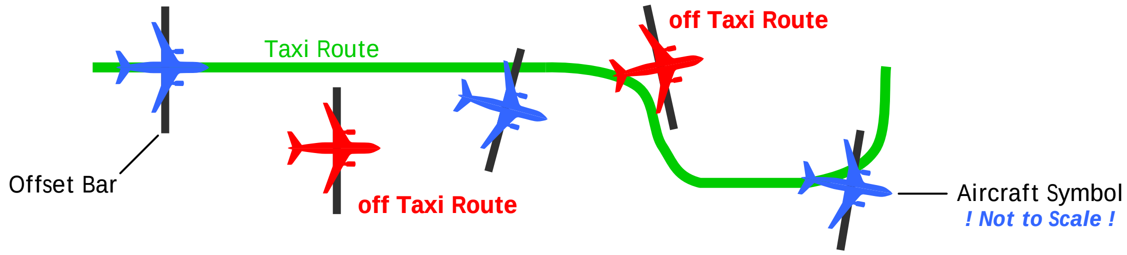

Figure 79: Illustration of Taxi Route Conformance checks

Pilots' adherence to the taxi instructions provided via CPDLC (if available) is also determined employing the so-called Offset Bar, which is already used in detecting the landing runway (cf. Section 5.5.4). Accordingly, on the movement area outside the runways, a deviation from the assigned route is considered as established whenever the offset bar, which is 20 m wide during surface movement, ceases to intersect the assigned taxi route. As can be seen from Figure 79, this approach is comparatively robust against the oversteering required when taxiing a large widebody aircraft, and also requires a substantial cross-track error.

In case a deviation from the assigned taxi route has thus been detected, the taxi route will start blinking to attract pilots' attention. At the same time, a text message **"CHECK TAXI ROUTE"** is displayed in white in the area designated for messages on the Navigation Display (ND). To supplement these attention-getting features, an ATTENSON was envisaged, but not implemented in the scope of this thesis. At any rate, the criticality of the advisory clearly does not justify a dedicated callout, and this Level 0 advisory was therefore chosen for a route deviation on the taxiway system. Initially, guidance cues back to the assigned route were also considered, but eventually dropped, since re-routing would be required for all non-straightforward cases, in which such guidance is superfluous anyhow, because current regulations allocate the task of assigning taxi routes to the controller [ICA01a].

A special case requiring careful consideration is a deviation from the assigned taxi route while crossing a runway or during a back-track manoeuvre. The resulting unexpected increase in runway occupancy time, e.g. if the flight crew erroneously performs a line-up manoeuvre on a runway when only approved to cross, may jeopardise the controller's planning and result in the need to instruct approaching aircraft to go around. Therefore, the alert is raised to Level 1 if the deviation occurs inside the runway protection zone.

By contrast, overshooting the end of an assigned taxi route can only be detected if the corresponding clearance limit is the holding position of a runway and provided that the approval to line up or to cross the runway is available via CPDLC. However, the corresponding situations are handled by the alerts associated with inadvertent runway infringement, as discussed in Section 5.5.5.2.

Alert Type/Condition	Alert Level	Callout	PFD Text Message
Unauthorised RWY Operations♠			
➢ Take-off clearance for non-FMS RWY♠	Advisory (Level 1)	-	CHECK FMS RWY†
➢ Landing without clearance (FMS-selected RWY)♠	Caution (Level 2)	"CLEARANCE MISSING"	CLEARANCE MISSING
➢ Risk of unauthorised entry onto any RWY♠	Caution (Level 2)	"RUNWAY AHEAD"	RWY AHEAD
➢ Unauthorised entry of any RWY♠	Warning (Level 3)	"RUNWAY INCURSION"	RWY INCURSION
➢ Take-off without CPDLC clearance♠	Warning (Level 3)		RWY INCURSION
Non-FMS Runway Operations			
➢ Attempted Take-off	Warning (Level 3)	"WRONG RUNWAY"	WRONG RWY
➢ Attempted Landing, while simultaneously not cleared to land♠	Caution (Level 2) Warning (Level 3)		WRONG RWY WRONG RWY
Closure Alerting			
➢ Alternate airport closed	Advisory (Level 0)	N/A	*CHECK ALTERNATE STATUS†*
➢ FMS-selected RWY to be closed in ≤ 30 min	Advisory (Level 0)		*RWY <ID> TO BE CLOSED IN <TIME>♣*
➢ FMS-selected RWY to be closed in ≤ 30 min	Advisory (Level 1)		*RWY <ID> TO BE CLOSED IN <TIME>♣*
➢ FMS-selected RWY to be closed in ≤ 15 min	Advisory (Level 1)		*RWY <ID> TO BE CLOSED IN <TIME>♣*
➢ FMS-selected RWY closed/restricted	Advisory (Level 1)		CHECK RWY STATUS†
➢ Destination airport closed/to be closed	Advisory (Level 1)		*CHECK AIRPORT STATUS†*
➢ Impending infringe-ment of closed TWY	Caution (Level 2)	*"TAXIWAY CLOSED"*	*TWY CLOSED*
➢ RWY infringement risk (airside/landside)	Caution (Level 2)	"CLOSED RUNWAY"	CLOSED RWY
➢ Infringement during surface operations	Warning (Level 3)		CLOSED RWY
➢ Attempted Take-off or Landing	Warning (Level 3)		CLOSED RWY
Taxiway Take-off Prevention (TTOP)			
➢ Attempted Take-off on TWY/outside RWY	Warning (Level 3)	"NOT ON RUNWAY"	NOT ON RWY
Taxi Route Conformance Monitoring (TCONF)♠			
➢ Taxi route deviation	Advisory (Level 0)	N/A	CHECK TAXI ROUTE♣
➢ ... on RWY	Advisory (Level 1)		CHECK TAXI ROUTE♣

♠ CPDLC environment only ♣ Text message on ND † Text message on ECAM

Table 10: Callouts and textual messages for preventive Surface Movement Alerting

As can be seen from Table 10, preventive Surface Movement Alerting only uses seven distinct callouts. Generally, cautionary callouts are issued once, whereas the voice callouts associated with warnings are continuously repeated until they are either silenced upon pressing the Master Warning Button or the hazardous condition ceases to exist. Messages and callouts presented in *italics* in Table 10 were not implemented in the SMAAS prototype used during the evaluation campaigns.

5.5.6 Reactive Surface Movement Alerting

Runway Incursions caused by ownship or other traffic, as well as those resulting from controller errors, may eventually manifest themselves in the form of traffic conflicts in the runway environment. Doubtlessly, these situations need to be addressed by alerts, as discussed in Sections 4.4.2.
As sketched in Section 5.5.3, conflicting runway traffic can be identified based on the incompatibility of the manoeuvres currently performed by ownship and the surrounding traffic. The classification of manoeuvres according to whether they require exclusive runway usage or not, as developed in Table 9, can subsequently be used to infer which combinations of manoeuvres require an alert, see Table 11. An asterisk in the table indicates that the compatibility depends on the actual constellation and the available margin. A detailed rationale for the choice of the alert level and the precise criteria for an alert are described in the following sections.

Ownship ...	*Crossing RWY*	*Lining Up*	*Taking Off*	*Final Approach*	*Landing*
Other Traffic ...					
Crossing RWY	compatible	compatible	WARNING	CAUTION	WARNING
Lining Up	compatible	compatible	compatible*	CAUTION	WARNING
Taking Off	WARNING	compatible*	WARNING	CAUTION	WARNING*
Final Approach	CAUTION	CAUTION	compatible*	CAUTION	compatible*
Landing	WARNING	WARNING	WARNING	CAUTION	WARNING*

Table 11: Alert matrix for conflicting traffic in the runway environment

5.5.6.1 Traffic alerting while entering or within the runway protection zone

Evidently, it is not safe for ownship to enter the runway protection zone while other traffic is taking off, on short final or landing on the same runway, as already indicated in Table 9. The same applies to crossing, back-tracking, lining up or holding on this runway[127]. However, approaching aircraft do not pose a hazard if they are still sufficiently high, and may be disregarded in this case.
The fact that other aircraft are on final approach can be detected as described in Section 5.5.4, but with the reported altitude above the corresponding threshold instead of radio altitude as criterion. Alerts for potentially hazardous traffic on final approach are therefore issued when other aircraft are less than 500 ft above the threshold while ownship is simultaneously within the runway protection zone, or less than $\tau \leq 2$ s from crossing the applicable holding position, in which case a **"TRAFFIC ON APPROACH"** caution alert is issued in accordance with Table 11. Subsequently, a **"RUNWAY INCURSION"** warning is raised if conflicting traffic is detected less than 250 ft above the threshold.

The intent of other aircraft to take off is more difficult to determine, since none of the parameters employed to establish the initiation of take-off for ownship is currently part of traffic surveillance data. Nonetheless, it seems reasonable to assume that runway traffic with a reported ground speed in excess of 20 kts may be in the initial stages of its take-off run, and to issue a **"RUNWAY TRAFFIC"** caution alert. Like-

[127] Simultaneously, this hazardous constellation may serve as an indication that ownship is either not authorised to operate within the confines of the runway, or that there must be some other procedural error. Reactive Runway Incursion alerting can thus be regarded as a back-up in case preventive alerting is not available due to the absence or failure of CPDLC.

wise, for traffic beyond 40 kts, a **"RUNWAY INCURSION"** warning appears to be justified. Apparently, these thresholds and alerts are also appropriate to address landing traffic in its roll-out.

The trigger criteria outlined above ensure that there will be no alerts for traffic simultaneously crossing the runway at other intersections, traffic taxiing or backtracking on the runway, or lining up while ownship is within the runway protection zone. Likewise, to prevent nuisance alerts in case ownship crosses the runway behind departing traffic or commences line-up while another aircraft in its landing rollout has already passed by, the above alerts are suppressed as soon as the distance between ownship and the respective traffic on the runway surface increases.

5.5.6.2 Alerting for conflicting traffic during take-off

Potential Runway Incursions due to existing or emerging traffic conflicts during ownship's take-off roll have to be detected as early as possible in order to maximize the margin available for remedial action, as discussed in Section 5.5.3. Accordingly, once it is established that the flight crew has initiated take-off – based on the criteria derived in Sections 5.5.4 & 5.5.5.3 – a **"RUNWAY INCURSION"** warning will be issued whenever other traffic is detected on the runway surface ahead of ownship or within the applicable runway protection zone and at risk of physically infringing the runway within 10 seconds.

In contrast to preventive Surface Movement Alerting, hazardous situations may emerge at any time during the entire take-off run. Therefore, to ensure that no runway traffic conflict is missed, this warning is triggered up to V_1, and reduced to caution level beyond V_1. Moreover, in order to minimize the risk of unnecessary RTOs in the high speed regime, the sensitivity of the alert will be reduced beyond 100 kts by only taking into account traffic directly on the runway surface. Irrespective of whether the conflict still persists, the alert is removed at 100 ft RA after lift-off.

These trigger conditions ensure that, in accordance with Table 9, there are no alerts if other traffic is present on the runway as long as ownship is merely lining up and waiting for the take-off clearance. Only when initiating take-off, pilots will receive the warning described above for any other traffic in the runway protection zone ahead of ownship. Furthermore, in an environment supporting CPDLC clearances for runway manoeuvres, an additional **"RUNWAY TRAFFIC"** caution alert will be triggered if ownship has acknowledged a take-off clearance while other traffic is on the runway surface, irrespective of the thrust settings. Consequently, this permits the detection of Runway Incursions before the take-off roll has actually commenced.

However, in current operations at hub airports, take-off clearances are sometimes given while a preceding aircraft taking off is barely rotating or while a previous landing aircraft is just turning off the runway. To reduce the risk of potential nuisance alerts in routine operations, therefore, additional measures to increase the specificity of reactive alerts may be necessary, irrespective of the applicable CPDLC scenario. Future research will therefore have to address whether this could be achieved e.g. by excluding traffic moving away from ownship for the first seconds of the take-off roll. Besides, once take-off has been initiated, the alerts for traffic on final approach described in the previous section will be suppressed for all aircraft approaching from behind, since a rejected take-off would definitely worsen the situation.

For airport configurations with intersecting runways, any take-off and landing operations on these runways must be considered as potentially conflicting while ownship is taking off. In line with the criteria derived in the previous section, corresponding aircraft are characterised by having an altitude of less than 250 ft above the runway threshold and a groundspeed in excess of 40 kts. If the intersecting runway supports LAHSO operations, only traffic on the runway surface will be considered to exclude aircraft on final approach, which will be assumed to hold short of the runway used by ownship. Besides, a distinction between accelerating and decelerating surface traffic must be made to ensure that aircraft taking off are still taken into account, and that only landing aircraft are filtered.

Low-speed traffic rolling out, taxiing or back-tracking on intersecting runways that might be of risk of infringing ownship's take-off runway will be treated like any other traffic infringing the runway protection zone from the taxiway system. Accordingly, the **"RUNWAY INCURSION"** warning will be triggered when traffic on intersecting runways either infringes the LAHSO location or, alternatively, the core protection zone (cf. Section 5.5.4) and is within 10 s from entering the surface of the runway used for take-off by ownship.
Approximately halfway through the low speed regime, when ownship accelerates through 50 kts, there appears to be a need to limit the scope of traffic on intersecting runways taken into account for alerting to avoid spurious RTOs; thus warnings are limited to conflicting traffic that might enter the intersection in less than 15 s.
Clearly, this rudimentary initial approach to detecting conflicting traffic on intersecting runways calls for further sophistication, which may be a rewarding topic for future work in the field. One approach might be to use type-specific approach and runway deceleration profiles for other aircraft on crossing runways to compensate for the lack of acceleration/deceleration in ADS-B and TIS-B traffic data.

5.5.6.3 Conflicting traffic during final approach and landing

During approach, when ownship descends below 1500 ft RA, the landing runway established by SMAAS is continuously monitored for potentially conflicting traffic. At 450 ft RA or less, if any other aircraft are detected on the runway or within the applicable protection zone, a **"RUNWAY TRAFFIC"** caution alert is triggered. At or below 250 ft RA, if traffic fails to vacate the runway or if the conflict persists otherwise, the alert is raised to a **"RUNWAY INCURSION"** warning. Likewise, if conflicting traffic emerges below this altitude, the warning is issued immediately without preceding caution. Aircraft which are already airborne, i.e. more than 50 ft above the runway surface, form the only exception.
When this warning occurs during final approach, the flight crew is expected to initiate a go-around unless they can visually establish that the alert is spurious. At any rate, while the aircraft is still airborne, the flight crew can initiate a go-around at any time without endangering the safety of flight[128]. Nevertheless, unnecessary go-arounds due to nuisance or premature alerts must be avoided, since this might even-

[128] Initiating a go-around is safe provided that a sufficient amount of fuel is available and that there are no major technical problems, such as e.g. an engine fire. Besides, the corresponding Runway Incursion warning could be inhibited in case of an engine fire or insufficient fuel resources.

tually decrease the operational acceptability of the system, because frequent go-arounds will jeopardize the airline's efforts on fuel efficiency, punctuality or reduced maintenance costs, and thus cause economic disadvantage.
Particularly for high-density operations, there might consequently be a necessity to fine-tune the trigger conditions while maintaining the general fundamental principle. As an example, other aircraft with a groundspeed beyond 80 kts in the second half of the landing runway could be regarded as having taken off by the time ownship lands, and thus not be classified as conflicting. A similar exception might be applied to landing aircraft during turn-off when it can be established that they will have vacated the runway surface within the next 15 s.

Potentially conflicting traffic on intersecting runways is comparatively difficult to identify for the landing case, because the actual collision hazard depends on the precise geometry of the intersection, and on whether LAHSO operations are in use. If this is the case for ownship's landing runway, it is generally assumed that the flight crew will manage to respect this constraint, and consequently, any traffic on runways crossing beyond the LAHSO location is completely ignored. Based on a similar rationale, all landing traffic on intersecting runways featuring LAHSO operations is therefore excluded from conflict alerting. To minimize the risk of spurious alerts as far as possible, traffic on runways intersecting the landing runway in the last third of its length is only taken into account after touchdown.
For all other traffic on other runways moving towards the intersection and not subject to these constraints, fundamentally the same criteria as for conflicting traffic during entry into the runway protection zone from the taxiway system are applied:

- A **"TRAFFIC ON APPROACH"** caution alert will be issued for any traffic on final approach to crossing runways, i.e. all aircraft below 250 ft above the threshold of the intersecting runway, while ownship is simultaneously less than 450 ft RA above its landing runway.
- A **"RUNWAY TRAFFIC"** caution alert is triggered for any traffic on the intersection runway with ground speed beyond 40 kts; which is assumed to be either taking off or landing.
- A **"RUNWAY INCURSION"** warning is issued when, in otherwise identical conditions as above, ownship is less than 250 ft RA above the threshold of its landing runway.

It must be emphasised that these criteria are mainly safety-driven and intended for an initial evaluation of the principal functionality. In an operational context, particularly at busy airports, the will consequently most likely be a need for further fine-tuning to prevent nuisance alerts. As in the case of traffic turning off the runway in a single runway scenario (see above), these aspects will have to be addressed by future research. To make alerting more specific in the landing case, a coupling of SMAAS to a potentially available Brake-to-Vacate functionality, cf. [Vil09], should be envisaged. The selected runway exit and predicted landing distance from this system could be employed for a more specific identification of the part of the landing runway to be protected against intrusions by alerting. Again, these aspects have to be recommended to detailed investigation by future research.

5.5.6.4 Traffic alerting outside the runways

Outside the runways, and during low-speed operations in the runway environment, a TCAS-like CPA protection against conflicting traffic is used to minimize the risk of colliding with other traffic. Generally, any traffic in the immediate proximity within a radius of 50 m will be highlighted (Level 0) to attract the attention of the flight crew. Furthermore, if other traffic is predicted to infringe the type-specific protection zone around ownship within less than 10 seconds, a **"TRAFFIC"** callout as for ACAS will be raised. In this case, pilots should try to acquire the intruder visually as with current ACAS procedures, and to slow down or stop their aircraft in case of doubt, i.e. if external conditions do not permit to visually acquire the conflicting traffic. Since the hazards associated with a collision during low speed taxi operations are rather low in comparison to Runway Incursions, the use of warning level alerts by SMAAS is reserved to these immediately live-threatening situations.

In order to prevent that aircraft queuing for take-off do not receive nuisance alerts, there may be the need to reduce the threshold for this alert when other traffic is moving nearly in the same direction as ownship.

5.5.6.5 Constraints

A prerequisite for reactive Surface Movement Alerting is that data covering all relevant traffic on the manoeuvring area is available in sufficient quality, i.e. with the nominal update rate and minimum latency. Performance requirements are significant, since traffic in the runway environment is highly dynamic. TIS-B data reflecting a traffic situation 5 or 10 seconds in the past is of very limited use for reactive Runway Incursion alerting, particularly when trying to establish whether other traffic is taking off or has entered the runway protection zone.

Therefore, an issue with alerts based on traffic surveillance information is that there is no guarantee that information is complete, unless ADS-B out equipage is mandatory and potential equipment failures are addressed. Consequently, integrity, accuracy, update rate, latency and reliability of traffic data might limit the possibility to generate high-level traffic alerts.

Condition	Alert Type	Callout	PFD Text Message
➢ Taxiway/Apron Traffic conflict ➢ Traffic conflict on runway with both aircraft/mobiles < L2 speed limit	Caution (Level 2)	"TRAFFIC"	TRAFFIC
➢ Ownship approaching runway (landside) with traffic beyond L2/L3 speed limit present ➢ Ownship approaching runway (airside) below L2/L3 height limit with traffic present on runway ➢ ownship taking off with traffic beyond L2/L3 speed limit towards intersection on converging runway (non-LAHSO)	Caution (Level 2)	"RUNWAY TRAFFIC"	RUNWAY TRAFFIC
	Warning (Level 3)	"RUNWAY INCURSION"	RUNWAY INCURSION
➢ Ownship approaching runway (landside) with approaching traffic 500 ft above ownship altitude or less	Caution (Level 2)	"TRAFFIC ON APPROACH"	TRAFFIC ON APPROACH
➢ Ownship approaching runway (landside) with approaching traffic 250 ft above ownship altitude or less	Warning (Level 3)	"RUNWAY INCURSION"	RUNWAY INCURSION

Table 12: Summary of reactive SMAAS alerts

Table 12 summarizes the callouts provided by the reactive part of SMAAS. Additionally, whenever a runway traffic conflict requiring a warning alert has been resolved, an TCAS-style **"CLEAR OF CONFLICT"** is sounded. Consequently, there are, in addition to the seven callouts for preventive Surface Movement Alerting, only four additional ones for the reactive functionality. Therefore, the introduction of SMAAS would result in the addition of only nine new callouts to the flight deck, because **"TRAFFIC"** and **"CLEAR OF CONFLICT"** are already known from TCAS and used in an identical fashion. Given the complexity of the Surface Movement Alerting functionality, this appears to be a reasonable number.

5.5.7 Human-Machine Interface for Surface Movement Alerting

The commonly accepted design principles for flight deck alerting systems [SAE88a] as well as the need for consistency and adequate prioritisation with mandatory other onboard alerting systems [SAE88] impose considerable constraints on the Human-Machine Interface (HMI) design for Surface Movement Alerting, as discussed in Section 5.5.2. The integration into an existing cockpit environment with its potentially unique design philosophy may, depending on the aircraft type, further limit the design choices available. Therefore, these boundary conditions resulting from airworthiness and standardisation constitute the main challenge in defining a suitable HMI for Surface Movement Alerting.

In line with the flight deck alerting philosophy derived in section 5.5.2, Surface Movement Alerting cautions and warnings are accompanied by voice callouts to alert the flight crew, whereas the localisation of the hazard causing the alert is conveyed by an accompanying visualisation on the airport moving map. Both the callout and the display simultaneously provide further explanation of the situation, and can be supplemented by additional explanatory textual information where necessary. This is intended to ensure commonality between the presentation of surface movement and particularly Runway Incursions alerts.

5.5.7.1 Visualisation and callouts for preventive Runway Incursion alerting

The visualisation of Runway Incursion alerts is an example of how the need for consistency with existing systems de facto dictates design choices. Upon alert, onboard surveillance systems such as TCAS or TAWS highlight the part of the external environment to which the threat relates, not the ownship symbol, probably because a colour change of the ownship symbol to amber or red is not considered to be sufficiently conspicuous. In analogy to this, therefore, the corresponding runway or runway elements will have to be highlighted in case of a Runway Incursion alert.

Kubbat *et al.* were the first to suggest using a colour change of the runway surface to indicate a potentially hazardous condition or Runway Incursion [Kub99]. This choice seems reasonable for several reasons. First of all, in the typical airport moving map ranges, the representation of the runway surface usually covers a significant part of the display area, which is likely to make a colour change of that area an efficient visual cue or attention-getter to induce the immediate awareness or immediate reaction required in case of a caution or warning. Using the whole runway surface, as opposed to the part of immediate concern (such as a closed runway segment), additionally minimizes the risk that the alert visualisation is hidden by particular combination of range or mode. By contrast, only an automatic range and/or mode adaptation in case of an alert, as discussed in Section 5.5.7.2, can fully eliminate this issue.

Conversely, using merely the runway outline to convey an alert condition appears to be inappropriate. Due to the smaller resulting area that will eventually be highlighted in an alert colour, it is considered as a much less efficient visual cue, and therefore not deemed suitable to convey information that requires the crew's immediate awareness or reaction. Accordingly, the runway outline is used for different purposes within SMAAS, such as highlighting the FMS-selected runway and the presentation of take-off and landing clearances, see Sections 5.3.2 and 5.4.3, which do not necessitate immediate awareness.

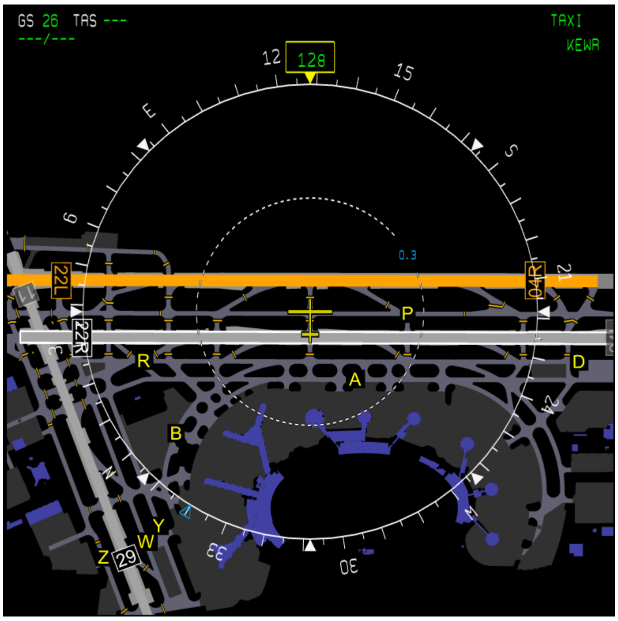

Figure 80: Common visualisation of all Runway Incursion caution (Level 2) alerts

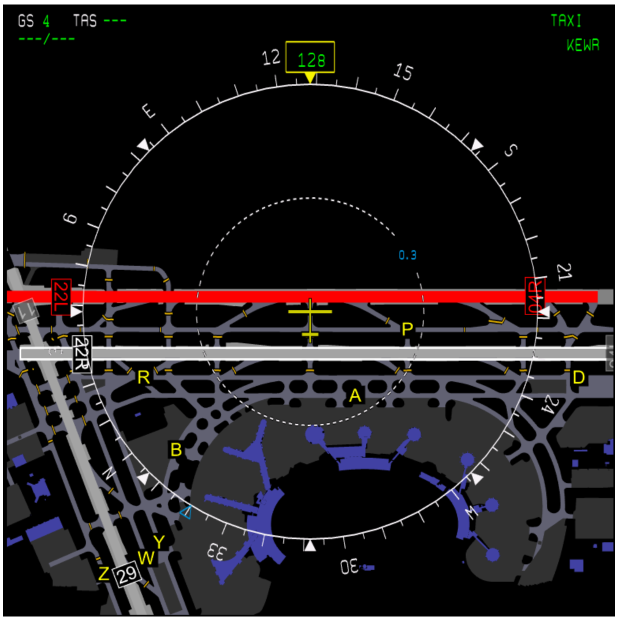

Figure 81: Runway Incursion warning alert (Level 3) visualisation

Figure 80 and Figure 81 show the resulting visualisation of Runway Incursion caution (Level 2) and warning (Level 3) alerts, respectively, that was used for the simulator evaluation campaign described in Chapter 8. The entire runway surface, including the runway outline, is highlighted in the colour corresponding to the applicable alert level (cf. Table 13) as long as the alert condition persists. Simultaneously, any runway or other pertinent airport markings are removed in the ranges where they would normally be displayed. Furthermore, the runway labels also change font and outline colour according to the alert level, using the default black background. The design intention behind this is twofold: first, the label of the runway concerned by the alert is itself highlighted through the use of a signal colour like amber or red. Secondly, this helps to maintain a visually integral runway representation. Otherwise, if the labels retained their default or even dimmed representation as described in Section 5.3.3 (see Figure 49), this would result in three seemingly fragmented runway sections in amber or red on the display, separated by the runway labels.

The integration of the runway outline into the alert visualisation is based on the philosophy that the caution or warning condition takes precedence over any other information normally conveyed via the runway outline, such as FMS-selected runway (or restrictions thereof), for the duration of the alert. The representation of take-off and landing clearances forms a slight exception, because any existing clearance information is permanently removed following a traffic-related Runway Incursion warning. The underlying rationale is that a Level 3 Runway Incursion alert, particularly when resulting in a rejected take-off, will necessitate at least a new take-off clearance. Likewise, since the crew is expected to execute to a go-around manoeuvre during a Level 3 alert prior to landing, a new landing clearance will be required as well. Conversely, in case of a caution alert, which hints more to a developing situation than to an acute problem, the crew may still choose to proceed with the originally intended manoeuvre, and clearance information is returned once the alert has ceased.

Other visual cues, such as the use and placement of textual messages or the behaviour of the Master Caution and Master Warning lights are highly airframe-specific. In the frame of SMAAS simulator evaluation campaign, textual messages briefly summarizing the nature of the alert were presented on the PFD for Level 2 and Level 3 alerts (see Table 10), in accordance with the Airbus cockpit philosophy as described in [Air05]. Additionally, the Master Caution/Master Warning lights, respectively, were lighted, and pressing them enabled flight crews to silence aural alerts.

For the field trials with the Navigation Test Vehicle (cf. Chapter 7), the standalone airport moving map configuration featured a marginally different alerting HMI. Instead of a steady colour change, the runway surface would pulse in the colour associated with the corresponding alert level, alternating with a framed message box in the display centre presenting the runway threshold names and in the same alert colour. For Level 0 alerts, however, the threshold name was displayed in magenta for the FMS-selected runway, superseded by a cyan/green representation whenever a line-up or take-off clearance was assigned/acknowledged for the respective runway. Furthermore, for Level 0 alerts, the colour of the runway surface was changed to yellow instead of white. Besides, text messages were presented in a status line below the airport moving map instead of the PFD.

In accordance with the commonly accepted principles of Flight Deck Alerting, cf. [SAE88a], all Level 2 and Level 3 alerts are accompanied by a callout detailing the nature of the alert. Callouts also ensure that flight crews do not miss an alert even if the currently selected display configuration does not permit them to see the airport moving map in sufficient detail.
Any deviations from this principle and the precise wording of the SMAAS aural alerts have already been detailed in the previous section describing the corresponding alerts. Table 10 provides a summary of callouts and textual messages for preventive Surface Movement Alerting.

5.5.7.2 Visualisation and callouts for Reactive Runway Incursion Alerting

Since all traffic alerting systems aboard an aircraft have to be consistent in the way alerts are presented to avoid confusion, the visualisation of conflicting traffic in the aerodrome environment must strive for maximum commonality with TCAS as mandatory system, in line with the discussion in Sections 5.5.1 and 5.5.2. Consequently, the traffic alerts provided by SMAAS will also have to be visualised by changing colour and/or shape of the symbol associated with conflicting traffic.
Apparently, if conflicting aircraft traffic is not supplying valid track or heading information, the same shape-modified traffic alert symbols as for TCAS (amber circle, red square, cf. Figure 20 in Section 3.2.1) can be used for Level 2 and Level 3 alerts, respectively. This seems necessary to avoid the discrepancies with TCAS that would inevitably result from presenting an amber or red diamond symbol. However, since it may be essential for pilots to perceive at a single glance whether conflicting traffic is entering or leaving the runway, directional information – where available – must be retained throughout an alert, which precludes a general use of the TCAS caution and warning symbols for Surface Movement Alerting. Nevertheless, since the aero-

drome traffic symbology derived in Section 5.2 is already quite complex and uses symbol shape to code the type of traffic, an additional dedicated shape change for the different alert levels that preserves directionality does not seem appropriate.
Consequently, aircraft or vehicle symbols are merely highlighted in the colour corresponding to the applicable alert level, see Table 13, which summarizes symbol and runway colours associated with the different alert levels, for details. Accordingly, amber and red symbols are used to indicate Level 2 (caution) or Level 3 (warning) alerts, respectively. The distinction between Level 1 and Level 2 alerts is made through the presence of a callout – every caution is accompanied by a callout, whereas there is no aural alert for Level 1. This approach is consistent with both TCAS implementations and the standards for flight deck alerting systems and colour coding [SAE88, SAE88a].

Alert Level	Traffic Symbol	Runway
No alert	white	*default*
Level 0	**yellow**	**white**
Level 1	amber	amber
Level 2	amber	amber
Level 3	red	red

Table 13: Colour coding for different alert levels

It is crucial that the flight crew does not miss an alert due to display configuration, and that an identification of the traffic in conflict occurs as soon as possible. Therefore, irrespective of pilot settings with respect to the presentation of aerodrome traffic, at least the conflicting aircraft or vehicles have to be displayed in case of a SMAAS traffic alert, again in analogy to TCAS, cf. [RTC97]. Nevertheless, an open issue in this context is whether merely the conflicting traffic or the complete traffic picture should be activated automatically upon alert. The latter would be intended to provide the crew with adequate situational awareness for conflict resolution, thus ensuring that any corrective action taken by the crew does not lead to a consecutive traffic conflict. However, an interview with two airline captains having an official function in the IFALPA aircraft design and operations committee during the design phase yielded that, in contrast to TCAS, only the conflicting traffic itself should be presented while on the ground, because both the options for conflict avoidance and the risk of consecutive alerts are much more limited on the ground. Furthermore, it should be considered that there is usually an operational reason for de-selecting the display of traffic. Therefore, it was decided to limit the automatic pop-up to conflicting traffic only.

While the behaviour of traffic symbology in case of alert is thus largely predetermined by standardisation, the presentation of the traffic labels offers a certain degree of freedom for HMI design. For improved conspicuity, displaying the traffic triggering the alert along with its associated label appears to be reasonable. Therefore, for Level 1 alerts and higher, the traffic label is always displayed irrespective of potentially differing crew settings with respect to traffic labels.
At the same time, the presentation of reactive, traffic-related alerts should also be consistent with the way preventive SMAAS alerts are visualized. In particular, it seems appropriate to present Runway Incursion alerts in a similar fashion irrespective of whether they are triggered due to traffic or other causal factors. In this context, the concept for the visualisation of reactive Runway Incursion alerts should be regarded as an extension of the HMI for displaying preventive SMAAS alerts.

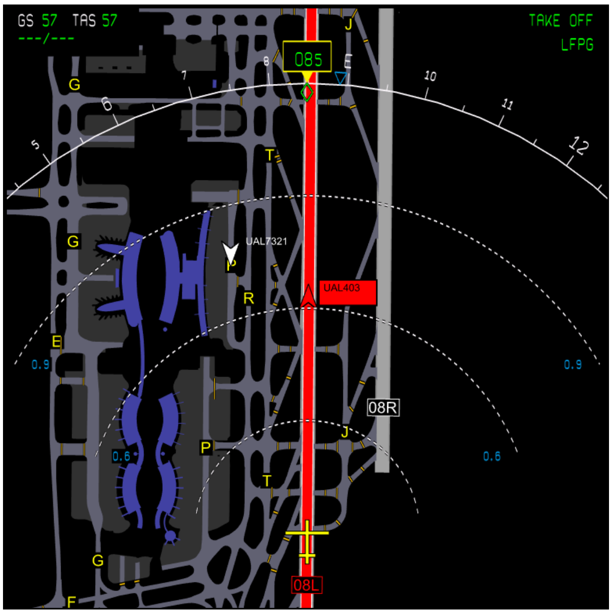

Figure 82: Visualisation of reactive Runway Incursion warning (Level 3 alert)

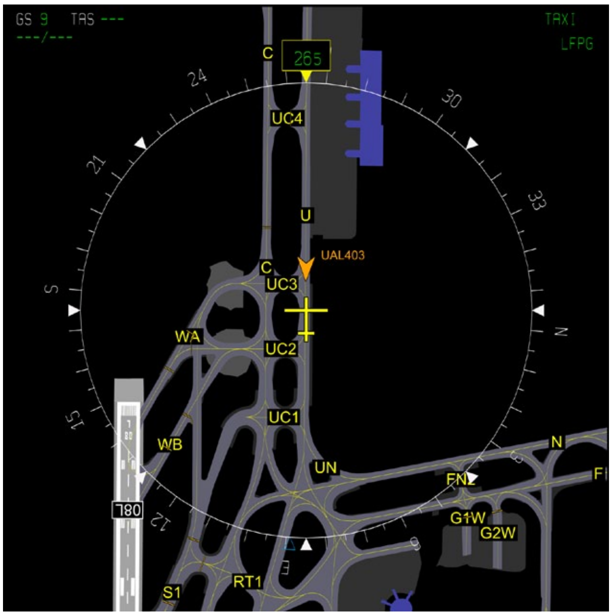

Figure 83: Reactive Surface Movement Alert (caution) not related to a Runway Incursion

In conclusion, reactive Runway Incursion alerts are therefore visualized by highlighting both the runway surface (as described in Section 5.5.7) and the intruder causing the alert in the colour corresponding to the applicable alert level, cf. Figure 82. For intersecting runways, only the surface of the runway used by ownship is highlighted in addition to the conflicting traffic, unless an infringement of intersecting runway by ownship necessitates a simultaneous preventive alert.
Since this design may evidently result in an intruder being displayed on a runway highlighted in exactly the same colour, intruder symbols are given a black halo to make them discriminable from the background in this case. Additionally, the intruder label is 'inverted' for all Runway Incursion alerts: black text is displayed on a label background coloured according to the applicable alert level. This is intended to serve as another measure to make the intruder more conspicuous in the runway environment. Conversely, for all traffic alerts not related to a Runway Incursion, only the colour of the label text is changed. Consequently, the style in which the traffic label is presented introduces some redundancy beyond colour.
Figure 82 shows the HMI for a Runway Incursion warning that was evaluated in the simulator evaluation campaign described in Chapter 8. Since the conflicting traffic is directly on the runway surface, the traffic label simultaneously serves as an additional visual cue where to look for the intruder. Furthermore, this solution maintains the readability of the callsign even if the label of the conflicting traffic intersects with the runway surface. For traffic alerts not related to Runway Incursions, such precautions are not necessary, as shown on the example of a traffic caution alert on the taxiway system in Figure 83, where just the colour of the label text is changed.

Since pilots may choose range and mode for the display hosting the airport moving map at their discretion, there is a non-negligible risk that conflicting traffic might be out of range or otherwise outside the selected display field of view. However, to understand the precise nature and severity of the traffic conflict, and to react adequately, the flight crew must be made aware of the precise location of the traffic trig-

gering the Runway Incursion alert. Besides, having the conflicting traffic in view on the display is also a well-established requirement for ACAS, cf. [RTC97].
Of course, one could procedurally prescribe or recommend that at least one pilot always uses the AMM in a range where the whole runway, including potentially intersecting runways, is visible during take-off. But even then, there is no guarantee that the crew adheres. When taking off into a difficult and rapidly changing weather situation, or with potentially conflicting traffic at a runway intersection close to the own aircraft, displaying the airport moving map may probably not be best suited to the task at hand, and there might be valid reasons to deviate from such a procedure.

Consequently, this raises the question which measures should be taken in HMI design to address situations in which the display is not configured appropriately when a SMAAS alert occurs. From the considerations above, it is evident that pilots should nevertheless be provided with an appropriate visual alert indication in this situation. Therefore, to ensure that the crew is alerted efficiently, additional visual cues might be required for cases where the conflicting traffic is outside the current range set for the display in a given mode.

In view of the situations in which a Runway Incursion alert for conflicting traffic is required, it is immediately evident that ownship will be either on the runway surface or approaching it when a corresponding SMAAS alert is triggered. Consequently, at least part of the runway should be visible on the display in most cases, irrespective of the precise display settings. Thus, highlighting the runway surface is believed to be an efficient visual alerting cue in virtually all cases where conflicting traffic is momentarily not in view. Apart from the consistency issues mentioned above, there are consequently further practical reasons to highlight not only the conflicting traffic, but also the runway surface in case of a Runway Incursion alert.
However, this still does not provide pilots with cues concerning the location of the conflicting traffic. One potential approach, which is currently used on Airbus aircraft, consists of requesting the flight crew to change range and mode. If ranges beyond 40 NM are selected and a TCAS Traffic Advisory (TA) or Resolution Advisory (RA) occurs, a text message "TCAS: REDUCE RANGE" is displayed on the ND in amber or red, respectively. Likewise, if the ND is set to PLAN mode, a "TCAS: CHANGE MODE" text message will appear in exactly the same fashion [Air05].

Alert Level	Condition	ND Text Message coloured according to the associated alert level.
Level 3 Level 2 Level 1	PLAN-Mode selected	[CALLOUT TEXT], CHANGE MODE
	ARC-Mode selected, conflicting traffic behind	[CALLOUT TEXT], CHANGE MODE
	Range > 10 NM selected	[CALLOUT TEXT], REDUCE RANGE
	Conflicting traffic out of range	[CALLOUT TEXT], INCREASE RANGE

Table 14: Proposal for ND text messages for off-scale reactive SMAAS alerts

Table 14 summarizes an analogous Airbus-style solution for traffic-related SMAAS alerts, which seems favourable from a flight deck consistency perspective, given that the A320 aircraft family is used as reference for this thesis. Accordingly, for Level 1 alerts and higher, the ND would show a text message equivalent to the callout associated with the alert, followed by an instruction to change mode or range.

Nevertheless, particularly in case of a safety-net alert, which requires immediate pilot reaction and may create an environment of very high workload, the flight crew's resources should not be spent on reconfiguring a display. Since pilots need to focus on addressing the alert, including potentially associated recovery procedures, a manual display reconfiguration is consequently sub-optimum in terms of priorities and thus appears questionable from a human factors perspective.

To avoid this, and to relieve the flight crew of the task of finding an appropriate range/mode combination for conflicting traffic, an automatic or semi-automatic display reconfiguration upon alert could be envisaged. Other aircraft manufacturers have followed this approach. On the McDonnell-Douglas MD-11, for example, a dedicated TCAS mode can be selected on the ND via the EIS Control Panel (ECP), cf. Figure 84. When the corresponding button is depressed, the ND changes to a 10 NM default range, and all other information, such as weather radar, bearing pointers, flight plan etc. is removed [McD90]. In case of a TCAS resolution advisory, this virtually guarantees that the conflicting traffic is in view, and that other information is de-cluttered. In fact, asking a flight crew to push a single button in an alert situation appears as a reasonable compromise between fully automatic and completely manual display reconfiguration, because it keeps the flight crew in the loop.

Figure 84: McDonnell-Douglas MD-11 EIS Control Panel (ECP) on Captain's side with selector for dedicated TCAS mode

The available range and mode controls are, however, the main factor determining the feasibility of an automatic or semi-automatic adaptation of range and mode to bring conflicting traffic into view. Since many EFIS control panels use knob shape, notches and legends or other hardware means to indicate pilot selections, a mismatch of hardware controls and actual display configuration is an almost inevitable consequence of an automated range or mode adaptation. Evidently, though, this has to be avoided to prevent potential pilot confusion[129]. By contrast, there is no issue when the indication of EFIS configuration is decoupled from selector hardware. On the MD-11, for example, ND range is adjusted via an INCR or DECR pushbutton on the EIS Control Panel (ECP), while the selected range is only displayed on the display[130], cf. Figure 84. Similarly, on the Airbus A380, the selector position is no longer only indicated by a hardware notch, but through the illumination of a green LED triangle corresponding to the current selection[131].

[129] Reverting the display to the originally selected range and mode once the alert condition is over might seem to be a potential solution to this issue at first glance, but misses a crucial point: If pilots want to override - with an alert still persisting - the automatically established setting, e.g. by choosing a range/mode combination providing more detail, they will have to start out from a hardware setting inconsistent with their display. This, in turn, might induce further workload and confusion in an already very demanding situation.

[130] While this solution facilitates the introduction of new display ranges through modified EFIS software, since no hardware modifications are required in this case, a potential disadvantage associated with indicating the range selection only on the ND itself is that the flight crew needs to go head down to confirm the range setting.

[131] Due to lack of publicly accessible information, however, it was not possible to infer whether the A380 FCU design was established in this way with an automatic range/mode adaptation in view or not.

5.5.7.3 HMI Design for other Surface Movement Alerts

Concerning the HMI design for the Taxiway Take-off Prevention, there is a significant dilemma concerning the visualisation on the airport moving map. From a conceptual and alerting philosophy perspective, cf. Section 5.5.2, this alert should be accompanied by dedicated visual cues on the display. The problem, however, is that a taxiway surface highlighted in amber or red was considered to be far too evocative of the Runway Incursion alerts, and was therefore a priori excluded to avoid potential confusion. After all, the purpose of the Taxiway Take-off Prevention is to alert the flight crew that they are **not** on a runway. Accordingly, it was decided that runway surfaces would remain the only airport areas to be highlighted in an alert colour. Several other modifications of the taxiway presentation were considered as well, among others pulsing taxiway labels and/or highlighting the taxiway centre lines in the colour corresponding to the alert level, but eventually discarded during the prototyping sessions with test and technical pilots since neither guidance lines nor labels are displayed in all available airport moving map ranges. Eventually, a simple text message “TWY [*TWY Name*]” reminding the flight crew of the taxiway they are currently located on remained as sole visual cue on the display. The only other related indication that the crew received when exceeding 30/40 kts of ground speed was a change from a green to an amber numerical groundspeed indication.

Likewise, finding an appropriate callout for this alert turned out to be difficult. A repetitive callout instructing the flight crew to abort take-off, such as “STOP”, seems a natural choice, because cancelling the erroneously initiated take-off is anyhow the only option in this case. Accordingly, the considerations in Section 4.4.4 on conflict resolution instructions apply to Runway Incursion alerting only.
Nevertheless, potential ambiguities and failure modes have to be taken into account a priori. While a “STOP” callout may be perfectly appropriate on a taxiway, it might induce a potentially hazardous rejected take-off if aircraft positional accuracy or integrity degrades such that an apparent shift to a parallel taxiway occurs during the take-off roll. Therefore, after a “TAXIWAY TAKE-OFF” callout during the evaluation with the Navigation Test Vehicle had been criticised by most evaluation participants, cf. Section 7.7, a basic “NOT ON RUNWAY” callout was eventually chosen to alert the flight crew that they are trying to take off outside the runways.

5.5.8 Schematic SMAAS Logic

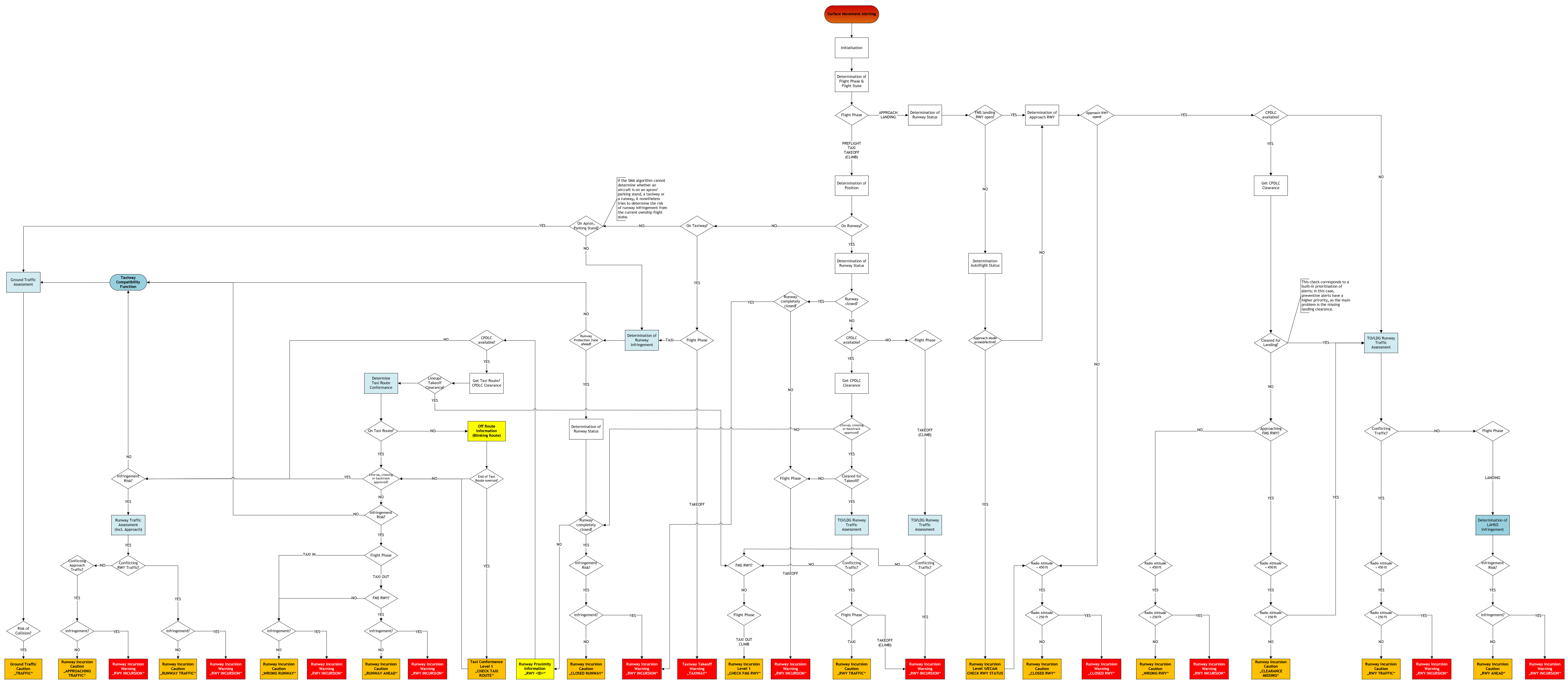

Figure 85: Schematic overview of overall SMAAS logic (simplified)

5.5.9 Prioritisation with Other Cockpit Alerts

The alerts generated by Surface Movement Alerting must be properly prioritised in relation to other flight deck alerts, particularly those generated by other onboard surveillance systems, cf. [SAE88a]. While a fixed or dynamic prioritization scheme helps to prevent conflicting alerts, this may not always be sufficient to address the issue of consecutive alerts, i.e. a subsequent alert triggered by a second surveillance system as a result of a recovery manoeuvre instructed (either procedurally or system-wise) by a first surveillance system. This has led to the development of Integrated Surveillance Systems (ISS) in research, cf. [Ver05], and industry, resulting in the ARINC 768 standard [ARI05]. Although this document explicitly mentions "runway alerting" as future growth potential, it does not contain any considerations regarding the prioritisation of the corresponding alerts.

For Surface Movement Alerting, the only major competitive alert on the ground is the take-off configuration warning, which should always have priority as already established in Section 5.5.4. Consequently, alert prioritisation is of particular concern only for the SMAAS alerts triggered during final approach and landing. ARINC 768 contains the same static alert prioritisation table as the one required for TAWS according to TSO-C151b [FAA02c], except for the spare V_1 (Priority 5) and engine fail (Priority 6) callouts. Therefore, extending this table by the SMAAS alerts appears to be a good starting point, based on the principle that the alerts provided by the Windshear Warning System and TAWS must have priority over SMAAS and TCAS, because windshear and terrain hazards will almost inevitably result in a crash if not mitigated. The necessary modifications are highlighted in Table 15; which is otherwise identical to references [ARI05, FAA02c].

Priority	Alert Type	Level	Comments
1	Reactive Windshear Warning	WARNING	
2	Sink Rate Pull-Up Warning	WARNING	continuous
3	Excessive Closure Pull-Up Warning	WARNING	continuous
4	RTC Terrain Warning	WARNING	
5	**FLTA Pull-Up warning**	**WARNING**	**continuous**
6	**PWS Warning**	**WARNING**	
7	**SMAAS Runway Incursion Warning**	**WARNING**	
8	**TCAS Resolution Advisory**	**WARNING**	
9	RTC Terrain Caution	CAUTION	continuous
10	Minimums	Information	
11	FLTA Caution	CAUTION	7 s period
12	Too Low Terrain	CAUTION	
13	PDA ("Too Low Terrain") Caution	CAUTION	
14	Altitude Callouts	Information	
15	Too Low Gear	CAUTION	
16	Too Low Flaps	CAUTION	
17	Sink Rate	CAUTION	
18	Don't Sink	CAUTION	
19	Glideslope	CAUTION	3 s period
20	Predictive Windshear Caution	CAUTION	
21	Approaching Minimums	Information	
22	Bank Angle	CAUTION	
23	Reactive Windshear Caution	CAUTION	
24	**SMAAS Caution Advisories**	**CAUTION**	
25	**TCAS TA ("*Traffic, Traffic*")**	**CAUTION**	**Continuous**

Table 15: Integrated Surveillance System (ISS) alert prioritisation with SMAAS extension

5.6 Summary

In this chapter, the different layers of protection against Runway Incursions offered by the envisaged Surface Movement Awareness and Alerting System (SMAAS), each of which addresses an individual deficiency of current flight decks with respect to either availability or accessibility of information required for safe operations in the aerodrome environment, as identified by the ***High-Level Requirements***, have been discussed in detail. It could be shown that there are no fundamental technology hurdles precluding the realisation of such an onboard surveillance system, although there are clearly still substantial challenges in the domain of Controller-Pilot Data Link Communication (CPDLC).

A basic, but essential level of protection against disorientation is provided by the presentation of the airport topology contained in the Aerodrome Mapping Databases (AMDB) in the form of an airport moving map (Section 5.1), which can easily be enhanced by a visualisation of the departure or landing runway planned in the FMS, and alerts in the style of an extended Take-off Configuration Warning whenever the flight crew attempts to take off outside this FMS-selected runway[132]. These features alone, which require only an AMDB and the availability of a Global Navigation Satellite System such as GPS to supplement current inertial navigation, would most probably have been sufficient to alter the sequence of events in the Runway Incursion accidents involving disorientation at Madrid (1983), Anchorage (1983, Korean Airlines), Detroit (1990), Taipei (2000) and Lexington (2006), cf. Table 2 in Section 2.2.
Additionally, a flight deck representation of the surrounding traffic (Section 5.2), based on e.g. ADS-B technology, might have reduced the collision hazard in those cases where visual acquisition of conflicting runway traffic was impossible due to visibility conditions or conspicuity issues, in particular the accidents at Tenerife (1977), Anchorage (1983, Japan Airlines), Sioux Falls (1983), Atlanta (1990), Los Angeles (1991), St. Louis (1994), Paris Charles-de-Gaulle (2000) and Milano-Linate (2001).

Essentially, it may therefore be concluded that an airport moving map with a presentation of the surrounding traffic could already have contributed substantially to prevent all of the accidents studied in this thesis. Furthermore, the additional visualisation of short-term or temporary changes and other details on the aerodrome's operational status (Section 5.3) as well as displaying ATC instructions and clearances (Section 5.4) would clearly have interrupted the chain of events at some stage for several accidents, as discussed previously.
Nevertheless, it cannot be stated with certainty that the mere presentation of additional information for enhanced situational awareness would have been sufficient to prevent all of these accidents, although this appears plausible. Accordingly, an additional alerting functionality is clearly required. In this context, it has been shown Section 5.5 that preventive Surface Movement Alerting can be a highly specific and thus very powerful means of detecting and avoiding ownship Runway Incursions, particularly when based on CPDLC data.

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[132] Nevertheless, the underlying FMS logic might have to be modified, since present systems sometimes use the initiation of take-off for a position update by setting the coordinates of the FMS-selected runway, whereas SMAAS requires that the GPS-based position is used to determine the runway the aircraft is located on.

Nonetheless, as already outlined in Section 4.2.2, an approach solely relying on preventive functions is vulnerable in at least three aspects. First of all, a hypothetical mandate for equipage with SMAAS would, as past experience with ACAS and TAWS suggests, require several years to become effective. Consequently, many aircraft will not be equipped with a corresponding system any time in the near future, and therefore continue to cause Runway Incursions at a rate similar to today. Besides, less than 100% equipage is not only a temporary issue for a transition period following a potential mandate, but may remain reality for vehicles or airfields with mixed commercial and general aviation operations.
Secondly, in view of the incidents and accidents in which controllers erroneously assigned clearances resulting in Runway Incursions, there is sufficient evidence that ATC does not always work flawlessly, cf. Section 2.3.5. However, the correctness of controller instructions is at the heart of the assumption that preventive alerting alone will provide sufficient protection against Runway Incursions.
Last but not least, as discussed in Section 5.4, there are still considerable unsolved issues concerning the availability and operational impact of runway-related CPDLC services, which would be required to achieve full preventive coverage. Even when assuming that these issues will eventually be resolved, the aspect of worldwide availability and contingency measures in case of CPDLC failure must additionally be taken into account. Consequently, this necessitates an approach to runway safety that does not exclusively depend on the availability of runway-related CPDLC clearances.

Therefore, reactive Surface Movement Alerting is additionally required. Evidently, it is impossible for Surface Movement Alerting to infer whether ownship is authorised to operate within the confines of the runway protection zone, which includes take-off and landing, in the absence of the respective CPDLC information. However, as soon as traffic detected in the runway environment is performing a manoeuvre incompatible with the operation conducted by ownship, this evidently indicates that the procedural safeguards associated with runway operations are have been violated, and an alert to address the resulting Runway Incursion hazard is triggered before there is an actual collision hazard. Consequently, analysing the manoeuvres performed by the surrounding traffic for potential incompatibilities permits indirect conclusions on authorisation to use the runway at least to the extent that, in the presence of conflicting traffic, either ownship or the other traffic will necessarily have been authorised either in error or not at all.
In conclusion, the availability of data on the surrounding traffic can thus be regarded as a potential compensation and back-up for missing runway-related CPDLC services, since this permits to detect obvious conflicts in the authorisation for runway operations. As an example, if ownship fails to hold short of a runway in a conventional R/T environment while other traffic is taking off, an alert can be triggered solely based on the traffic information. Conversely, in a CPDLC environment, the preventive alert will be triggered irrespective of the presence of other traffic if ownship attempts to take off without clearance. Preventive and reactive Surface Movement Alerting can therefore be regarded as supplementary in many situations. Generally, SMAAS offers several redundant layers of defence against Runway Incursions, and therefore exhibits a certain degree of robustness against the unavailability or failure of a certain source of information.

6 Considerations on Verification and Validation

Verification checks a system against the specification documents and determines to which extent the requirements set therein are met, thus establishing whether the realisation coincides with the system conceived. In other words, verification is the process of answering the question whether a system was 'built right'.
By contrast, according to the CAATS glossary, validation is "*the process by which the fitness-for-purpose of a new system or operational concept being developed is established*" [Eur07]. Validation can thus be defined as the process of answering the question "Are we building the right system?" and usually involves prospective users of the system under evaluation, such as pilots or air traffic controllers.
In the context of this thesis, the verification process was coupled to the integration of the SMAAS components on the selected evaluation platform and therefore generally completed before an assessment with pilots took place. All pilot-in-the-loop evaluations conducted in the frame of this thesis are therefore considered as validation activities.

6.1 Validation Objectives

The global validation objective concerning the Surface Movement Awareness and Alerting System (SMAAS) conceived in the previous chapter is to determine whether an onboard surveillance system is an appropriate means of addressing the problem of Runway Incursions. Accordingly, one approach to validation could consist of establishing the capability of SMAAS to prevent and mitigate hazardous situations in the airport environment, particularly Runway Incursions, and thus its potential contribution to improve runway safety. An assessment of safety *per se*, however, is extremely difficult, because there is a profound lack of directly accessible objective metrics, which is often referred to as the 'criterion problem', cf. [Fit51]. Accordingly, any impact on runway safety can only be inferred indirectly, e.g. by studying the impact of SMAAS on the number of Runway Incursions. However, in spite of the increase in recent years, as discussed in Section 1.4, Runway Incursions are still comparatively rare events with typically less than 10 occurrences per one million operations. Therefore, achieving a statistically sound proof in a realistic, representative simulator exercise with a cumulative duration of less than 150 hours is simply impossible. Besides, previous experience from another flight simulator experiment assessing terrain-related onboard surveillance systems has already shown the futility of an approach attempting to induce specific flight crew errors through scenario design, cf. [Ver05].

Consequently, a different approach to validation will have to be used. Essentially, the necessity of making certain information accessible to flight crews for the avoidance of Runway Incursions has already been established, albeit theoretically, as result of the analysis of selected incidents and accidents in Section 2.2, and expressed in the form of ***High-Level Requirements*** in Section 2.3. This reduces the validation task to establishing that SMAAS conveys the additional information necessary according to the

High-Level Requirements in a suitable and efficient form. Due to the modularity of SMAAS, this can be deduced from an assessment of its individual sub-functions.

In assessing and understanding complex human-centred systems, the three interdependent categories technical usability, domain suitability and user acceptability introduced by Harwood have proven helpful [Har93]. Domain suitability refers to the appropriateness of information presented on the flight deck in supporting the cognitive requirements of the task at hand, whereas user acceptability addresses usability and user satisfaction. With technical usability already covered by integration and verification activities, including shakedown sessions, the main objective of the SMAAS validation campaigns can therefore be restated as assessing the operational relevance (Harwood's domain suitability) and the usability (Harwood's user acceptability) of the additional information items and alerts provided by SMAAS.
Since one of the central goals of SMAAS is to compensate deficiencies of current flight deck instrumentation by enhancing pilot situational awareness through a series of new display features, validation has an intrinsic focus on human-machine interface aspects. Nevertheless, it must be stressed again that the main purpose is to validate the underlying SMAAS concept itself. Therefore, the interest in validating the particular Human-Machine Interface (HMI) implementation chosen for this thesis is limited to demonstrating that a consistent, integrated solution based on an airport moving map is feasible. Consequently, special care was taken regarding the design of the prototypic HMI, because an immature or inappropriate HMI can and will negatively influence conceptual evaluation results. In other words, a deficient realisation might lead to negative feedback on the underlying concept, since it is often very difficult for external evaluators to discriminate whether the perceived deficiencies are due to the realisation or the concept. Even when an inappropriate implementation is apparent, e.g. in case a colour concept violating commonly accepted design principles is used for a flight deck display, this is still likely to have a detrimental effect on the evaluation, because it diverts participants' attention, resulting in a wealth of feedback on display colours, whereas the primary objective of the evaluation might have been entirely different.

In evaluating the domain suitability and usability of SMAAS, human factors aspects will therefore play a central role. This encompasses establishing the impact of the new display features on pilot situational awareness as well as an assessment of workload, at the level of ensuring that the SMAAS does not cause excessive extra workload in routine operations. Additionally, for the alerts, the adequacy and appropriateness in terms of timing, trigger conditions and reliability is of key interest.
Furthermore, it is worthwhile to assess the potential impact of the novel system on operations, including ATC and other stakeholders. In this context, it might be worthwhile to analyse at least the perceived impact on safety.
Last but not least, an assessment of the particular HMI design chosen must be conducted to identify potentially critical design issues, including possible certification concerns, which may be applicable to the concept in general. Besides, evaluation results on the HMI itself can later be used as an indication as to whether validation results on the functionality *per se* might have been impacted by issues or dissatisfaction with the particular HMI implementation of SMAAS chosen for this thesis.

6.2 Validation Strategy

6.2.1 Objective versus Subjective Techniques

A fundamental decision to be made in determining the validation strategy for SMAAS concerns the use of objective assessment techniques, because this has a substantial impact on experimental design, particularly on the setup of evaluation scenarios. Besides, objective measurements require the recording of certain aircraft parameters for later analysis, which is usually no problem in a simulator or an instrumented Navigation Test Vehicle. Generally, though, objective and subjective techniques can be applied in parallel.

Objective validation exercises typically compare different systems on the basis of certain pre-defined performance indicators and metrics, such as flight technical error, reaction time or minimum terrain separation in an evasive manoeuvre. Less frequently, binary criteria such as success in executing a certain manoeuvre or recognition of a conflict are employed. In most cases, an experimental system is assessed versus a baseline (see Section 6.4.1 for details) in order to determine to what extent the extended or modified features of the novel system constitute an improvement. Some authors, such as Newman and Greeley, regard objective measurements as the ultimate method of testing new aircraft systems [NG01]. However, a word of caution seems appropriate. The design of experiments measuring objective data requires exceptional care, particularly in human factors evaluations.
The main problem is that finding suitable objective metrics having a proven and contextually valid interrelation with system performance aspects such as situational awareness, workload or usability constitutes a formidable challenge. A typical assumption in this context is that improved situational awareness will lead to faster recognition of conflicts or quicker response to system failures, or alternatively a better adherence to an intended manoeuvre or trajectory, cf. [NG01]. While this is not necessarily wrong, this approach is abundant with pitfalls. Measured recognition time may be confounded by individual reaction times or bias induced by the experiment scenario (see below). Likewise, a low flight technical error does not necessarily correlate with high situational awareness concerning the flight path (or even the surrounding terrain), but may simply result from perfect adherence to flight director commands on a PFD. In this case, measurements would be confounded by pilot skill.
A further issue is the potential influence of scenario design on performance-based, objective measurements. As an example, for traffic conflict detection, experimenters may introduce bias by inadvertently designing scenarios in which conflicting traffic is always easier to detect with a CDTI, compared to visual acquisition. Such bias may be quite subtle and not immediately evident.
Besides, an issue often overlooked is that the pilots participating in the evaluation have to constitute a representative sample of the prospective user group for objective data to be meaningful. Otherwise, e.g. if airline pilots are used to evaluate a system intended for General Aviation, the experience and flying skills of these professional pilots might mask the actual difference between the baseline and the advanced system. In the other extreme case, their familiarity with complex avionics might help airline pilots to achieve objectively better performance with a system that is actually unusable for the average General Aviation pilot due to its complexity.

Last but not least, objective measurements result in far stricter requirements regarding the stability of the overall evaluation setup. Initial software prototypes sometimes lack this stability, which is crucial, because any technical failures usually invalidate all the objective data collected during a run, and due to potential training effects, it is often not possible to repeat a run. In this context, simulator fidelity is an aspect not to be neglected. Performance measurements on a certified flight simulator, on which pilots with the corresponding type rating can perform any procedure almost blind-folded, have a different level of validity than those in a generic research simulator, where both familiarity and fidelity aspects might act as confounders.

A huge advantage of subjective validation techniques is that pilots' expertise and experience concerning the operational environment can be harnessed to the fullest extent. Techniques for collecting subjective feedback encompass open loop comments, structured interviews and standardized or custom questionnaires, which in either case frequently involve Likert-style rating scales to collect participants' quantitative level of agreement (or disagreement) with certain aspects of the system under evaluation or the overall scenario.
Standardised questionnaires for assessing workload (e.g. NASA TLX) or situational awareness, such as SART (cf. Section 6.5.1), frequently transform feedback on individual questions into a single performance index according to pre-defined rules, which may then be used in a quantitative comparison. At any rate, variance analysis methods can in principle be applied to any quantified subjective feedback, irrespective of whether the original ratings or a performance index is used. Nonetheless, such comparisons do not have the same statistical power as those based on objective data.

Nevertheless, validation experiments without collecting subjective pilot feedback are virtually unthinkable, since early system prototypes such as the proposed SMAAS are hardly ever perfect and typically suffer from various smaller or larger deficiencies impairing operational usability. Since design processes are iterative, detailed subjective feedback is essential in determining which aspects of the system under study require improvement and why. Essentially, only open loop feedback, either during evaluation sessions or in a debriefing after the experiment can yield this information. Accordingly, the ultimate benefit of subjective techniques is that the feedback obtained can look beyond the limitations and constraints of the experimental setup, and may thus help in extending knowledge about further relevant operational or system design aspects. Additionally, pilot feedback thus obtained may contain hints at important operational aspects that are well-known to practitioners, but not immediately accessible or evident to the researcher based on the theoretical material available. By contrast, while objective measurements may result more precise results on a particular issue, is impossible to obtain such additional insight by using them. In this sense, objective techniques are self-contained.
Evidently, while pilots do not deliberately decrease their performance or make mistakes to emulate an 'average pilot' in an experiment measuring performance, their subjective feedback may take into account, albeit from an individual perspective, the interests and concerns of the pilot community as a whole, particularly if they have a flight test, technical or certification background.

6.2.2 Validation of Caution and Warning Alerts

As mentioned earlier in this section, Runway Incursions are still very rare events in relation to the vast number of flight operations. While this is reassuring for passengers, it creates substantial problems for the design of scenarios suitable to validate the caution and warning alerts provided by SMAAS.

Due to the high professionalism of flight crews, it is therefore questionable whether a validation approach waiting for participants to cause Runway Incursions during a simulator experiment will see any of the preventive Runway Incursion Alerting functions triggered with a limited number of participants. This situation is aggravated further by the fact that briefing and training prior to the actual evaluation session will necessarily disclose the purpose of the experiment and thus pre-trigger pilots concerning Runway Incursion hazards. Consequently, they will possibly dedicate more attention to these aspects during the evaluation than in everyday routine flight operations. Apart from higher vigilance, there will also be certain expectations as to what might happen during the evaluation scenarios, which, in turn, gives pilots cues to anticipate dangerous situations construed to trigger an alert.

In order to ameliorate these effects, creating high workload in scenarios to distract pilots might, on the one hand, increase the chances that there is a crew error leading to the triggering of an alert, but on the other hand, could generally distract the crew from the SMAAS, with the effect that its normal indications and advisories might not be noticed (and thus not evaluated) by participants.

These problems are less pronounced for reactive Runway Incursion scenarios, because conflicting other traffic can be introduced at any time. Nevertheless, repeatedly occurring Runway Incursions – as required for a thorough assessment of the reactive alerts – decrease the operational realism of scenarios. In conclusion, any validation approach counting on the 'natural' occurrence of Runway Incursions is prone to fail.

It was therefore decided to pursue an explorative approach with respect to the validation of the alerts, which consisted of employing demonstration scenarios explicitly and deliberately triggering the alerts and collecting exclusively subjective pilot feedback.

6.2.3 Conclusion

In view of the validation objectives for SMAAS, it is essential to capture pilots experience concerning the tasks associated with surface operations by letting them judge the operational relevance and support provided by SMAAS in a subjective fashion. Besides, the overall complexity of both SMAAS and surface operations suggests using an explorative approach.

Since participants of the evaluation with the Navigation Test Vehicle could not be in control of the vehicle, it was not possible to apply any objective measurements, because the limitations of the experiment forced pilots into a passive observer role. Besides, the use of real-time traffic data prevented reproducible scenarios.

Likewise, the simulator experiment was also limited to the use of subjective validation techniques, since the number of individual SMAAS functions to be assessed precluded both the inclusion of a baseline set-up as well as a strict separation of scenarios objectively establishing e.g. situational awareness and scenarios aimed at demonstration the alerting functionality.

6.3 Considerations on Participants

6.3.1 Participant Requirements

SMAAS as the system under evaluation is based on current-generation glass cockpit technology and, in principle, applicable to all aircraft types from turboprops, business and regional jets to large widebody passenger aircraft and freighters. Furthermore, the Institute's Research Flight Simulator is sufficiently generic for type-specific training requirements not to be an issue.
Consequently, there are no particular requirements regarding the aircraft type flown. Nevertheless, experience with an Electronic Flight Instrument System (EFIS) is mandatory, because the training effort would be too high otherwise[133]. Prospective experiment participants were therefore required to have a type rating for at least one aircraft type with a glass cockpit. Besides, while SMAAS can in principle be adapted to General Aviation aircraft, the focus of this thesis is on an air transport operational environment, and it was therefore decided that participants must have an Air Transport Pilot Licence (ATPL) and at least 500 hours of relevant experience, preferably with an airline, although pilots from high-end business aviation were also welcome.
There were no particular requirements regarding rank, age or gender, although an even distribution of Captains and First Officers and a wide range of ages was sought, provided that there was sufficient choice among prospective participants, to alleviate the risk of obtaining feedback only from a specific group of pilots.

6.3.2 Participant Recruiting

Apart from the formal requirements to be fulfilled, the way of recruiting pilots for the trials and the general conditions for participation deserve some attention. Trials were generally announced publicly through contacts to the German airline pilots' association Vereinigung Cockpit (VC) and a German airline, who then employed internal mailing lists or bulletin systems to disseminate information about the planned trials. In parallel, participants of previous evaluation campaigns at either the Institute or the Nationaal Lucht- en Ruimtevaartlaboratorium (NLR) in Amsterdam were contacted individually. Furthermore, when travelling by air, the author tried to contact the flight crew prior to or after the flight to motivate them to participate in the SMAAS evaluation campaign. Contacts obtained this way were also utilized in recruiting participants, which adds a certain random component to participant selection.

It is important to note, however, that the Institute is not able to pay pilots for participation in either simulator or field trials, and there is no financial compensation for any travel or accommodation expenses participants might have, either. Likewise, with very few exceptions, e.g. when pilots from one the Institute's partners in the European research projects EMMA or FLYSAFE were sent to Darmstadt by their companies, the trials were not part of the normal crew scheduling or duty time. Most pilots therefore participated in the trials on a voluntary basis and in their spare time.

133 It is also assumed that the first-time exposure to glass cockpit technology constitutes a significant cultural shock for 'old school' pilots, and that therefore a significant part of their feedback and system-related questions will be on the glass cockpit itself, rather than on the SMAAS.

Of course, this has a significant effect on the sample of the airline pilot community obtained, because the sole remaining motivation for participation in the trials is of idealistic nature: a true interest in the subject and/or willingness to support aviation research. Consequently, only very motivated pilots will commonly volunteer to participate under these circumstances. It is assumed that these pilots are generally also more open to new technologies. In fact, several of the pilots participating in the trials stated that they were always interested in new technical developments.

From the considerations above, it can be concluded that the pilots volunteering for the evaluation will, almost irrespective of the actual number of participants, not form a representative sample of their profession. This must be kept in mind when analysing the results. Besides, this an important aspect to be considered when choosing between objective and subjective evaluation methods, since a non-representative pilot sample diminishes the significance of objective measurements.

6.4 Experimental Factors

This section discusses the most important experimental factors that are of relevance for both the field trials with the Navigation Test Vehicle and the Institute's Research Flight Simulator, and details how these factors were eventually controlled or addressed during evaluation. More details can be found in the respective chapters on the evaluation campaigns.

6.4.1 Baseline versus Experimental System

Comparing the system under evaluation with the current baseline (paper charts, classic ND, visual observation) results in a quantitative indication on how the new system performs in relation to the standard. This necessitates that the baseline used in the experiment is sufficiently representative of the 'real' baseline. However, both of the available evaluation platforms exhibited substantial discrepancies with respect to the current baseline for surface operations, see Sections 7.3.4 and 8.3.3 for details.
Besides, a drawback of this comparative approach is that the time experiment participants spend on the actual experimental system may be substantially reduced. Therefore, since the time available for each evaluation session was very limited during both evaluation campaigns, given the complexity of the proposed new system, a comparison of SMAAS with the current baseline was not carried out. However, several questions addressed the advantages or disadvantages of the AMM over current technology, which all pilots know by heart due to the nature of their job. This partially compensated for the lack of a baseline setup.

6.4.2 Visibility Conditions

Both the airport moving map and the other SMAAS functions aimed at increasing flight crew situational awareness are expected to achieve the greatest benefits in degraded or marginal visibility conditions, when visual observation as sole conventional surveillance technique fails. Consequently, wherever the validation platform permits to control visibility conditions, this should be utilised to determine whether there is any interdependence between visibility and pilots' feedback.

6.4.3 Airport Complexity

SMAAS is expected to achieve substantial benefits in terms of situational awareness mainly at large and complex airports. Nevertheless, there is also a need to improve safety and to avoid accidents like the Comair 5191 crash at smaller airfields. In principle, several different airports with varying complexity (e.g. from medium to high) could be used to make airport complexity an experimental factor. Since the SMAAS prototype supports direct loading of ED-99 files, there are no immediate technical constraints that would prevent this approach. Nevertheless, the definition of truly comparable scenarios with respect to other factors, such as complexity of taxi routes, traffic patterns etc. at different airports is very difficult.

6.4.4 Traffic Density

Traffic density is expected to have a substantial impact on usability and design issue of the Cockpit Display of Traffic Information (CDTI), because a large number of surrounding aircraft could eventually result in clutter when shown indiscriminately on the AMM. Conversely, in an environment with only a few other aircraft present, this might not be perceivable as an issue at all. In field trials, the actual traffic density is dependent on airport complexity and several other factors, e.g. the time of day. By contrast, traffic density may be controlled in the simulator, but if it does not match with airport complexity, this could impair the perceived realism of the scenario.

6.4.5 Familiarity with Airport

It is expected that the safety and efficiency benefits will be most notable at airports the crew is not very familiar with. However, with respect to experiment design and pilot invitations, it is almost impossible to control the participating pilots' level of familiarity with a specific airport *a priori*, because participation to the trials is voluntary. Although participants were expected to be mainly recruited from the Frankfurt/Main area and the local airlines, and may thus be expected to be very familiar with Frankfurt Airport (EDDF), the detailed level of familiarity with any other airport is an unknown variable prior to the experiment.

After the evaluation, however, it might be possible to compare results for different levels of airport familiarity, because the Pilot Intake Questionnaire contains a self-assessment with respect to airport familiarity. If a statistically sufficient sample is obtained, i.e. if it turns out after the experiment that sufficiently large groups of different familiarity levels have incidentally formed, a *post-hoc* analysis on the impact of airport familiarity can be made.

6.4.6 Pilot Background and Rank

Like familiarity with a particular airport, this experimental factor is difficult to control if public announcements requesting participation in simulator experiments are made. However, a post-hoc grouping of pilots according to rank might shed some light on whether the typically younger first officers, having grown up with computers and therefore often jocularly referred to as 'Nintendo Kids', assess the SMAAS significantly different than the 'old school' captains who started flying well before the introduction of both glass cockpits and personal computers. Depending on the actual distribution of pilots participating in the trials, the following possibilities for a post-hoc formation of sub-groups are:

- **By rank:** There is a high interest to determine whether the early naturalisation with computers and electronic displays the generally younger first officers are likely to have had influences their acceptance of the proposed novel functions, which heavily rely on electronic displays.
- **By age:** Participants can be allocated to a minimum of two groups, e.g. 20-40 years and 41-60 years of age, with the same motivation as above.
- **By type of operation:** Additional clues may be obtained from grouping participants according to the type of operation, e.g. regional/short haul versus long range, or passenger versus freight.
- **By aircraft type/manufacturer flown:** Although no significant differences are expected, it might be useful to validate this assumption based on the data collected.
- **By airline:** Verify whether association with a particular airline and thus the pertinent company philosophy and culture have an impact on the results.

Depending on the actual number and sample of participants, further groupings might be envisaged; however, since pilots volunteered to participate in the trials, the factors above were difficult to influence a priori.

6.5 Methods and Metrics

6.5.1 Methods and Techniques for Measuring Situational Awareness

Since one of the main objectives of the SMAAS is to improve crew situational awareness in different domains, it seems appropriate to review some of the techniques that can be used to measure situational awareness.

In human factors literature, there are two major objective techniques to assess situational awareness, the Situation Awareness Global Assessment Technique (SAGAT) and the Situation Awareness Probe (SAP). SAGAT stops simulation at random intervals and inquires the crew for an assessment of the current situation. As an example, pilots could be asked for bearing and distance to certain other traffic. Their answers can then be compared to the actual values and thus give an apparently objective assessment of situational awareness. The fact that it delivers objective results is often quoted as a major advantage of SAGAT. It must be noted, however, that the objective data obtained from the crew are not as infallibly 'hard' objective as parameters recorded by the flight test instrumentation, but rather 'soft' objective[134]. At any rate, the main disadvantage of SAGAT is that it is very intrusive and decreases operational realism of a simulated scenario, and may thus divert evaluators' attention. Often, it is not possible to continue the scenario after the interruption. For obvious reasons, SAGAT cannot be used in a flight test, either. SAP tries to avoid these disadvantages by asking pilots during simulation or flight [NG01]. The major drawback of both of these techniques, however, is that they require profound and *a priori* knowledge about the factors relevant for situational awareness in a certain situation, and concerning a specific task.

This can be avoided when using subjective measurements of situational awareness, which are usually based on questionnaires using a more or less intricate self-assessment. The most commonly used tests are [NG01]:

- China Lake Situation Awareness (CLSA)
- Crew Situation Awareness (CSA)
- Situation Awareness Rating Technique (SART)
- Situation Awareness Subjective Workload Dominance (SA-SWORD)
- Situation Awareness Supervisory Rating Form (SASRF)

CLSA is a direct, subjective situational awareness rating scale originally developed for flight testing. The pilot directly rates situational awareness from 1 (Very Good) to 5 (Very Poor). A variant of the CLSA is having pilots rate the improvement or deterioration of situational awareness compared to a baseline system using a Likert scale. A disadvantage of CLSA and its variants is that factors influencing situational awareness cannot be characterised in detail. CSA is an exception in the above list, because it uses expert observers to rate pilots' situational awareness. SART computes

[134] Again, the experiment must be designed with care to minimize undesired effects. In the example above, the scenario must be designed in such a fashion that pilots can easily derive bearing and distance from the HMI. Otherwise, there is a risk that the results yield more information on pilots' ability to estimate distance and bearing than on situational awareness. This potential pitfall is often not addressed, cf. [NG01].

a value for situational awareness from the Likert-style ratings on a series of questions related to situational awareness. While SART is in principle rather complex and powerful, its main disadvantage is that it is hardly useful when pilots are not trained to use it, particularly if they are not English native speakers.

Through their training, pilots are familiar with the concept of situational awareness, and consequently capable of a direct self-assessment. It was therefore decided to address this aspect directly in the post-exercise questionnaires and in the debriefing by letting pilots rate the perceived impact of certain SMAAS features on situational awareness using a Likert-style rating scale. From a formal perspective, therefore, this approach is equivalent to CLSA.

6.5.2 Considerations on Workload

Whenever new functionality is added to the flight deck, this usually leads to additional crew tasks, unless existing systems or procedures are replaced. Therefore, it is important to capture the impact on workload that is associated with any additional system in the cockpit. For SMAAS, it is important to verify that the proposed functions do not cause excessive workload, since this may be a source of errors. The following considerations apply:

- Workload must be in line with the criticality of the situation. This means that it may be high in a critical situation, but there should not be any significant impact on workload induced by SMAAS during routine operations.
- Workload must be consistent with the relative frequency of the situation encountered. If an event or a situation is occurring frequently, the impact of introducing SMAAS on workload should be low.

In general, it is assumed that improved situational awareness will free attentional resources and consequently lead to lower levels of workload.
Neither the validation campaign with the Navigation Test Vehicle nor the simulator experiment were considered suitable for applying standard workload tests, because pilots' role was entirely passive in the field trials, and the workload in the simulation is not representative of an air transport environment, mainly due to the single pilot configuration eventually used. Besides, a fine-grain workload analysis did not appear to be appropriate in view of the overall maturity of the SMAAS functions assessed. It was therefore deemed more appropriate to address workload aspects directly in questionnaires and de-briefing sessions.

6.5.3 Human-Machine Interface, Operational Relevance and Usability Aspects

Evaluation scenarios were developed based on the assumption that cockpit procedures for using an airport moving map display and associated functions will give the role of monitoring the display to the pilot non-flying (PNF) to avoid that the aircraft is taxied head-down by the pilot flying (PF).
Subjective pilot feedback (custom questionnaires, comments) and direct observation were used to validate the SMAAS functions, to identify potential additional operational needs and to detect potential HMI issues. Likewise, custom questionnaires were use to obtain initial reactions and estimates of pilots pertaining to the perceived level of safety when using the additional onboard functions. In this context, pilot comments on potential certification issues were regarded as an indication that the safety objectives may were not or only partially fulfilled.

In the questionnaire, the statements to be rated by participants were deliberately worded in a strong and suggestive fashion to provoke and spawn discussion. As outlined previously, discussion and open loop comments are essential, because one of the main problems in exploring new flight deck functionality is that potential issues or essentially important aspects might not always be in the areas expected. Thus, potentially critical design issues or even showstoppers might eventually not be covered by a questionnaire.

7 Field Trials with a Navigation Test Vehicle

Between November 2005 and February 2006, an initial prototype of the Surface Movement Awareness and Alerting System (SMAAS) was evaluated in live trials at Frankfurt (EDDF) and Prague (LKPR) airport with a total of 15 airline pilots from five European airlines in the scope of the European Research Project EMMA. TUD's Navigation Test Vehicle, a Volkswagen LT 28 van equipped with a Honeywell H764 INS, various GPS receivers and a Filser RT60 ADS-B receiver (1090 ES), was used in this validation exercise to simulate an aircraft taxiing on an airport. The passenger seat was fitted with an LCD display and a basic Crew Control Device (CCD) and served as a very basic cockpit mock-up. This particular test bed was chosen because it enables low-cost live field tests of onboard functions in a real airport environment. Thus, it provides not only unparalleled realism that can hardly be achieved in simulators, but also a possibility to assess the potential impact of environmental factors such as database and navigation accuracy (e.g. INS drift due to GPS outages) or the quality of ADS-B data. Nevertheless, the main purpose of the trials was a validation of the overall SMAAS concept, including a design validation of selected onboard functions.

7.1 Evaluation Objectives

The objective of the validation tests performed with TUD's Navigation Test Vehicle was a first conceptual assessment of SMAAS integrated surveillance system approach with special emphasis on operational aspects, i.e. its relevance and adequacy to address Runway Incursion-related problems.

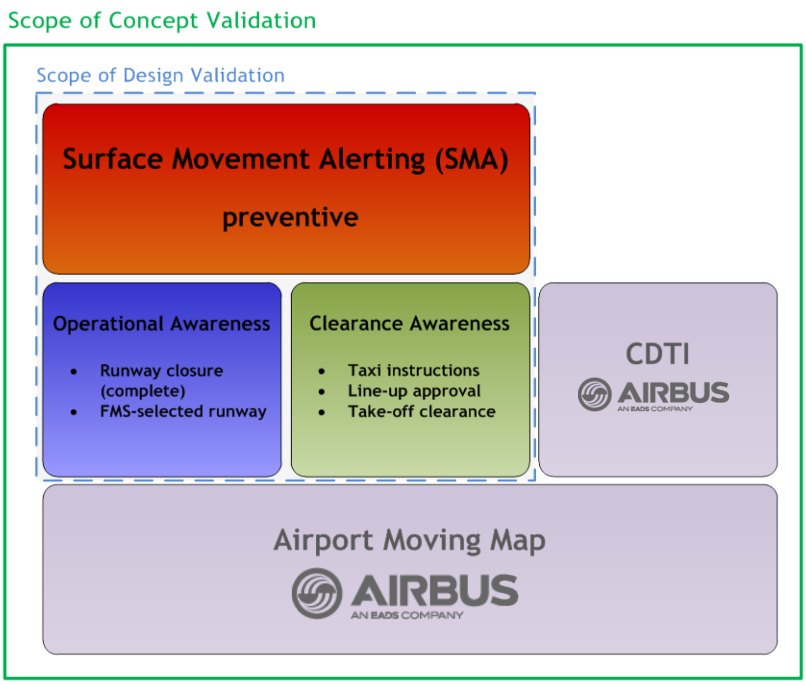

Figure 86: Configuration of the SMAAS prototype employed in the field trials

Figure 86 illustrates the configuration of the initial SMAAS prototype used for the field trials with the Navigation Test Vehicle. One of the most notable discrepancies from the SMAAS architecture presented in Figure 29 on p. 137 is the absence of reactive Surface Movement Alerting, i.e. the SMAAS prototype did not yet support traffic alerting. Likewise, the Operational and Clearance Awareness Functions did not yet feature their full scope. The functions assessed on the Navigation Test Vehicle and their respective discrepancies compared to the design described in Chapter 5 were:

- **Airport Moving Map (AMM):** Instead of the AMM described in Section 5.1, the so-called Moving Map Standalone (MMS), a software prototype of the Onboard Airport Navigation System (OANS) used on the Airbus A380, cf. Section 3.1.1, was used due to contractual aspects of the EMMA project.
- **Ground Traffic Display (CDTI):** Traffic symbology, provided as an integral part of the Airbus MMS application, was limited to a copy of the ownship symbol in white, accompanied by a label consisting of the callsign.
- **Operational Awareness Function (OAF):** The features available were a representation of the FMS-selected RWY (in magenta) and a visualisation of completely closed RWYs (using amber crosses), as shown in Figure 43 on p. 168.
- **Clearance Awareness Function (CAF):** The functions supported were taxi route representation, line-up approval and take-off clearance.
- **Preventive Surface Movement Alerting (SMA)**

The fact that a different AMM and CDTI implementation can be accommodated due to the modularity of SMAAS may already serve as an indication for its independence of a particular HMI design for these functions. Accordingly, conceptual validation encompassed SMAAS as a whole, whereas design validation was limited to Operational Awareness, Clearance Awareness and Surface Movement Alerting to gain confidence in the adequacy of the HMI solution proposed for these advanced features, as shown in Figure 86. The performance of the technologies required to support SMAAS, such as GPS, AMDB accuracy and integrity, traffic data link etc. (i.e. technical usability), were not themselves subject of the assessment, and it was generally tried to minimize their effect on validation results. However, in the case of the ADS-B traffic data link used in the trials, this proved to be impossible, which compulsorily led to evaluation feedback on both the HMI function (CDTI) and quality and reliability of ADS-B data at the implementation level in late 2005/early 2006.

Pilots would first be asked to evaluate the core element, an airport moving map display, supplemented by Operational Awareness (OAF) and Clearance Awareness Function (CAF) elements intended to increase situational awareness. In a second session, the preventive Surface Movement Alerting concept was demonstrated to the maximum extent possible with respect to airport safety, i.e. up to advisory level in Frankfurt and up to warning level in Prague, where a runway permanently closed for take-offs and landings creates ideal prerequisites for the assessment of Runway Incursion alerting. Evaluation sessions concluded with a presentation of ADS-B ground traffic on the airport moving map display. Subjective feedback was collected using questionnaires filled by the pilots during and after the trials (both electronically and on paper) and open loop comments recorded during the sessions.

7.2 Experimental Design

7.2.1 Experimental Factors

7.2.1.1 Baseline system

In line with the considerations in Section 6.4.1, no baseline system (conventional ND, paper charts) was used in the validation activities carried out on TUD's Navigation Test Vehicle. Given the overall setup of the evaluation (see Section 7.3 for details), a baseline experiment would have consisted of driving pilots around the airport with paper charts as sole navigation reference. In view of the limited time available for evaluation, this was considered as not relevant.

7.2.1.2 Experimental system

A software prototype of the SMAAS as described in Chapter 5 was used, but with the discrepancies and limitations listed in Section 7.1.

7.2.1.3 Visibility conditions

All of the trials were carried out at daytime, with sessions starting either in the morning or in the early in the afternoon. Due to pilot scheduling constraints and the very nature of live trials, visibility conditions were not a factor that could be controlled in the evaluation exercise performed, e.g. by performing evaluation sessions only if visibility is greater than a certain pre-defined value.
Incidentally, nevertheless, all trial sessions in Frankfurt and Prague were carried out in good visibility conditions, i.e. in Visibility Condition 1 or Visibility Condition 2 as defined by the ICAO European Manual on A-SMGCS, and more or less dry weather (only some light rain or drizzle), with mostly overcast skies. Only one session was carried out in light fog. The lowest visibility encountered during the Frankfurt trials was 1 mile during the test session with Pilot #6 on January 20th, 2006, deduced from METAR information recorded on an hourly basis.
One of the Prague sessions was carried out during a period of heavy snowfall, but still in fair visibility, with taxiways and roads partially covered by snow and slush. Although visibility was periodically impaired by snowfall, it never dropped below Visibility Condition 2. For the other Prague sessions, the conditions were similar to the Frankfurt trials, with mostly calm and cold winter weather.

7.2.1.4 Airport complexity

To ensure that the results obtained do not contain potential artefacts resulting from features specific to just one airport, and to obtain more confidence in the general applicability of results, it was decided to use at least two airports.
Therefore, the choice was made to include Frankfurt Airport (EDDF) as test site, to have a hub airport close to TUD's facilities available for integration and testing. Prague airport (LKPR), as official EMMA test site, was chosen because it is the closest and most complex of the three EMMA airports.

At any rate, performing trials at airports with low complexity is not really useful, because the challenges the crew faces there are believed to be relatively minor. Therefore, at any rate, airports with high complexity are expected to be the places where the benefits of the new onboard functions will become most apparent. Regarding the AMM functionality, several pilots eventually confirmed this by commenting that the application would be extremely helpful at congested hub airports like New York's Kennedy Airport (KJFK).

Taking into account the various factors determining airport complexity, it can be concluded that both Frankfurt (EDDF) and Prague (LKPR) airports fulfil several of the criteria each and can thus be regarded as complex airports, while Prague is certainly near the threshold from medium to high complexity.

7.2.1.5 Traffic density

In contrast to airport complexity, which can be selected by the simple choice of the test site, traffic density is not as easy to control in live trials. Of course, the desired average traffic density can be achieved by picking a certain airport, but actual traffic density varies with seasons, the time of day (hub peaks) and the weather. Thus, for an individual experiment session, the actual traffic density is hard to control. Even when scheduling all evaluation sessions exactly at the same time of day, there can be variations in traffic due to delays, which might even be independent of weather conditions at the test airport.

With respect to the test sites chosen, traffic density is nearly always heavy at Frankfurt, as there are usually many more than 26 take-offs and landings per hour (the criterion for heavy traffic density), although there are certain distinct hub peaks over the day with maximum traffic density. In comparison to Frankfurt, the density of traffic is significantly lower at Prague airport (LKPR), where it varies from medium to low, depending on the time of day and the area of the airport used. Near the closed RWY 04/22 and the South Apron, where a significant part of the evaluation was carried out, traffic density is comparatively low.

7.2.2 Conduct of Experiment

7.2.2.1 Assessment team

The core assessment team for all the trials consisted of two TUD research scientists. One of them was a systems engineer responsible for the operation of the systems on the Navigation Test Vehicle, and – in the majority of evaluation sessions – for driving around the airport for all of the experiment sessions taking place at Frankfurt Airport (EDDF), since he was in possession of a special driver's license for the airport. The other research scientist was the author of this thesis, acting as an experiment leader, conducting the briefing as well as the familiarisation, taking down pilots' comments and assisting pilots in filling the questionnaires.

With three exceptions, all the Frankfurt sessions were carried out with only those two TUD research scientists and the experiment pilot present on the Navigation Test Vehicle. The first exception was a combined session for Pilot #7 and Pilot #8, who took turns in observing the AMM and additional functions from the passenger seat of the van. This experiment session and the subsequent session for Pilot #9 on the same day were also attended by an Airbus engineer as an observer. The third exception consisted on another combined session for Pilot #10 and Pilot #11, who are father and son, and thus asked for an opportunity to participate together.
In addition to the two TUD systems engineers and the experiment pilots, all of the four Prague experiment sessions were also attended by two officials from Prague airport authority, who took turns in driving the van.

7.2.2.2 General Experiment Schedule (EDDF)

Since nearly all of the pilots participating to the trials in Frankfurt were flying for an airline sustaining operations there, all evaluation sessions except one started at the airline's base. Before going through the security checks, pilots were given a briefing of the AMM and a short period of time to familiarise with the application and its controls. When entering the apron area after the security checks, the actual experiment would begin.
First, the AMM only configuration was assessed, supplemented by OAF and CAF elements. At the end of this session, before completing the first set of questionnaires, a Level 0 alert for increased runway awareness was demonstrated to the crew. Subsequently, the presentation of traffic on the AMM using ADS-B equipped traffic was assessed.

7.2.2.3 General Experiment Schedule (LKPR)

For the experiment in Prague, with access to the taxiway system and a closed runway, the experiment schedule compared to Frankfurt was slightly altered. After briefing and familiarisation, each trial session consisted of three parts:

- Airport moving map assessment (ca. 20 min), afterwards questionnaires. The preventive alerting part of SMAAS was available, but would only trigger Level 0 advisories in the scenarios presented.

- Airport moving map, OAF/CAF functions and Preventive Surface Movement Alerting, afterwards questionnaires.

- Airport moving map, OAF/CAF functions and traffic presentation, afterwards questionnaires. The preventive alerting part of SMAAS was available, but would only trigger Level 0 advisories in the scenarios presented.

7.2.3 Data Collection and Analysis

7.2.3.1 Data collection

Subjective pilot feedback was collected through questionnaires at the end of each evaluation run and comments taken down by the experiment leader during sessions.
After the AMM evaluation scenarios, which will be described in detail in Section 7.4, had been carried out, pilots were requested to fill a digital AMM questionnaire on a laptop. This questionnaire is an extended variant of a questionnaire originally designed by DLR for EMMA. Subsequently, the scenarios with activated traffic presentation were conducted. To collect pilot feedback on the CDTI, a paper questionnaire with exclusively traffic-related questions devised by the author was used after the corresponding scenarios.
After both the AMM and the traffic session, pilots were additionally asked to fill a slightly modified standard System Usability Scale (SUS). The modifications of the SUS consisted of shortening the questions to more precise statements and in a rewording of the question relating to 'support of a technical person', which is not applicable in an aircraft environment, see Figure 87 for details.

1. I would like to use this system frequently.
2. The system is unnecessarily complex.
3. The system is easy to use.
4. I would need training to be able to use the system.
5. The various functions in this system are well integrated.
6. There is too much inconsistency in this system.
7. Most pilots will learn to use this system very quickly.
8. The system is very cumbersome to use.
9. I feel very confident using the system.
10. I needed to learn a lot of things before I could get going with the system.

Figure 87: Modified System Usability Scale (SUS)

7.2.3.2 Analysis methods

The main analysis methods used were a direct analysis of the questionnaires and a correlation of the data with pilots' comments during and after the test sessions, along with an analysis of the experiment leader's observations of during the sessions. Furthermore, consistency of pilots' answers for similar and directly opposite questions was checked. Last but not least, a two-sided Kolmogorov-Smirnov test was performed on the questionnaire results for each individual question to check whether there are potential deviations from a normal distribution.
Unfortunately, only four pilots participated in the Prague experiment (compared to 11 for Frankfurt), and thus a comparison of the results for statistically significant differences between the two test sites is questionable in its validity.

7.3 Assessment Platform

7.3.1 Overview

Figure 88: Navigation Test Vehicle during tests on the closed RWY 04/22 at Prague airport (LKPR), February 6th, 2006

TUD's Navigation Test Vehicle, a Volkswagen LT 28 van shown in Figure 88, is operated by the Institute of Flight Systems and Automatic Control and was originally conceived as a mobile test platform for the development and validation of navigation sensors and equipment. It features an array of sensors suited for precise navigation and a measurement data acquisition and logging system. A post-processing software allows to generate highly precise reference trajectories with a CEP_{95} of 0,44 m based on sensor logs [Sch04].

Furthermore, as a by-product, a high-precision online navigation solution also provides the prerequisites for the verification and validation of equipment used on aircraft, particularly in the domain of flight guidance displays for surface movement, either in the form of software prototypes or real hardware. Consequently, the Navigation Test Vehicle can be used to simulate a taxiing aircraft and enables low-cost live field tests of such onboard functions in a real airport environment. Thus, it allows not only an evaluation of the novel onboard functions themselves, but also an assessment of the potential impact of factors such as database or navigation accuracy (e.g. IRS drift and GPS outages and/or multi-path effects), or the quality of the data obtained via data link, e.g. ADS-B traffic data, as well as the data link itself.

7.3.2 Navigation System

A Honeywell H764 inertial reference system forms the core of the van's precision navigation system, which is supplemented by an array of various GPS receivers ranging from off-the-shelf to high accuracy measurement models (cf. Figure 89). The sensor mounting positions were measured within centimetre accuracy to correct errors caused by different sensor locations. An overview to the sensor equipment is given in Table 16.

Figure 89: Antenna mounting plate on the roof of the Navigation Test Vehicle

A Wiener filter is used for the implementation of an optimum sensor data fusion combining inputs from the H764 and a Novatel RT20 GPS receiver with D-GPS capabilities. To provide differential correction data to the onboard receivers, a portable reference station can be installed at points of which the exact position is known. The range of the D-GPS broadcasts depends on the surrounding environment and can vary between several dozens and some hundred meters, provided there is a free line of sight between rover- and reference station. As a backup, D-GPS can be obtained from the ALF service, which is available within 600 km of Frankfurt/Main, Germany. For the EMMA trials, however, no D-GPS correction data were used, because the shakedown trials had shown that a sufficient real-time navigation precision in the order of a few meters could be achieved with GPS only.

7.3.3 Equipment

In the back of TUD's Navigation Test Vehicle, one row of seats has been removed to make room for two custom-built, interconnected racks that hold the hardware and computer equipment (Figure 90). Two inverters in the back are used to convert the 12V DC supplied by the vehicle's electric bus to 250V/50 Hz AC required to drive the PC equipment.

In its standard configuration, the Navigation Test Vehicle is equipped with at least two PCs interconnected by Ethernet. The Navigation PC is responsible for collecting sensor data and the real-time calculation of the GPS/IRS sensor data fusion. It is equipped with both a MIL-1553 and an ARINC 429 card to interface with common aircraft avionics. The other PC is used for multiple purposes, such as data logging, acquiring traffic data and calculating a traffic data fusion or hosting software prototypes of onboard functions such as an airport moving map. Space permitting, further PCs can be added and connected to the vehicle's Ethernet network.

Figure 90: Hardware and computer racks in the back of the vehicle

ADS-B live traffic can be received using a Filser RT60 ADS-B receiver (purchased via Eurotelematik) that sends out traffic data via Ethernet. Furthermore, the vehicle is equipped with Wireless LAN (WLAN), which can be used to access TIS-B traffic acquired through Frankfurt airport's Cooperative Area Precision Tracking System (CAPTS), a Mode-S multilateration surveillance system developed by Thales and Sensis. The TIS-B over WLAN data link was developed for the ETNA project, where this feature was employed to bring traffic awareness to airport vehicles, particularly the airport fire engines [Kra04].

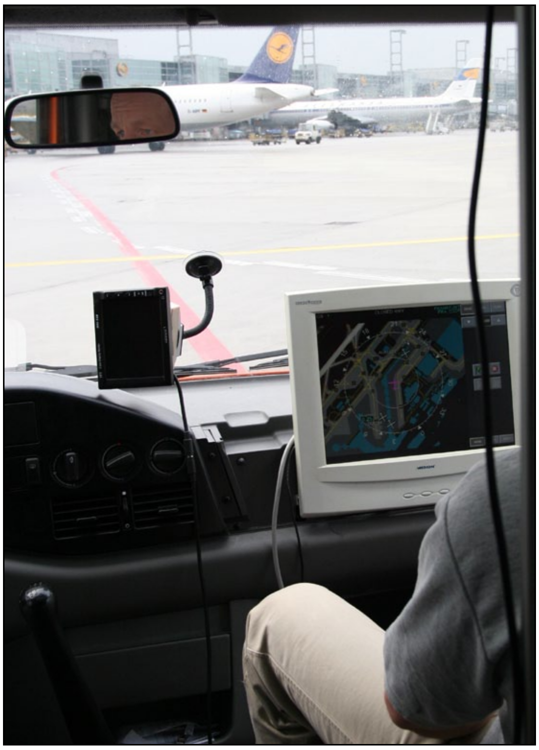

Figure 91: LCD screen installation in front of passenger seat

The passenger seat served as a very simple cockpit mock-up for the pilot evaluations and was therefore fitted with a 15″ off-the-shelf LCD display (see Figure 91) and a Logitech trackball as a basic Crew Control Device (CCD), both provisionally mounted by the help of Velcro® tape.
Although the LCD used is far from the ruggedised, high-contrast AMLCD screens used in aircraft cockpits, the display readability was very good even in back light conditions. Another limitation of the screen used is that its diagonal is a factor of 1.5 larger than the 6″ x 8″ screens currently used in the Airbus A380.

The test van has the permissions necessary to operate on the movement area of Frankfurt Airport (EDDF). For evaluations on the manoeuvring area, the van was equipped with a turning light, and licensed drivers with the required radio permissions were kindly supplied by Frankfurt and Prague airport authorities. In Prague, additionally, an autonomous ADS-B transponder requiring only power supply was installed on the van's roof.

Sensor/ HW	Manufacturer	Technical Data	Remarks
H764 (INS)	Honeywell	Position <1.0 [nmi/hr] CEP velocity <1.0 [m/s] RMS Heading 0.1 [deg] RMS Pitch, Roll 0.05 [deg] RMS	INS medium accuracy
RT20 L1 (GPS)	Novatel	12 channel L1 20 cm CEP50 (RT2 DGPS)	High accuracy
RT2 L1/L2 (GPS)	Novatel	12 CH L1/L2 2 cm CEP50 (RT2 DGPS)	High accuracy
SK8 (GPS)	Trimble	8 CH L1 2 m CEP50 (DGPS)	Low cost receiver
GPS 35	Garmin	12 CH L1 5 m RMS (DGPS)	Low cost receiver
Ashtech G12	Thales	12 channel L1 40cm CEP50 (DGPS)	GA certified
reference station RT2, Hermes modem (DGPS, VHF link)	Novatel, Phillips	L1/L2 RTCM Type 59N RTCA Type 7 VHF Modem: 459,57Mhz	reference point required.
Odometer	Bosch	56 pulse/round	ABS controller
ALF receiver (DGPS)	DeTex	RTCM-104 v2.0 122,5 kHz	Available within 600 km radius of Frankfurt
MS5535 (Barometer/ Thermometer)	Intersema	-40°C to +125°C 1-12 bar	Parport PC Interface
RT60	Filser	1090 Mhz, Enhanced Squitter	ADS-B receiver

Table 16: Sensor equipment of TUD's Navigation Test Vehicle

7.3.4 Testbed Limitations

7.3.4.1 Material constraints

In the following, a list of the physical limitations of the set-up for the evaluation setup is given, which relate mainly to the test bed itself and associated constraints:

- **Very basic cockpit mock-up**: The passenger seat of the Navigation Test Vehicle is obviously not at all representative of a real cockpit environment (cf. Figure 91); its use also enforces a single pilot configuration. Furthermore, a consumer COTS TFT monitor was used, but the lower contrast and brightness ratio was of no significance for display readability due to the mostly overcast skies encountered during the trials. A constraint that might have had a small influence on results was the lower position of the seat above the airfield compared to real aircraft.
- **Experiment pilot physically not in control of vehicle**: This is not relevant due to envisaged PNF role of the pilot monitoring the AMM and the several add-ons.
- **Availability and quality of ADS-B data**: Not all of the aircraft encountered at Frankfurt and Prague airport were equipped with ADS-B, and the quality of the data provided by those equipped showed a substantial variance. As pilot comments show, this clearly had an impact on evaluation results.
- **Absence of CPDLC and other data link services:** Pre-stored ATC instructions and clearances were used, but this should not have any influence on results.

7.3.4.2 Experimental conditions

This section describes limitations related to experimental conditions, i.e. constraints in terms of operational realism, which partially result from physical constraints:

- **Passive observer role of experiment pilot**: Due to the envisaged task-sharing for airport moving map use, which allocates the task of SMAAS monitoring to the pilot non-flying (PNF) to avoid that the aircraft is taxied head-down by the pilot flying (PF), the passive, monitoring role that pilots assumed in the van trials is not crucial. Therefore, the impact on the results is believed to be very low.
- **Lower workload than in real life:** Given the absence of an operational cockpit environment with responsibility for e.g. checklist reading and managing radio communications, the workload of a PNF will be higher in reality, compared to the assessment on the van.
- **Use of vehicle roads:** Instead of driving on taxiways, TUD's Navigation Test Vehicle used airport vehicle roads during the assessment of AMM and AMM with additional traffic presentation (CDTI) at both Frankfurt and Prague airport. The impact on evaluation results, however, is believed to be negligible, because the general principle of an electronic presentation of aerodrome mapping information is the same for taxiways and vehicle roads; the same applies to the CDTI. Besides, the vehicle roads used were mostly parallel to the taxiways.
- **Absence of interaction with CPDLC and other data links:** There was no interaction with ATC via CPDLC, which lowered workload and operational realism, but is believed to be of virtually no impact on results.

7.4 Evaluation Scenarios

7.4.1 Scenarios for Frankfurt Airport (EDDF)

7.4.1.1 AMM Scenarios

Due to the high traffic density at Frankfurt airport, using the taxiway system during daytime was impossible. However, there are vehicle roads largely adjacent to the long major taxiways A, D and N that extend parallel to the main runways all along the northern part with the two terminals and the cargo apron, and these were used for the trials. Typically, a scenario for the moving map standalone assessment would consist of driving from Terminal 1C up taxiway N and N North up to taxiway Z, and then back on A and down to position V102 near the eastern end of Terminal 2. At the edge of this parking position, the Level 0 alert for approaching a holding position in LVP conditions could be demonstrated without actually entering the manoeuvring area. After this scenario, pilots were asked to fill a first set of questionnaires and a first System Usability Scale (SUS).

7.4.1.2 AMM and Ground Traffic Scenarios

Subsequently, for the traffic assessment scenarios, ADS-B equipped aircraft were chosen and, where possible, being followed, mostly along their taxi route to RWY18 or while taxiing in, using largely the same vehicle roads as in the AMM only sub-experiment. During debriefing, as second set of questionnaires including another SUS was filled. It was found that recently delivered Airbus A320 and A330/A340 family aircraft were generally suitable targets, providing positional data with good accuracy, nominal update rate and also track data. Thus, the experiment leaders tried to spot and follow these aircraft, which was eased by the fact that they grew more and more familiar with the flight schedule at Frankfurt as the experiment progressed. Initially, it had been planned to use TIS-B data in the Frankfurt experiment as well. Unfortunately, however, due to technical problems on the server side, the experimental TIS-B multilateration data broadcast via WLAN was only available during the integration and shakedown trials, but not during the experiment itself.

7.4.1.3 Surface Movement Awareness and Alerting Scenarios

For a presentation and assessment of the OAF functionality, Runway 25R was set as a fictitious FMS-selected runway, and Runway 25L was marked as closed.
The CAF functionality was presented as well, using a pre-defined taxi route, but due to the limitation of the Navigation Test Vehicles movement to the apron and vehicle roads, the route was not being followed.

7.4.2 Scenarios for Prague Airport (LKPR)

7.4.2.1 Airport Moving Map

The briefing on the AMM included a first hint at the existence of additional Surface Movement Awareness and Alerting functions and a quick explanation of the Runway Proximity Information advisory (cf. Section 5.5.5). The AMM evaluation was carried out in a similar fashion as in Frankfurt. Starting out from the South Apron, the vehicle roads up to and around the passenger terminal (North Terminal) were used to evaluate the AMM only functionality. A typical scenario would use the vehicle roads around the three distinct terminal fingers and then go to the Cargo Apron alongside taxiway Z.

7.4.2.2 Additional Surface Movement Awareness and Alerting Functions

Prague airport with its RWY 04/22 permanently closed for take-offs and landings provides an ideal location for live trials on Runway Incursion alerting. As opposed to a long straight taxiway, an actual – though closed – runway provides sufficient realism in terms of layout, holding positions etc. Furthermore, a closed runway can be used without influencing or being influenced by scheduled flights landing and taking off. This is not only important from a runway safety point of view, but also from a scenario design perspective. As an example, for a future experiment, a dedicated ATC frequency could be set up for the closed runway, thus permitting the simulation of an active runway. Of course, coordination with regular ATC will be required for safety reasons.

7.4.2.2.1 Runway Incursion Alerting for FMS-selected runway (missing clearance)

In the briefing, pilots were told to imagine that Runway 04/22 was used as an active runway again. In the first scenario (see Figure 92), RWY 22 was assumed to be the runway assigned for take-off entered in the FMS. Starting out from the South Apron, the pilot would discover that the direct route to the runway via taxiway N was blocked by a fictitious aircraft that had blown a tyre.

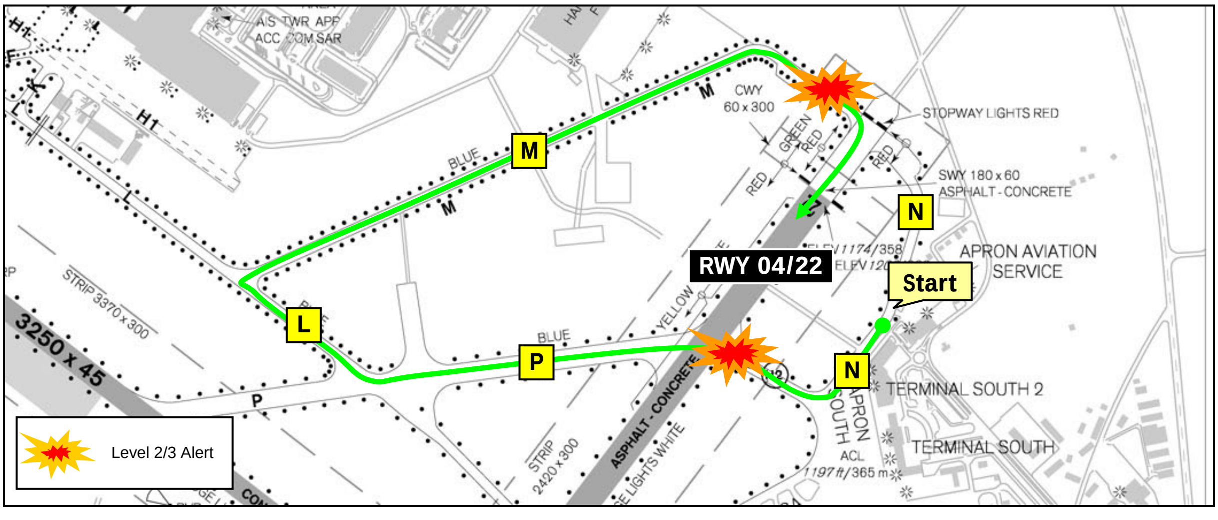

Figure 92: Runway Incursion alerting for FMS-selected runway scenario

Thus, a detour via N – P – 04/22 – P – L – M – 22 had to be taken, which would require crossing the runway. The corresponding taxi route was not shown on the display in this scenario, because a segment-wise allocation of the taxi route up to a predefined holding position, permitting to model the behaviour of the taxi route during runway crossing as described in Section 5.4.3, was not yet feasible with the SMAAS prototype. With RWY 22 set and clearly marked as the FMS-selected runway, the alerting concept (Level 2 and Level 3) for approaching and entering the FMS-selected runway without appropriate clearance was evaluated at the intersection of P with RWY04/22. Another aspect of the same alert was shown before receiving the line-up clearance on M. Last but not least, the normal behaviour of the function in the presence of appropriate clearances was shown during line-up on RWY 22.

7.4.2.2.2 Runway Incursion Alerting for non-FMS-selected runway ("wrong" runway)

This scenario was aimed at evaluating the alert presented to the crew if they inadvertently enter a 'wrong' runway, i.e. a runway that has neither been selected in the FMS nor approved for any operation on the runway surface (crossing, line-up etc). The experiment pilot was briefed to imagine a flight crew in a totally wrong mindset, missing a turn and then heading straight onto the runway that is neither in the FMS nor part of the assigned taxi route.

For this scenario, RWY 31 was set and unambiguously marked as the FMS-selected runway. The assigned taxi route (as displayed in green in Figure 93) was displayed on the AMM, and the behaviour of the SMAAS when leaving the assigned route was demonstrated: at the intersection of R and RR, the actual path would diverge from the assigned route (red line). At the intersection with taxiway L, the error was not corrected, and the van would turn right instead of left (to the departure/FMS RWY 31), causing an alert for unauthorised infringement of RWY 04/22.

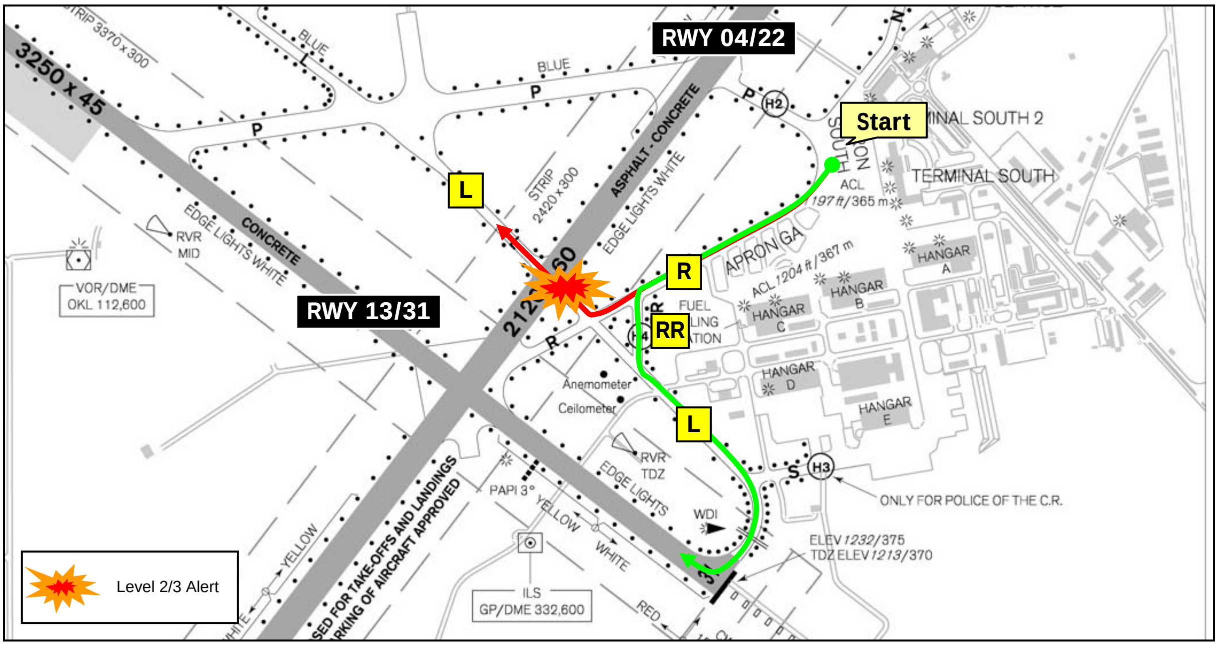

Figure 93: Runway Incursion alerting for FMS-selected runway scenario

7.4.2.2.3 Runway Incursion Alerting for completely closed runway

The purpose of this scenario was to assess the behaviour of the SMAAS if the aircraft is inadvertently heading for a runway that is completely closed. For the briefing, pilots were told to imagine that Runway 04/22 was planned to be re-opened as an active runway again, and that for this reason, there was heavy construction work in progress. The starting point would be on taxiway L, with the aircraft scheduled for take-off on RWY 31. The controller would then make an error and not correctly advise the 'detour' via M as expected (green route in Figure 94), but give a route via L instead (red route). Assuming that the crew would be busy with some PAX problems (the purser is in the cockpit for some reason, e.g. not enough business meals), this controller error would go unnoticed, and the aircraft would go straight ahead on L and eventually come dangerously close to the runway under reconstruction.
For this scenario, RWY 31 was set and displayed as the FMS-selected runway, and RWY 04/22 was set and displayed as closed. No taxi route was displayed for this scenario in order to emphasize the independence of the alerting for closed runways from the availability of a taxi route presentation to the participating pilots.

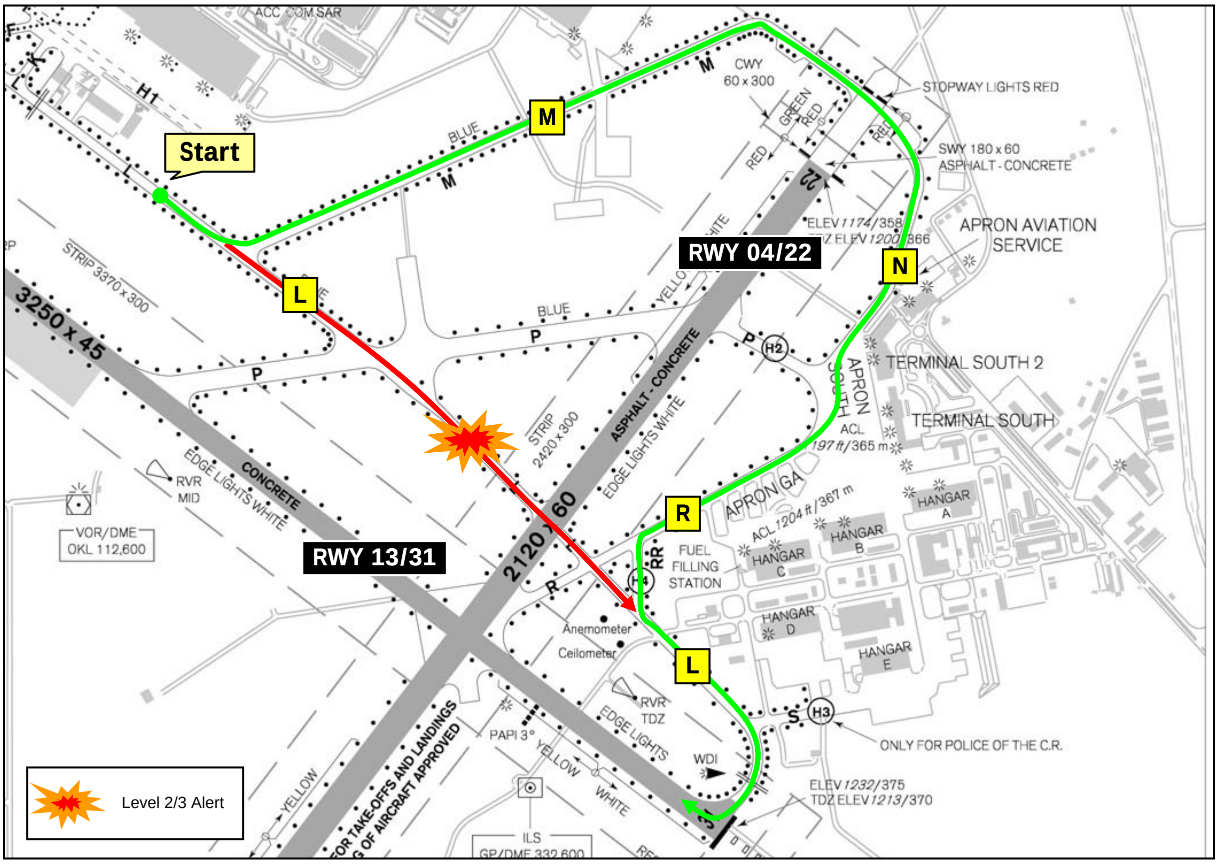

Figure 94: Scenario for the assessment of Runway Incursion alerts for a closed runway

7.5 Experiment Participants

7.5.1 Overview

A total of 15 male airline pilots with an average age of 43.2 years (between 26 and 59 years old), among them nine Captains (CPT), three Senior First Officers (SFO) and three First Officers (FO), from five European airlines participated in the field trials with the Institute's Navigation Test Vehicle.
During their entire career in commercial aviation, the participating pilots had logged between 1,500 and 20,000 hours (ø 9335 h). The distribution of aircraft types currently flown was as follows:

- Airbus A320 family: 2
- Airbus A330/A340 family: 4
- Boeing B-737 Classic (B733, B735,…): 4
- Boeing B-747-400: 2
- Boeing B-777: 1
- McDonnell-Douglas MD-11: 2

Incidentally, there was thus an almost even distribution over Airbus and Boeing aircraft types. Familiarity/type-specific experience with the current aircraft type ranged from 200 to 9,000 hrs (ø 3287 h). On average, pilots had spent 15.1 years with their current airline, with a minimum of two years and a maximum of 37 years. One pilot had a flight testing and certification background, and several others were technical pilots and/or instructors with their present airline.

Num	Background (Flight test, Airlines Training)	Nationality	Native Language	Sex (F/M)	Age	Hierarchical (Captain/ [Senior] First Officer)	Amount of flight hours	Application knowledge
1	Airline	German	German	M	N/A	Senior First Officer	3500	AMM (other)
2	Flight test, Airline, Certification	Dutch	Dutch	M	59	Captain	11000	AMM (other)
3	Airline	German	German	M	40	Captain	9000	-
4	Airline	German	German	M	39	Senior First Officer	7130	-
5	Airline	German	German	M	50	Captain	13000	-
6	Airline, Training	German	German	M	51	Captain	20000	-
7	Airline	German	German	M	29	First Officer	2400	MMS
8	Airline, Tech. Pilot	German	German	M	57	Captain	18000	-*
9	Airline, Training, Tech. Pilot	German	German	M	57	Captain	20000	-*
10	Airline	German	German	M	29	First Officer	2900	N/A
11	Airline, Training	German	German	M	55	Captain	18500	-
12	Airline	Czech	Czech	M	26	First Officer	1500	MMS
13	Airline, Training, Flight test	Czech	Czech	M	42	Captain	7000	MMS
14	Airline	Czech	Czech	M	31	Senior First Officer	1900	MMS
15	Airline	Czech	Czech	M	40	Captain	4200	MMS

Table 17: Overview of the background of pilots participating in the trials

With 11 pilots, the majority of sessions took place in Frankfurt. Unfortunately, due to scheduling constraints and the limited time available on site, eventually only four pilots participated in the Prague experiment.

7.5.2 Background in Traffic-related Systems

In order to enable a better post-hoc classification and understanding of assessment results, pilots were asked for relevant experience in the domain of traffic-related systems such as TCAS (cf. Section 3.2.1) and ADS-B (Section 3.2.2). Regarding TCAS experience, seven of the pilots had experience in the old TCAS I, while 12 pilots stated they were familiar with TCAS II. Given their current aircraft types, all 15 participants can be expected to have TCAS II experience, but two pilots skipped the whole question altogether, and a third one claimed ADS-B experience only. But given the aircraft type he flies, he should be familiar with TCAS II, and thus it seems reasonable to assume that he accidentally forgot to check the TCAS II box on the questionnaire.

A total of four pilots claimed familiarity with ADS-B, but none was actually using any applications based on ADS-B in daily operations. Experience was limited to research and development.

7.5.3 Experience in Runway Incursions and RAAS

In view of the scope of the evaluation, pilots were asked whether they had ever experienced a Runway Incursion themselves. One pilot did not answer to this question; it could not be determined whether this was due to the sensitive nature of the question, or simply by oversight. Of the remaining pilots, 10 (or 71.4%) had never personally encountered a Runway Incursion. Four pilots (or 28.6%) stated that they had first-hand experience with Runway Incursions, although typically only once in their career. One Captain with 20,000 flight hours (Pilot #9) reported more than one encounter. Another pilot (Pilot #15) had merely experienced a Runway Incursion in a simulator scenario.

Pilot #1 gave a more detailed description of his encounter and stated that Bangkok Don Mueang Airport (VTBD) was very dangerous with respect to Runway Incursions at the time, because there was a large portion of taxiway parallel to the runway **behind** the holding position. He had experienced this once, when the crew overlooked this in their Boeing 747-400 with three crew members in the cockpit (including a check-pilot), and were taxiing across this holding position onto this TWY in parallel to the runway when another aircraft landed. The remaining wingtip separation was around 10 m.
Another pilot (Pilot #5) also stated he had missed a holding position once, and added that there might probably several more that he had missed over the years, without even noticing. Pilot #9 reported encounters with other aircraft on the active runway, opposite taxiway traffic and others.

Participants were also asked for relevant experience with Honeywell's Runway Awareness and Alerting System (RAAS; see Section 3.3.1 for details), an add-on function to the TAWS that provides only aural alerts and advisories for various runway safety-related cases.
Eight of the participating pilots, or 53.3%, had never heard of the RAAS before. Three pilots, or 20%, had heard or read of the RAAS, and another three had seen it in a simulator. One of the pilots had been involved in the testing of RAAS for his airline.

7.5.4 Background in Research Projects and Airport Moving Map

Two thirds of the participants had previously participated in research projects and/or product development. The four Czech pilots had all participated in EMMA trials in Braunschweig, three of the German pilots had been involved in simulator trials for the European research project ISAWARE II, cf. [Ver05].
Roughly half of the participating pilots had already previous experience with airport moving map displays. Two further pilots, although they did not claim corresponding experience, had already been demonstrated the MMS during an earlier visit at Airbus facilities; these are marked with an asterisk in the table[135]. For all pilots, however, this experience was limited to research projects and simulator trials, none of the pilots had actual operational experience with airport moving map displays.
Three of the four participating Czech pilots had participated in a simulator evaluation with exactly the same airport moving map display from earlier EMMA trials in DLR's cockpit simulator, using Paris – Charles de Gaulle (LFPG) as scenario location. Two of the German pilots had also been given a demonstration of this display at Airbus facilities. Furthermore, another three pilots had participated in the ISAWARE II ND taxi display evaluation. One pilot did not answer this question.

7.5.5 Familiarity with Test Airport

Pilots were requested to rate their familiarity with the airport at which the tests took place on a six-step scale with text statements, ranging from "It is my first time here" to "I know the layout of this airport almost better than that of my flat". The vast majority of pilots (80%) stated that they knew the airport in question very well. While it was the first-ever visit to the test airport for one pilot (6.67%), another one had been at the corresponding airport several times before, and one pilot claimed to know the airport better than the layout of his flat.

[135] In retrospect, it seems that the corresponding question (see questionnaire in the appendix) was not precise enough, as it did not discriminate operational experience and experience with the technology in research projects.

7.6 Assessment Results

7.6.1 Basic Airport Moving Map Display

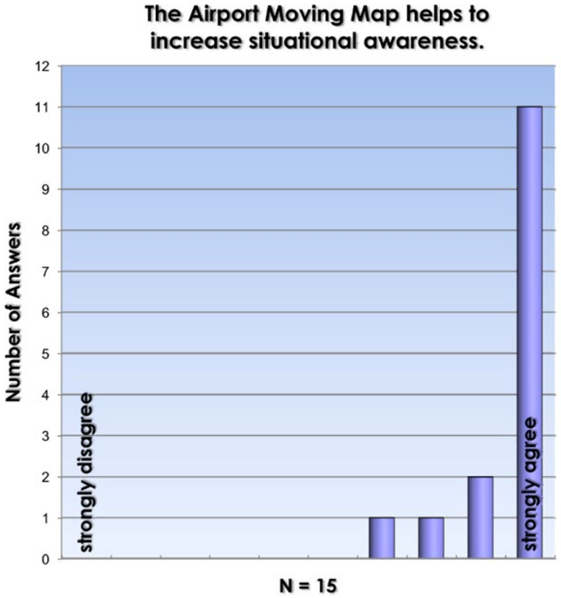

Figure 95: Perceived contribution to situational awareness

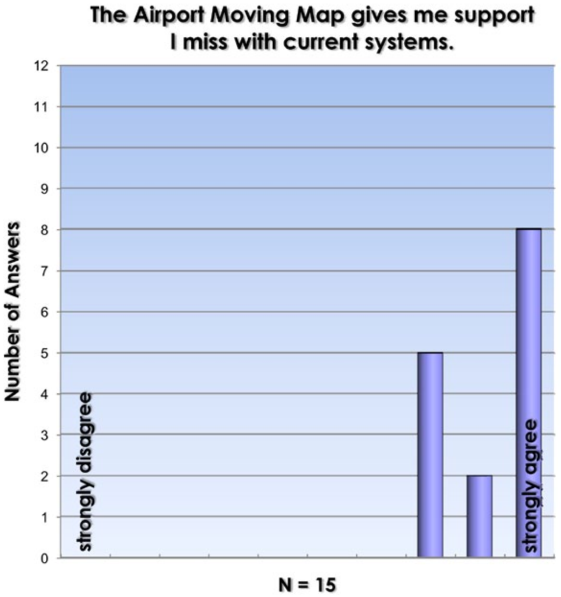

Figure 96: Operational relevance of airport moving map

Overall feedback and comments on the airport moving map were very positive. According to pilot's perception, the AMM helps to increase their situational awareness, as shown in Figure 95. With 11 pilots, almost three quarters of the participants opted for the highest rating on a Likert-style scale from 1 (strong disagreement) to 10 (strong agreement), resulting in an average rating of 9.53 and a significant deviation from normality (1% confidence level). Pilot #4 commented that while the AMM clearly increased situational awareness, he feared that it might also be a distraction.
The questionnaire results displayed in Figure 96 clearly indicate that the AMM corresponds to an operational need, since all participants agree that it gives them support they miss with current systems (Mean = 9.20, Standard Deviation = 0.94).

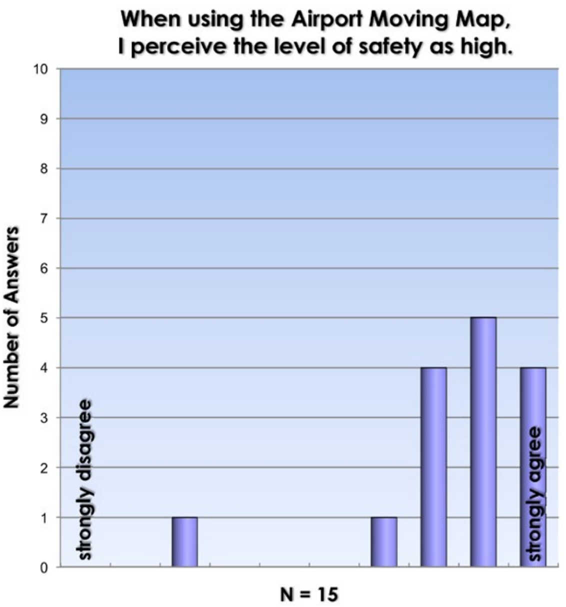

Figure 97: Perceived impact of airport moving map on safety

Although the perceived level of safety when using the AMM was generally high according to the results presented in Figure 97 (M = 8.47, SD = 1.77), it is noteworthy that the mean rating is markedly lower than for situational awareness. The senior captain (Pilot #11) disagreeing on this was also somewhat reluctant with his confidence in the presentation on the display (see Figure 104). Nevertheless, he acknowledged that the AMM gives him support that he misses with current systems (cf. Figure 96).

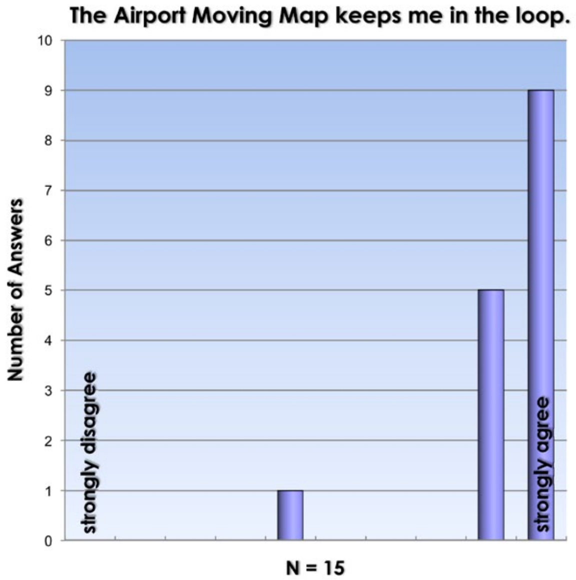

Figure 98: Impact of AMM on pilot involvement

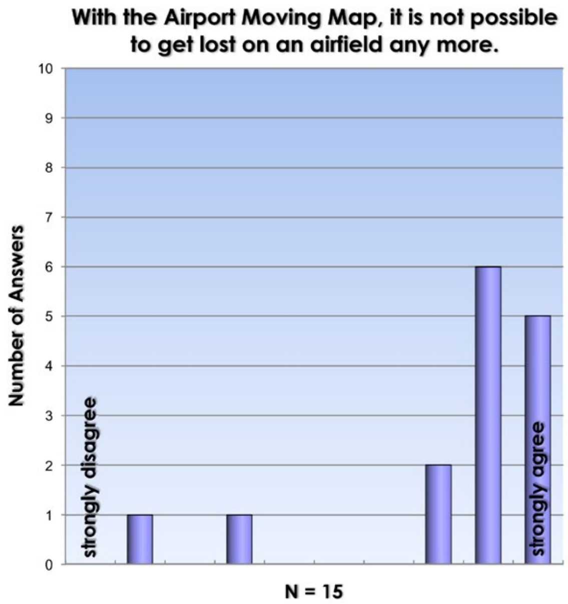

Figure 99: Capability of AMM to prevent flight crew disorientation

As is evident from Figure 98, pilot feedback suggests that the AMM keeps pilots in the loop (M = 9.33, SD = 1.29). Only Pilot #15 gave a neutral rating with negative tendency on this statement, but did not specify a particular reason for this assessment.

Thirteen out of fifteen pilots (or 86%) think that it will not be possible to get lost on an airfield with an AMM (see Figure 99), while two participants consider this still possible, particularly if the crew is distracted by other tasks (M = 8.40, SD = 2.32). The slight disagreement of a senior captain (Pilot #11) on this matter is consistent with his somewhat more reserved attitude towards the AMM. The young first officer (Pilot #14) who clearly disagreed did not give an explicit reason or a comment that would elucidate his choice, but it can be speculated that it is due to a healthy level of mistrust in human capabilities, since one of the other pilots who eventually rated positively also made a comment to that effect. In conclusion, therefore, the results indicate that the AMM is perceived as a potential solution to airport disorientation, especially in bad weather and on large and complex airfields, as the comments taken during the session confirm.

Furthermore, there is a clear pilot preference for an ND-integrated airport moving map display (see Figure 100), which confirms the SMAAS concept (M = 8.80, SD = 2.04). Only Pilot #13 favoured the standalone AMM as presented. However, a concern expressed by some participants was that a conventional ND screen in today's glass cockpits might be too small for the display to be easily legible.

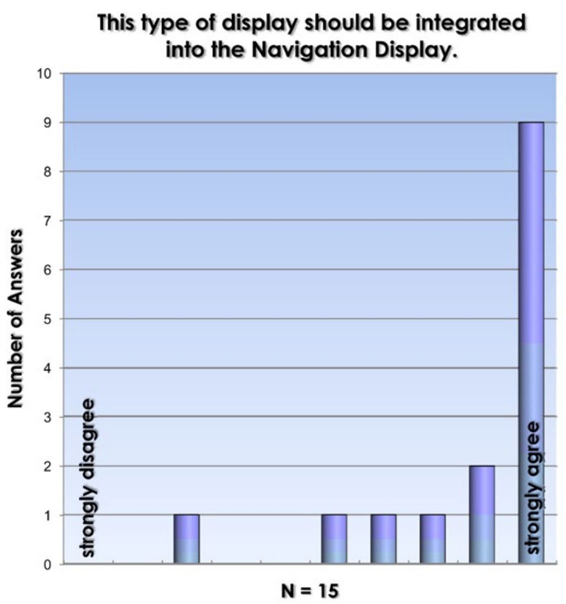

Figure 100: Pilots' preferences on ND-integrated airport moving map

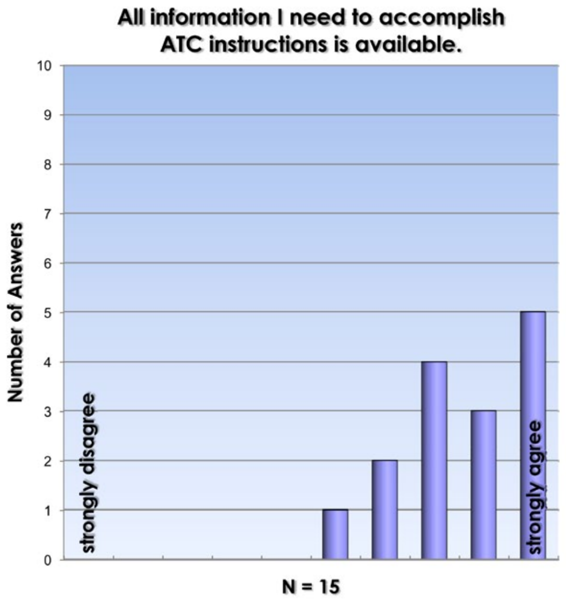

Figure 101: Appropriateness of AMM information to accomplish ATC instruction

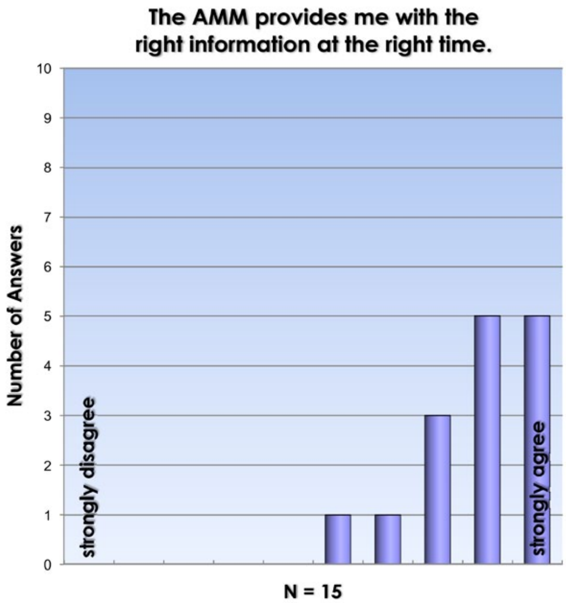

Figure 102: Relevance of AMM information

Pilot feedback presented in Figure 101 (M = 8.60, SD = 1.30) and Figure 102 (M = 8.80, SD = 1.21) suggests that the AMM provides pilots with sufficient and adequate information to accomplish routine operations in a timely fashion.
Since the accuracy of the ownship position received exclusively positive feedback from participants, as evidenced by Figure 100 (M = 9.20, SD = 0.68), any detrimental impact of potential inaccuracies on the evaluation of the AMM functionality *per se* can be safely excluded. Accordingly, Figure 104 indicates that all but one of the participants had confidence in the AMM presentation (M = 8.40, SD = 2.23). The strong disagreement from Pilot #5 is somewhat puzzling and may be inadvertent, since the same pilot made very positive comments on the AMM ("*…it is super to assess distances and to get orientated…*") and gave high ratings for related questions.

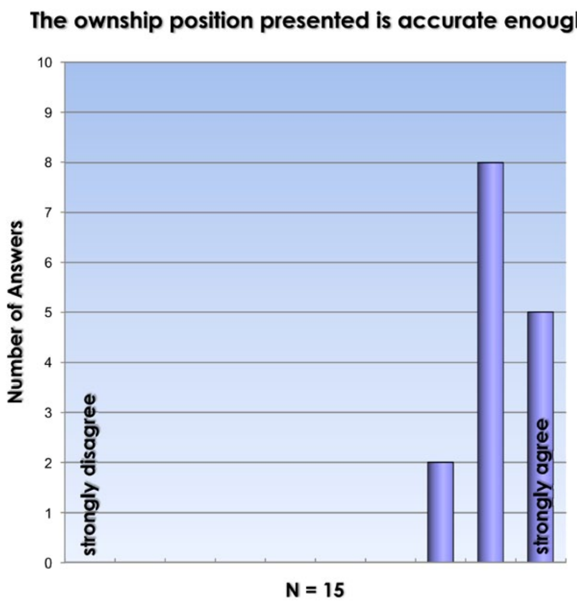

Figure 103: Adequacy of position accuracy during field trials

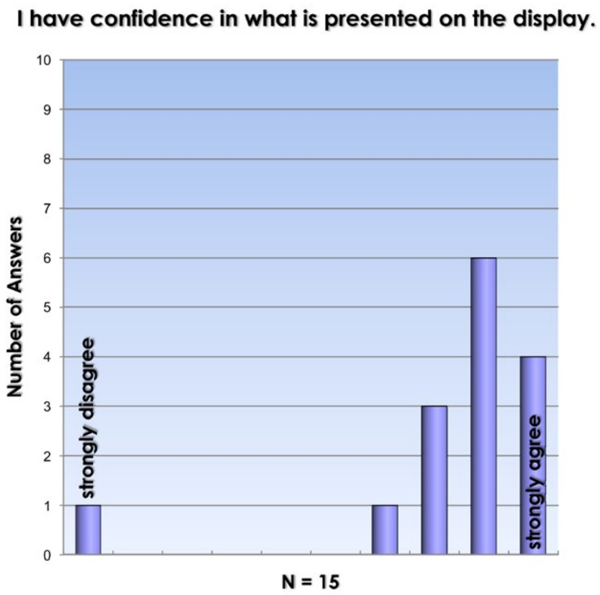

Figure 104: Perceived trustworthiness of AMM presentation

The questionnaires presented after the evaluation sessions contained further questions on particular design aspects of the airport moving map, but since an Airbus A380 airport moving map prototype and not the design described in Section 5.1 was used during the field trials, it is not relevant to discuss the corresponding results, which can be found in [EMM07], in this section. Therefore, the analysis in this section is limited to the generic characteristics and overall impact of an airport moving map, in line with the goals of this thesis. For exactly the same reason, the assessment results concerning traffic symbology are excluded from the following section.

7.6.2 Airport Moving Map Display with Traffic Display

7.6.2.1 Overall Impression

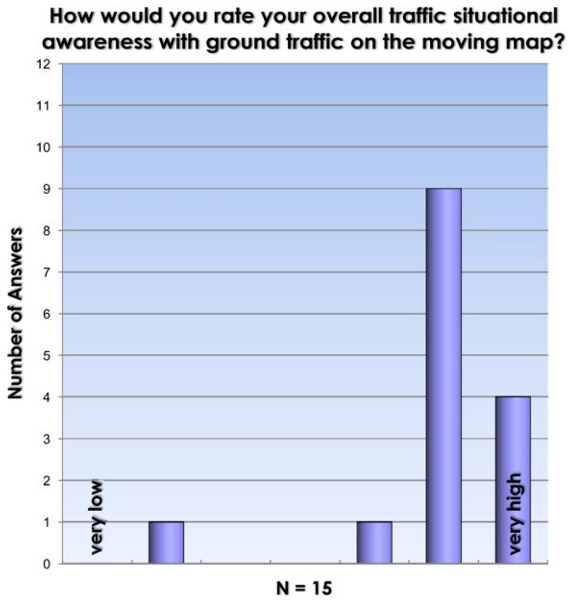

Figure 105: Perceived situational awareness with ADS-B traffic on AMM[136]

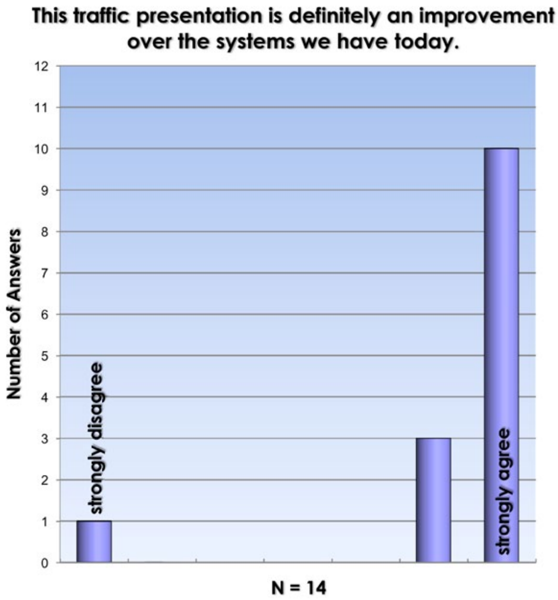

Figure 106: Improvement with respect to current systems

Most pilots rate their traffic situational awareness with ADS-B traffic displayed on the airport moving map very positively, as shown in Figure 105 (M = 4.93)[137]. The only negative feedback came from Pilot #2, who criticized both the quality of the ADS-B data presented as insufficient and the percentage of equipped aircraft (see discussion further below for details), which made the display unusable in its present form. Nevertheless, he acknowledged the enormous potential of traffic display on AMM. Given the flight testing and certification background of this pilot, and the fact that he was the only participant from this domain, his criticism needs to be considered very carefully. Likewise, as can be inferred from Figure 106, participants considered the traffic presentation to be a definite improvement over systems available today (M = 5.36). Again, Pilot #2 gave a negative rating on this question, but reiterated his comment that potential for traffic on this display was enormous, and that his

[136] For each questionnaire results diagram shown, the number *N* of valid answers is given. Occasionally, pilots skipped individual questions by error, and sometimes, the presentation of an individual function failed due to a system error, rendering certain questions not applicable.

[137] To collect feedback on the traffic presentation, a seven-stage Likert-type rating scale from zero to six was used.

negative rating was due to the unreliable traffic data. It may therefore be concluded that all pilots acknowledged the principle of displaying traffic on an AMM as an improvement over current systems. Last but not least, it should be noted that the distribution of results significantly deviates from normality for both questions.

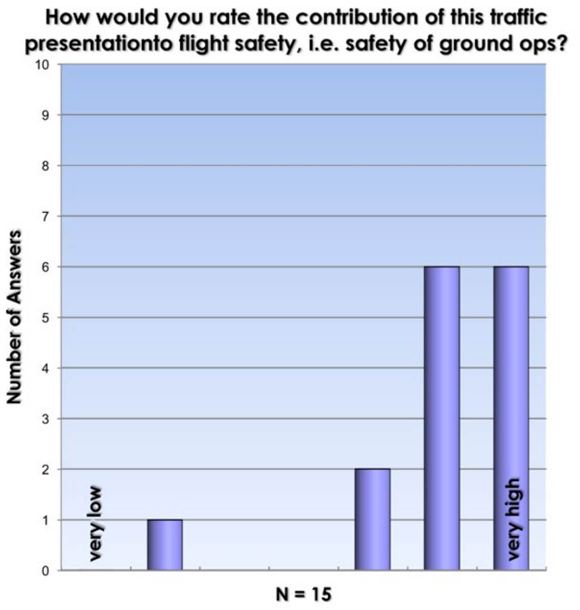

Figure 107: Perceived impact of traffic presentation on safety

Pilots were also asked to assess the potential contribution of the traffic presentation on safety. The distribution of results, as presented in Figure 107, is similar to the previous two questions, with Pilot #2 giving a low rating due to his already expressed concerns (M = 5.00, SD = 1.31). Furthermore, Pilots #7 and #13 were a bit more reserved in their rating. Again, the results indicate that all pilots clearly acknowledge the potential of the ground traffic presentation, while the technology was not fully deployed and mature at the time of the trials.

Concerning the ADS-B traffic data available for the trials, a majority of pilots accepted the accuracy of ADS-B traffic with respect to position, see Figure 108 (M = 5.73, SD = 1.39). Disagreement came from Pilot #7, and Pilot #4 provided a neutral rating. Pilot #15 erroneously skipped the question. In conclusion, therefore, the main issue with ADS-B traffic is not its positional accuracy, but – as evident from Figure 109 – the sporadic unavailability traffic data as well as the update rate, which resulted in negative feedback and several critical comments (M = 4.67, SD = 1.50).

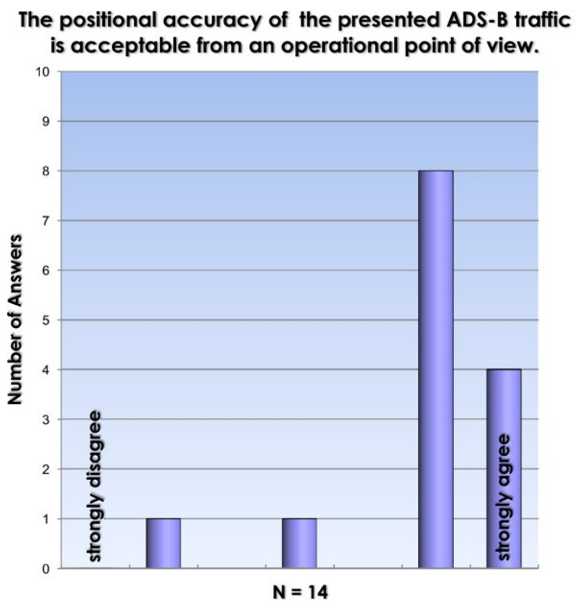

Figure 108: Acceptability of positional accuracy of ADS-B traffic data during live trials

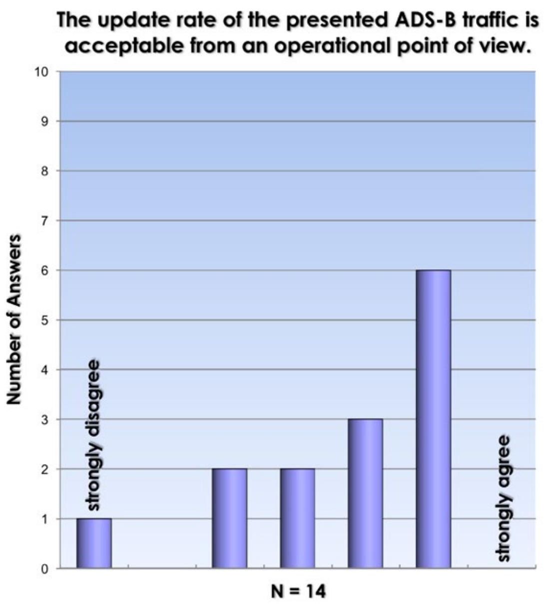

Figure 109: Pilot feedback on operational suitability of ADS-B data update rate

To explain his strong disagreement on the acceptability of the update rate, Pilot #2 stated that the refreshment rate of traffic was often too slow for a pilot to build confidence, and that heading and position of traffic were partially unstable. His main concern, however, was that an aircraft symbol not appropriately updated could be perceived as stationary. Since it is essential whether an aircraft is stationary or moving, he regarded this as unacceptable. Further negative feedback came from Pilot #1 and Pilot #7, but they did not make any comments to elucidate their point of view, which can be assumed to be similar to Pilot #2's. Even pilots who eventually rated positively made similar comments. Pilot #9 also complained about the position jumps due to the non-nominal update rate, but admitted that similar jumps existed on the TCAS display today. A further issue during the trials the exclusive use of a directional traffic symbol, which resulted in an incorrect heading/track presentation for those ADS-B targets not supplying this information, or when track information was lost for stopped aircraft. In both cases, a default heading of 0° would be used, and this incorrect information additionally irritated pilots.

As Figure 110 shows, a majority of the participating pilots agreed that the AMM traffic presentation helped them to establish a correspondence with traffic they saw outside the window (M = 5.00, SD = 1.36). Pilot #2 disagreed, but again not in principle, but rather due to the deficiencies of ADS-B data coverage and reliability.
Concerning pilots' confidence in the presented traffic, the picture becomes more complex, which is not surprising in view of the issues with ADS-B traffic discussed above. Pilots #2 and #4 did not have any confidence, stating that missing position updates while the aircraft was actually moving are not acceptable from an operational point of view. In addition, Pilot #2 remarked that the display of traffic seemed to lack stability, and that the fact that targets were sometimes appearing and disappearing quickly did not help to build confidence. Pilot #1, Pilot #7 and Pilot #11 also disagreed, though less vigorously.

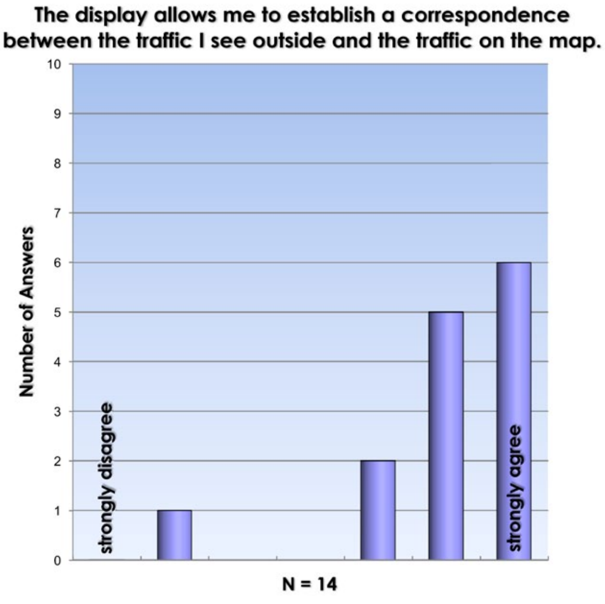

Figure 110: Support of traffic presentation for visual acquisition

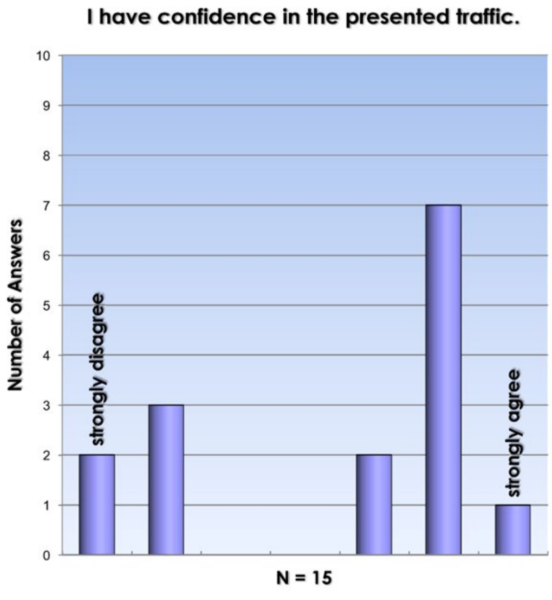

Figure 111: Pilot confidence in traffic presentation

The choice of Pilot #7, and probably that of others, might have been influenced by the confusing heading information that was presented for those ADS-B intruders that did not transmit valid heading or track information. Pilot #9 also referred to the wide range of headings and position jumps, but as he found the latter similar to the jumps on TCAS today, he most likely did not consider this issue severe enough to give negative feedback. Generally, he found traffic information very good.

7.6.2.2 Scope of Traffic Presentation

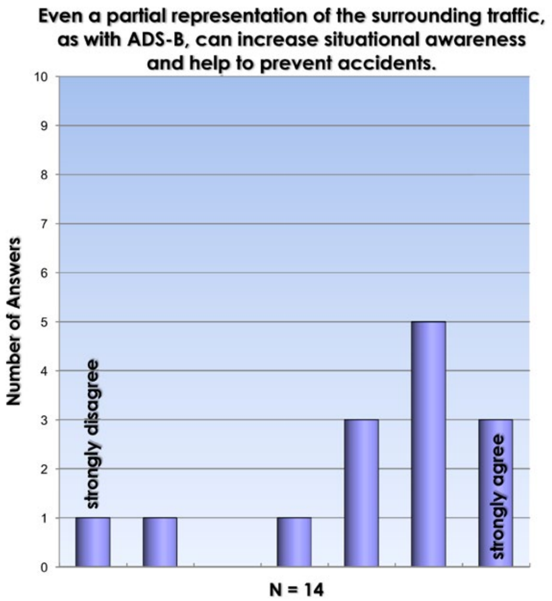

Figure 112: Operational usefulness of incomplete traffic surveillance picture

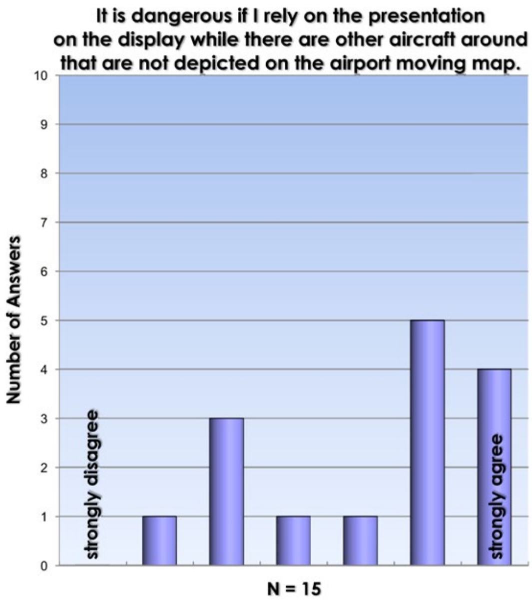

Figure 113: Dangers associated with using incomplete traffic surveillance picture

It is evident from the questionnaire results shown in Figure 112 that a majority of pilots considered even a partial visualisation of the surrounding traffic as having a positive impact on situational awareness (M = 4.21, SD = 1.81), while two pilots – Pilots #2 and #7 – opposed an incomplete representation. Pilot #2 commented that all traffic that can visually be acquired has to be presented on the display as well, and saw a certification issue if this cannot be guaranteed by a suitable implementation process for ADS-B technology. Pilot #4 gave a neutral rating, and Pilot #15 erroneously skipped this question.
At the same time, almost two thirds of the participants also acknowledge the potential hazards arising from an incomplete traffic presentation, as shown in Figure 113 (M = 4.20, SD = 1.74). Conversely, Pilot #15 did not regard this as a problem and therefore disagreed. Pilots #3, #6 and #14 also rather dissented, while Pilot #5 gave the neutral rating. Although the questions in Figure 112 and Figure 113 are somewhat antagonistic, similar or even identical ratings – as provided e.g. by Pilots #8 to Pilot #12 – do not necessarily indicate inconsistencies. Apparently, the positive rating on questions both given by these pilots indicates that they think a new technology with limitations – of which they are aware – is still advantageous over the current situation. Conversely, others like Pilot #2 and Pilot #4, demonstrated by their strong agreement on the question in Figure 113 that the issues outweigh the benefits in their view in the current environment.

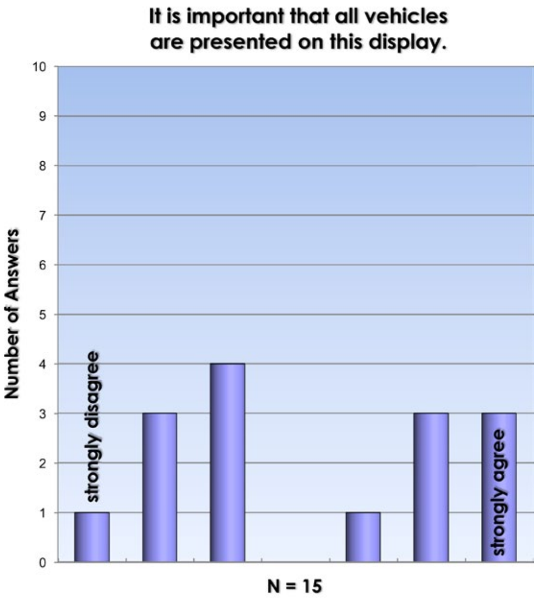

Figure 114: Operational relevance of displaying airport vehicles

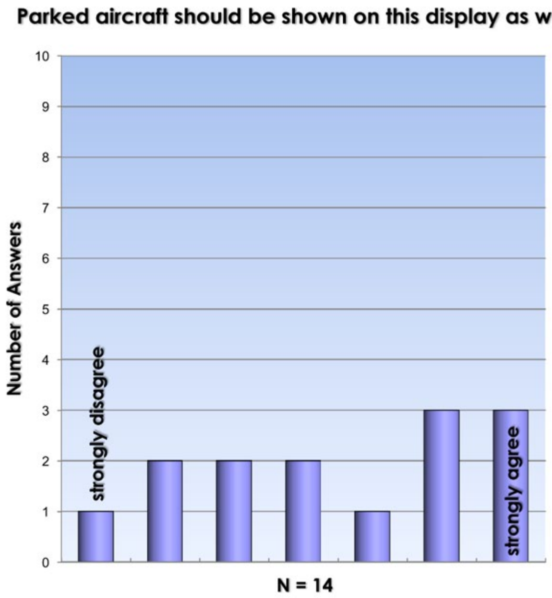

Figure 115: Importance of visualising parked aircraft

Pilots' feedback concerning the necessity of displaying all airport vehicles on the AMM is divided in two distinct groups, as shown in Figure 114 on the next page (M = 3.20, SD = 2.14). A majority of the experiment participants did not consider a visualisation of all airport vehicles on the airport moving map as useful feature; Pilot #2 even strongly disagreed on the necessity. Only Pilots #8, #11 and 15 strongly agreed that there is a need of presenting all vehicles.

As Figure 115 shows, participants had diverging opinions concerning the presentation of parked aircraft (M = 3.50, SD = 2.07). Pilot #11 agreed on the need for displaying parked aircraft and commented that a valid operational reason was the possibility to check whether an assigned parking position or gate is already vacant or not.

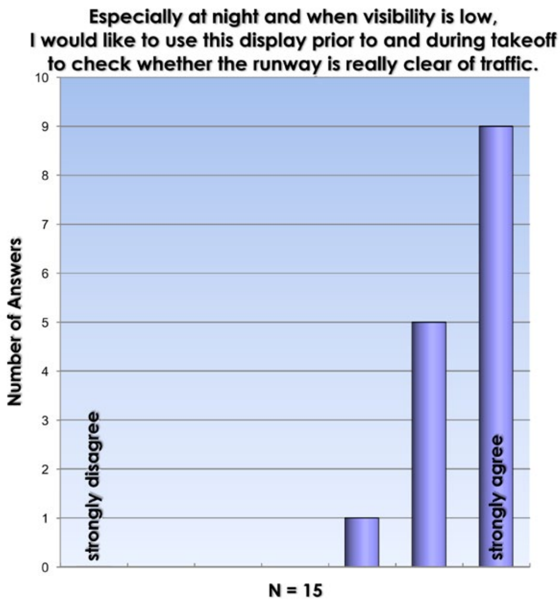

Figure 116: Usage of AMM traffic depiction for runway surveillance

The results presented in Figure 116, which significantly deviate from a normal distribution according to a one-sided Kolmogorov-Smirnov test, clearly illustrate that awareness of traffic in the runway environment is indeed the key concern for pilots, since all of them agree – 60% strongly – that they would apply the AMM with its traffic representation to verify that the runway is really clear of traffic, especially at night and in low visibility (M = 5.53). In this context, Pilot #14 commented that checking that the runways are clear was the main use for a traffic presentation on the AMM in his eyes.

7.6.2.3 Workload and Display Clutter

Figure 117: Perceived impact of ground traffic presentation on workload

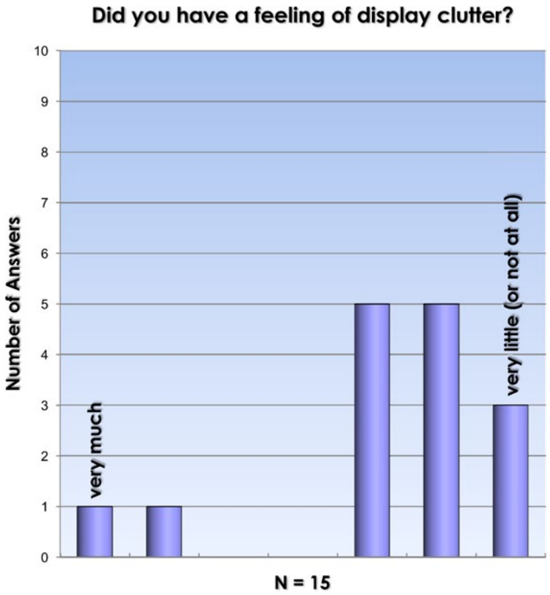

Figure 118: Subjective feeling of display clutter

Pilots were asked to rate the influence of the AMM with additional traffic presentation on their perceived workload. The results presented in Figure 117 indicate that most pilots experienced little or no increase in workload (M = 4.27, SD = 1.53). However, since these results were not obtained in an environment representative of actual pilot tasks and associated workload, it would be premature to draw any definite conclusions based on this feedback. Nevertheless, it is encouraging that only two pilots, Pilot #7 and Pilot #12, felt their workload increased by the ground traffic presentation.

Additionally, participants were asked whether they regarded the display as cluttered with the additional traffic presentation. It is evident from the results presented in Figure 118 that the majority of pilots did not have an impression of display clutter (M = 4.27, SD = 1.71). Only Pilots #2 and #7 confirmed the presence of clutter.
Given the comparatively number of aircraft and vehicles effectively equipped with ADS-B during the field trials, however, these results should be treated with care. While apparently not a major issue, display clutter caused by traffic should be monitored closely.

7.6.3 Operational Awareness Function (OAF)

7.6.3.1 FMS-selected runway representation

After having seen the FMS-selected runway representation on the airport moving map display, pilots were asked to rate this feature both in general and with respect to the particular implementation chosen in post-run questionnaires, using a Likert-style rating scale offering seven distinct steps from “strongly disagree” (0) to “strongly agree” (6). The results are presented in the following. First, pilots were asked for the operational relevance of the FMS-selected runway presentation on the standalone airport moving map application, the so-called “Moving Map Standalone” (MMS).

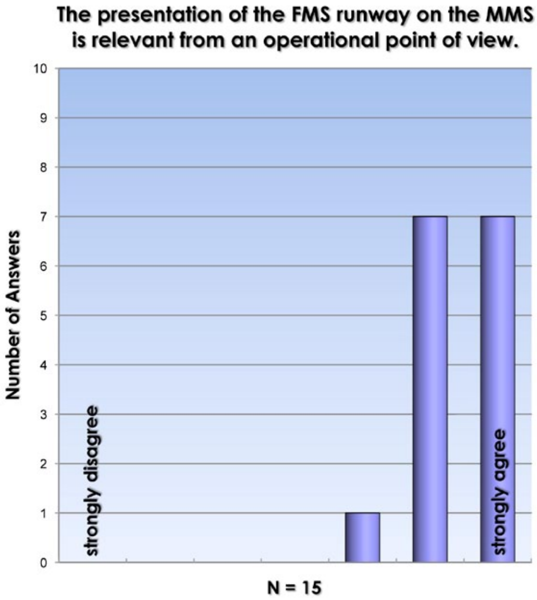

Figure 119: Operational relevance of FMS-selected runway presentation on AMM

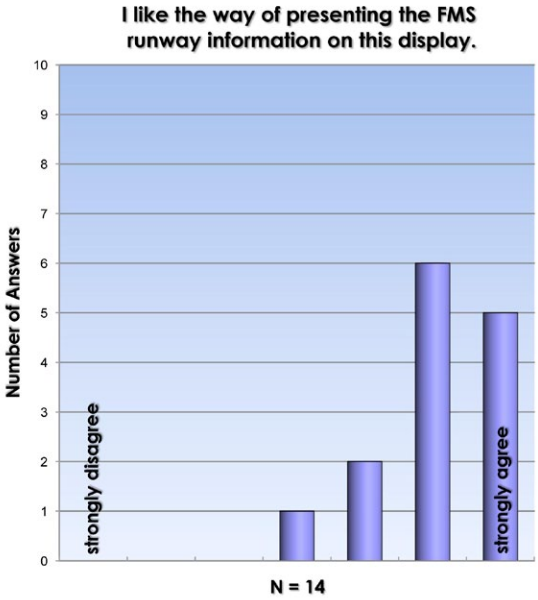

Figure 120: HMI design of FMS-selected runway representation on AMM

As can be seen from Figure 119, all pilots appreciated the concept of presenting the FMS-selected runway on the airport moving map, thus confirming the assertion that this feature has operational relevance (M = 5.40, SD = 0.63). With seven pilots, almost half of the participants gave the highest rating, and the same number of pilots chose the second-highest rating. Only Pilot #11 was somewhat hesitant in his agreement, which is in line with his general reservations towards airport moving map technology.

Apart from the general concept, a majority of pilots also liked the particular design choice made for the representation of the FMS-selected runway on the airport moving map display (see Figure 120), although only 36% gave the highest possible rating. The level of agreement is both qualitatively and qualitatively slightly lower than for the concept itself (M = 5.07, SD = 0.92), with Pilot #8 giving a neutral rating and Pilots #2 and #10 only rather agreeing on the HMI solution for the FMS-selected runway. Pilot #11, most likely by error, skipped answering this question. Nonetheless, the data suggests that the concept of using the runway outline to represent the FMS-selected runway on the airport moving map seems valid.

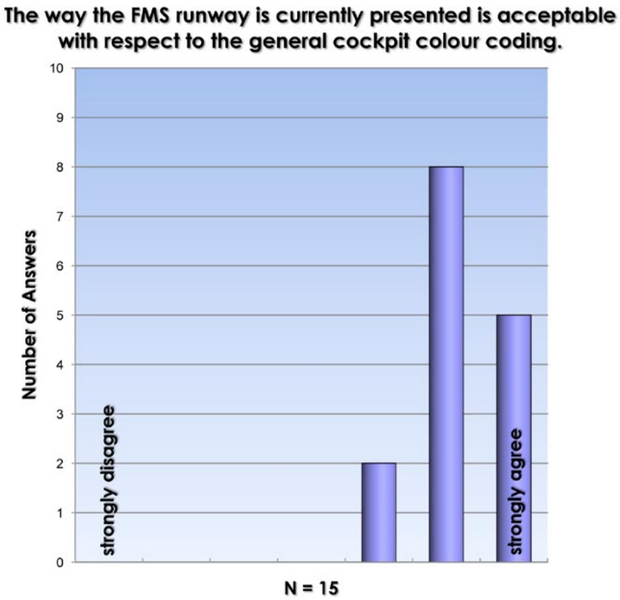

Figure 121: Colour of FMS-selected runway representation on AMM

The ratings shown in Figure 121 refers to the initial FMS-selected runway representation colour concept, the magenta outline as presented in Figure 43 on p. 168.

There is no negative feedback, i.e. all participants considered the choice of colour acceptable. However, only one third of the pilots opted for the highest possible rating, and Pilot #4 and Pilot #11 gave a feedback that is still positive, but already close to a neutral rating, indicating that they do not wholeheartedly agree with the colour choice (M = 5.20, SD = 0.68). The colour choice thus received a slightly better rating than the symbology (cf. Figure 120), the runway outline. Nevertheless, this might be explained by the fact that the EFIS of current transport category aircraft commonly uses magenta to display parameters derived from the FMS.

7.6.3.2 Representation of Closed Runways

Figure 122 illustrates that all of the participating pilots acknowledged the operational relevance of displaying closed runways on the airport moving map display (M = 5.60). Again, there is a complete absence of dissenting feedback. With nearly three quarters of the participants opting for the highest available rating, it is not surprising that a one-sample Kolmogorov-Smirnov test yields that the results deviate from a normal distribution, even at a 1% significance level. Only Pilot #1 and Pilot #14, who also considered presenting closed runways relevant, were more reluctant in their feedback and 'rather' agreed with the statement presented, but generally considered presenting closed runways relevant. Nevertheless, the overall level of agreement is very high and almost achieves the same magnitude as the presentation of the taxi route, cf. Figure 128.

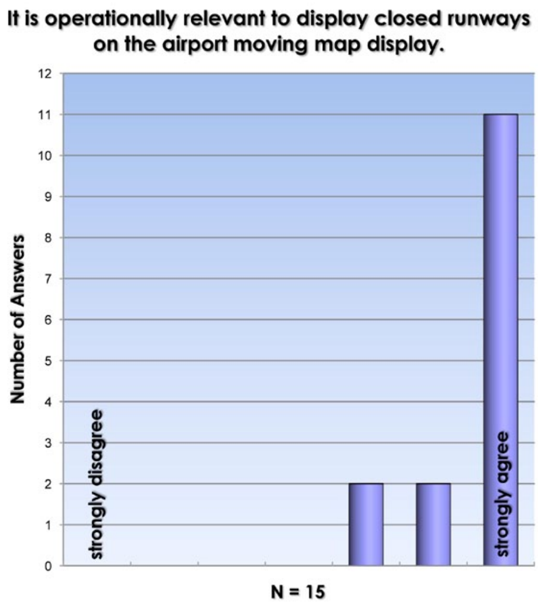

Figure 122: Operational relevance of closed runway representation

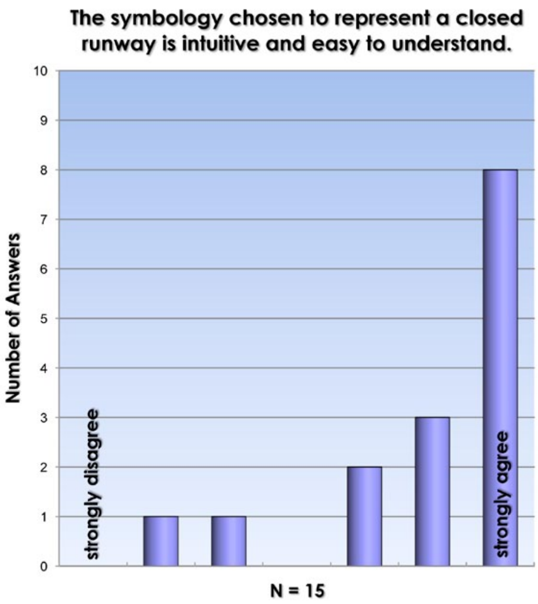

Figure 123: Assessment of closed runway representation

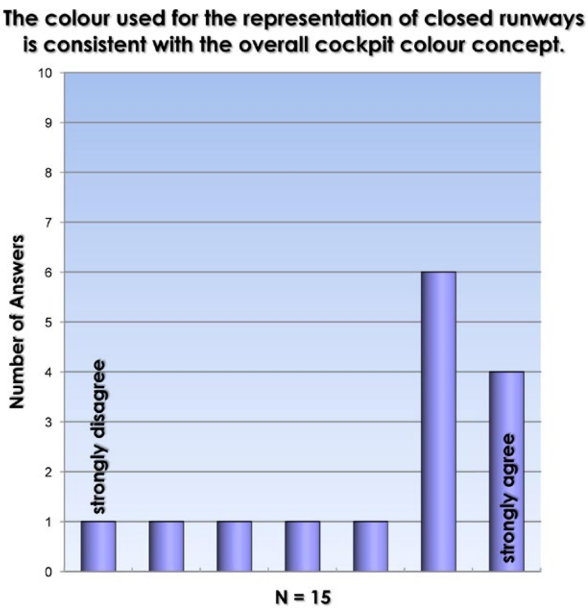

Figure 124: Colour of Closed Runway representation

Figure 123 illustrates that the majority of pilots found the symbology used to display a closed runway intuitive and easy to understand without reservations (M = 4.93, SD = 1.58). While Pilot #3 and Pilot #4 still agreed with the symbology, there was also some negative feedback. Pilot #10 disagreed on the intuitiveness of the closed runway symbology, and Pilot #11 was also rather dissenting. Unfortunately, their comments during the sessions did not shed any light on the reasons for their rating.

The choice of amber symbology to represent the closed runway was mostly appreciated, but, as Figure 124 shows, not all of the pilots agreed on this choice (M = 4.27, SD = 1.91). Pilot #8, who highly appreciated the symbology itself, even strongly disagreed that the colour used for the representation of closed runways was consistent with the overall cockpit colour concept. Pilot #4, who disagreed, commented that red would be a better colour for the closed runway symbology, because it creates more contrast than orange, which has too little contrast with yellow. Slightly negative and neutral feedback on the colour choice came from Pilot #10 and Pilot #11, respectively, which might shed some insight on the reason why they also rated the closed runway symbology low.

7.6.4 Clearance Awareness Function (CAF)

7.6.4.1 Runway clearance presentation

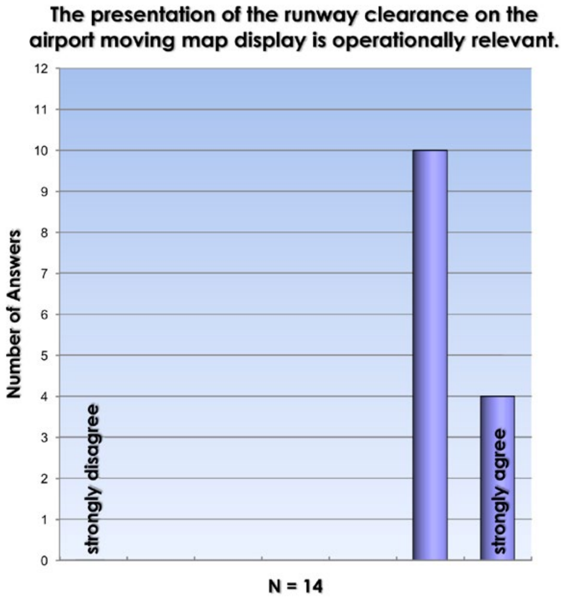

Figure 125: Operational relevance of Runway Clearance representation on AMM

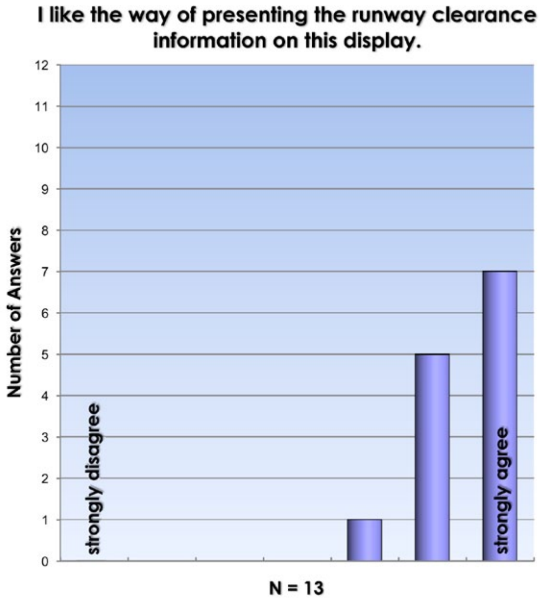

Figure 126: HMI design of Runway Clearance representation

The results shown in Figure 125 confirm that, from a pilot's point of view, the presentation of ATC instructions and clearances related to runway operations on the airport moving map is operationally relevant (M = 5.29). The level of agreement, with only the two highest ratings chosen, and the complete absence of dissent indicate a high operational relevance. Again, the normality of the distribution can be rejected at a 1% significance level. Pilot #13, probably erroneously, skipped answering the question.

According to the results presented in Figure 126, pilots not only acknowledged the principle, but also appreciated the particular HMI design chosen for the implementation of the runway clearances on the AMM (M = 5.46, SD = 0.66). Only Pilot #2 was agreeing to a lesser extent; Pilot #1 and Pilot #13 did not provide any rating on this question.

Furthermore, as can be deduced from Figure 127, all pilots agreed on the colour choice (green) made for representing runway-related ATC instructions and clearances as expected (M = 5.50, SD = 0.52). Pilot #13 also skipped this particular question.

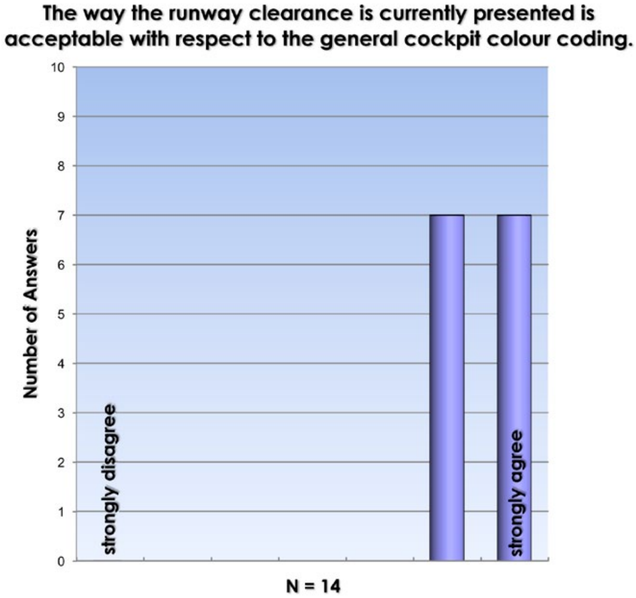

Figure 127: Colour of Runway Clearance representation

7.6.4.2 Taxi route presentation

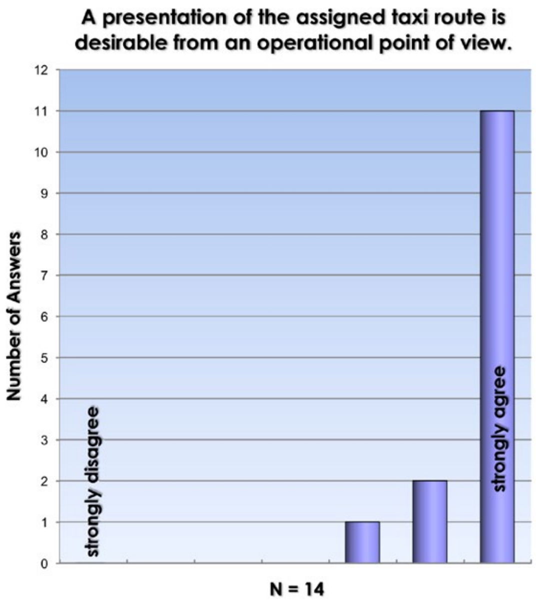

Figure 128: Operational relevance of Taxi Route representation on AMM

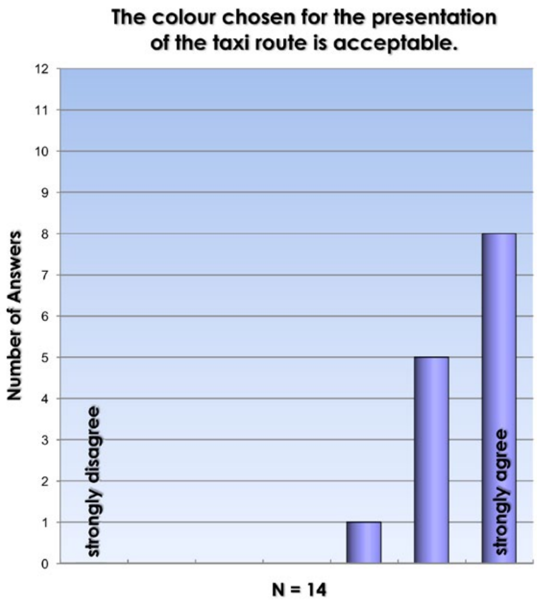

Figure 129: Colour of Taxi Route representation on AMM

The results shown in Figure 128 prove that a presentation of the assigned taxi route on an airport moving map display is definitely one of the functions most desired by pilots (M = 5.71). Otherwise, there would not be strong agreement on the operational relevance of the taxi route from 79% of the participating pilots. Only one pilot (Pilot #15) was apparently not fully convinced of the operational relevance, but still rated slightly possible, and did not voice any concerns regarding this feature. Again, the normality of the results distribution can be rejected at a 1% significance level.

Since the trials did not contain any interactivity with respect to the assigned taxi route, which was presented after activation by the experiment leader, several pilots raised the question whether the taxi route was envisaged to be up-linked via data link or manually entered by the crew, or whether both options would be foreseen. In this case, the rationale for not permitting manual entry presented in Section 5.4.1 was briefly explained.

The green colour chosen for the assigned and acknowledged taxi route was apparently also accepted by virtually all the participating pilots, because all but one made their choice between the two highest available rating options, and almost 60% selected the highest possible rating (M = 5.50, SD = 0.65). Only Pilot #2 was not fully convinced of the colour chosen, but still provided a positive rating, see Figure 129 for details.

Pilot #6 did not provide a rating on these two questions for unknown reasons.

7.6.5 Preventive Surface Movement Alerting

7.6.5.1 General aspects of Runway Incursion Alerting

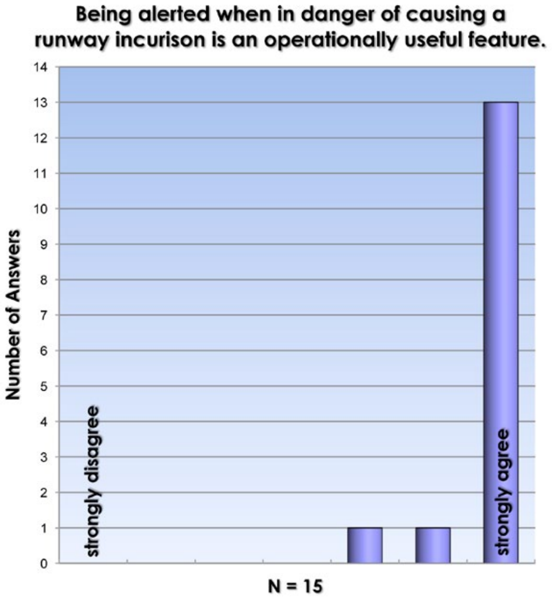

Figure 130: Operational relevance of preventive Runway Incursion alerting

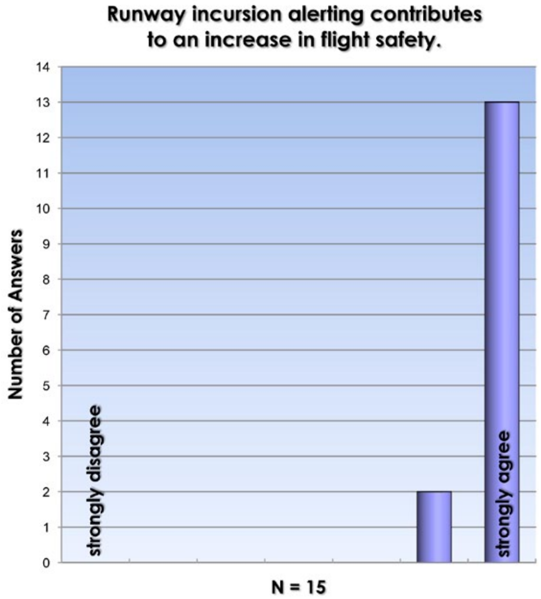

Figure 131: Contribution of (preventive) Runway Incursion alerting to flight safety

As can be deduced from Figure 130 and Figure 131, an overwhelming majority of pilots (86%) strongly agrees that being alerted when in danger of causing a runway incursion is an operationally useful feature (M = 5.80) that will contribute to an increase in flight safety (M = 5.87). The only tentative agreement on the operational usefulness of runway incursion alerting was given by Pilot #15, who nonetheless commented that the alerting was very useful. A one-sided Kolmogorov-Smirnov test yields that the distribution of answers for both of these questions exhibits a strongly significant deviation from a normal distribution.

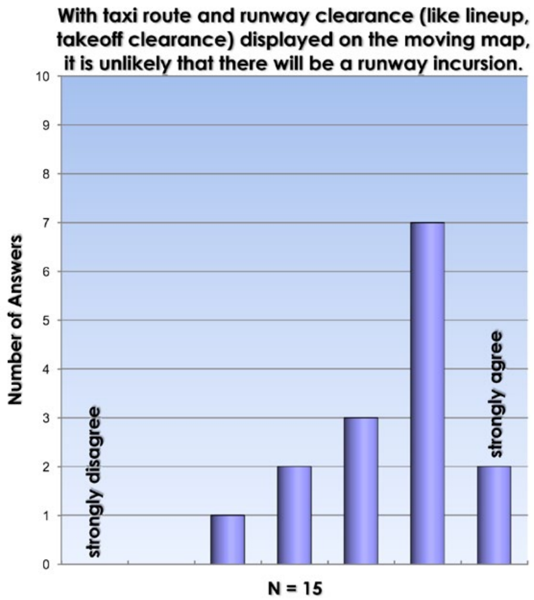

Figure 132: Relevance of Runway Incursion Alerting in presence of airport moving map, taxi route and runway clearance

It should be noted, though, that only the last four pilots, the participants of the Prague experiment session, were exposed to the full scope of runway incursion alerting from Level 0 to Level 3, whereas the other pilots commonly only experienced the Level 0 advisory (Runway Proximity Information, see next section). Therefore, the results shown here have, at least partially, more the character of a survey to capture operational needs, at least for caution and warning level.

To differentiate the feedback on Runway Incursion alerting a bit better, additional questions on the relation of Runway Incursion alerting to the basic situational awareness information (taxi route, runway-related clearances) were asked to obtain more insight into the impact of each technology. In the question presented in Figure 132, pilots were asked to comment on the likeliness of Runway Incursions in the presence of an airport moving map with taxi route and clearance information. 60% of the participants agreed without limitations that a Runway Incursion would be an unlikely event with these onboard functions available (M = 4.47, SD = 1.13). Only one pilot rather dissented (Pilot #1), while the rest gave neutral or slightly positive feedback.

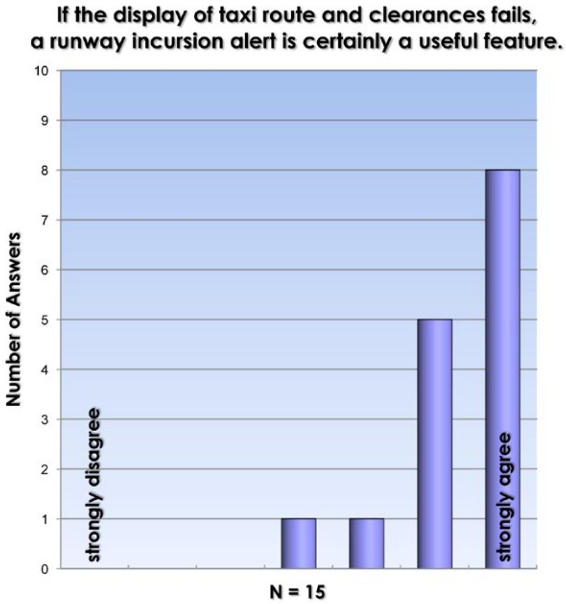

Figure 133: Relevance of Runway Incursion Alerting in absence of taxi route and runway-related clearances

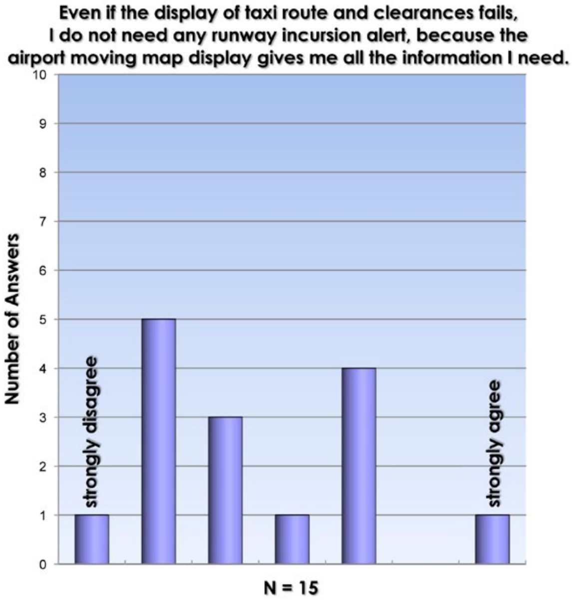

Figure 134: Sufficiency of airport moving map display to prevent runway incursions

With only the basic airport moving map present, though, all but one of the pilots (Pilot #15, neutral rating) agree that Runway Incursion alerting is a useful feature, cf. Figure 133 (M = 5.33, SD = 0.90). Conversely, only Pilot #15 strongly agreed that he did not need a Runway Incursion alert even if the display of taxi route and clearances failed, because the airport moving map provided him with sufficient information. Pilots #5, #6, #11 and #13 expressed some sympathy for this position by rather agreeing to it, and Pilot #4 provided a neutral rating. However, as can be seen from Figure 134, the majority of the pilots dissents with the statement that the airport moving map gives them all the information they need to avoid a Runway Incursion (M = 2.40, SD = 1.68). Besides, pilot feedback on these feedback can be regarded as strong evidence that, from an operational perspective, Runway Incursion alerts should not solely be based on ATC instructions and clearances.

7.6.5.2 Taxiway Take-off Alerting

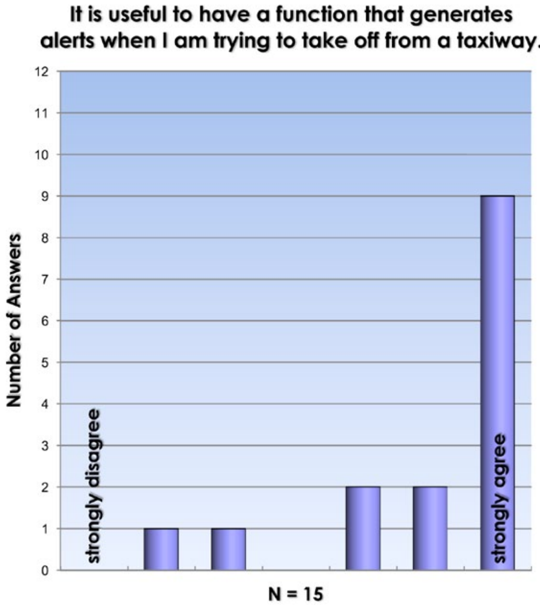

Figure 135: Operational relevance of Taxiway Take-off alerting

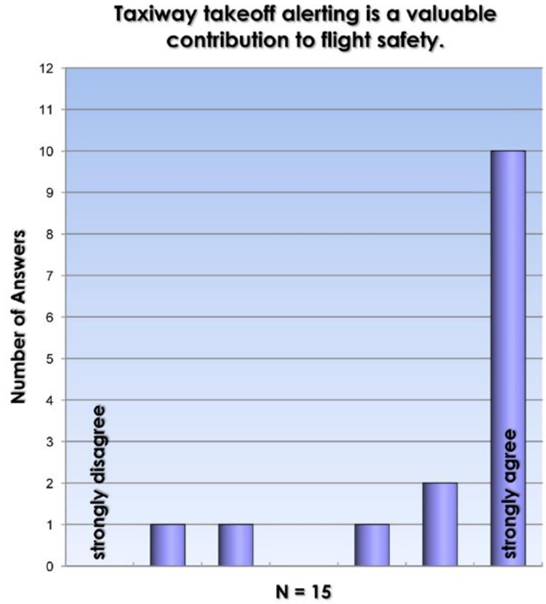

Figure 136: Contribution of Taxiway Take-off alerting to flight safety

With the exception of Pilot #6 and Pilot #13, pilots confirmed the operational relevance of an alert triggered when the crew is attempting to take-off from a taxiway, see Figure 135 (M = 5.00, SD = 1.60). Consistently, these two pilots also denied that taxiway take-off alerting constitutes a valuable contribution to flight safety, as evidenced by Figure 136 (M = 5.13). The distribution of feedback on this latter question exhibits a significant deviation from a normal distribution at a 5% level.

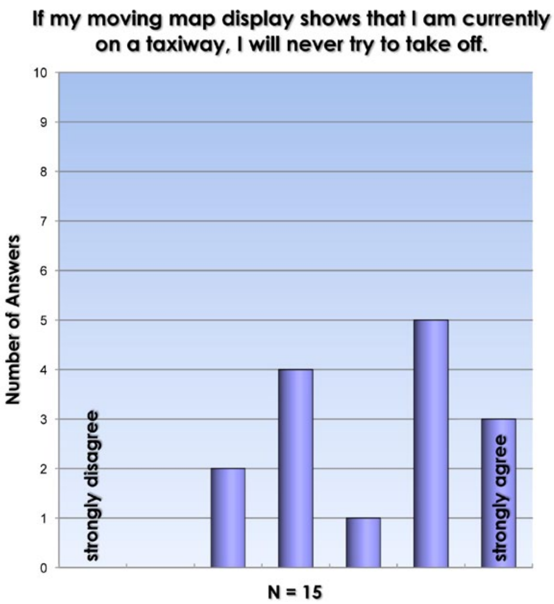

Figure 137: Relevance of Taxiway Take-off alerting in view of airport moving map

The question presented in Figure 137 was intended to gather pilots' opinions as to whether the basic airport moving map is sufficient to prevent them from taking off from a taxiway or not. A majority of the participant is indeed of this opinion (M = 4.20, SD = 1.42). As could be expected from his rating on the last two questions, Pilot #13 strongly agrees, and Pilot #6 rather agrees. However, Pilot #1 and Pilot #14 rather disagree, and four pilots (#7, #8, #9 and #11) provided a neutral rating.

This may be taken as evidence that although the presence of an airport moving map decreases the likelihood of taking off from a taxiway in pilots' perception, an alert as proposed by SMAAS is nevertheless operationally relevant to address cases when pilots are not using or the airport moving map or otherwise distracted.

7.6.5.3 Closed Runway Alerting

Assuming that most pilots would most likely be more familiar with the FAA definition of Runway Incursions, which does not include closed runways explicitly, it was decided to treat Runway Incursions due to operation on closed runways separately in the trials questionnaire. Furthermore, this provides an opportunity of checking pilot ratings for consistency, as the principles of alerting for closed runways are exactly the same as for all other Runway Incursion alerts.

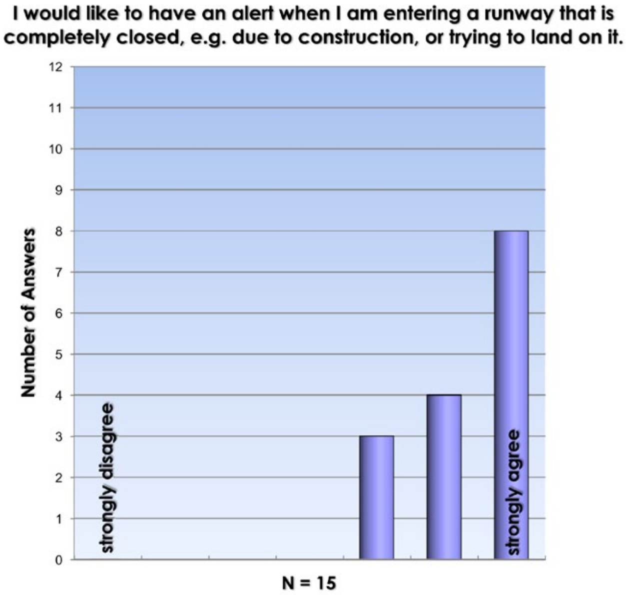

Figure 138: Operational relevance of Closed Runway alerting

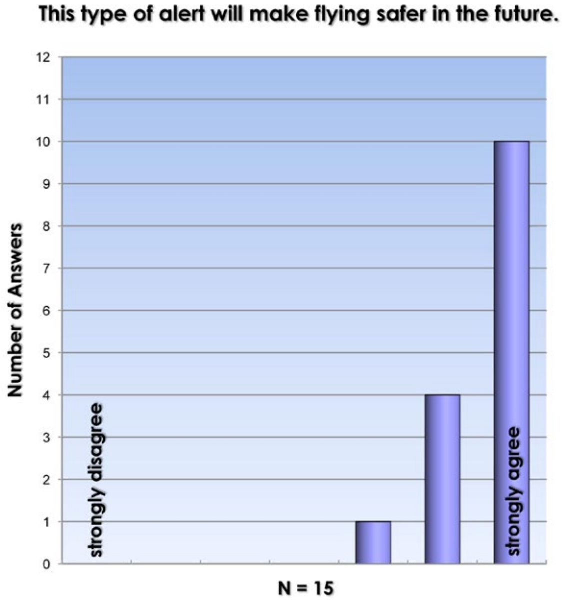

Figure 139: Contribution of Closed Runway alerting to flight safety

In comparison to the global Runway Incursion alerting functionality (see Figure 130), it is noteworthy that the operational desirability of alerts pertaining to a closed runway is somewhat lower with respect to the level of agreement from pilots (M = 5.33, SD = 0.82). In terms of mean ratings, Closed Runway alerting is rated by almost 0.5 rating steps lower than Runway Incursion alerting in general.
While Pilots #1, #12 and #13 strongly agree on the necessity of global alerting, they only rather agree with Closed Runway alerting. Nonetheless, the necessity to provide alerts if the crew is about to operate on a closed runway is indisputably acknowledged by pilots, as evidenced by Figure 138.

As Figure 139 indicates, there is also unanimous agreement that a corresponding alerting functionality would have a positive impact on safety (M = 5.60, SD = 0.63). With two thirds of the pilots strongly agreeing, the safety impact is rated qualitatively higher than the operational relevance.
Only Pilot #13 is somewhat more hesitant in his agreement, consistent with his opinion on operational desirability. Compared to Runway Incursion alerting in general, it is noteworthy, though, that the difference between the mean ratings concerning the impact on safety is much lower than for the operational relevance.

The assessment results in Figure 140 exhibit largely the same characteristics as the results for the other Surface Movement alerting functions, notably Runway Incursion alerting. A majority of pilots is of the opinion that the basic representation of closed runways on the airport moving map display will reduce the probability of Runway Incursions due to closed runways (M = 4.53, SD = 1.41). However, there is also dissent from Pilot #9 and Pilot #14, whereas Pilot #7 gave a neutral rating.

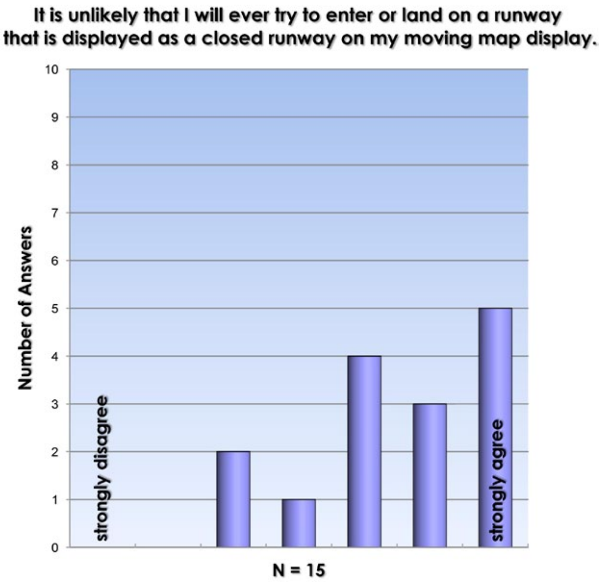

Figure 140: Relevance of Closed Runway alerting in view of closed runway presentation on airport moving map

7.6.5.4 Taxi Route Conformance Monitoring

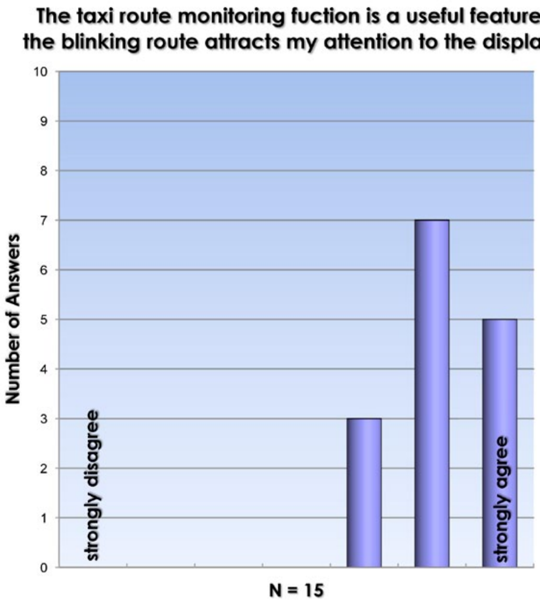

Figure 141: Operational relevance of Taxi Route Conformance monitoring advisory

Figure 142: Relevance of conformance monitoring when route is presented on AMM

Figure 141 indicates that pilots generally considered the Taxi Route Conformance Monitoring functionality, which provides a Level 0 alert in case of deviation from an assigned taxi route, as a useful feature that attracts the crew's attention to the display (M = 5.13, SD = 0.74). However, it can be inferred from Figure 142 that a majority of pilots was also of the opinion that the taxi route presentation on the airport moving map is sufficient to enable them to monitor conformance to the assigned route themselves (M = 4.73, SD = 1.49). Pilot #5 disagreed, and Pilot #1 rather disagreed on this, stating that the crew might be distracted from the moving map by other operational and procedural duties.

7.6.6 Detailed Assessment of Runway Incursion Alert Design

Despite criticism on certain detailed aspects of the Surface Movement Alerting functionality, all pilots participating in the Prague trials considered the concept a valuable addition to the flight deck. Only one pilot (Pilot #15) perceived conceptual issues that would apparently necessitate a conceptual and functional refinement in his opinion. At the same time, however, he commented that the alerts were very well designed.

Seen altogether, pilots acknowledged the definitions of the alerting functions and thought them to be quite mature already, although the level of consent clearly varies. Pilot #15 provided, with slight agreement, the lowest albeit still positive rating. The overall rating is in line with the pilot comments recorded during the sessions, which emphasized that the alerts were very well-designed and that the function itself was very useful. In this context, Pilot #12 commented that he would like to have these functions on his aircraft even today.

7.6.6.1 Runway Proximity Information

In a more detailed assessment of the Preventive Runway Incursion Alerting concept conducted only with the four pilots participating in the Prague experiment, the visual Runway Proximity Information function (Level 0) was acknowledged as operationally relevant and capable of preventing Runway Incursions by all pilots.
Furthermore, the HMI of the function was liked and the timing of the alerts considered as appropriate. While pilot feedback indicates that there may still room for improving the precise timing of the Runway Proximity Information advisory, the solution presented in the experiment sessions seems more or less correct, since participants were neither clearly in favour of triggering this advisory earlier nor later. Additionally, nobody voiced any concern that would hint at the necessity of a fundamental revision of the trigger conditions.

7.6.6.2 Runway Incursion Alerting

As the only pilots in the first evaluation campaign with the Navigation Test Vehicle, the four participants of the Prague session had an opportunity to assess the Runway Incursion caution and warning alerts provided by the SMAAS. Scenarios contained caution and warning alerts for entering a runway without clearance in a CPDLC environment providing both taxi routing and runway-related clearances, as detailed in Section 7.4.2.

Participants reconfirmed the operational necessity of these high-level Runway Incursion alerts. The general design of the alerts was also appreciated very much. With respect to HMI design, the high-level Runway Incursion alerting received the same positive rating as the basic Runway Proximity Information and was considered to be consistent with the latter by all pilots. Except for Pilot #15, pilots acknowledged additionally acknowledged the distinction between Level 2 and Level 3 alerts as desirable. Irrespective of this feedback, however, the Pilot #15 commented that alerts were very well designed. The distance from the stop bars at which the alerts were triggered was found suitable by all pilots except one. Pilot #14 commented that caution alerts could be triggered just a bit earlier, but that the system was great otherwise.
The only aspect that was actually criticised was the alert for the missing clearance for the FMS runway; this item should be reviewed. Furthermore, when applying global Runway Incursion Alerting to the special case of closed runways, a slight drop in the quality of pilot agreement on operational usefulness becomes apparent. However, pilots unanimously appreciate not only operational relevance, but also efficiency in actually preventing incursions nonetheless. The timing of the alerts receives even slightly better feedback compared to the RIA.

Apart from Pilot #15, who perceived a slight tendency towards nuisance alerts, experiment participants denied the existence of nuisance alerts that would reduce system usability, which in a way confirms the rating on timing and trigger conditions. There is full consensus among all four pilots that the Runway Incursion Alerting might actually help to prevent Runway Incursions.

7.6.7 Reactive Surface Movement Alerting

7.6.7.1 Operational Relevance and Desirability of Traffic Alerting

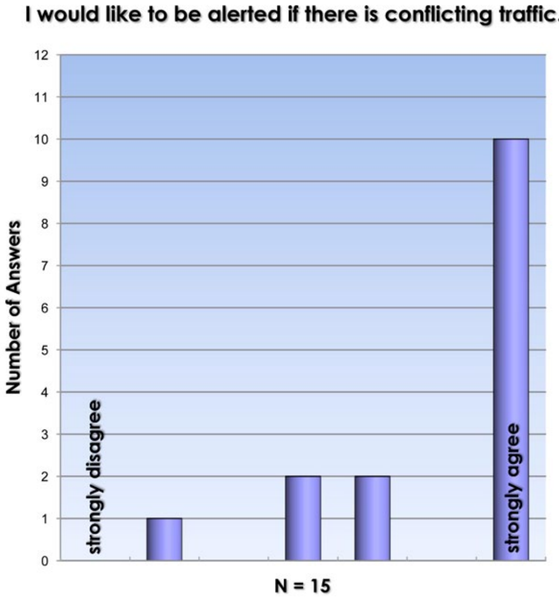

Figure 143: Desirability of traffic alerting

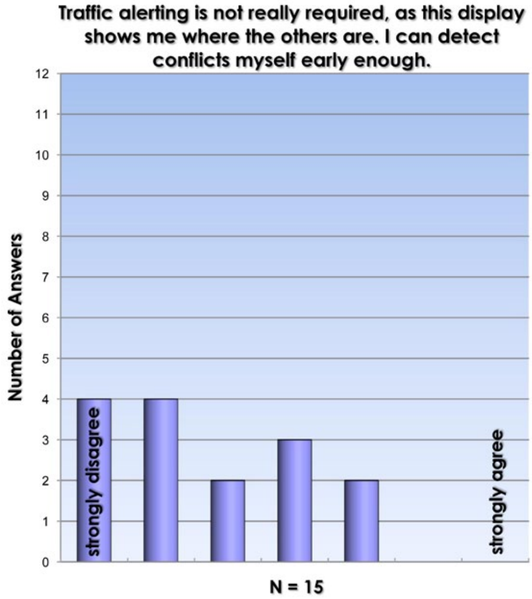

Figure 144: Relevance of traffic alerting

After having seen the basic ADS-B traffic representation without any alerting, pilots were asked to rate the operational relevance and desirability of traffic alerting. According to the results presented in Figure 143, which are not distributed normally (2% significance level), two thirds of the pilots strongly agreed that they would like to have an alert if there is conflicting traffic (M = 5.00). Another two pilots (Pilots #5 and #13) were more hesitant with their agreement, while Pilot #14 apparently did not want any alert in case of a traffic conflict.

Consistently, he thus rather agreed – along with Pilot #5 – that traffic alerting is not really required, as pilots are able to anticipate conflicts due to the basic traffic display (see Figure 144). Apart from three neutral ratings (Pilots #11, #13 and #15), a clear majority of the participants disagreed, in various strengths, that the traffic display would enable them to detect traffic conflicts early enough themselves (M = 1.67, SD = 1.45).

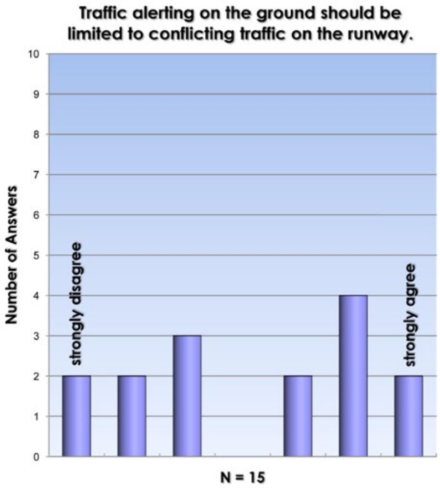

Figure 145: Required scope of ground traffic alerting

Questionnaire results shown in Figure 145 indicate that pilots are divided into two distinct groups concerning the scope of traffic alerting (M = 3.20, SD = 2.14). Eight of the participants support the position that traffic alerting on the ground should be limited to conflicting traffic on the runway. Four pilots disagree on this, Pilots #3 and #8 (strongly), as well as Pilot #4 and Pilot #9. Pilots #1, #10 and #15 rather disagree on this limitation.

7.7 Discussion

7.7.1 Airport Moving Map

Both questionnaire results and pilot comments clearly indicate that the AMM corresponds to an operational need, which is confirmed even by those participants who were somewhat more reluctant or critical towards the particular implementation demonstrated during the evaluation sessions, or who discovered certification concerns. In pilot's perception, the airport moving map helps to increase their situational awareness and provides them with aerodrome mapping support they miss with current systems. Accordingly, thirteen out of fifteen pilots think that it is not be possible to get lost on an airfield with an airport moving map, while two participants consider this is still possible, particularly if the crew is distracted by other tasks. Furthermore, there is a preference for an ND-integrated airport moving map display, which confirms the approach taken by SMAAS. Additionally, the overall usability of the basic AMM was rated very positively with an average of 88.8 out of 100 on a standard System Usability Scale (SUS).
All of these results demonstrate that the AMM is a viable onboard solution to the issue of disorientation and may therefore help to prevent Runway Incursions, since it increases positional awareness, especially in bad weather and on large and complex airfields, as the comments taken during the session confirm. With respect to the navigation solution, pilot feedback indicates that an ownship position derived from a Wiener filter fusion of GPS and INS data provides sufficient positional accuracy; differential GPS via GBAS or SBAS is thus not necessarily required.

7.7.2 AMM-based Cockpit Display of Traffic Information

Assessment results confirm that all pilots acknowledge the large potential of an AMM-based traffic visualisation to increase flight crew awareness of the surrounding traffic, although several participants expressed concerns about the operational usability of the incomplete and partially unreliable traffic data available during the experiment. In principle, though, the traffic presentation is considered as a definite improvement over systems available today, and believed to have a beneficial impact on safety, particularly when used for traffic surveillance in the runway environment.
The limitations of the real-time ADS-B traffic data used during the trials had a detrimental impact on pilots' confidence in the presented traffic. The fact that not all aircraft were equipped with this technology was a major issue for some pilots. Nonetheless, a majority of pilots believes that even a partial representation of ground traffic on an AMM will result in increased situational awareness and a higher level of safety. Virtually all participants were also concerned about the reliability of the ADS-B traffic data received. It was found that several ADS-B equipped aircraft sent out incomplete or unreliable data, the main issue being the update rate with outages of more than 20 s.
The average SUS of the traffic representation on the moving map was 74.2 and thus slightly, but significantly lower than for the airport moving map itself. However, this result may easily be explained by the issues with the available ADS-B traffic data mentioned above.

In conclusion, evaluation results confirm the potential of this technology to bring relevant surrounding traffic to the attention of flight crews (cf. ***High-Level Requirement II***), but both equipment rate and adherence to published standards are still a concern with respect to ADS-B. Clearly, a mandatory, standardized ADS-B equipment of aircraft is necessary to use the full potential of this technology, especially with respect to the use of traffic data by alerting systems (see Section 7.7.5). It should be noted, though, that the level of equipage is not a problem endemic to ADS-B, but applicable to any data link used for the exchange of traffic surveillance data.

7.7.3 Information on Operational Environment and ATC Instructions

Supplementing the AMM with information on the operational status of runways was confirmed as important and desirable by pilots, particularly the presentation of closed runways with an average rating of 93%[138]. While the symbology was also appreciated (82%), there is still room for improvement regarding the colour concept (71%). The operational relevance of highlighting the FMS-selected take-off or landing runway on an airport moving map was confirmed by all participating pilots with an average rating of 90%. The HMI design was also generally appreciated (85%). A presentation of the FMS-selected runway is a valuable addition to the basic airport moving map functionality, and its introduction should be considered for the near future, all the more since all the required data are currently available aboard the aircraft.

Likewise, the visualisation of ATC instructions and clearances on the AMM was received very well by pilots. A presentation of the assigned taxi route is a feature which pilots unanimously desire. With an average rating of 95%, it one of the SMAAS elements with the highest level of appraisal in this evaluation campaign. Due to concerns about the party line effect and the timeliness of CPDLC, the level of agreement with respect to take-off and landing clearances is slightly lower, but still at an average of 88%.

In conclusion, the airport moving map has been proven a suitable basis for conveying information – by means of additional symbology – on both the operational status and configuration of the aerodrome, as well as ATC instructions and clearances.

7.7.4 Preventive Surface Movement Alerting

Alerting when pilots are at risk of causing a Runway Incursion themselves, irrespective of the presence of other traffic, was a rated as an operationally highly desirable feature by all pilots participating in the trials. With a mean rating of 97%, it is the SMAAS functionality with the best rating concerning operational relevance. Its potential contribution to flight safety, and thus the prevention of Runway Incursions, was assessed even slightly higher (98%) on average.

While most pilots agree that presenting the taxi route and runway clearances on an airport moving map will reduce the overall risk of a Runway Incursion, there is also clear dissent that this alone eliminates the necessity for alerting, which reconfirms the need for alerting. The necessity to address impending infringement of completely closed runways by alerts was also acknowledged by participants. However, the level

[138] The average rating is given as percentage of the mean rating in relation to the maximum achievable value.

of agreement is somewhat lower than for Runway Incursion alerting in general (89%). Again, with an average of 93%, the impact on flight safety is estimated higher than the operational necessity itself.
Furthermore, an alert when trying to take off from a taxiway is also desired by a majority of pilots, although the level agreement is not as unanimous as for Runway Incursion Alerting itself and only 83% on average, since pilots consider the risk of taking off from a taxiway when using an AMM as low. Again, the positive impact on safety is rated slightly better (86%) on average than the operational relevance (83%).
The fact that the safety impact of the high-level alerts is consistently rated higher than their operational relevance is an interesting phenomenon, but not necessarily contradictory, even if it may seem so at first glance. Operational relevance focuses on the overall importance for operations, whereas the safety impact assesses the efficiency to address critical situations. Last but not least, the operational significance of Taxi Route Conformance Monitoring was unanimously confirmed by pilots, but most of them admitted at the same time that the taxi route presentation in relation to the airport moving map would enable them to monitor adherence to the route themselves.
While only four pilots evaluated the full scope of alerts, all of them gave positive feedback concerning the capability of the system to prevent incursions, the chosen HMI design, and the trigger conditions of the alerts. In conclusion, therefore, it could be shown that preventive Surface Movement Alerting is a valid means of mitigating the risk of ownship Runway Incursions in the eyes of pilots.

7.7.5 Alerting for conflicting traffic

Pilots' ratings on the survey-type questions concerning traffic alerting clearly indicate that participants consider alerts for potentially conflicting ground traffic as useful feature, which is deemed necessary regardless of the basic traffic presentation. Since the majority of pilots disagrees that they could detect traffic conflicts themselves, the assumption that a mere display of traffic is not sufficient to prevent incidents and accidents can be regarded valid. Conversely, only a minority of eight pilots would like to see alerting limited to conflicting traffic on the runway.
In conclusion, alerting for conflicting traffic in the airport environment is desired, focussing on – but not limited to – potentially conflicting traffic in the vicinity of the runway and obviously on the runway itself. However, for a more detailed assessment of the scope of traffic alerting, this survey-type evaluation is not sufficient; the envisaged traffic alerting functionality must be implemented and evaluated in a realistic context (see Chapter 8) to obtain substantiated feedback on this matter.

7.7.6 Summary

Evaluation results confirm that the approach taken by SMAAS is a valid contribution to mitigate the problem of Runway Incursions, because it supplies pilots with operationally relevant and desirable information. Furthermore, the different levels at which information was conveyed, ranging from the mere display of information to warning level alerts, were acknowledged and deemed suitable by participants.

8 Evaluation on a Research Flight Simulator

While the initial evaluation campaign of the Surface Movement Awareness and Alerting System (SMAAS) concept with the Institute's Navigation Test Vehicle featured the unprecedented realism of field trials, assessments were limited in two aspects. First of all, and most importantly, traffic functionality had not evolved beyond the mere display of surrounding ground traffic, with reactive Surface Movement Alerting already conceived, but yet to be developed. Secondly, apart from the fact that an assessment of Runway Incursion alerts involving other traffic in a real airport environment is unacceptable from a flight safety point of view, a proper evaluation of onboard functionality requires a more sophisticated and representative cockpit environment than the setup on the Navigation Test Vehicle, particularly with respect to the possibility of pilot interaction. As an example, assessing pilot reactions to Runway Incursion alerts during take-off requires both an adequate modelling of aircraft dynamics and a Pilot Flying (PF) role of the evaluator, as opposed to evaluation pilots in the Pilot-Not-Flying (PNF) role on the passenger seat of the van with its vehicle dynamics. Furthermore, for immediately obvious reasons, an assessment of landing scenarios with the Navigation Test Vehicle is not possible.

Therefore, the second major evaluation campaign in the frame of this thesis was conducted on the Institute's modular fixed-base Research Flight Simulator, focussing on, but not limited to, an evaluation of the traffic and traffic alerting functionality within the SMAAS concept. Once the refinement of the SMAAS system concept based on the results of the first evaluation campaign with the Navigation Test Vehicle had been completed, the software prototype was upgraded and integrated on the Institute's flight simulator for a detailed human factors assessment with airline pilots.
Sessions typically lasted seven hours and covered a broad range of the system's aspects from the basic airport moving map to Runway Incursion alerts in the high-speed regime during take-off. In terms of flight phases, the focus of the evaluation was on taxi out and take-off.
Apart from two shakedown trials (see Section 8.2.1), up to 19 airline pilots from two major and one smaller European airlines participated in experiment sessions in two phases. Phase one, performed immediately after the initial shakedown in the Spring of 2007, encompassed three airline pilots and was intended as a 'pilot' experiment to validate not only the basic setup, but also the scenarios and the assessment methodology, particularly the questionnaires. The second phase commenced with a project pilot with system knowledge, followed by external airline pilots from October 2007 to January 2008. Since the simulator experiment was conducted in the frame of the European research project FLYSAFE and aimed at evaluating a broader scope of functionality, including Airborne Sequencing and Merging, the evaluation had to address traffic functions for use during cruise and approach provided by project partners as well. Consequently, to achieve this, the last six participants of the experiment were only exposed to a reduced SMAAS assessment focussing on airport moving map and traffic representation, with a brief demonstration of reactive alerting, but did not address Operational and Clearance Awareness functionality.

8.1 Evaluation Objectives

As outlined in Section 6.1, the main objectives of the SMAAS evaluation campaign were an assessment of the overall operational relevance (domain suitability) and usability of the system (suitability and user acceptability), associated with the identification of potential critical design issues, especially in the field of Human-Machine Interface (HMI).

The SMAAS onboard functions evaluated were representative software prototypes of the envisaged system as detailed in Chapter 5, with the following limitations to the Operational Awareness Function (see Section 5.3):

- The visualisation of aerodrome status information derived from D-ATIS was limited to active runways, runway and taxiway closures. Interaction on the MCDU was limited to changing runway status.

- There was no integration with the simulator's ECAM simulation, i.e. consistency advisories and alerts were only displayed on the ND screen and in the MCDU scratchpad.

- A notification concept concerning short-term and temporary information becoming effective or expiring during the flight was not implemented; these aspects were therefore not addressed in the experiment.

The main reason for these constraints was that the scope of the functionality to be assessed by pilots had to be reduced due to the need to limit simulator evaluation sessions to one full day. Besides, an in-depth assessment of these more detailed functional aspects is only useful once the fundamental principles of the OAF have been validated.

8.2 Experimental Design

8.2.1 Shakedown Trials

Two shakedown trials were performed by two former experimental flight test pilots, assisted by a flight test engineer, a pilot and former air traffic controller working for Italian authorities, and a German airline captain. None of these pilots participated formally in the subsequent evaluation campaign, i.e. there are no questionnaire results for these pilots. Only open loop comments were recorded.
The main purpose of these trials was a fine-tuning of the SMAAS prototype system in terms of both functionality and HMI, with a focus on the latter. A further important goal of the shakedown was to evaluate the operational realism of the chosen experiment scenarios (see Section 8.4) with pilots.

8.2.2 Experimental Factors

This section surveys the experimental factors that have been considered in setting up the SMAAS evaluation experiment on the Institute's Research Flight Simulator, and discusses the selections eventually made. The experimental factors to be considered relate to the external environment (irrespective of whether simulated or real) and the participants, and are thus completely independent of the particular design features of the system to be evaluated.

8.2.2.1 Airport complexity

The choice between airports of different complexity was limited by simulator constraints, particularly the availability of a suitably detailed and up to date visual database. The visual database for the simulator is typically generated based on a commercially available scenery, which is then merged with AMDB information to ensure consistency between the AMM and the outside visual. This process involves a significant amount of manual adaptation.
Another aspect that limits the usability of airport complexity as experimental factor is that the effort with respect to the generation of scenarios is doubled. This is particularly relevant when considering the set-up of traffic scenarios. Therefore, one large and complex airport was eventually chosen, Paris Charles-de-Gaulle airport (LFPG). To give participants at least an impression of the SMAAS technologies at an alternative airport, Frankfurt Airport (EDDF) was chosen for the training scenarios.

8.2.2.2 Airport familiarity

As discussed in Section 6.4.5, participants' familiarity with the airport selected for the evaluation trials is extremely difficult to control prior to the experiment. Again, the choice of Paris Charles-de-Gaulle Airport (LFPG) proved to be adequate in this context, since it is representative of a very complex hub airport, while simultaneously ensuring that the trials do not take place at Frankfurt airport (EDDF) as the presumable home base of most of the participants.

8.2.2.3 Visibility

Any positive effects on safety and efficiency are expected to be particularly, but not exclusively, visible in degraded visual environments. In order to assess this, visibility was used as an experimental factor in the simulator validation exercise, and three different partially degraded visibility conditions were employed as levels of this experimental factor. However, a post hoc analysis yielded that visibility did not have a measurable influence on pilot feedback.

8.2.2.4 Traffic density

An operationally meaningful variation of traffic density was very difficult to realise in the Institute's Research Flight Simulator environment, because the outside visual based on X-Plane was limited to a maximum of 10 aircraft at a time, see Section 8.3.3 below for details.

8.2.2.5 Pilot rank and role

A potential effect of the pilot's role as PF or PNF in the simulator sessions on evaluation results cannot be ruled out a priori, but is generally believed to be negligible, because pilots typically take turns in everyday operations and are thus current with respect to the information needs for both roles. This experimental factor is strongly linked to the issue of single pilot or crew evaluations (see Section 8.2.3 for details).

8.2.2.6 Conclusion

In conclusion, the only external environmental experimental factors that are fully controllable with reasonable effort in the simulator experiment setup are visibility and PF/PNF role. Nevertheless, the PF/PNF role was excluded as experimental factor due to the single pilot setup that was eventually chosen for the evaluation, see Section 8.2.3 below. Since the van trials had been performed with participants in the monitoring role, it was therefore decided to conduct the simulator experiment with pilots in the PF role. Consequently, as outlined above, only visibility was eventually varied as experimental factor during the experiment.

8.2.3 Single Pilot vs. Full Cockpit

This section discusses the advantages and disadvantages of single pilot and full cockpit experiments, and relates them to the validation objectives and constraints for this particular validation exercise. In essence, there are three options for the validation exercise:

a) Full Cockpit. Two pilots, preferably from the same airline and with different ranks, form an evaluation flight crew:

- Allows – at least in principle - realistic evaluation with respect to crew task sharing, crew resource management and workload (+)
- Allows the assessment of procedures related to the new system (+)
- Allows, depending on experiment design, grouping of results according to PF/PNF role.
- Discussion among crew members is likely to lead to more detailed and more extensive verbal feedback (i.e. pilot comments), since aspects any single pilot might not have thought about or considered important are now discussed by both (+)
- Allows an assessment of how flight crew members influence each other with respect to situational awareness. This is particularly interesting with respect to accident analyses, because it might help to explain how two or three highly professional, highly trained and highly skilled crew members fail to maintain adequate situational awareness (+)
- Crew members potentially influence each other, consciously or subconsciously, in their subjective ratings and other applicable questionnaire answers. This effect is almost impossible to determine; this would require audio/video recordings of the experiment for a post-hoc assessment and could then still only give indications about the way that crew members influence each other. (-)
- Double number of pilots or runs, with alternating PF/PNF roles, required for the collection of objective data compared to single pilot experiment. Duplication of runs does not always work out, especially for the assessment of alerting systems.
- Pairing of crew members from different airlines that are likely to use different procedures may lead to undesirable and hardly controllable side effects or distractions (e.g. discussion about differences in procedures instead of discussion on the system to be evaluated) (-)
- A higher organisational effort for the trials is required (coordination of crews, pairing of captains and first officers preferably from the same airline, cancellation of a single pilot requires either cancellation of the whole experiment session or replanning) (-)
- Pairing of two captains or first officers is not considered an issue in this context.
- Social climate and relationship between pilots forming a flight crew may influence the outcome of the experiment in a way (both positive and negative) that is virtually impossible to control, but this is considered a minor issue in this context.

b) Single Pilot. One pilot at a time performs the evaluation in the simulator:

- Provides the opportunity to collect unbiased single pilot feedback, both in terms of comments and questionnaires/rating scales (+)
- Lower organisational effort with respect to pilot scheduling (+)
- Pilot will always perform a combination of PF/PNF role
- Not suitable for assessing workload due to missing crew task sharing etc. (-)
- Strong limitations with respect to the assessment of procedures related to the new system apply; procedures involving crew task sharing cannot be assessed (-)

c) Single Pilot with "Sparring Partner". The single external pilot who is the experiment subject is aided by a member of the evaluation team (or a certain other pilot who is the same for all trials):

- Provides the opportunity to collect unbiased single pilot feedback, both in terms of comments and questionnaires/rating scales (+)
- Allows – at least in principle - realistic evaluation with respect to crew task sharing, crew resource management and workload, but is greatly dependent on the skill of the experimenter pretending to be a pilot (+)
- Allows the assessment of procedures related to the new system, but is dependent on the qualification of the sparring partner (+)
- Allows the introduction of deliberate flight crew errors by the "sparring partner", which might be particularly helpful when assessing alerting systems; but usage is limited to 1-2 occurrences per participating pilot. (+)
- Lower organisational effort with respect to pilot scheduling (+)
- Allows controlled variation of PF/PNF role.
- Requires additional evaluation team member; rehearsal of procedures etc. required. Insufficient professionalism of sparring partner may negatively influence the outcome.

Before crew procedures and task sharing can be developed at the level of detail expected by airline pilots, any novel onboard functions and their associated HMI have to be sufficiently mature. Furthermore, particularly for an assessment of workload in a realistic context, the fidelity of the simulation must be high, and both type-ratings and airline SOPs become an issue. Otherwise, there is a risk that an eventually inseparable mix of HMI, usability, task sharing, simulator constraints, procedural and design issues influences the results obtained. This is clearly not desirable for the experiment, where one strives to control as many factors as possible in a reproducible manner. Furthermore, the objective is to obtain the unbiased opinion of the participants regarding the novel system. These factors, taken together, suggested **not** pursuing the Full Cockpit approach for the evaluation. Therefore only single evaluators were eventually used, aided by a "sparring partner" where necessary from a scenario point of view.

8.2.4 Conduct of Experiment

8.2.4.1 Assessment Team

The author participated in all of the described experiments as experiment leader. On some occasions, he was assisted by other research associates from the Institute who mainly aided in simulator operation and troubleshooting. Furthermore, an Italian Human Factors Specialist attended several sessions and supported the experiment leader in taking comments and during the debriefing phase. One session was attended by the Dutch flight test engineer who had already participated in the shakedown trials.

8.2.4.2 Briefing

At the beginning of each session, prior to the familiarisation runs in the simulator, the briefing for the experiment was conducted in a separate meeting room. The actual briefing consisted of a series of Power Point slides outlining the objectives and characteristics of SMAAS, mainly using screenshots illustrating the various HMI features. Pilots were encouraged to ask any questions that they might have during or – if they preferred – after the presentation. While the explanation of the display features was exhaustive, information about the alerting functionality was deliberately kept sparse. Participants were only shown screenshots of the airport moving map display with Runway Incursion caution and warning alerts displayed, using the example of an intrusion into a completely closed runway. Pilots were also informed that these alerts would be accompanied by a callout, which – in the case of a warning – could be silenced by pressing the Master Warning Button. There was no review of the different alert types with the associated trigger conditions and callouts, since this would have preconditioned pilots[139], and the slides contained only a single screenshot illustrating a Runway Incursion warning with other traffic present. The presentation concluded with a clarification that not pilots' skills, but rather the performance of the new onboard system were being assessed, and an encouragement to be critical. Pilots were then asked to fill in a so-called Pilot Intake Questionnaire on their background in commercial aviation and research project experience.

8.2.4.3 Familiarisation

After the briefing, pilots were given the opportunity to familiarise themselves with the TUD simulator environment and the airport moving map. Once they had adjusted their seats in the CM-2 position, familiarisation commenced with a quick simulator briefing, focusing on the location of the most important controls. In particular, the workaround for the airport moving map range selection, using the Barometer Reference Selector and employing the CSTR pushbutton on the EFIS control panel to alternate between QNH and AMM range, was explained with emphasis on

[139] With a detailed briefing on trigger conditions and the different callouts, the alerts occurring during evaluation sessions would always have been according to pilot expectations, provided that the system worked correctly. The objective of the experiment, however, was not to assess whether the system worked as specified, but rather whether trigger conditions, visualisation, callouts and alert levels were appropriate and generally consistent with pilot expectations concerning a Runway Incursion alerting system.

the fact that this was **not** the solution envisaged for a real aircraft, and should thus not be considered as part of the assessment. Participants were then encouraged to make themselves familiar with the airport moving map controls through hands-on experience prior to the start of the actual familiarisation runs.
Once pilots indicated that they felt comfortable with the AMM controls, two successive familiarisation scenarios set at Frankfurt Airport (EDDF) were performed, as described in Section 8.4.2. The familiarisation scenarios could be repeated if desired by participants, or when deemed necessary by the experiment leader, e.g. following a simulator malfunction.

8.2.4.4 Evaluation sessions

Upon successful completion of the familiarisation scenarios, pilots were exposed to a series of evaluation scenarios set at Paris Charles-de-Gaulle airport (LFPG), which was chosen for its complexity, its hub character and the relatively lower level of familiarity with this airport (compared to Frankfurt) expected from prospective participants. Evaluation scenarios, which are described in detail in Section 8.4.3, consisted of a mixture of uneventful, line-oriented taxi out operations and Runway Incursion scenarios, with incursions occurring in a wide range of ownship speeds, from the setting of take-off power to approximately 100 kts IAS. Wherever possible, line-oriented and event scenarios were alternated during evaluation sessions.

During the runs, the experiment leader recorded all pertinent pilot comments, along with other relevant observations, such as errors made or usage of features beyond the scope originally envisaged in the design[140]. When present, the Human Factors Specialist also took notes and additionally made video recordings of the trials for subsequent analysis. Apart from this, subjective pilot feedback was collected after the runs in the form of customized questionnaires on specific topics and standardized rating scales (Cooper-Harper).

After the first evaluation scenario, pilots were guided through the completion of a dedicated Airport Moving Map Questionnaire, along with a first Cooper-Harper rating scale.
Since the airport moving map is the basis all additional SMAAS functionality is built upon, it was deemed important to capture the participants' unbiased opinion on this technology before exposing them to specific SMAAS functionality. While no radically new insights on the already well-researched airport moving map itself are expected, pilots' feedback on this topic will subsequently help to contextualise the results on the SMAAS itself. As an example, a pilot rejecting the basic airport moving map technology for whatever reason is likely to be very critical about the SMAAS add-ons as well, and it is crucial to be aware of this when interpreting results.

[140] The term 'intended function' should be avoided in this context, since it is mainly used in the certification of systems that have reached product maturity. The description of intended function defines the boundary conditions for certification, with the resulting legal and liability implications. In a research environment, however, the distinction between valid use cases the system engineers might have overlooked and potentially hazardous alternative usage has yet to be determined.

After a minimum of two further scenarios with the surrounding traffic displayed on the airport moving map, participants were requested to fill in a questionnaire on the traffic presentation, followed by another Cooper-Harper rating scale. After every Runway Incursion scenario, pilot comments were triggered where necessary by asking evaluators for their first impression of the alert and whether they thought the alert was appropriate or not. Pilots completed the two questionnaires related to SMAAS display features and alerts at the end of the evaluation sessions, along with a final Cooper-Harper rating scale concerning the overall system.

8.2.4.5 Debriefing

In a detailed debriefing session, a consolidated overall pilot feedback on the SMAAS was obtained. Along with open loop feedback, which gave participants an opportunity to bring up any specific points they wanted to address, the choices made by pilots in the various questionnaires were discussed in detail to capture both the rationale for pilots' ratings and potential developments in pilots' attitude towards the system as evaluation sessions progressed. While experimental test pilots are specifically trained to comment extensively during evaluation sessions, which enables a subsequent correlation of their comments and their questionnaire ratings, airline pilots have a tendency to adhere to the sterile cockpit procedure, and often silently focus on the scenario task. Therefore, the importance of discussing questionnaire ratings with pilots during the debriefing cannot be emphasised enough.
Finally, specific topics of particular interest were then addressed by going through a de-briefing guide with pilots. Pilots were mainly asked about their general impression of the SMAAS concept and on some flight deck integration aspects. The debriefing guide can be found in the Appendix.

The debriefing had the following main objectives:

- To obtain, after the experiment(s), an overall feedback from pilots on the systems they have evaluated. This feedback is important because pilots may change their attitude towards the systems from the initial scenarios to the end of the simulation day, and it is highly relevant to capture both this process of attitude change as well as pilots' consolidated opinion on the system. It is also an opportunity to gather ideas and suggestions for improvements to the systems.

- To capture, by going through the post-exercise questionnaires with pilots again, the rationale for the choices they have made, as far as these are not covered by the comments made during the evaluation session. The feedback obtained by this process was subsequently consolidated.

8.3 Assessment Platform

8.3.1 Overview

The fixed-base Research Flight Simulator of TUD's Institute of Flight Systems and Automatic Control is a modular research simulator, featuring a sophisticated collimated visual system consisting of a three-channel retro-projection with a viewing frustum of 180° horizontally and ± 20° vertically. Pilots perceive the resulting image, which seems to be located at infinity, through a mirror. Consequently, refocusing occurs whenever pilots change their view from head-down activities inside the cockpit to the outside visual, and this approach guarantees an excellent approximation of reality for human factors evaluations [Wip05].

The cockpit is not an exact reproduction of the flight deck of any specific aircraft, but deliberately kept at the more generic level of a modern 'glass cockpit' with two flight crew members. The inside dimensions of the cockpit correspond to those of a modern widebody aircraft of the Airbus A330/340 family. While the flight simulation employs the flight mechanical model of an Airbus A300 B2, a fly-by-wire flight control system with side sticks was chosen because it represents the state of the art and allows an unobstructed view of the flight guidance displays.
The cockpit features all primary and secondary controls; in some cases actual aircraft parts, such as an original A320 Flight Control Unit (FCU), contribute to enhance the level of immersion and realism. In other cases, as for the MCDU, parts obtained from a commercial supplier of flight simulation equipment have been used, and even some developments of the Institute were installed. As an example, the simulator features active side-sticks, which can also be operated in a standard mode. Flight guidance and system displays are presented on large 15" LCD screens, which can either be arranged in portrait or landscape mode.

Figure 146: Flight simulator during night taxi scenario at Frankfurt Airport (EDDF)

8.3.2 Experimental Environment for SMAAS Evaluation

8.3.2.1 Cockpit Configuration

The First Officer (CM-2) crew station was used for the SMAAS evaluation, mainly because this position is already equipped with a MCDU hardware mock-up. The two LCD displays for PFD and ND were arranged in portrait configuration, thus resembling the A380 display arrangement. The outer screen was used to display a standard Airbus PFD, with the only enhancement compared to the current single aisle and long range aircraft families consisting of the additional text messages displayed by the SMAAS. The inner screen featured a conventional Airbus ND supplemented by the airport moving map and other SMAAS features as described in Chapter 5.
Display control was achieved via the conventional EFIS Control Panel, which featured the following workaround for the ranges below 10 NM: When selecting the constraints (CSTR) button, pilots could use the Barometric Reference Selector (QNH) to control AMM range. Additional software switches on the overhead panel touchscreen enabled pilots to de-select the airport moving map (except for the runways) and to activate or de-activate the display of the surrounding traffic, with separate controls for the traffic labels.

8.3.2.2 Research Flight Management System (RFMS)

In spite of the fact that there have been efforts to develop a corresponding functionality in-house over the past years, the Institute's Research Flight Simulator was not equipped with a Flight Management System (FMS) when the evaluation took place. Instead, the Research Flight Management System (RFMS) developed by NLR was kindly supplied within the ISAWARE II project [Ver05], and then re-integrated into the Institute's simulation environment in the frame of FLYSAFE.
The RFMS is a powerful software tool covering virtually all aspects of flight plan and performance calculation functionality contained in a real FMS. It can be configured to emulate either an Airbus or Boeing-style FMS and the corresponding MCDU pages, and is complemented by an application named SoftCDU, which is used to visualize the MCDU crew interface, either limited to the MCDU screen itself, or including a software keyboard for the respective aircraft family as well.
According to a specification supplied by the author, which was subsequently refined based on NLR feedback (see Appendix III: MCDU Pages), NLR kindly enhanced the RFMS to include the ePIB concept and the majority of the dedicated MCDU pages defined for ePIB and SMAAS.
In the scope of the SMAAS evaluation, the RFMS (Version 10.0) and the SoftCDU were therefore mainly used to simulate the ePIB supplying the SMAAS prototype with runway status information, and the corresponding MCDU pages, including the Airport Menu. Furthermore, the RFMS was used to define a flight plan, with SIDs adapted to the departure runway selected in the individual scenarios. In order to avoid lengthy periods of manual data entry when loading scenarios, the RFMS encompasses an intricate batch file system that accomplishes all required crew entries to achieve a certain FMS configuration within seconds. The batch files, called 'keystack files', are automatically loaded when the corresponding pre-defined scenario identifier is sent by a simulator control application.

8.3.2.3 Traffic Simulation

The simulation of other traffic is an essential component in the assessment of the traffic-related SMAAS functionality. The first part of this section contains an estimate for the number of aircraft that would have to be simulated to achieve a realistic traffic density, which is crucial for a usability evaluation, while second part is dedicated to a description of the traffic simulation software used for the flight simulator experiment.

The ICAO manual on A-SMGCS defines traffic density by the mean busy hour (arithmetic mean over the busiest hour of the day) and irrespective of visibility conditions. Traffic density is classified as 'heavy' whenever there are 26 or more movements per runway or typically more than 35 total aerodrome movements [ICA04a]. However, this definition only sets the order of magnitude and is of little value when it comes to a particular airport. For representative results, traffic at the hub airports chosen for the evaluation would have simulated in a realistic fashion.

Frankfurt Airport (EDDF) recorded 489,406 aircraft movements in 2006, resulting in an average of 1,341 flights per day. September 15, 2006 was the busiest day ("*absolute peak*") to date, with 1,470 movements on a single day. Since the airport is officially closed from 23:00 to 5:00 local time, and neglecting the few exceptions, this corresponds to a maximum of nearly 82 movements per hour [Fra07a]. This figure is almost identical to the maximum hourly slot capacity of 81 (forenoon) and 83 (afternoon) [Fra07]. Paris Charles-de-Gaulle Airport (LFPG) has a significantly higher capacity with 120+ nominal slots per hour, the maximum capacity achieved to date is 127 movements per hour [Che05].

Assuming a nearly equal distribution of take-offs and landings, and under the further constraint that scenarios will be too short to cover the complete turnaround process of any of the simulated aircraft, an estimate for the number of distinct aircraft that have to be simulated can be derived. However, the number of aircraft to be simulated cannot be limited to the number of aircraft movements at the airport itself within 20-30 minutes, because this would result in a highly unrealistic traffic pattern, with all aircraft scheduled to land within the duration of the scenario still airborne and all others taxiing out. At the end of the scenario, there would be no further aircraft on approach, and all aircraft on the ground would be taxiing to the gate. To avoid this, all aircraft taking off or landing 15 minutes prior to the scenario start time and after the scenario end time will have to be simulated as well. This means that 130 aircraft would have to be simulated for realistic traffic density at the hub peaks. However, the generation of traffic scenarios of this complexity is obviously beyond the scope of this thesis.

At the time of the evaluation, the in-house traffic simulation capabilities for the Institute's flight simulator were limited to the replay of pre-recorded data [Wip05]. This means that the tracks to be flown and routes to be taxied have to be recorded real-time in the simulator for each of the other aircraft, and then combined into a traffic recording for every individual scenario. Apart from the tremendous effort this requires, the resulting setup is completely rigid and inflexible, incapable of accounting for the inter-individual variations of pilots performing the scenarios, particularly with respect to taxi time. A realistic interaction of traffic in the highly dynamic runway environment, particularly with respect other departing traffic and the intruders causing Runway Incursions, can only be realised at the expense of individually controlling replay for other aircraft. Consequently, a different solution had to be found. While an event-based traffic simulation tool was under development in parallel to the evaluation campaign described in this thesis, it was clear that it would not be available in time and initially be limited to a simulation of airborne traffic. Therefore, NLR's Traffic Manager (TMX) simulation tool, version 8.1, also supplied in the frame of the FLYSAFE project, was used to simulate traffic in this validation exercise.

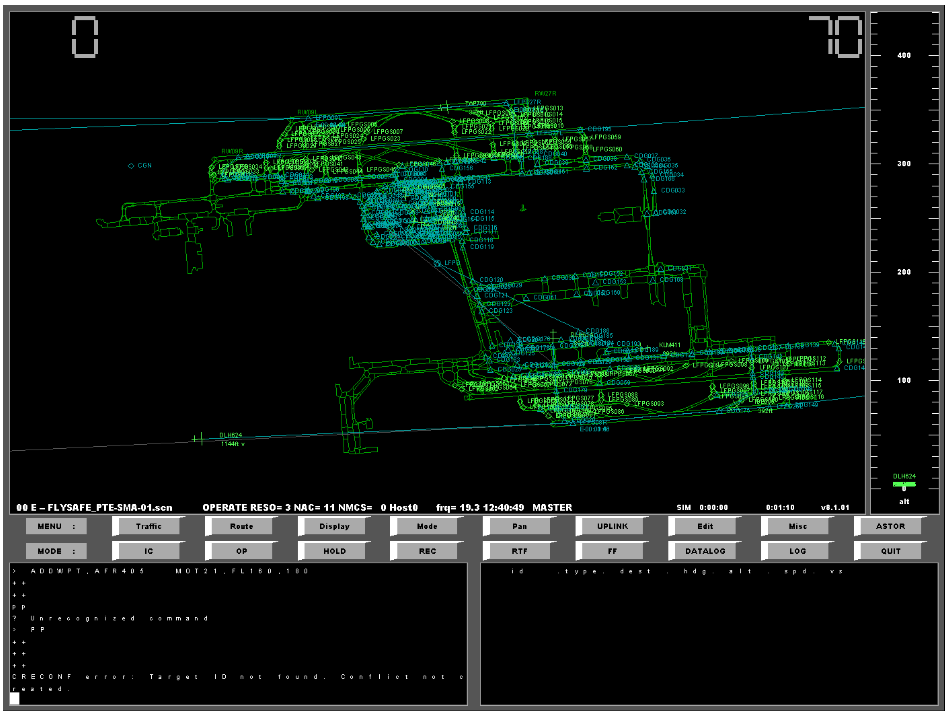

Figure 147: Traffic Manager (TMX) with Paris Charles-de-Gaulle airport layout

The Traffic Manager is a very complex and mighty research tool used, among others, to simulate the traffic environment for flight simulator experiments at NLR. Originally conceived in 1996 for a simulation of high traffic densities in the scope of a Free Flight experiment, the TMX is a performance-optimised software capable of simulating 600+ aircraft both fast-time and real-time, using aircraft models with six degrees of freedom (required for a realistic pitch/bank behaviour) based on performance parameters for over 200 aircraft types obtained from Eurocontrol's BADA database. Aircraft models feature a FMS with route-following capabilities along with a complete autopilot including all basic altitude, speed and heading modes as well as the FMS-coupled LNAV and VNAV modes. Besides, there are further components such as a pilot model taking into account reaction time and recovery manoeuvres. A graphical user interface (ref. Figure 147) visualizes all simulated traffic and any connected simulator aircraft [HHR01].
A so-called 'command stack' forms the core of the TMX, providing a series of commands to create, manipulate and delete aircraft. These commands do not only enable the creation of scripts for scenarios of the desired complexity, but also allow for a real-time manipulation of traffic while these scripts are being executed. Consequently, any of the simulated aircraft can be influenced individually by the simulator operator/experiment leader during runs whenever necessary from a scenario point

of view. As an example, traffic can be stopped to wait for the simulator aircraft[141] on the ground, and airborne aircraft can be assigned to other flight levels, given heading or speed changes and directed to specific waypoints. Besides, traffic is fully interactive, and aircraft react to each other, connected simulator aircraft and airport features such as red stop bars. Particularly the latter feature proved to be extremely helpful in setting up the Runway Incursion scenarios, because intruders could be released under reproducible conditions simply by switching stop bar status.

The traffic scenarios created for Paris CDG were based on scenarios originally conceived for ISAWARE II. Scenario-specific traffic was added to these scenarios, which served to provide background traffic.

8.3.2.4 ATC Environment

Interaction with ATC through either conventional Radiotelephony (R/T) or Controller-Pilot Data Link Communication (CPDLC) is one of the essential pilot tasks, which virtually always assigned to the Pilot Non-Flying (PNF) in a multi-crew environment. A realistic simulation of the ATC environment is therefore a crucial factor determining the fidelity of a simulation and the level of immersion pilots experience.

The main challenge in simulating a Radiotelephony environment is the communication between the controller and the simulated other traffic, or more precisely, the read-back of clearances and the usual requests or reports by these virtual aircraft. For a realistic simulation of the resulting mix of voices, several pseudo-pilots[142] would have been required, which would – apart from a tremendous effort for scripting, training and rehearsing of scenarios – have complicated scheduling of experiments significantly, and this idea was consequently abandoned. Likewise, the alternative approach of pre-recording ATC requests and responses for the simulated other traffic and then playing the corresponding sound files when appropriate was not pursued any further due to time constraints, but should be seriously considered for future experiments.

As a result, the trials took place in a considerably simplified ATC environment, in which the experiment leader also acted as controller. Interaction was limited to the simulator aircraft, i.e. no clearances were issued to other traffic, and there was consequently a total absence of voice communication between ATC and these aircraft. Whenever a scenario required conventional taxi instructions via R/T, the corresponding clearances were drafted as part of the scenario script, which then served as a memory aid to the experiment leader. All runway-related clearances were always provided via voice, even in case they were additionally available via CPDLC.

Although the Institute's simulator has facilities that enable the use of headsets, it was decided that in view of the overall realism of the ATC environment, the additional effort to adjust and validate a corresponding setup was not justified. Therefore, the pilots evaluating the SMAAS and the experiment leader always communicated directly.

[141] Another tremendous advantage over records is that accurate speed data are sent when stopping an aircraft in the TMX, whereas the last known speed values typically persist in the simulation when pausing records. Apart from unrealistic dynamics when resuming motion, which may or may not be perceivable by participants, the persistence of speed data might lead to nuisance alerts.

[142] Since traffic was simulated by the TMX, the term "pseudo-PNF" would be more appropriate. In the ATM research community, pseudo-pilots usually control their respective "aircraft" as well.

Apart from these considerable limitations in the simulation of ATC via R/T, the realism of CPDLC communication with ATC was also significantly reduced due to the fact that no DCDU was available. However, the focus of the CPDLC-related features of SMAAS is on the visualisation process and operational implications, and not on the interaction process between pilot and controller *per se*. Therefore, the initial assumption was that the absence of the DCDU would not have a significant impact on the results. In an attempt to keep pilots in a line-oriented mindset, the following procedures were used in conjunction with the CPDLC clearance display: Voice and CPDLC clearances were always combined, and given simultaneously. For a taxi route, the controller would instruct pilots as follows when the taxi route appeared on the airport moving map: "Lufthansa Four Tango Uniform, taxi to holding position RWY XY via up-linked taxi route." Apart from this specifically created phraseology, standard terminology would be used for all other clearances, accompanied by the specific visualisation for the respective clearance described in Section 5.4.

8.3.3 Limitations of Testbed and Simulator Environment

This section is dedicated to a survey of limitations of the Testbed, i.e. the SMAAS prototype and the display, and the simulator environment. It is essential to capture these limitations, since they provide the context in which the evaluation results have to be seen.

8.3.3.1 Material constraints

This section summarizes the technical limitations of the evaluation setup, i.e. constraints resulting from the hard- and software employed. For each of the items below, the impact the constraint may have had on the evaluation is estimated and classified.

8.3.3.1.1 Visual system

In several ways, the visual was the limiting factor for the evaluation. The main limitations were its performance and stability. The latency issues described below had a negative impact on the realism of the simulation, and also confused several pilots. It is believed that several of the errors observed during the runs can be attributed to conflicting information in the outside visual and on the displays resulting from the latency effects. Furthermore, the latency effects might have had a detrimental effect on the controllability of the simulator aircraft when flying visual approaches. Since the roll axis is the most dynamic, any latency effects in the visual will become most obvious during roll motion, which is consistent with the pilot-induced oscillations in the roll axis observed during the shakedown trials, which occurred when pilots tried to re-capture the localizer.

- **Performance.** Particularly with other traffic visualized, the performance of the simulator visual system was unsatisfactory. Especially during fast turns, the update rate would visibly deteriorate. While this is undesirable, latency effects occurring simultaneously were far more critical in their impact on the evaluation. In general, the aircraft position in the outside visual was updated with delay compared to the core simulation. By corresponding comments made during the runs, it is evident that all pilots noticed the latency effects. Most pilots became aware of the latency effects when they had brought the aircraft to a stop at a runway holding position and set the parking brake. At this point, looking outside, they would observe that the aircraft still seemed to move forward slowly, and it could take up to 10 seconds until the (correct) position on the display and in the visual coincided again. Furthermore, these latency effects resulted in unintended deviations from the taxiway centreline during turns.

- **Stability.** Difficulties of varying severity were encountered when setting up the visual for different scenarios. When switching from Frankfurt to Paris, the visual software would often crash, sometimes not only necessitating a restart of the software on the corresponding machine, but a complete reboot of all computers running the visual software. Apart from wasting precious evaluation time (up to 90 min in one occasion), with the risk of the pilot becoming bored, unmotivated and/or frustrated, this put the Experiment Leader/Simulator Operator under considerable strain, with the danger of subsequent mistakes in the intricate experiment configuration.

- **Conspicuousness of taxiway signs and markings.** In daytime VMC conditions, the conspicuousness of the taxiway signs and markings in the simulator visual was significantly lower than in reality.

- **Database consistency.** AMDB data can be merged with X-Plane sceneries to create consistency between the airport moving map and the simulated reality. The existing Frankfurt visual database was therefore updated with the up-to-date AMDB provided by Jeppesen, and subsequently validated. For unknown reasons, however, a rollback to the previous visual database occurred at some point in time between the validation test and the beginning of the trials, resulting in smaller inconsistencies between the AMDB and the visual database.

- **Stopbars.** There was no connection between the Traffic Manager (TMX) stop bar settings and the stop bars in the visual.

8.3.3.1.2 Flight Simulator

- **Flight mechanics and flight controls.** The handling qualities of the custom-built CM-2 sidestick were classified as unrealistic, and most pilots had difficulties in controlling the aircraft.

- **Autoflight system.** Due to the limitations of the flight controls and the autoflight system, it was decided – upon recommendation of the former experimental flight test pilots participating in the shakedown - not to use any approach scenarios for the SMAAS evaluation, since pilot workload in manual flying was found to be excessive without extended familiarisation, thus limiting the attention participants could devote to the system under evaluation.

- **MCDU keys not fully connected.** The keyboard layout of the MCDU mock-up installed in the cockpit only partially coincided with the keys used by the SoftCDU application provided by NLR, and an application written to map those keys proved faulty. Therefore, only the LSKs on the left hand side, the 1R and 2R keys, as well as the alphanumerical keys, with the exception of CLR, were operational. None of the function keys, such as MENU or PROG, was available.

- **Missing radio management panels.** There are no radio management panels installed in the cockpit, which means that the transfer to the next control authority in an R/T environment, either on ground or in the air, cannot be simulated in a realistic fashion. Particularly in the enroute phase, however, the associated frequency changes are a major source of crew workload.

- **Missing FANS DCDU.** There was not FANS DCDU, either as software mock-up or hardware, available for the evaluation. Consequently, HMI aspects related to the CPDLC application itself could not be covered.

- **Display size.** The size of the displays (15”) in the simulator cockpit is significantly larger than in current airliners. The 6” x 8” displays of the Airbus A380 have an equivalent diagonal of 10”. Only business jets like the Gulfstream G550 feature similarly large displays (14”) [Gul10]. This issue was noted by several participating pilots.

8.3.3.1.3 Traffic Simulation

The density of the simulated traffic was comparatively low and definitely below the usual density at daytime. Apart from that, there were the following other limitations:

- **Single aircraft type.** All simulated traffic was visualized using an Airbus A380 model in the Airbus corporate livery as default, because the converter from the TUD simulation environment to the visual system was not yet capable of automatically selecting the correct airline livery from the airline code contained in the callsign.

- **Limited number of aircraft models.** The simulator visual can only use 19 distinct aircraft models, i.e. there is a limitation to 19 airline/aircraft combinations, while the overall number of other aircraft that can be displayed is only limited by performance. Currently, the visual system is limited to 10 other aircraft due to performance limitations of the computers rendering the simulator visual. While the limitation in the number of models can be easily compensated by an intelligent combination of a larger number of hub airline aircraft of similar type (e.g. Lufthansa/Air France A320s at Frankfurt and Paris, respectively), thus leaving sufficient margin for a realistic number of other airlines, the current performance limitation to 10 other aircraft is significant, since it prevents an assessment of high traffic densities where display clutter issues might become relevant for the CDTI.

- **Missing ground vehicles.** Due to technical constraints of both the traffic simulation and the simulator visual, a simulation of ground vehicles and aircraft under tow was not possible, which mainly decreased operational realism on the apron and is therefore believed to be a minor limitation.

Furthermore, the traffic patterns used for Paris CDG were not fully realistic, but this was successfully masked.

8.3.3.2 Experimental conditions

This section is dedicated to a description of the limitations related to the operational realism of the evaluation setup that are not necessarily a consequence of the technical limitations described in the previous section.

The main operational limitation of the experiment was that a single pilot configuration was used, which, apart from excluding Crew Resource Management (CRM) issues, drastically reduces the realism with respect to workload and procedures.
Furthermore, the realism of the ATC environment was very limited due to the fact that ATC instructions were only given for ownship, resulting in a total absence of all radio communications of ATC with simulated other traffic. However, an accurate simulation of the ATC environment would have required at least one pseudo-controller and several pseudo-pilots reading back the clearances issued to the simulated other traffic.

On the one hand, this lowered pilot workload with respect to monitoring a certain frequency, but on the other hand, this also resulted in a complete loss of the party line effect, with the previously discussed detrimental impact on pilot situational awareness. At any rate, in the context of single pilot operations, the added negative impact of an incomplete ATC environment can be regarded as small. Of course, the fact that no real controllers were used also decreased the realism of the simulation, but the associated effect is believed to be negligible compared to the other limitations in the ATC setup.

A promising approach towards a more realistic simulation of ATC could consist of linking the Institute's simulator to existing ATC/pseudo pilot environments, such as the training tower of DFS at Langen. Furthermore, the Internet has fostered the formation of a wealth of virtual airlines and air traffic control facilities, and it would be worthwhile to survey this enthusiast community to assess whether they could potentially be employed in a pseudo controller/pseudo pilot setup for future validation exercises. Of course, there is always a trade-off between realism and reproducibility when working with many human operators in large-scale simulations, irrespective of whether enthusiasts or professionals are used.

8.4 Scenarios

8.4.1 Scenario Rationale

For practical reasons, individual simulation scenarios were limited to a maximum of 20-30 minutes. If scenario duration had exceeded this value significantly, the number of runs per day would have been too limited to cover an acceptable number of experimental factors.

8.4.2 Familiarisation Scenarios

Familiarisation scenarios were set at Frankfurt Airport (EDDF) for several reasons. First of all, since the number of different realistic scenarios at Paris Charles-De-Gaulle is limited due to the fact that the longer inner runways (08L/26R and 09R/27L, ca. 4200 m) are preferentially used for departures to achieve optimised arrival and departure rates, it was clear that a different airport had to be used for familiarisation to prevent undesired training effects, such as pilots getting used to standard taxi routes etc.

Since it was expected that most of the participating pilots would be from the region, with Frankfurt Airport as home base, it seemed reasonable to use an airport they would know very well as a familiar 'anchor point' in an otherwise new environment (flight simulator, novel systems) to facilitate familiarisation.
Furthermore, the choice of Frankfurt also seemed advantageous from a technical and organizational perspective, because Frankfurt Airport is also the virtual home base of the Institute's flight simulator, and thus both an Aerodrome Mapping Database (AMDB) and an outside visual were available without further integration effort.

8.4.3 Evaluation Scenarios

Including familiarisation, sessions typically lasted seven hours and covered a broad range of the system's aspects from the basic airport moving map to runway incursion alerts in the high-speed regime during take-off. The focus of the evaluation was on the taxi out and take-off phases of flight.

Pilots were exposed to a series of evaluation scenarios set at Paris Charles-de-Gaulle airport (LFPG), which was chosen for its complexity, its hub character and the relatively lower level of familiarity with this airport expected from prospective participants. Evaluation scenarios consisted of uneventful, line-oriented taxi out operations alternated with runway incursion scenarios, with incursions occurring in a wide range of ownship speeds, from the setting of take-off power to approximately 130 kts IAS, slightly less than V_1 for the given ownship configuration. In total, there were seven different scenarios, which could be conducted in three different visibility conditions and were also varied in sequence for different participants. Typically, 10 - 15 other aircraft were simulated in these scenarios.

8.5 Experiment Participants

8.5.1 Overview

A total of 19 male pilots with an average age of 41.7 years (between 27 and 62 years old), among them 13 Captains (CPT), two Senior First Officers (SFO) and four First Officers (FO), participated in the experiment sessions conducted on the Institute's Research Flight Simulator, see Table 18. All pilots except one, who is an experimental test pilot to a European aerospace research centre, had an airline background and were working for three different European airlines[143] at the time of the trials.

Num	Background (Flight test, Airlines Training)	Nationality	Native Language	Sex (F/M)	Age	Hierarchical (Captain/ [Senior] First Officer)	Amount of flight hours	Application knowledge
1	Airline	German	German	M	58	Captain	20,500	-/RAAS
2	Airline Instructor	German	German	M	27	First Officer	1,600	-/-
3	Airline	German	Greek	M	40	Captain	12,500	AMM/-
4	Airline	Slovenian	Slovenian	M	32	Captain	2,500	AMM/-
5	Airline Flight Test/Technical	Dutch	Dutch	M	40	Senior First Officer	6,000	AMM/RAAS
6	Airline Flight Test/Technical	Dutch	Dutch	M	41	Captain	5,000	AMM/RAAS
7	Airline	German	German	M	33	First Officer	3,700	-/-
8	Airline Instructor	German	German	M	53	Captain	15,000	-/-
9	Airline	German	German	M	40	Captain	7,000	-/RAAS
10	Airline	German	German	M	43	Captain	10,000	-/RAAS
11	Airline	German	German	M	42	Captain	10,000	-/-
12	Airline	German	German	M	37	Senior First Officer	5,000	-/-
13	Airline Instructor	German	German	M	29	First Officer	1,800	AMM/-
14	Airline Instructor	German	German	M	42	Captain	14,500	-/RAAS
15	Airline	German	German	M	44	Captain	10,000	-/-
16	Airline	German	German	M	**	First Officer	4,000	AMM/RAAS
17	Airline Instructor	German	German	M	62	Captain	20,000	-/-
18	Airline Flight Test	Dutch	Dutch	M	35	Captain	3,500	-/-
19	Flight Test	Dutch	Dutch	M	53	Captain	3,500	AMM/-

Table 18: Background of simulator experiment participants

During their entire career in commercial aviation, the participating pilots had logged between 1,600 and 20,500 hours (ø 8200 h). The distribution of aircraft types currently flown was as follows:

- Airbus A300-600: 3
- Airbus A320 family: 1
- Airbus A330/A340 family: 4
- Boeing B-737: 5
- Boeing B-747-400: 1
- McDonnell-Douglas MD-11: 2
- Fokker 70/100: 1
- Saab 340A: 1
- Cessna C550 /Fairchild Metro II: 1

[143] Cargo and regional divisions of an airline were regarded as belonging to the main airline.

Incidentally, there was thus an almost even distribution over Airbus and Boeing aircraft types. Familiarity/type-specific experience with the current aircraft type ranged from 500 to 7,500 h (ø 3000 h). On average, pilots had spent 15.4 years with their current airline, with a minimum of 3.5 years and a maximum of 39 years. All of the four Dutch participants had a flight test background, with two of them also serving as technical pilots to their airline. Five of the pilots were qualified as Instructors.

8.6 Evaluation Results and Analysis

8.6.1 Basic Airport Moving Map

This section analyses pilot feedback on the AMM functionality, which forms the basis of all other visualisation components of SMAAS. The analysis in this section is based on the AMM Questionnaire results and pilot comments during the runs in the simulator and in the debriefing session.

8.6.1.1 General Impression

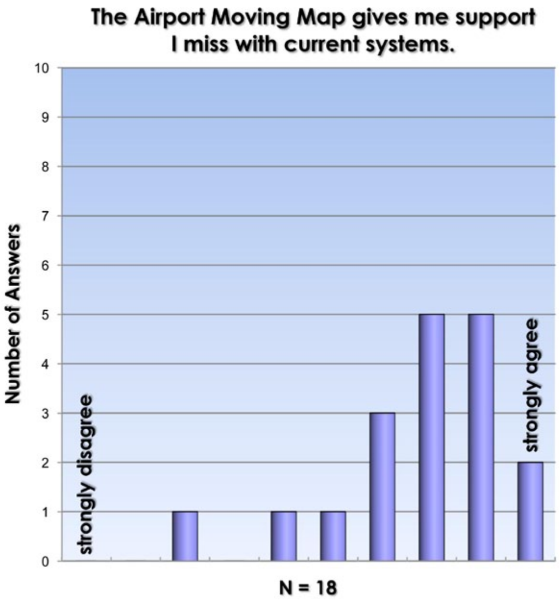

Figure 148: AMM operational relevance

Overall pilot feedback on the AMM was very positive. The AMM was highly appreciated by all participants and deemed mature from a conceptual point of view.

During the debriefing session, pilots stated that having AMM technology would greatly support them in the every day task of navigating around complex airfields, and several pilots spontaneously recalled recent operational situations where it would have been of great help.

Interestingly, virtually all of the pilots suggested the introduction of a panning/scrolling function for AMM, because this was the only feature they missed when interacting with the airport moving map. Some of the participants even suggested that, provided they were given a scrolling function, conventional paper charts could be completely replaced by the airport moving map.

In pilots' perception, the main deficiency of the AMM prototype shown to them from an implementation point of view was the fact that some taxiway identifiers were missing due to the immature labelling algorithm used. This drastically reduced the usability of the AMM prototype for surface navigation, and necessitated the parallel use of conventional paper charts.

As can be seen Figure 148, a majority of the pilots was of the opinion that the AMM gave them support they missed with current systems when asked to provide a rating on a Likert-style scale from 1 to 10 (M = 7.78, SD = 1.77). The pilots who gave feedback in the dissenting or only slightly positive domain stated that the current way of airport navigation worked out fairly well for them and that they did not really miss any technological support.

Several pilots mentioned that they would now no longer be forced to keep their finger permanently on the map while taxiing, and that both crew members could now share the same map picture. Compared to today, this would not only free resources (map tracking with finger no longer required), but additionally give the pilot taxiing the aircraft the opportunity to take a brief glimpse down to verify the position on the airfield. Another aspect that was positively mentioned was the fact that the AMM relieved pilots of the task of switching between paper airport charts covering different levels of details.

As expected, the issue of potentially increased head-down times was raised again by many pilots, like in previous AMM-related experiments, e.g. in the frame of ISAWARE and ISAWARE II. Pilots feared that eventually both crew members would be taxiing head-down. One participant stated that already with the Airbus A340-600's video-based Taxi Camera System (TACS), which shows, among others, an overview from the aircraft's tail and a detailed view of the location of the main gear with respect to the taxiway, he had sometimes caught himself looking at the head-down picture with fascination instead of looking outside. Another pilot voiced a concern that particularly the low AMM range settings with the realistic aircraft symbol might suggest to pilots that taxiing solely based on the head-down presentation was possible. When asked for potential solutions to this problem, participants suggested that this issue should be addressed through procedures and training; some were also of the opinion that a presentation on a head-up display might be beneficial in this context.

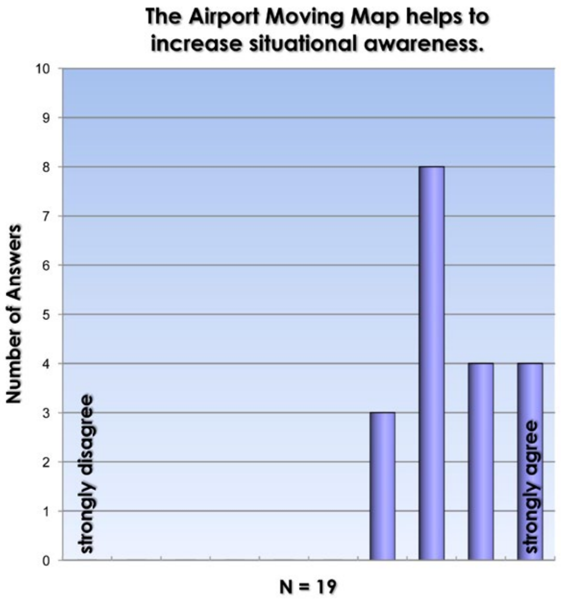

Figure 149: Contribution of AMM to situational awareness

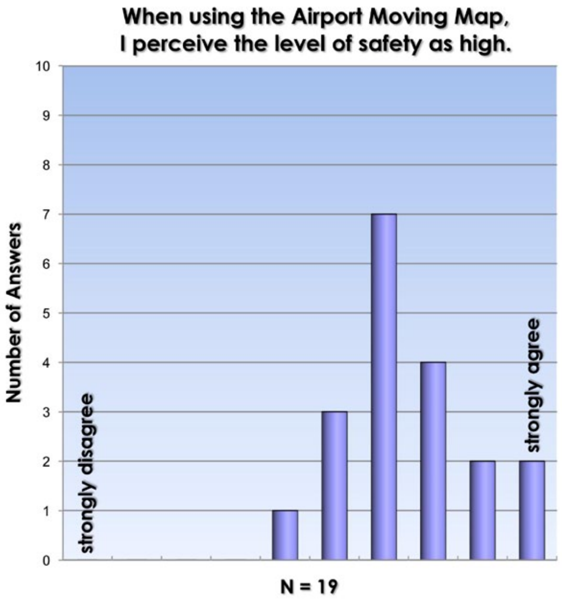

Figure 150: Perceived impact of AMM on safety

Figure 149 and Figure 150 illustrate pilots' subjective feedback on the impact that AMM usage has on situational awareness and on safety. Since only the four highest ratings were chosen, the pilot feedback presented in Figure 149 confirms that using an AMM subjectively helps to increase situational awareness (M = 8.47, SD = 1.02). Only the intensity of agreement varies, but, as both the high mean value, the comparatively low standard deviation and a median of 8 indicate, at a very high level.
At first glance, it seems that increased situational awareness does not automatically translate into an equal level of safety. As is evident from Figure 150, the distribution of feedback on safety is markedly shifted compared to pilots' rating on situational awareness (M = 7.47, SD = 1.35).

A closer look at pilot comments reveals that the reason for the lower rating on the safety question is related to pilot concerns about increased head-down times. Pilot SIM-#3, who gave the lowest rating on the safety question, was concerned that focussing inside on the AMM, pilots might forget to look outside and miss e.g. an ambulance car crossing their way. Pilot SIM-#2 made a similar comment and expressed a concern that the AMM might be a distraction. Participants generally also acknowledged the potential of the AMM to prevent flight crew disorientation, see Figure 151 (M = 7.11, SD = 1.88). Those pilots dissenting on the statement presented in the questionnaire commented that they would not rule out the possibility of getting lost due to potential distraction or inattention.

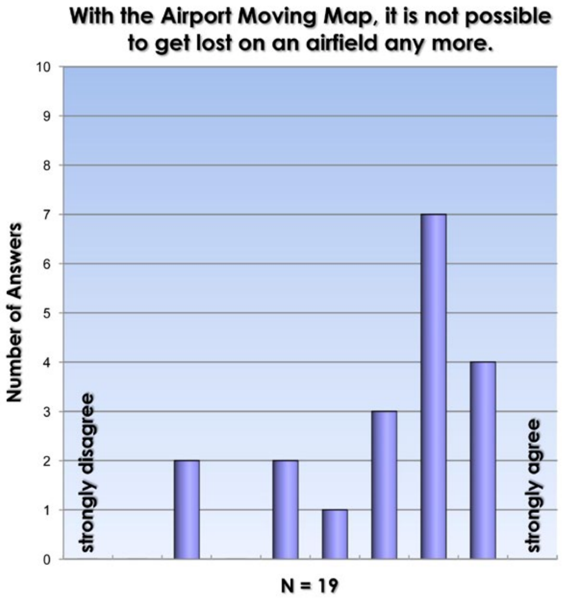

Figure 151: Capability of AMM to prevent flight crew disorientation

The evaluation in the simulator also revealed the importance of an effect that had not been given sufficient attention during the design and development phase. In the initial runs with the AMM, some pilots were slightly irritated by the fact that the cockpit cut-off angle gave them a visible position seemingly ahead of the aircraft symbol position presentation on the AMM. All of the participants, however, quickly adapted to this shift. Nonetheless, this inevitable discrepancy must be addressed in training to avoid early turns in AMM operational use. The only mitigation that can be provided without adulterating the ownship symbol is borrowing from Synthetic Vision EFIS design, where the PFD field of view is indicated on the ND. Likewise, the cockpit field of view could be indicated on the AMM on pilot request.

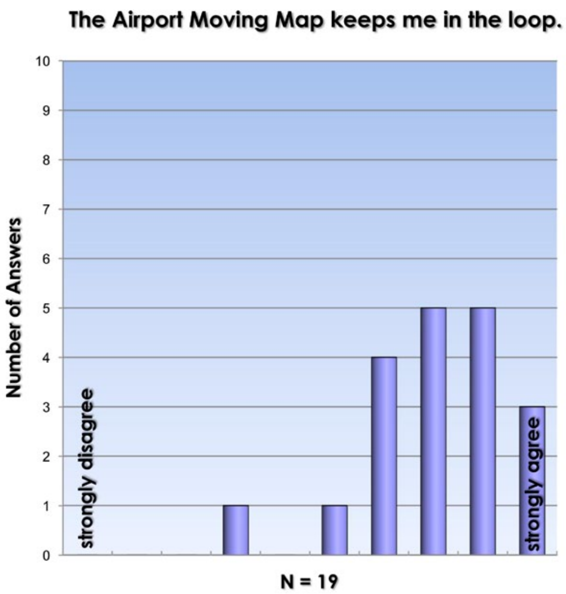

Figure 152: Impact of AMM on pilot

As can be seen from Figure 152, the AMM was perceived as keeping pilots in the loop (M = 8.05, SD = 1.51), which reaffirms the potential support during surface movement provided by this technology.

Since the focus of this thesis is safety-related, it was not attempted to assess potential efficiency benefits in a comparative analysis of scenarios with AMM and with conventional paper charts, all the more as it is not the intended function of the AMM to enable flight crews to taxi faster, even in low visibility. However, it is evident from pilot comments on the current situation

and potential disorientation they have experienced in real operations that crews often have to slow down or even to stop to orientate themselves or to check back with ATC. A potential contribution of the AMM to the efficiency of surface movement, therefore, might be that it enables crews to maintain a continuous taxi speed through better orientation and navigation.
It was also observed that most pilots, due to the missing audio and motional feedback cues from the taxiway centreline lights, were taxiing much faster than they would in reality. Most of the pilots realised this themselves ("*We are taxiing fast – like* [Airline name]*!*"), and subsequently slowed down.

8.6.1.2 Information presentation and accessibility

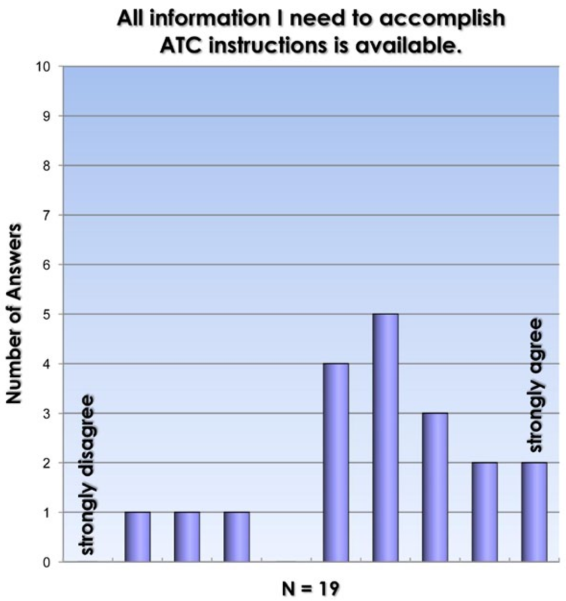

Figure 153: Appropriateness of AMM information to accomplish ATC instruction

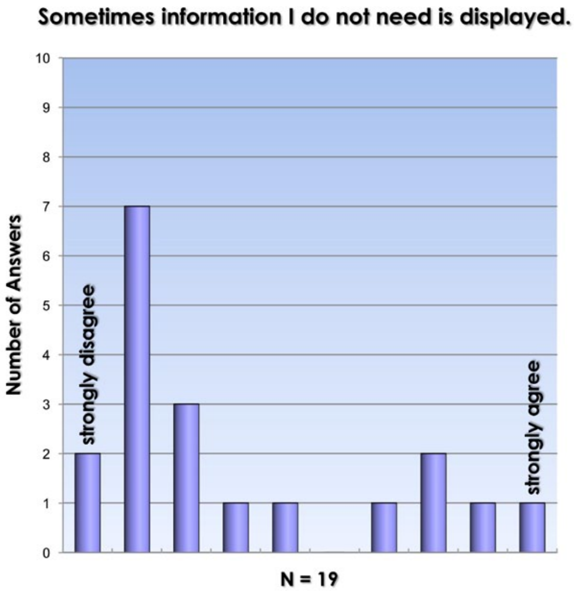

Figure 154: Relevance of AMM information

Figure 153 clearly shows the impact of the immature labelling function. While most pilots generally agreed on the fact that the AMM gives the support required to accomplish ATC instructions, the fact that some taxiway labels were missing was perceived as a significant deficiency, which is reflected by the fact that the distribution of pilot feedback in Figure 153 has its peak at a rating of 7/10, which corresponds to agreement with some limitations (M = 6.84, SD = 2.14). Dissenting feedback came from pilots who were of the opinion that both a correctly working labelling algorithm and a panning function were necessary to understand and carry out ATC instructions.
The pilot rating shown in Figure 154 addresses the reverse case, the presence of superfluous information. 12 of the 19 participants made their choice among the three levels of highest dissent (M = 4.36, SD = 3.08). Interestingly, even the pilots who agreed that unnecessary information was sometimes displayed had difficulties in giving reasons for their choice. Only two of the pilots explicitly stated that the low-range presentation with the realistic aircraft symbol gave them information they did not really need.

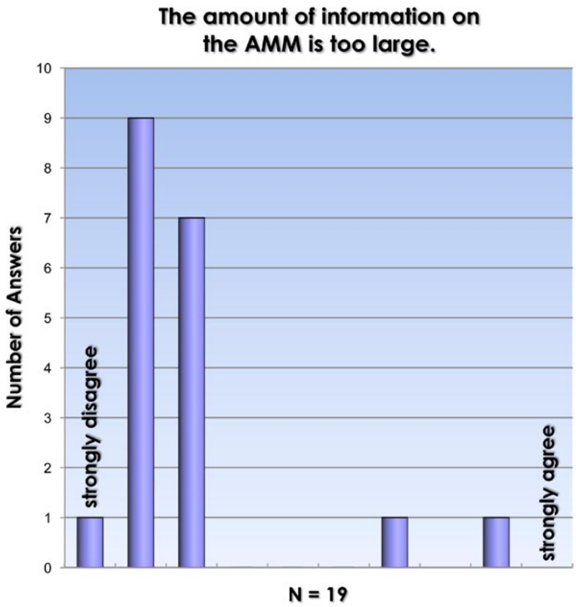

Figure 155: Potential information overload on AMM

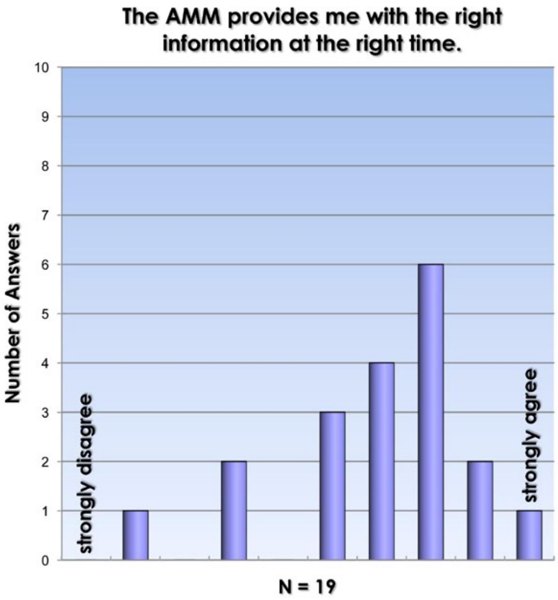

Figure 156: Appropriateness of AMM information in different situations

The questionnaire statement in Figure 155 addresses the same issue, although from a slightly different perspective, with a more generic scope and implicit coverage of display clutter. The distribution of pilot feedback, which deviates from normality (1% significance level), shows that all except two participants found the information density on the display acceptable (M = 2.95).
By contrast, the question presented in Figure 156 addresses the timeliness and appropriateness of information in different situations (M = 6.95, SD = 1.96). Again, the slightly broadened feedback can, according to de-briefing comments, be attributed to the fact that the sub-optimal labelling did not give pilots sufficient information in certain situations.

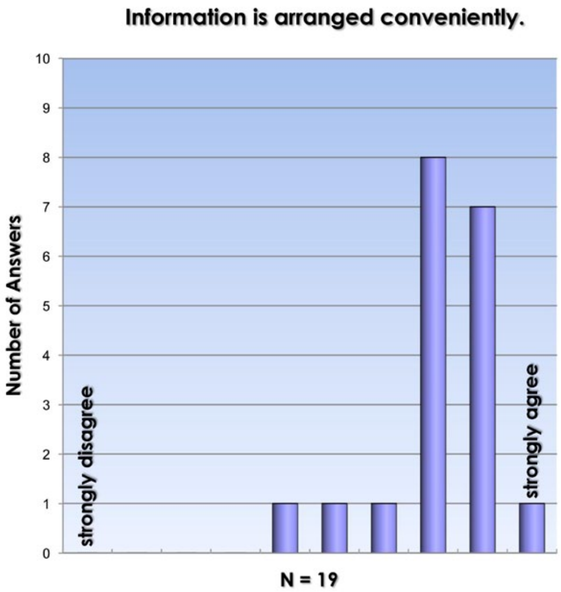

Figure 157: Assessment of AMM information presentation

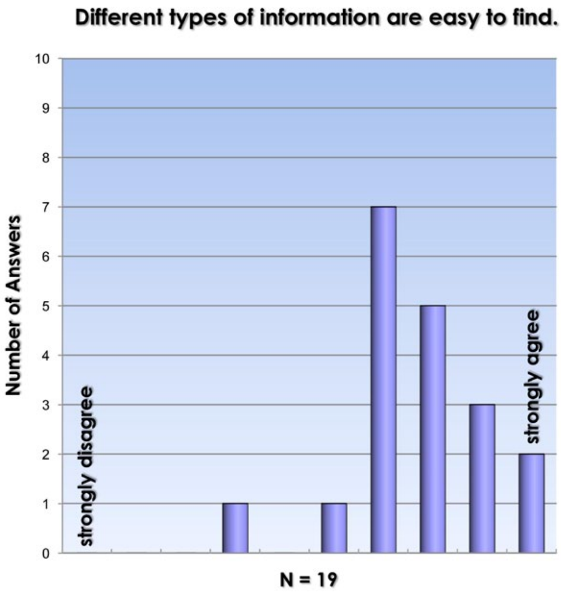

Figure 158: Pilot feedback on information accessibility

The results presented in Figure 157 and Figure 158 clearly demonstrate that a majority of pilots appreciated the way information was arranged on the airport moving map (M = 8.16, SD = 1.17), and that information accessibility was generally perceived as good (M = 7.68, SD = 1.42). The only problem pilots reported with respect to information accessibility was that, in the absence of a panning function, they would have trouble in locating a certain gate when taxiing in. In this context, it should be noted that all the scenarios in the simulator evaluation were taxi out.

8.6.1.3 Interaction with AMM

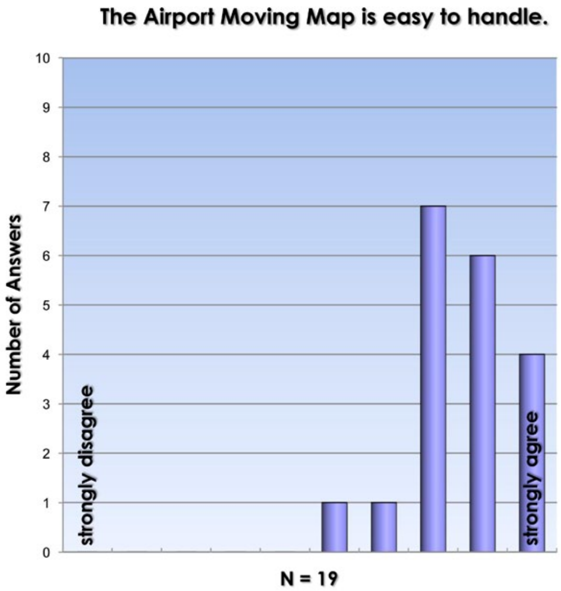

Figure 159: AMM handling qualities

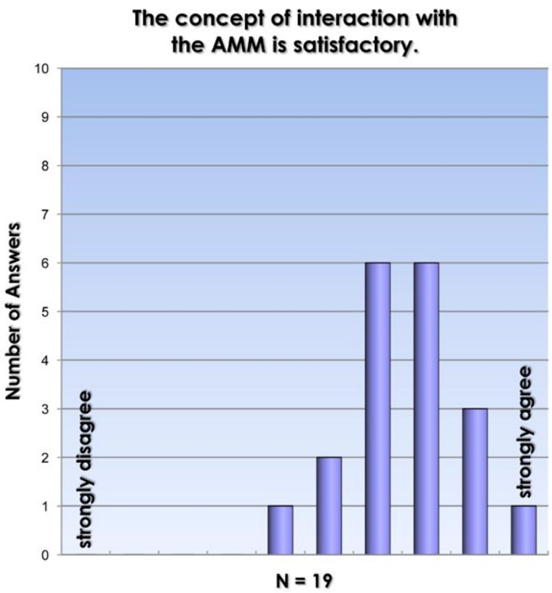

Figure 160: AMM interaction concept

As a comparison of the results shown in Figure 159 and Figure 160 shows, the overall AMM handling was rated somewhat better (M = 8.58, SD = 1.07) than the interaction concept (M = 7.58, SD = 1.22). The reason for this is that the handling rating addresses existing handling qualities only, whereas the interaction concept rating includes overall conceptual aspects as well. An analysis of the de-briefing comments yielded that, by and large, pilots were satisfied with the way the existing handling functions (range, mode) worked, but missed, as previously described, a panning function, which may serve as an explanation for the on average lower rating of the interaction concept vs. the handling.

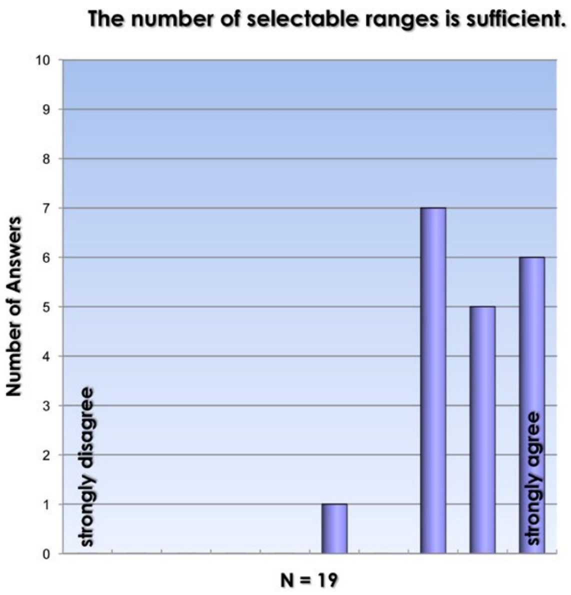

Figure 161: Appropriateness of available AMM ranges

Figure 161 presents the results of the survey on the adequacy of the available moving map ranges (M = 8.79, SD = 1.08). Most pilots were of the opinion that the number of selectable ranges was sufficient; only one pilot (Pilot SIM-#10) was more hesitant in his rating (6/10), because he thought that there were too many ranges, and questioned the use of the lowest AMM ranges. In this context, he commented that inaccurate positional information might yield a dangerously misleading picture.

Pilot SIM-#2 stated that the smallest AMM ranges contained too much information in his opinion. In addition, Pilot SIM-#5 missed an explicit indication of the selected range for the smallest AMM ranges. Several of the pilots also remarked that a changeover from nautical miles to meters should be considered to indicate the selected range. In fact, a corresponding solution had been considered in the design and prototyping phase, but the project test pilots had not been able to reach consensus in this matter; the main concern voiced was that the use of two different length scales on the same display might eventually confuse pilots.

8.6.1.4 Symbology and Labels

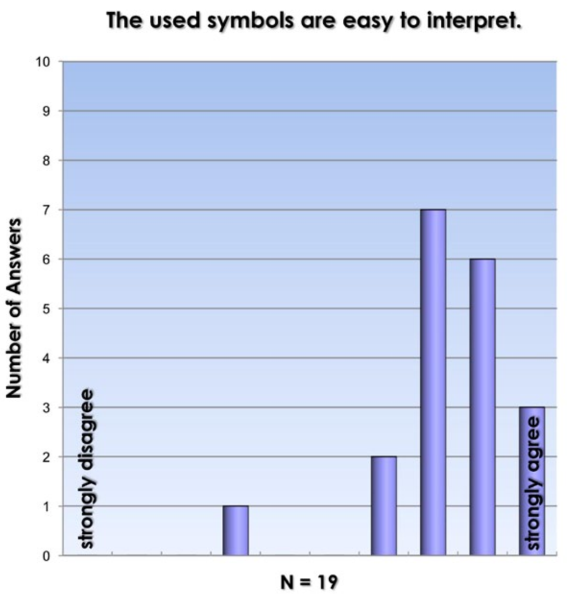

Figure 162: Assessment of AMM symbology

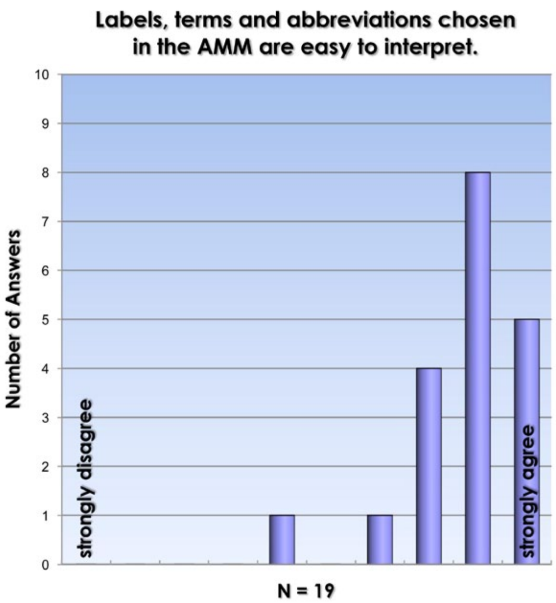

Figure 163: Assessment of AMM labels

Except for Pilot SIM-#13, pilots generally rated the symbols used as easy to interpret, as can be inferred from Figure 162. Pilot SIM-#13 stated that he missed a differentiation of CAT I and CAT II/III holding positions on the AMM. This criticism had also been voiced by other participants, but with less significant impact on their overall rating of AMM symbology (M = 8.32, SD = 1.38). The assessment results regarding AMM labels and abbreviations shown in Figure 163 clearly support the design choices made in this domain (M = 8.74, SD = 1.24). Pilot SIM-#5 only gave a rating of 5/10 for this statement because he found that the automatic removal of labels with increasing range, i.e. the de-clutter function, was not totally transparent to him.

Pilot ratings and debriefing comments clearly prove that pilots had no problems with the size of the textual information presented on the AMM (cf. Figure 164), mostly in form of labels. However, several pilots criticised the font used as less legible than the fonts they were used to on their aircraft (M = 8.84). Nonetheless, the fact that almost 74% of the pilots made their choice among the two highest ratings, and that the distribution of results exhibits a significant deviation from normality, clearly indicates that this issue is relatively minor, all the more since the custom TUD font used can easily be replaced by a different one.

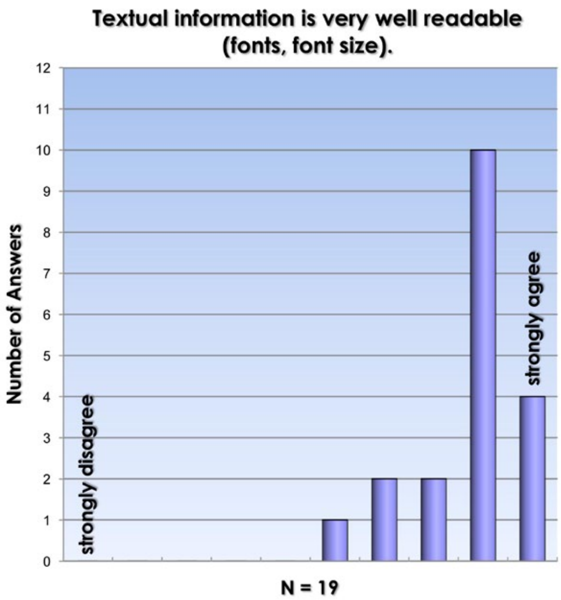

Figure 164: Textual information readability

8.6.1.5 Colour

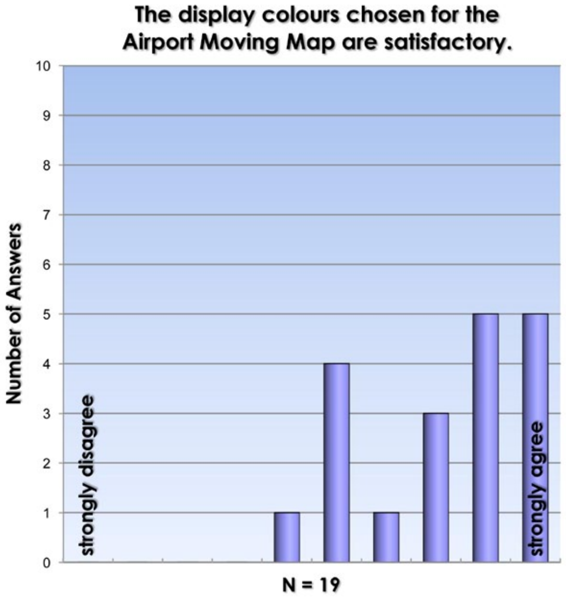

Figure 165: Assessment of AMM colours

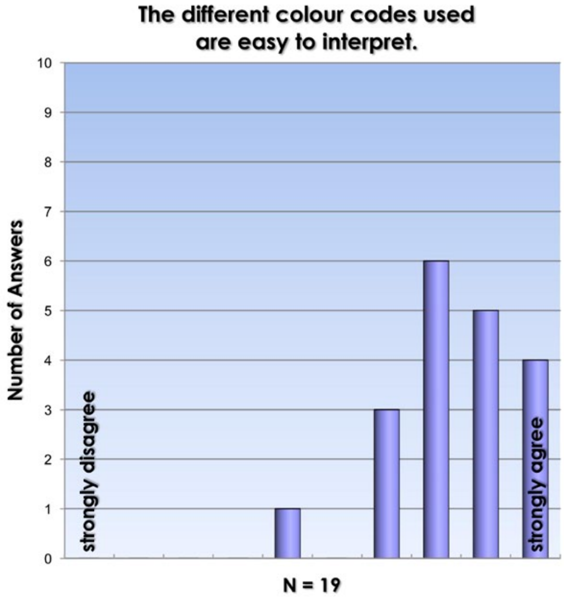

Figure 166: AMM colour coding

Figure 165 shows how pilots rated the colours employed for the AMM. In the questionnaire, the term 'satisfactory' was deliberately chosen, because differences in personal taste otherwise easily distort results when participants are asked whether they like or appreciate colours. The focus of the question, however, is on usability, consistency and acceptability.

Given the fact that 13 of 19 pilots (or 68%) chose one of the three highest possible ratings, and with a mean rating of 8.16/10 (SD = 1.68), it is evident that a majority of pilots found the AMM colours satisfactory. Additionally, many pilots expressed their appreciation for the colours chosen in their comments during the runs and in the debriefing session. Particularly the blue colour of the buildings, enabling a good distinction from taxiways and other airport pavements, and the yellow coding for the taxiway guidance lines, were cited. Pilot SIM-#8 commented that the colours chosen blended well with the colours he was used to on his current flight deck.

Only Pilot SIM-#11 gave slightly dissenting feedback, because he felt that the stop bars should be displayed in a more prominent fashion. This criticism was shared by several other pilots, among others Pilots SIM-#10, #15 and #19, all of whom mentioned the colour chosen for the stop bars as a reason for giving a rating of only 6/10. They all would have preferred a more alerting colour like red for the visualisation of holding positions and stop bars.

The questionnaire results presented in Figure 166 shed a light on colour from a slightly different angle, colour coding, which was – on average – rated slightly better than the display colours themselves (M = 8.37, SD = 1.30). This may serve as an indication that the colours chosen, although not undisputed, are nevertheless efficient. Apparently, pilots' criticism with respect to the colours chosen also applies to the respective coding. In addition, Pilot SIM-#5 pointed out that the display appeared to be very calm and that he liked the colour coding.

8.6.1.6 Flight Deck Integration Aspects

Since the AMM concept chosen for this thesis was an ND-integrated solution, integration aspects were both surveyed in a questionnaire and discussed in the debriefing session following the trials.

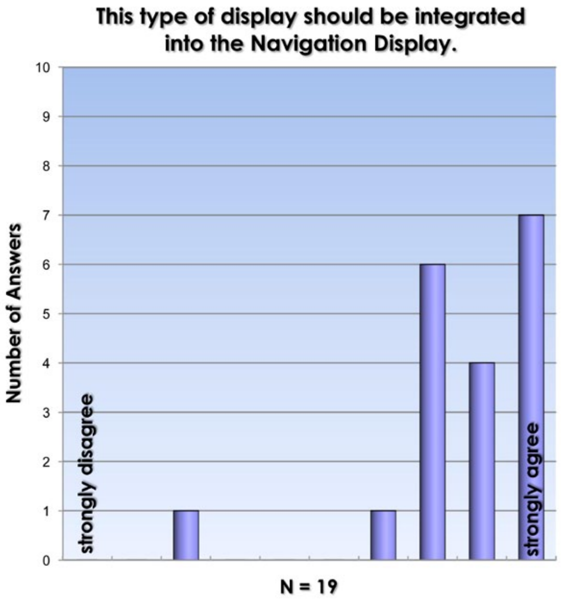

Figure 167: Appropriateness of Navigation Display (ND) for AMM integration

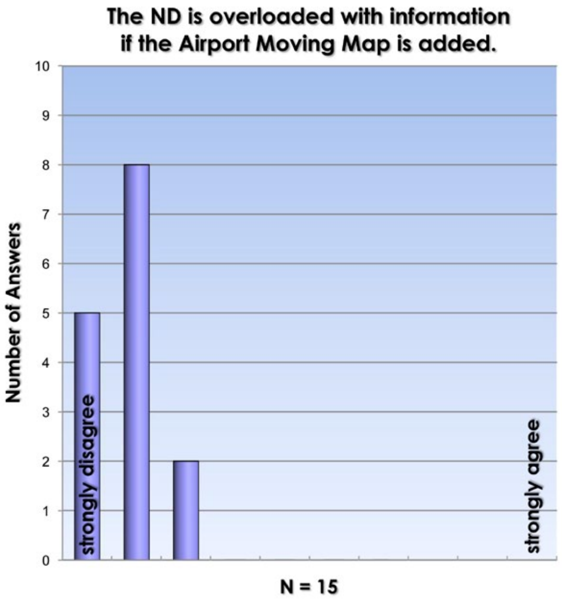

Figure 168: Information density aspects of ND integration

The questionnaire results shown in Figure 167 prove that there is a clear pilot preference to have the AMM integrated in the Navigation Display (ND), with an average rating of 8.63/10 (SD = 1.67).
Several pilots pointed out the necessity of having the AMM display aligned with the aircraft axis, and commented that this solution allowed them a quick glance down on the screen while taxiing to check whether they were at the correct location, without having to look on a paper chart. According to Pilot SIM-#9, this constitutes a huge advantage over the present situation, where the first officer is solely responsible for chart-based navigation in low visibility conditions and the captain is exclusively focussing outside. Consequently, the AMM enables Captain and FO to share essentially the same map information, and allows cross-checking even in adverse weather conditions.

Only Pilot SIM-#5 disagreed with the statement presented in the questionnaire. During the debriefing, he stated that the ND screen should either show the AMM display or the ‘classic’ ND, i.e. he was in favour of two distinct applications optimised for either operation, but did not question the fact that the AMM was presented on the EFIS screens – he suggested replacing the PFD, which is not used during taxi anyhow, with the AMM. It should be noted, though, that the problem with this suggestion is that the PFD screen is used for the Taxi Camera System (TACS) on some Airbus aircraft while on the ground, and, more importantly, that the PFD is required for take-off. Accordingly, all of the participants of the evaluation acknowledge the principle of presenting the airport moving map on the EFIS displays.

Figure 168 evidences that, in pilots' opinion, adding the AMM to the ND does not lead to an information overload (M = 1.80 , SD = 0.68). The lower number of answers is easily explained by the fact that this question was added to the questionnaire after the first four preliminary experiment sessions.
Simultaneous accessibility of 'classic' ND information and AMM information turned out to be an issue requiring further attention, though. Due to the fact that the ND is needed for the take-off briefing and familiarization with relevant weather and terrain in the departure area, Pilot SIM-#5 preferred to have a separate display other than the ND for the AMM, e.g. the PFD or a side display.
Pilot SIM-#8 stated that a combined display of AMM and FMS flight plan was not an essential feature due to the different length scales involved. Nonetheless, a corresponding solution would be appreciated if feasible. He classified the risk of confusing FMS flight plan and taxi route as very low.

As can be seen from Figure 169, a clear majority of pilots confirmed the relevance of having the "classic" ND modes such as PLAN, ARC and ROSE available for the airport moving map as well (M = 8.13, SD = 2.87). Two pilots, however, had a distinctly different opinion.

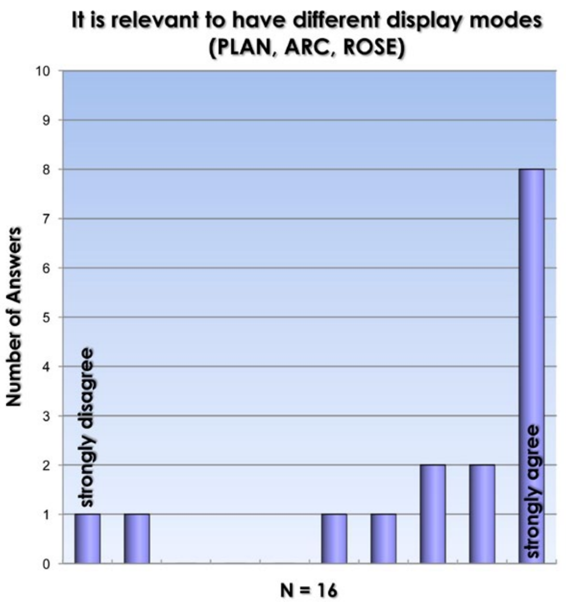

Figure 169: Relevance of classic ND modes for AMM

Pilot SIM-#11, who gave the 2nd-worst rating of 2/10, asked for a possibility to program a parking position in PLAN mode. Since a corresponding feature was not yet available, he probably could not see any necessity for a PLAN mode, and given his MD-11 background, the difference between ARC and ROSE was probably not sufficiently significant for him. The reason for the rating provided by Pilot SIM-#17 remains unclear, all the more since he selected the highest rating for the question regarding ND integration.
With respect to the necessity of different display modes, a noteworthy observation during the evaluation runs was that each pilot quickly found a preferred mode for himself, and then stuck to this mode for almost the entire assessment.

Pilot SIM-#7 commented that he found the ARC mode most interesting, and that he considered the ROSE mode as being less relevant. As for the conventional ND, the PLAN mode was only relevant to review a route if available. This explains his comparatively low, but still affirmative rating of 6/10. Conversely, Pilot SIM-#10 stated that the ROSE mode would be sufficient for him, but acknowledged that other pilots might prefer ARC mode. PLAN mode appeared to be altogether irrelevant to him initially, which explains his 7/10 rating. In the debriefing, he slightly revised his position by stating that the PLAN mode was important when planning/reviewing the route and for locating parking positions.

One pilot who generally agreed on the relevance of different modes was of the opinion that a PLAN for the AMM made only sense in combination with panning functionality. Several pilots also pointed out that the precise mode to be used for taxiing was a matter of personal preferences in most cases, and acknowledged that although they found a particular mode less relevant for themselves, it might nonetheless be the preferred mode for a colleague.

In conclusion, therefore, it appears that the concept of using the typical ND/map display modes for the airport moving map is a valid design choice, because it permits pilots to adapt the display according to the requirements of the current situation or their personal preferences.

Virtually all pilots found the size of the display acceptable (see Figure 170), but since the screens in the simulator cockpit were significantly larger than the screens in today's aircraft, several pilots voiced a concern that transferring the AMM concept shown to them to the smaller screens in their currently flown aircraft type might result in legibility issues. Nonetheless, the exclusively positive feedback shows that the HMI design was adequate for the display size chosen for the evaluation (M = 9.06, SD = 1.00). It is apparent that, for smaller screens, some more fine tuning or adaptation work would be required. It must be kept in mind, though, that there has been an almost universal trend towards larger displays in aviation in recent years, which culminates in the large screens now used in the Airbus A350 and the Boeing 787.

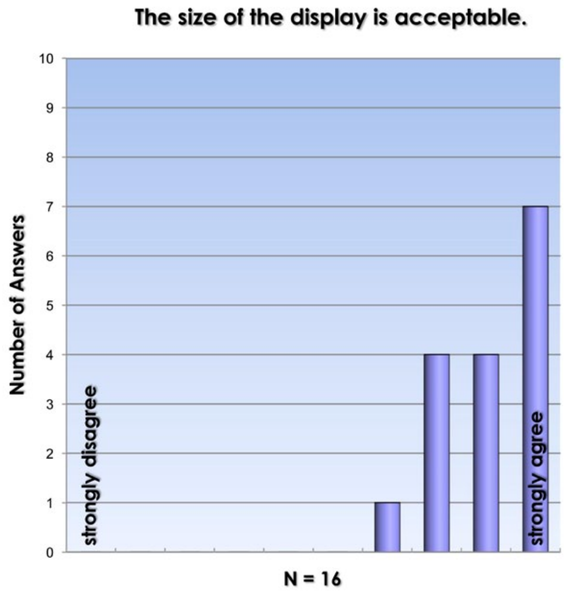

Figure 170: Assessment of AMM display size

8.6.2 Airport Moving Map with Traffic Presentation

8.6.2.1 Overall Impression

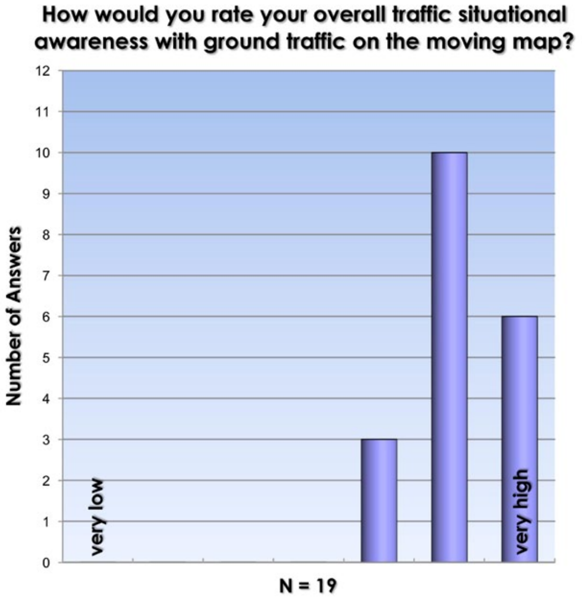

Figure 171: Impact of AMM traffic presentation on situational awareness

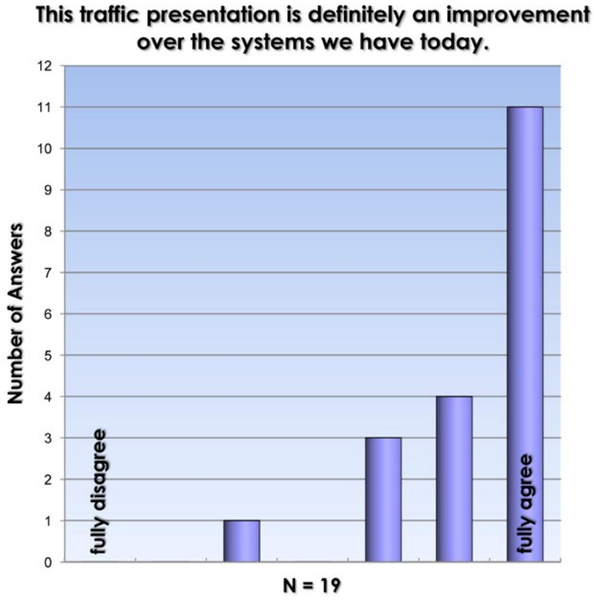

Figure 172: Operational relevance of AMM traffic presentation

Most pilots had a very positive overall impression of the traffic presentation on the AMM display. As Figure 171 shows, the participants' self-assessment on traffic situational awareness yielded only positive feedback. Some 84% of the pilots chose among the two highest ratings on a scale from zero to six (M = 5.16, SD = 0.69). Only three pilots were somewhat more reserved in their agreement. Pilot SIM-#3 stated that situational awareness was only improved in CAT III conditions with Low Visibility Procedures (LVP) in force. In addition, he considered information on who else was on a given taxiway was not that relevant, but pointed out the importance of runway-related traffic. Furthermore, he was slightly concerned that pilots might be focussed too much inside the cockpit, and miss e.g. an ambulance not captured by the available traffic surveillance data. Similarly, Pilot SIM-#12 stated that the display improved awareness of traffic to the sides and behind, whereas traffic ahead ownship should preferably be acquired visually. To Pilot SIM-#13, the crucial caveat with respect to situational awareness was the coverage of all relevant traffic. He stated that traffic situational awareness would be good with full coverage, but might be treacherous otherwise, and referenced to a similar issue with today's TCAS.
Although he chose the second-highest rating for this question, Pilot SIM-#2 was concerned that the traffic presentation with the labels could become a distraction in good visibility: "*So what's Air XYZ doing over there?*" He also questioned the operational significance of presenting the labels, since he was "*not an air traffic controller*."

With the exception of Pilot SIM-#3, whose reservations have already been discussed, all participants were of the opinion that the traffic presentation on the AMM was an improvement over current systems. Figure 172 indicates that almost 58% of the pilots opted for the highest rating (M = 5.26); the distribution of results accordingly exhibits a significant deviation from normality. Consistent with their rating on traffic situational awareness and with the same rationale, Pilots SIM-#12 and SIM-#13 gave only a slightly positive rating. Pilot SIM-#16 joined them with similar arguments.

Pilots were also asked to assess the potential contribution of the traffic presentation on safety. While, by and large, participants agreed there was an impact on the safety of ground operations (M = 4.68, SD = 1.00), one pilot dissented (cf. Figure 173).

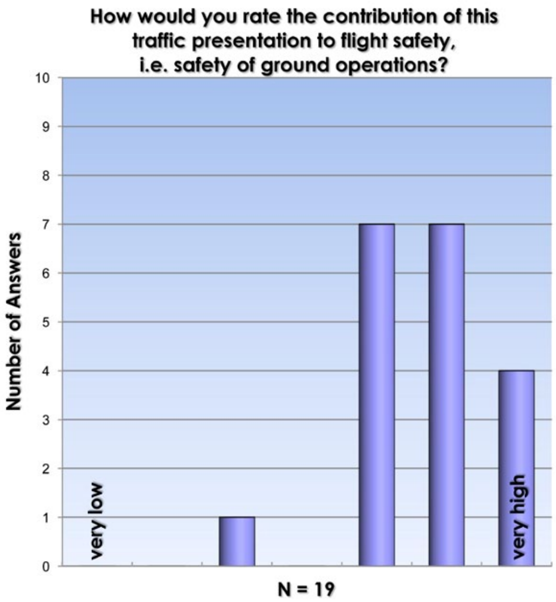

Figure 173: Perceived impact of traffic presentation on safety

Pilot SIM-#11 gave the lowest rating on this question, since the impact of the traffic presentation alone on safety was low with respect to potentially conflicting traffic in his opinion, because he found it difficult to anticipate intruder speed and movement status, particularly at large range settings. Nonetheless, this pilot acknowledged that the capability to anticipate where the others are was a benefit, though. His opinion was certainly influenced by the particular experiment configuration he experienced, with alerting de-activated during a Runway Incursion scenario.

Pilot SIM-#3, who rated the impact on safety as rather high, voiced his concern regarding the crew not looking outside and missing e.g. an ambulance, as discussed previously. But generally, he stated that the traffic display was "*of course a contribution to safety*". Furthermore, Pilot SIM-#4 commented that the traffic presentation would not solve the problem, but reduce the accident rate. In his opinion, it was "*a contribution, not a salvation*".

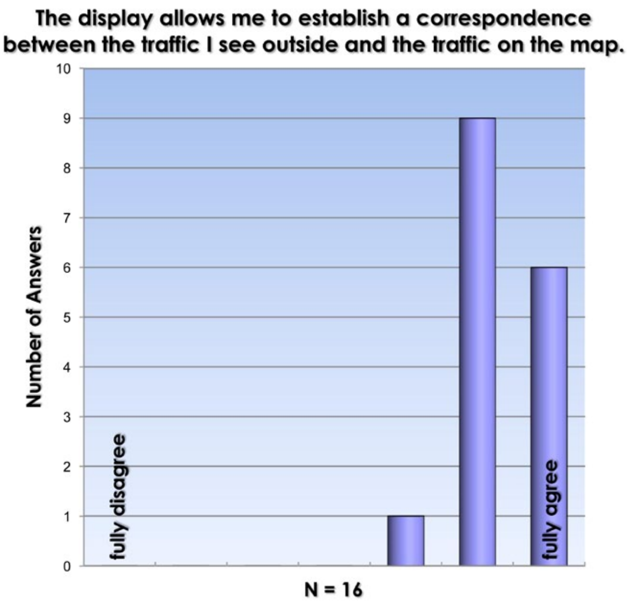

Figure 174: Support of traffic presentation for visual acquisition

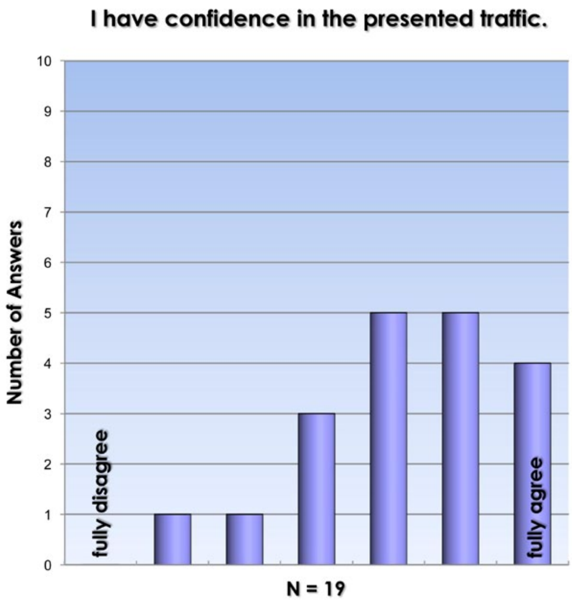

Figure 175: Pilot confidence in traffic presentation

Based on the presented traffic, all pilots were able to establish a correspondence between the traffic displayed on the airport moving map and the simulator outside visual, as evidenced by the results Figure 174 (M = 5.31, SD = 0.60). Several participants commented that the traffic presentation even allowed them to verify precisely on which taxiway traffic they saw visually was located, which is, according to these pilots, not always very easy to achieve in reality, particularly for parallel taxiways. In this context, Pilot SIM-#4 mentioned that in his daily operations, he always found it difficult to distinguish whether distant traffic moving in the opposite direction was on a parallel taxiways or a head-on conflict on his own taxiway.
Figure 175 indicates that a majority of pilots had confidence in the presented traffic (M = 4.26, SD = 1.41). However, the issue that not all other aircraft and particularly vehicles might be equipped (i.e. cooperative) made some pilots give neutral (Pilot SIM-#13) or negative ratings on this question; they stated that they would never rely solely on the display. During the debriefing, Pilot SIM-#11, who gave the lowest rating on this question, commented that he missed intent information for other traffic, i.e. "*what the others are up to*".

8.6.2.2 Symbology and Labels

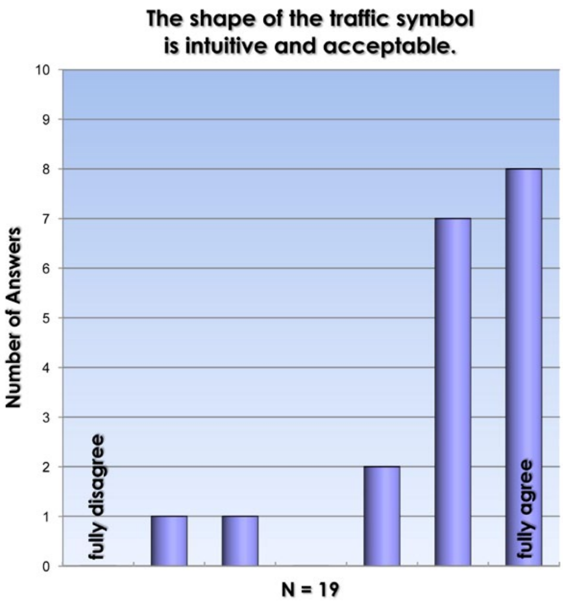

Figure 176: Assessment of traffic symbology

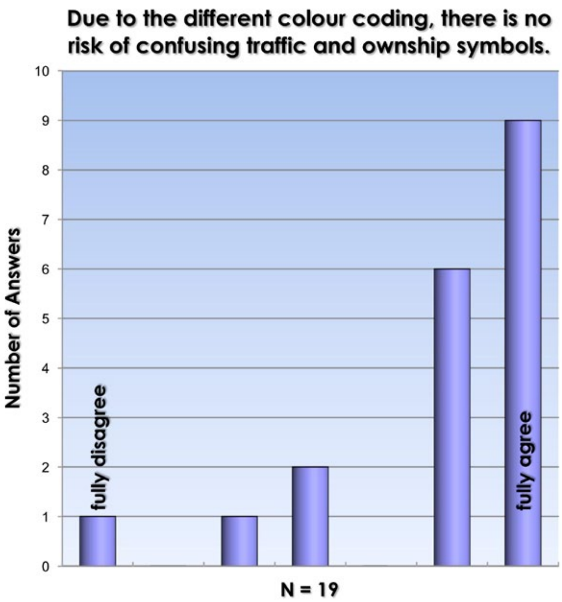

Figure 177: Risk of ownship/traffic symbol confusion

The symbology used for the presentation of traffic was found intuitive an acceptable by all pilots except Pilots SIM-#11 and SIM-17 (M = 4.95, SD = 1.39). Pilot SIM-#11 considered the white symbols for other aircraft too dominant, and suggested hollow and maybe see-through (transparent) traffic symbols, such that they would not obscure TWY labels on the AMM. Conversely, Pilot SIM-#17 would have wished a brighter and more attractive presentation of traffic. As Figure 177 shows, most pilots rated the risk of confusing ownship and traffic symbols as low (M = 4.85; not distributed normally). Pilot SIM-#11, who saw the highest risk of confusion, found the yellow ownship symbol difficult to see for range settings with the yellow taxi lines simultaneously presented. In the debriefing, he stated that he mistook a traffic symbol for ownship once during the runs.

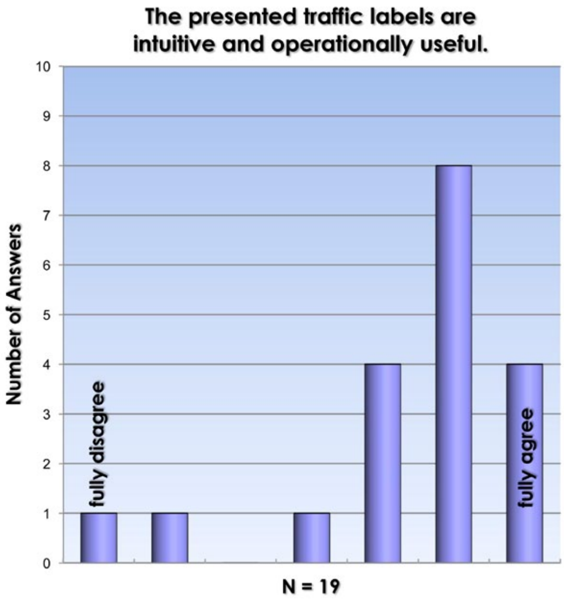

Figure 178: Rating of traffic labels

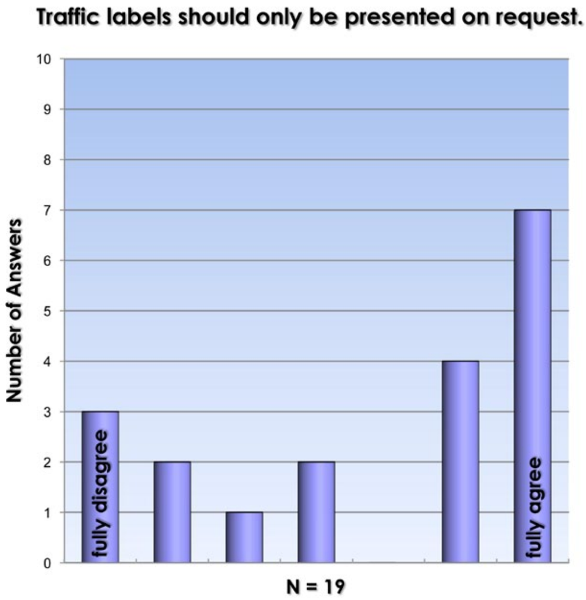

Figure 179: Label display policy

All pilots except Pilots SIM-#6 and SIM-#11 found the presented traffic labels intuitive and operationally useful, see Figure 178 (M = 4.42, SD = 1.61). These and several other participants stated that information on the aircraft type instead of the callsign would be more useful. Conversely, several other pilots considered the callsigns useful as labels, since it allowed them to understand the situation at hub airports, with many aircraft of the same airline present, much better.

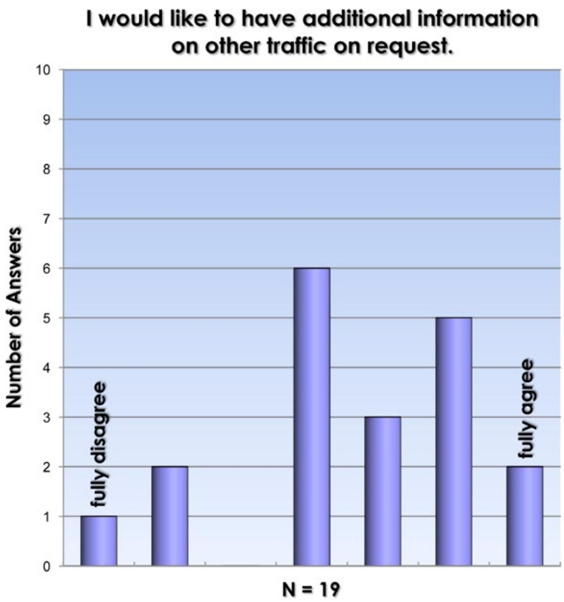

Figure 180: Assessment of additional optional label content

Effectively, a majority of pilots was in favour of displaying traffic labels only on request (cf. Figure 179). Accordingly, most of the corresponding participants made use of the corresponding controls provided in the simulator and deselected the display of labels. Nevertheless, pilots are essentially divided in two different fractions concerning this issue (M = 3.79, SD = 2.39), which indicates that further studies on this subject seem to be appropriate.

As Figure 180 shows, a narrow majority of participants desired additional information on other traffic on request, while a significant number of pilots had no pronounced preference (M = 3.63, SD = 1.67). Debriefing feedback on this question yielded that pilots considered intent information, aircraft type and registration the most important additional information that should be made available. Aircraft type and registration would, according to pilots, support visual acquisition and confirmation of the presented traffic.

8.6.2.3 Scope of Traffic Presentation

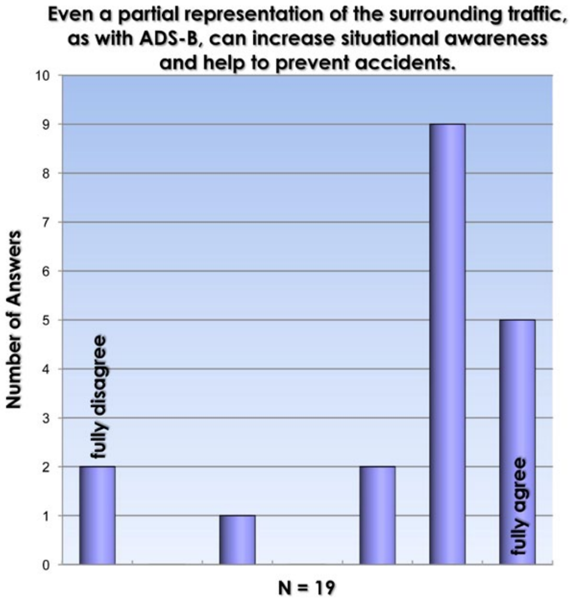

Figure 181: Impact of incomplete traffic surveillance picture

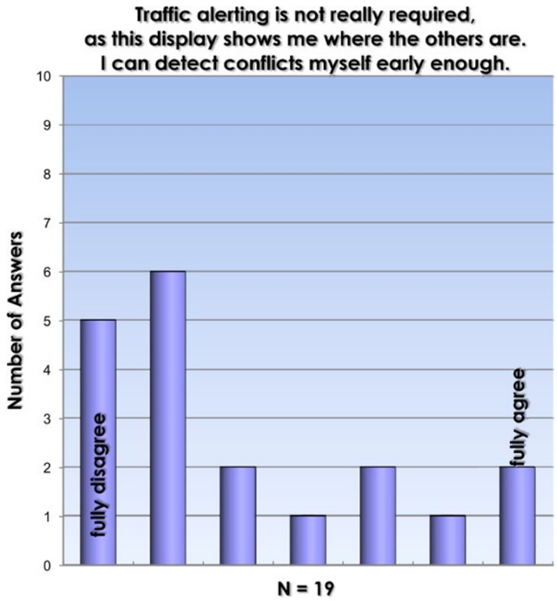

Figure 182: Issue of non-cooperative or non-detected traffic

The results presented in Figure 181 show that a majority of pilots considered even a partial presentation of the surrounding traffic as beneficial for situational awareness (M = 4.47), whereas three pilots – Pilots SIM-#4, SIM-#6 and SIM-#13 – strongly opposed an incomplete representation, stating that this might eventually be worse than no traffic presentation at all. With regard to the overall results of this question, there is a significant deviation from a normal distribution.

Furthermore, a majority of pilots also acknowledged that relying on an incomplete traffic presentation might be dangerous, as can be inferred from Figure 182 (M = 4.11, SD = 2.23). Nevertheless, irrespective of whether they agreed or dissented concerning this issue, many of the participants commented that flight crews should never solely rely on the traffic displayed. As a potential solution, one pilot suggested to suppress the presentation of an incomplete traffic picture, and to use the traffic for generating alerts in this case only.

This approach was also suggested as an option to avoid display clutter when presenting vehicles (see Figure 183 on the next page). Although the ratings diverge and do not show a clear tendency (M = 2.42, SD = 2.09), most pilots supported the idea of only displaying vehicles entitled to operate on the manoeuvring area, such as follow me cars, ambulances, fire engines and tow trucks. However, participants were concerned that an indiscriminate presentation of **all** vehicles operating in the airport environment would almost certainly result in tremendous clutter and a consequently hardly usable traffic display, which may serve as an explanation for the slightly dissenting tendency of the results.

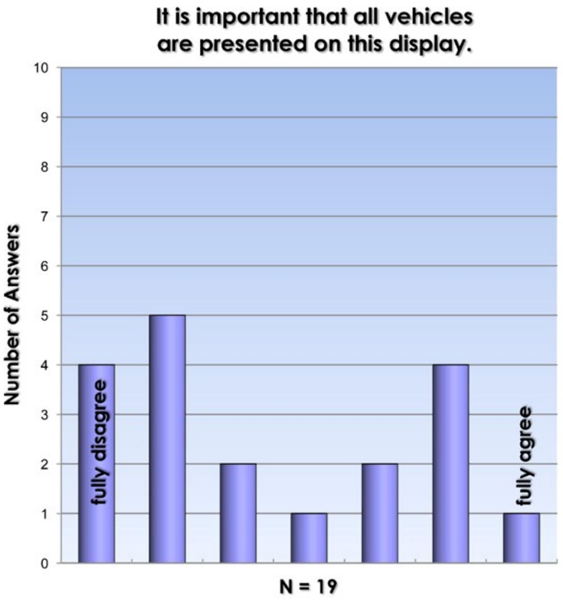

Figure 183: Vehicle display policy

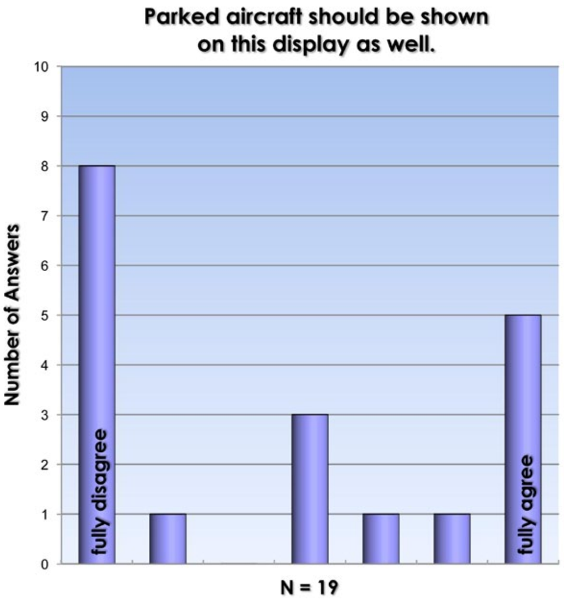

Figure 184: Importance of visualizing parked aircraft

As Figure 184 shows, participants had diverging opinions on the presentation of parked aircraft (M = 2.58, SD = 2.61). While some of the pilots considered only aircraft manoeuvring under their own power or ready for push-back as relevant, others pointed out that a corresponding information would be useful not only since parked aircraft might constitute relevant obstacles, but also because this feature could additionally be used to check gate occupancy, e.g. to check whether the assigned gate was already available after landing.

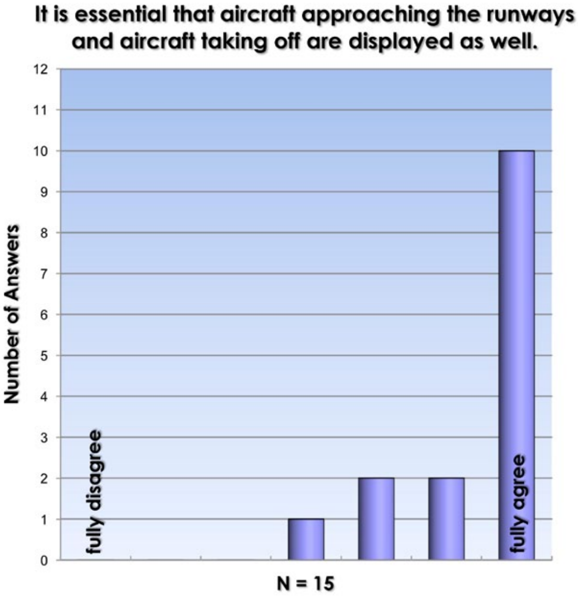

Figure 185: Importance of visualizing traffic landing and taking off

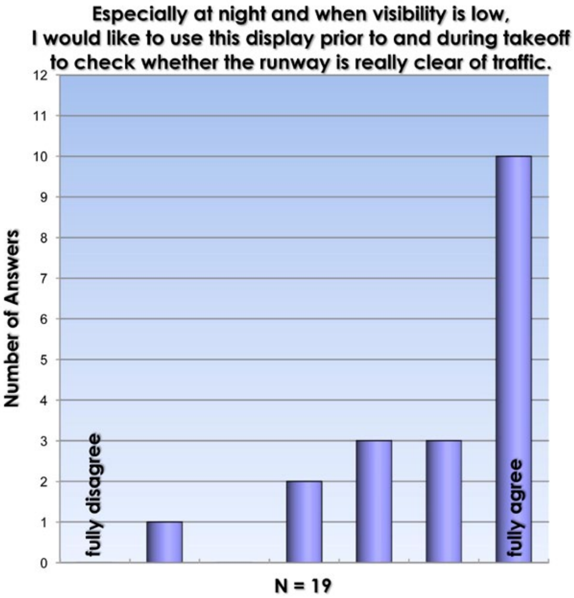

Figure 186: Usage of AMM traffic depiction for runway surveillance

Regarding the scope of the traffic presentation, the results presented in Figure 185 clearly indicate that pilots confirmed the concept of including traffic taking off or landing in the presentation (M = 5.40). Results exhibit a significant deviation from a normal distribution, which is not surprising in view of the fact that two thirds of the participants opted for the highest available rating.
Except for Pilot SIM-#13, who dissented for the general concerns already quoted in connection with the other questions, pilots confirmed the relevance of using the traffic presentation for runway surveillance in conditions of impaired visibility, as evidenced by Figure 186 (M = 4.95, SD = 1.43). In addition, some of the participants remarked that they already use TCAS for the same purpose today. That these pilots employ TCAS in spite of its limitations once more reaffirms the need for providing flight crews with information on pertinent traffic in the runway environment.

8.6.2.4 Workload and Display Clutter

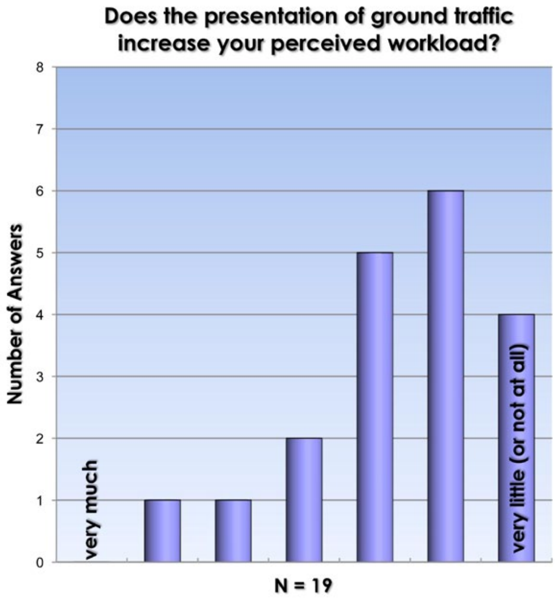

Figure 187: Perceived workload with traffic presentation on AMM

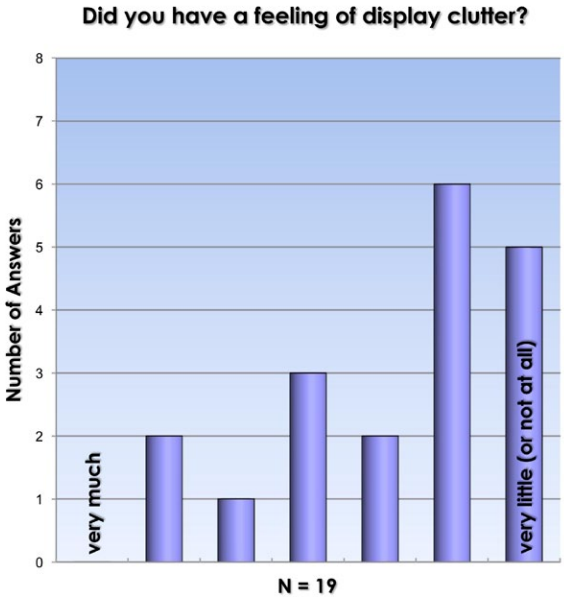

Figure 188: Subjective feeling of display clutter

The results presented in Figure 187 show that a majority of pilots perceived the additional workload caused by the traffic presentation as low (M = 4.37, SD = 1.38). Pilot SIM-#19, who rated that the traffic presentation appeared to increase his workload, commented that the traffic presentation slightly diverted his attention. As previously mentioned, Pilot SIM-#2 was also concerned that the traffic presentation might potentially distract pilots, and therefore also gave the feedback that the presentation rather increased workload.
While many of the pilots did not have a feeling of display clutter with traffic displayed on the AMM (M = 4.26, SD = 1.66), Pilots SIM-#6, SIM-#11 and SIM-#13 provided contrary questionnaire feedback (cf. Figure 188). According to Pilot SIM-#6, the fact that the traffic symbols remain at constant size even if display range is increased contributed to the slight clutter he observed. The concerns about the traffic representation brought forward by the two other pilots have already been discussed earlier in this section.

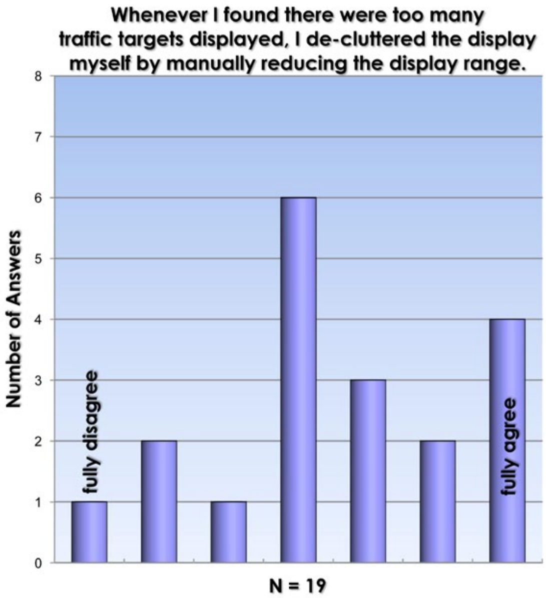

Figure 189: Usage of range selection for manual display de-clutter

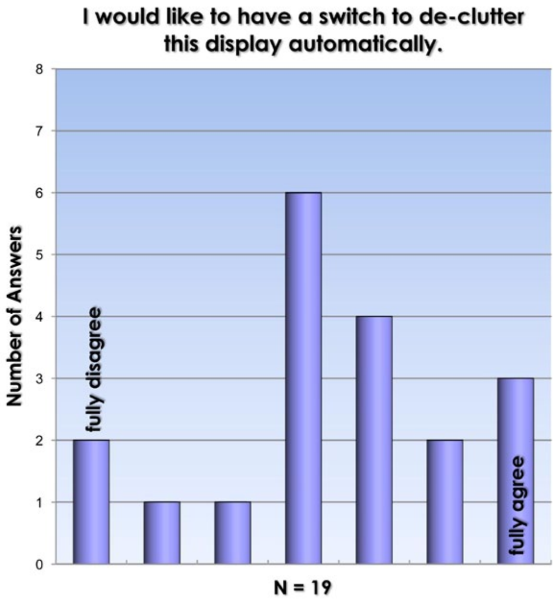

Figure 190: Desirability of automatic de-cluttering

The results presented in Figure 189 indicate that reducing range is not sufficient as a strategy for de-cluttering the display if pilots feel that too many other traffic targets are shown on the display. Conversely, though, pilots' opinions also diverge concerning an automatic de-cluttering (see Figure 190). Dissenting feedback is mainly due to concerns that the behaviour of the underlying automation might be difficult to predict for flight crews, which hints at a potential automation awareness problem.
Pilot feedback on both questions may be regarded as confirmation of the assertion in Section 5.2.1 that there is no trivial solution to the issue of traffic-induced display clutter at hub airports, and that further research on this matter is required.

8.6.3 Airport Moving Map with Operational Awareness Function

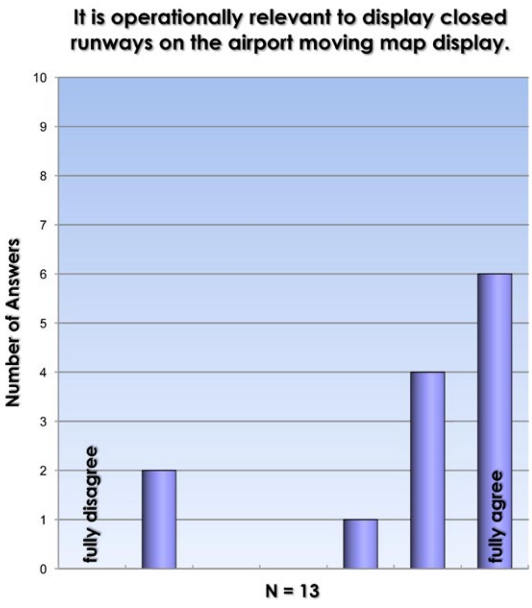

Figure 191: Operational relevance of presenting closed runways on the AMM

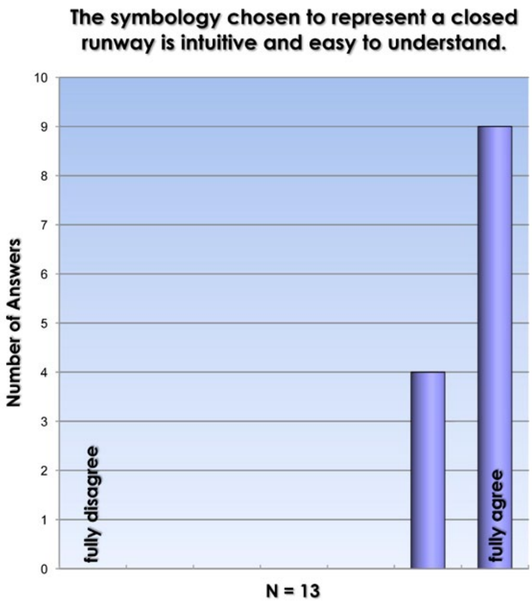

Figure 192: Assessment of symbology for closed runway presentation

8.6.3.1 Display of runway closures

All except two pilots confirmed the operational relevance of presenting closed runways on the AMM, as shown in Figure 191 (M = 4.77, SD = 1.79). Both of the dissenting pilots remarked that pilots should anyhow be aware of closed runways due to the mandatory pre-flight briefing. Additionally, Pilot SIM-#5 stated that he could live with a system merely telling him which RWY he was approaching, and that the importance of the added symbology was marginal compared to the safety benefit brought about by the AMM itself. Pilot SIM-#11, who was also dissenting on the operational relevance, commented that he mainly relied on his eyes regarding closed runways, and also remarked that NOTAM were often not up to date. This suggests that his rating was at least partially motivated by his lack of trust in the NOTAM system itself. In this context, it is noteworthy that the aspect of NOTAM data currency/integrity was also raised by several other participants.

However, none of the dissenting pilots raised any objections against presenting closed runways, and there was consequently only affirmative feedback on the corresponding symbology, as evidenced by Figure 192 (M = 5.69). Since participants only chose among the two highest available options, it is not surprising that the results are not distributed normally. Furthermore, according to the results in Figure 193, the need to distinguish the different levels of runway closure was acknowledged by all pilots except Pilot SIM-#11, who, consistent with his rating on the overall operational relevance of presenting closed runways, felt that the red crosses were too prominent (M= 4.89, SD = 1.96).

As Figure 194 shows, there was a wider distribution of feedback concerning the colours used (M = 5.15, SD = 1.46), with Pilot SIM-#5 dissenting on the consistency of the colour concept employed. Two thirds of the participants once more chose among the two highest ratings. In conclusion, there is little room for an optimisation of the symbology, and the colour concept also has high degree of maturity already.

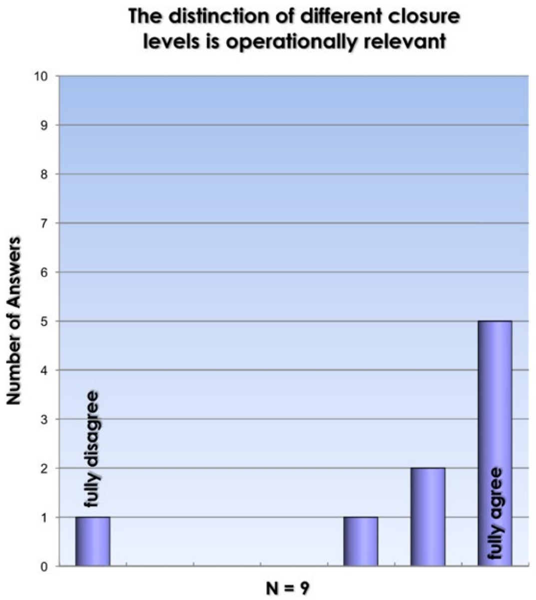

Figure 193: Relevance of distinguishing different levels of runway closure

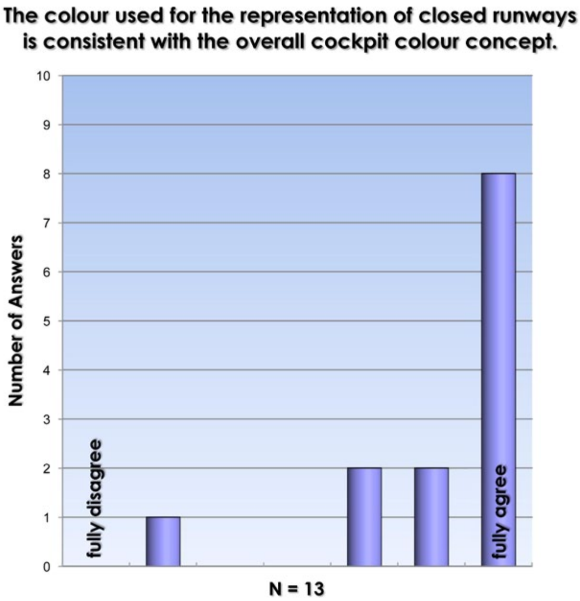

Figure 194: Assessment of colour coding employed for presenting closed runways

8.6.3.2 Presentation of FMS-selected runway

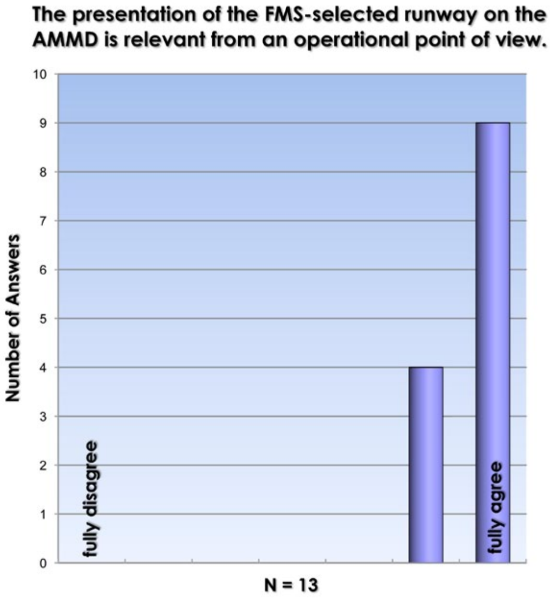

Figure 195: Operational relevance of presenting the FMS-selected runway on the AMM

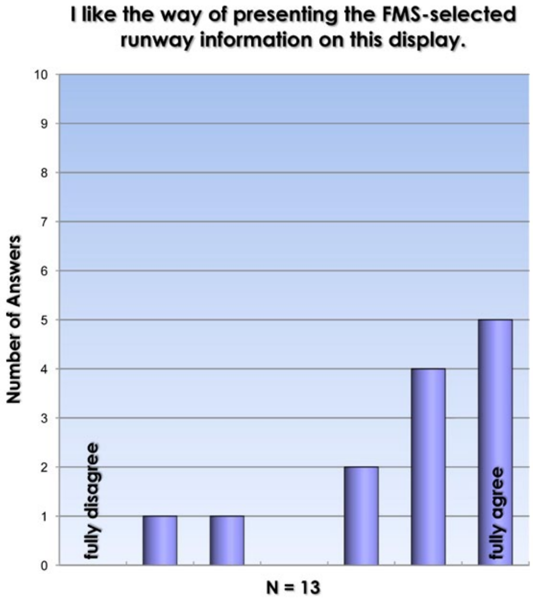

Figure 196: Assessment of symbology for FMS-selected runway presentation

Regarding the FMS-selected runway presentation, both the operational relevance and the particular HMI design choice made were confirmed by the pilots in the simulator trials. With an average rating of 5.69 (out of six), this feature is, along with the taxi route, one of the most desired airport moving map add-ons proposed by SMAAS, see Figure 195. Due to the fact that only the two highest ratings were chosen, the distribution of ratings significantly deviates from normality.

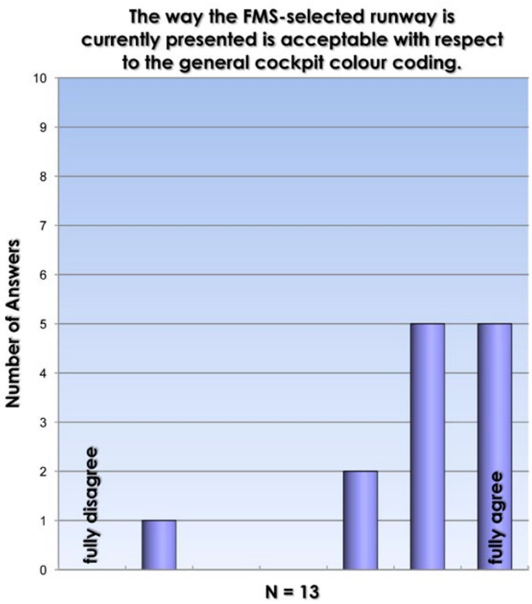

Figure 197: Assessment of FMS-selected runway colour coding

Concerning the associated HMI, it is noteworthy that the selected colour coding (see Figure 197) received a somewhat better average rating (M = 4.92, SD =1.38) than the symbology itself (M = 4.69, SD = 1.60), with results presented in Figure 196. However, it is evident from pilot comments that even the pilots who provided negative feedback on the HMI generally agreed on the symbology chosen, but criticised that the present combination of colour and line width lacks conspicuousness. Nevertheless, this is not critical, because this feature constitutes information actively accessed when needed, not an advisory.

Thus, it can be concluded that the FMS-selected runway presentation would make a valuable addition to the basic airport moving map functionality. All the data required to support it are available aboard virtually all airliners currently in production, no extra sensors are required. Therefore, its near-term introduction into AMM products is strongly recommended.

8.6.3.3 Presentation of active runway information

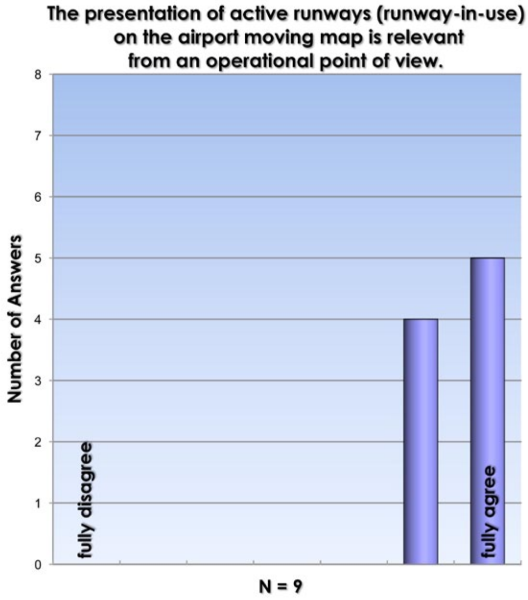

Figure 198: Operational relevance of active runway information integrated with AMM

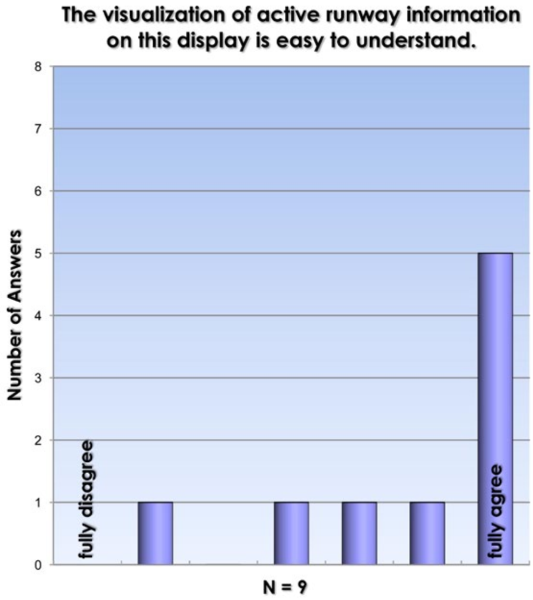

Figure 199: Pilot rating on intuitiveness of active runway visualisation

According to the results shown in Figure 198, it is evident that pilots fully acknowledged the operational need to present active runway information in conjunction with the AMM (M = 5.56, SD = 0.53). Concerning the visualisation employing the dimmed runway label (see Figure 199), all participants except Pilot SIM-#11, who regarded the difference between dimmed and un-dimmed label as too small, agreed that this representation was easy to understand (M = 4.78, SD = 1.79), although several other pilots also voiced slight concerns about its conspicuity.

8.6.3.4 Interaction with NOTAM and runway status information

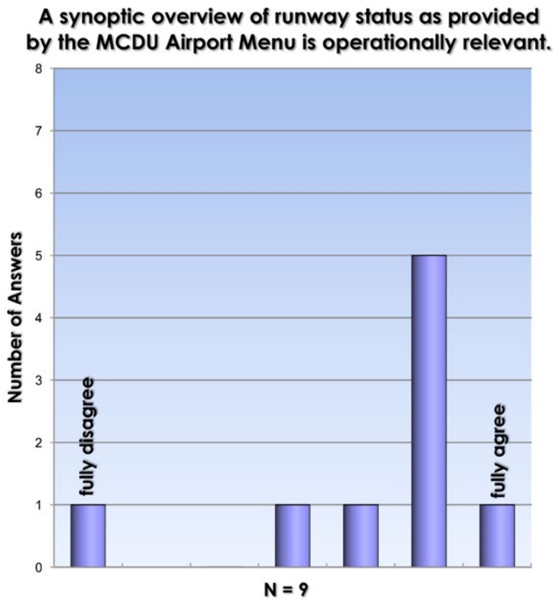

Figure 200: Need for synoptic runway status information as on MCDU Airport Menu

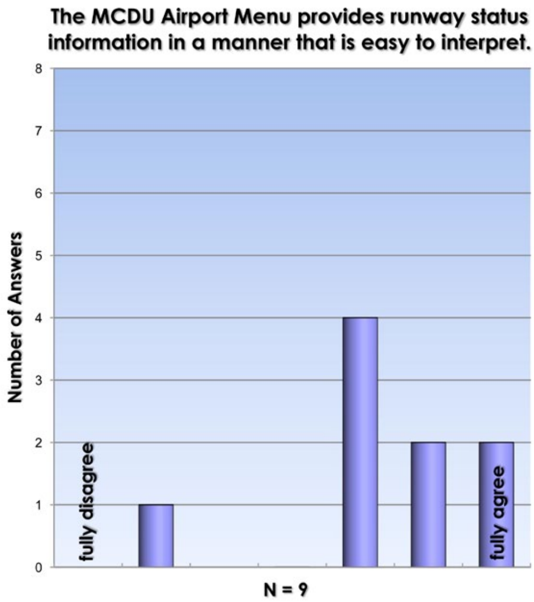

Figure 201: Pilot rating of taxi route colour coding

Since the MCDU keys in the simulator were only partially working at the time of the evaluation, it was decided to give participants a demonstration of the MCDU Airport Menu in lieu of a hands-on experience. This demonstration was conducted between formal scenario runs when appropriate, and encompassed changing the status of one runway from open to closed, or vice versa, while pilots could observe both the interaction process on the MCDU and the resulting changes on the ND. In addition, the ePIB Main Menu was briefly presented.

As can be seen from Figure 200, all pilots except two agreed on the necessity of having a synoptic overview of the runways available at an airport and their operational status (M = 4.22, SD = 1.79). Pilot SIM-#11 disagreed on the operational relevance, while Pilot SIM-#12 was neutral on this matter. Likewise, apart from Pilot SIM-#11, participants agreed that the way information was presented could be easily interpreted, see Figure 201 (M = 4.33, SD =1.50).

A majority of pilots also considered the MCDU as an appropriate means of interaction for the purposes demonstrated, as shown in Figure 202 (M = 4.11, SD = 2.03). Nevertheless, there was dissent from Pilots SIM-#11 and SIM-#12, while Pilot SIM-#13 gave a neutral rating. These and several other pilots would have desired a more sophisticated graphical user interface for interaction with SMAAS.

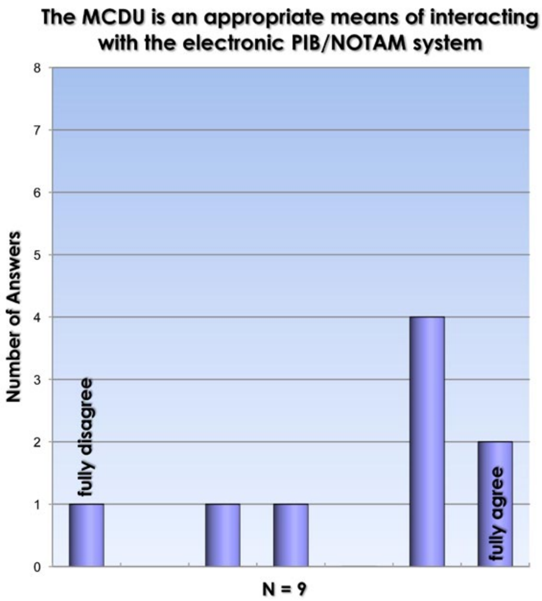

Figure 202: Appropriateness of MCDU as means of interacting with ePIB

However, in view of the well-known ergonomical limitations of the MCDU, and given the fact that most aircraft are only equipped with a MCDU, all pilots considered both the choice of the interaction means and the HMI realisation as generally adequate, as comments during the debriefing clearly indicate. As an example, Pilot SIM-#6 referred to the MCDU as "*ergonomical monster*", and stated that he would have preferred a direct interaction on the ND to change runway status.

Even Pilot SIM-#11, whose negative ratings on the use of the MCDU for interaction with SMAAS can be mainly attributed to concerns over potential pilot distraction, nevertheless acknowledged that the MCDU Airport Menu might be useful to retrieve airport information on potential alternate airports in case of emergency.

8.6.4 Airport Moving Map with Clearance Awareness Function

8.6.4.1 Visualisation of taxi routes

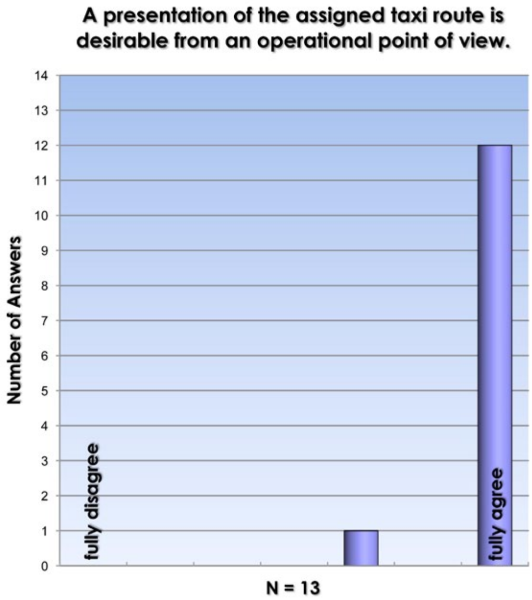

Figure 203: Operational relevance of taxi route presentation

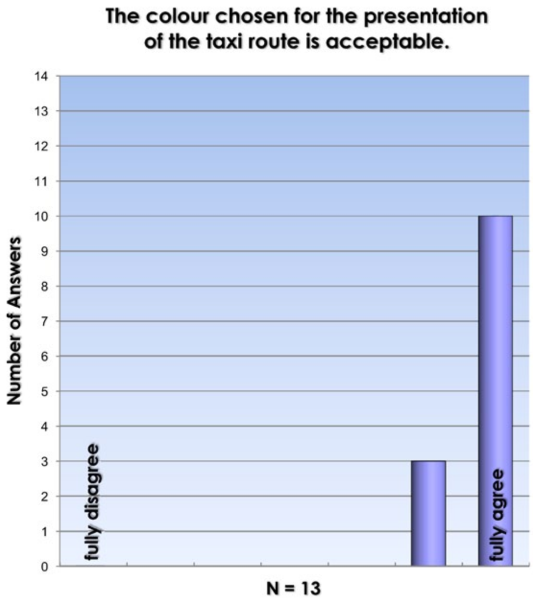

Figure 204: Pilot rating of taxi route colour coding

As can be seen from Figure 203, a graphical presentation of the assigned taxi route on the airport moving map was the most appreciated feature (M = 5.85), and the colour coding chosen was rated almost equally high (M = 5.77). Given the number of pilots opting for the highest rating, it is not surprising that results exhibit a highly significant discrepancy (1% confidence level) from a normal distribution in both cases.
Concerning the additional support provided, Pilot SIM-#5 remarked that the visualisation of the taxi route was very good in his opinion, because it relieved him from keeping his finger on the map. Only Pilot SIM-#12 was a bit hesitant in his agreement, particularly with respect to the operational relevance. Nevertheless, several of the participants, among them Pilot SIM-#13, commented that in following the green line, they sometimes caught themselves solely relying on the presentation and not keeping track of and double-checking their navigation as usual.

8.6.4.2 Display of runway-related clearances

With the taxi route already presented on an airport moving map display, the logical next step is handling all clearances related to surface movement via CPDLC, cf. Section 5.4.3. In the simulator experiment, this concept was assessed in scenarios where line-up and take-off clearances were simultaneously issued via voice and visualised on the airport moving map as CPDLC uplink. While this combination of R/T and CPDLC was initially owing to the limitations of the simulation, i.e. the unavailability of a DCDU mock-up, it eventually yielded highly interesting results, both with respect to quantitative feedback (see Figure 205) and pilot comments. At the quantitative level, all pilots except two (Pilot SIM-#5 and SIM-#12) acknowledged the operational relevance of visualising take-off and landing clearances on the AMM, with a majority of participants opting for the highest available rating (M = 4.85, SD = 1.86).

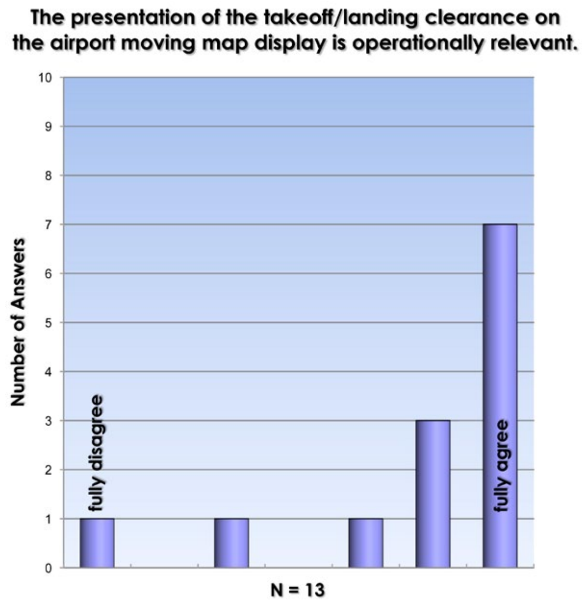

Figure 205: Operational relevance of presenting runway-related clearances on AMM

Pilot SIM-#5 was concerned that using CPDLC for take-off and landing clearances, which are tactical by nature, might take too long and was therefore not desirable in his opinion. This view was in principle shared by several other pilots. According to Pilot SIM-#12, who gave the second lowest rating, he entirely overlooked the visualisation of the take-off clearance, which he did not consider operationally relevant.

Pilot SIM-#10, whose rating was slightly positive, commented that runway-related clearances always need to be additionally available via normal R/T, since this is the only way of ensuring that other pilots have the same information. Although the simultaneous use of CPLDC and voice violates current ICAO regulations, cf. [ICA01a], pilot acceptance for this combined solution was surprisingly high.

Figure 206 and Figure 207 indicate that the way of presenting take-off or landing clearances was generally appreciated by participants, both with respect to symbology (M = 5.00, SD = 1.35) and colour coding (M = 5.23; not distributed normally). Pilot SIM-#10 provided a neutral rating on these HMI aspects, but since he expressed no specific criticism concerning the visualisation, this feedback may be explained by his reservations concerning the operational necessity of the feature *per se*. Dissenting feedback concerning these questions came from Pilot SIM-#12, which can also be attributed to his general criticism concerning the presentation of take-off and landing clearances.

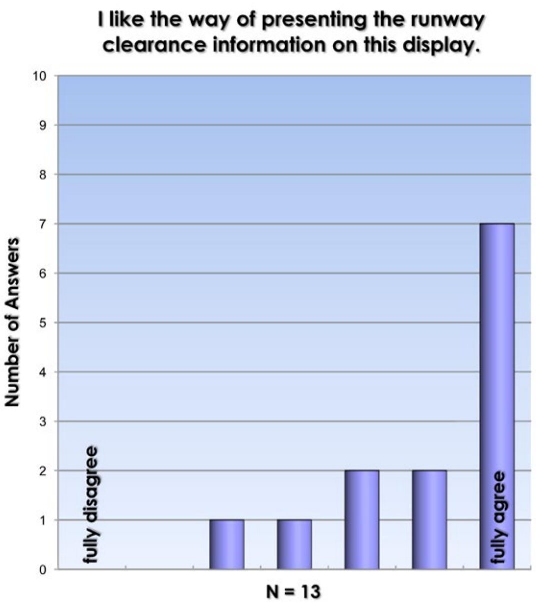

Figure 206: Assessment of symbology for take-off/landing clearances

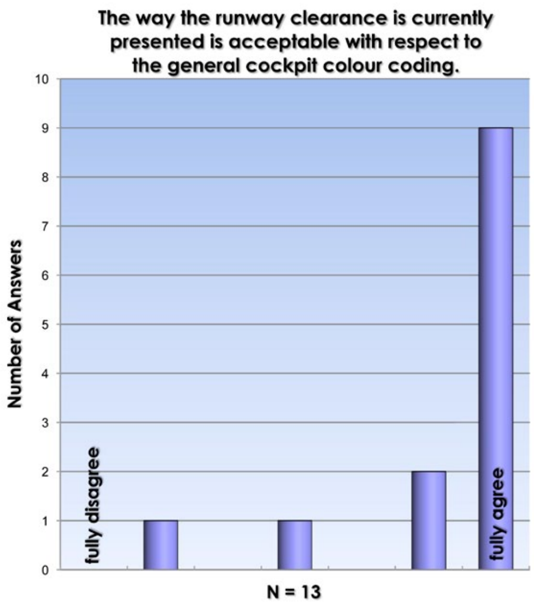

Figure 207: Assessment of the colour coding used for take-off/landing clearances

8.6.5 Preventive Surface Movement Alerting

8.6.5.1 General impact of preventive Runway Incursion alerting

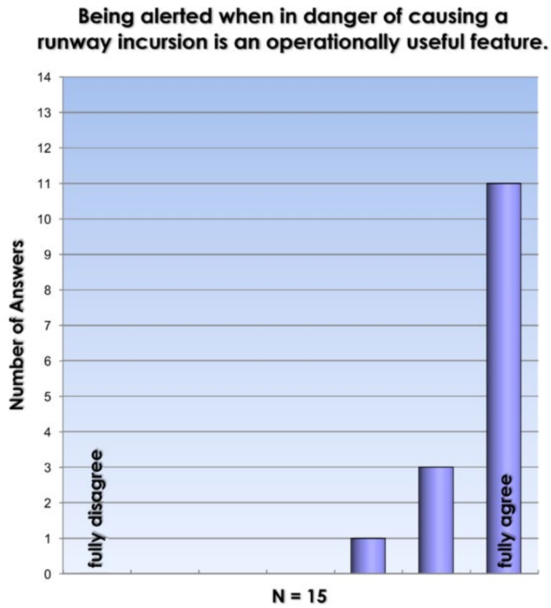

Figure 208: Relevance of preventive Runway Incursion alerting in general

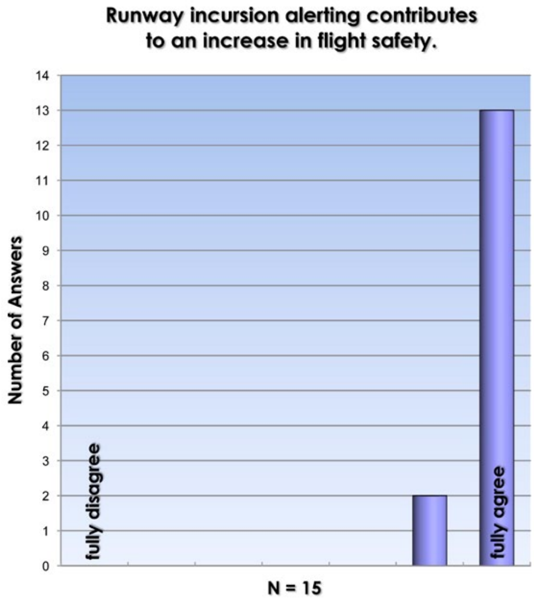

Figure 209: Perceived contribution of Runway Incursion alerting to flight safety

As can be seen from Figure 208, there is little doubt among participants that there is an operational need to alert flight crews when they are in danger of causing Runway Incursion (M = 5.68). Only Pilot SIM-#12 agreed to a lesser degree, because he was afraid that too sensitive alerts might eventually result in numerous unnecessary rejected take-offs in real life, but could not recall any alert that seemed too sensitive during simulator evaluation.

Interestingly, a phenomenon already known from the field trials with the Navigation Test Vehicle (cf. Section 7.6.5), a slightly higher rating for the safety impact of preventive alerts than for their operational relevance, reappears in the results of the simulator evaluation campaign in an almost identical fashion. According to Figure 209, all but two participants strongly agreed that Runway Incursion alerting contributes to an increase in flight safety (M = 5.84).

At a 1% confidence level, the results for both of these question exhibit a significant deviation from a normal distribution, which is not surprising given the accumulation of ratings on the right edge of the spectrum of potential answers.

8.6.5.2 Alerting for take-off from non-FMS or closed runway

The results presented in Figure 210 and Figure 213 on the next page illustrate that there was hardly any dispute among pilots that alerts when operating on a completely closed runway or when taking off from a runway other than the one selected as part of the FMS flight plan are operationally relevant and desirable. Alerting related to closed runways received a slightly higher average rating (M = 5.77) than the warning when taking off from a runway other than the one selected as departure runway in the FMS (M = 5.40). Again, results are not distributed normally (1% confidence level).

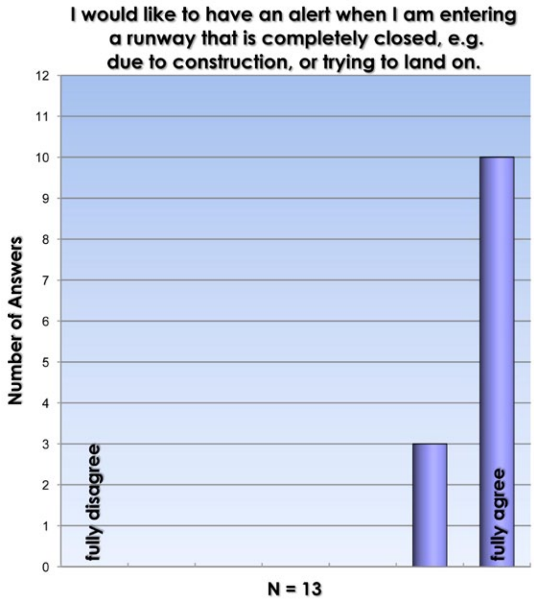

Figure 210: Operational relevance of closed runway alerting

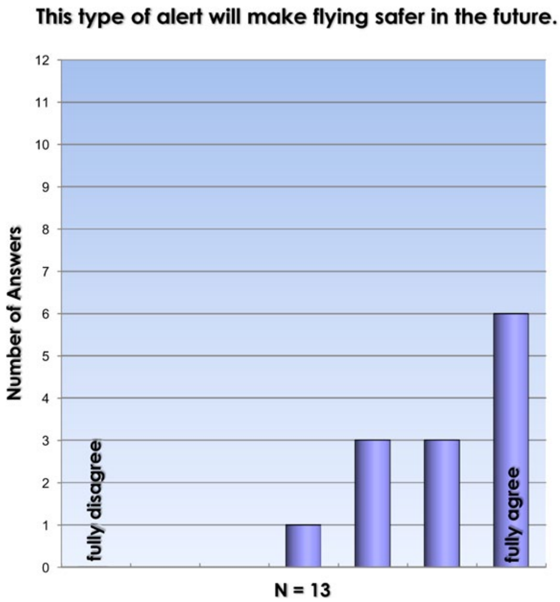

Figure 211: Safety impact of alerting when operating on closed runways

For alerts pertaining to closed runways, the safety impact was rated somewhat lower than the operational relevance (M = 5.08, SD = 1.04), cf. Figure 211, probably because there was consensus among participants that the presentation of closures on the AMM might be sufficient to prevent erroneous operation on closed runways, as shown in Figure 212 (M = 4.77, SD = 1.09). Both during post-run discussions and the debriefing, pilots acknowledged that Level 3 alerts (warnings) as presented during the scenarios were fully justified in these cases. The trigger conditions used were also fully accepted by pilots, as well as the presentation of the alerts. Overall feedback on preventive Surface Movement alerting was very positive, it was accepted with respect to both scope and alert levels. Some pilots requested a slightly different timing for triggering alerts, but there was no clear tendency in any direction.

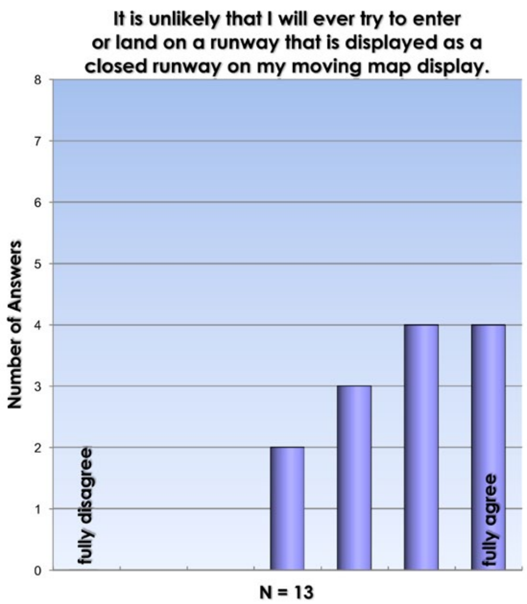

Figure 212: Capability of runway closure presentation to prevent inadvertent take-off

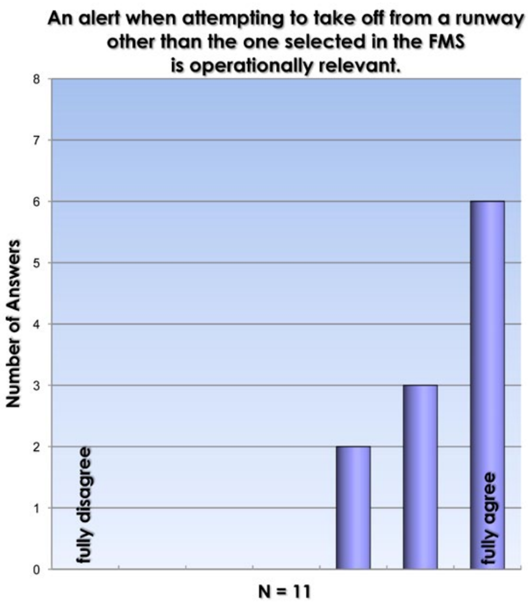

Figure 213: Relevance of alerting when taking off from non-FMS runway

8.6.5.3 Alerts protecting against inadvertent take-off from taxiway

Figure 214: Operational relevance of warning upon taxiway take-off

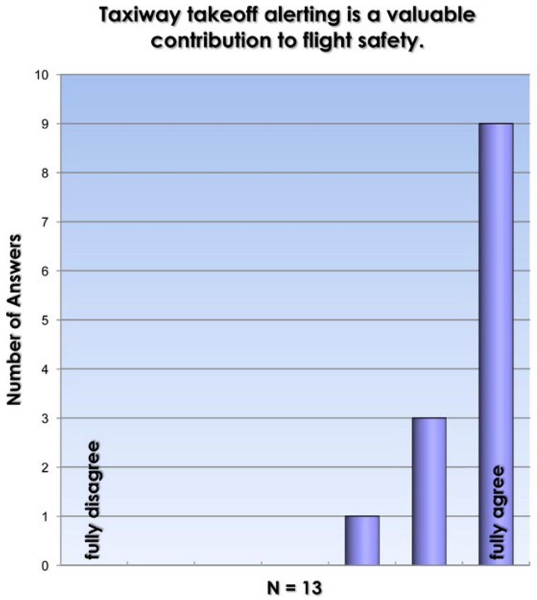

Figure 215: Safety impact of alert when taking off from a taxiway

The results presented in Figure 214 demonstrate that all participants acknowledged the need of a warning protecting flight crews against inadvertent take-off from a taxiway (M = 5.38, SD = 0.87), as well as the contribution of this alert to flight safety, as shown in Figure 215 (M = 5.62). The distribution of results for this latter question exhibits a significant deviation from normality.

Again, to gain insight in the operational need for this alert from a slightly different perspective, pilots were also asked to rate the likelihood of taking off when the AMM shows that ownship is located on a taxiway (results not shown). The distribution of feedback bears a stunning resemblance with the results gathered on the same question during the campaign with the Navigation Test Vehicle, see Figure 137 in Section 7.6.5. A majority of pilots agrees that they would never commence take-off in this case (M = 4.46, SD = 1.33).
In conclusion, pilot feedback confirms the operational necessity and relevance of an alert when take-off from a taxiway is attempted, although the basic AMM appears to decrease the probability of such occurrences in pilots' perception.

8.6.5.4 Monitoring of taxi route conformance

Figure 216 illustrates that there was some dissent on the need for an advisory when deviating the assigned taxi route (M = 4.46, SD = 1.39), mainly because a corresponding discrepancy is already sufficiently evident from the basic taxi route presentation in pilots' opinion, as can be inferred from the results shown in Figure 217 (M = 5.85), which exhibit a highly significant deviation from a normal distribution (1% confidence level). Besides, several pilots commented that the blinking route was only noticeable when actively looking at the display, and therefore suggested the introduction of an additional aural advisory.

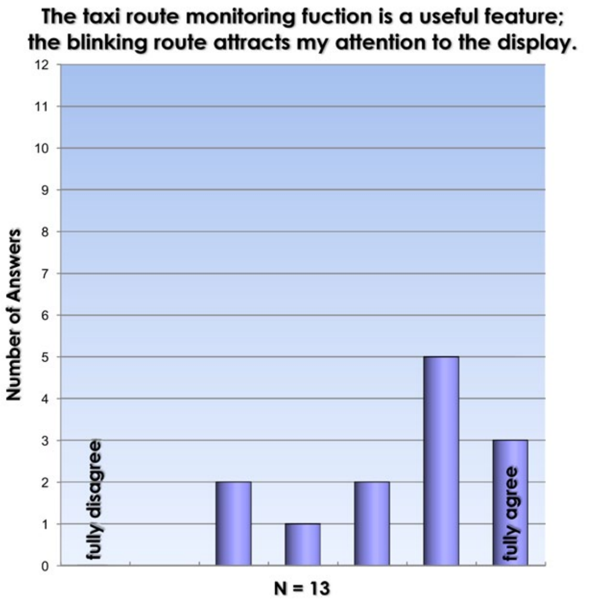

Figure 216: Need for advisory when deviating from the assigned taxi route

Figure 217: Suitability of taxi route presentation to detect deviation

8.6.6 Reactive Surface Movement Alerting

As shown in Figure 218, all pilots except one were of the opinion that alerting for conflicting traffic in the airport environment is an operationally relevant and desirable feature (M = 5.05, SD = 1.43). Several of these pilots remarked that conflict detection should be limited to conflicting traffic in the runway environment. Only Pilot SIM-#13 dissented, because he thought that the detection of conflicting traffic on taxiways was a task almost impossible to achieve without nuisance alerts by an onboard system. In his opinion, the prevention of traffic conflicts on the taxiways should be achieved through the routings assigned by the controller.

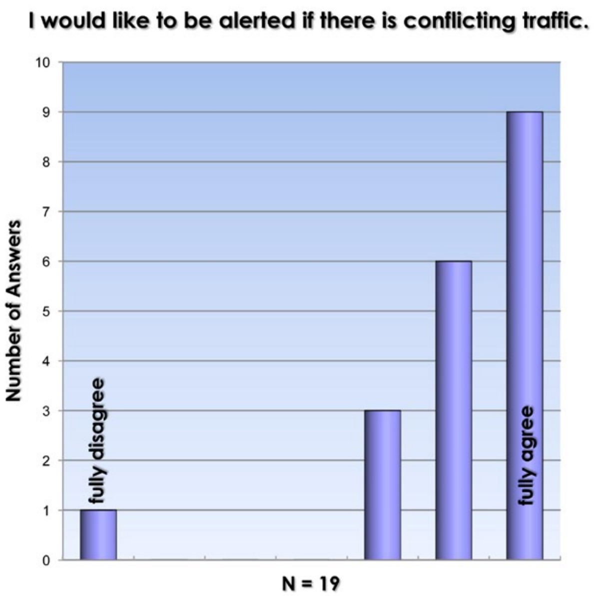

Figure 218: Operational relevance of traffic alerting

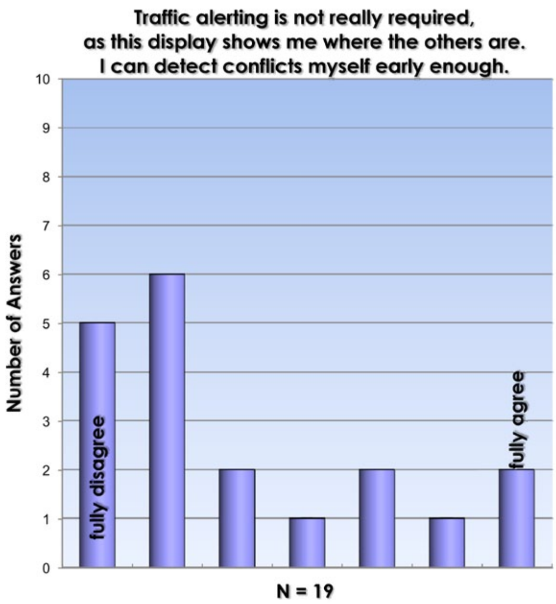

Figure 219: Assessment of intuitive traffic conflict detection (display only)

Generally, pilots had differing opinions on whether traffic alerting should be limited to conflicting traffic in the runway environment (not shown), as evidenced by the exactly neutral average rating (M = 3.00) and a comparatively large standard deviation (SD = 2.26). The current limitation of alerts for conflicting taxiway traffic to caution level was, however, accepted by all pilots.

The results shown in Figure 219 are, by comparison, less unambiguous. Although a majority of 13 pilots rejected the statement that traffic alerting is not really required, which is consistent with the distribution of feedback in the previous figure, there was one neutral rating, and 5 pilots agreed (M = 2.00, SD = 2.05). Nonetheless, the latter is not necessarily inconsistent with the results shown in Figure 218, since it focuses on the aspect of *desirability*, whereas the question in Figure 219 addresses the issue whether traffic alerting is *required* or not. Besides, several pilots commented that traffic alerting was only required for conflicting traffic in the runway environment, while conflicts involving other traffic on the taxiways or the aprons could and should be prevented or resolved using only the display and visual surveillance.

Pilot comments and the discussion both after alerting scenarios and during the debriefing indicate that trigger conditions as well as the timing of the alerts were generally accepted, as for preventive Surface Movement Alerting. The captain associated with Vereinigung Cockpit, who did not participate in the experiment, but was part of the prototyping team, suggested to take into account the timing of take-off and landing clearances for traffic-related alerts. When commencing take-off with other traffic present on the runway, it was therefore suggested to build in a kind of hysteresis by initially limiting the alert level to a caution, to cater for the buffer that is currently included in operations, since take-off and landing clearances are often issued while the previous aircraft is rotating or vacating the runway.
Concerning pilot reaction, it could be observed during the experiment scenarios that a warning in the low speed regime of take-off virtually always induced a rejected take-off. Conversely, in the high speed incursion scenarios, several pilots took the decision to take off in spite of the alert, which they successfully accomplished. This may be taken as initial evidence that the choice not to provide conflict resolution guidance along with the alerts is both acceptable and efficient.

8.6.7 Presentation of Alerts

In general, the aural and visual presentation of alerts was deemed intuitive and acceptable by most of the participants. With respect to the visualisation of alerts, there was exclusively positive feedback, since the corresponding part of the HMI was intuitively understood by pilots and fully consistent with their expectations.

Concerning the selection of wording for aural alerts, the callouts associated with caution level alerts were also unanimously appreciated, whereas the choice made for the warnings require further discussion.
In an effort to keep the number of distinct callouts minimal, a global "**RUNWAY INCURSION**" voice alert was associated with all warnings, irrespective of whether they related to other traffic or not, while the warning for entering a completely closed

runway formed the sole exception. Depending on the display range or mode selected by pilots, the precise reason for the alert would only be deducible from the display in this case. However, while the attempt to keep the number of different alerts low was generally appreciated by pilots, both the ad-hoc reactions of the pilots in the simulator and their comments nevertheless clearly show that the universal "**RUNWAY INCURSION**" callouts for warning alerts are not always sufficient to re-integrate pilots in the loop.
Particularly for the alerts associated with taking off from a runway closed for take-off and landing, but usable as taxiway, and with take-off from a runway other than the one selected in the FMS, nearly all pilots immediately stated that they found the "**RUNWAY INCURSION**" callout somewhat irritating and proposed a different wording. Several participants commented that a flight crew overlooking a runway closure or incorrect FMS setting would probably try to locate conflicting traffic when confronted with this callout, and then commence take-off anyhow if no traffic was detected, rather than re-assessing the situation. Only one pilot (Pilot SIM-#7) stated that a general "**RUNWAY INCURSION**" alert was acceptable, because there should not be too many different warnings and since the crucial point was anyhow to warn the crew that something is going wrong.
Consequently, for an attempted takeoff from a runway other than the one selected in the FMS, the originally conceived "**WRONG RUNWAY**" callout should be reintroduced, all the more as several pilots suggested precisely this wording in their first spontaneous reaction to the alert during the simulator sessions. Likewise, regarding take-off from a closed runway still usable as a taxiway, changing the warning callout to "**CLOSED RUNWAY**" as for the completely closed runway is a potential solution that should be assessed.

According to pilots, however, the main problem with the universal "**RUNWAY INCURSION**" callout is the missing distinction whether a warning relates to conflicting traffic or not, as illustrated by the above example. Therefore, it was proposed that any Runway Incursion alert associated with conflicting runway traffic should generally contain either the keyword "**TRAFFIC**" or "**INTRUDER**" in the callout. Consequently, both the callouts "**RUNWAY TRAFFIC**" and "**TRAFFIC ON APPROACH**" were appreciated as caution alerts in case of traffic hazards, whereas using the default "**RUNWAY INCURSION**" also for traffic-related warnings was rejected.

In conclusion, the presentation of alerts was generally considered acceptable, intuitive and in line with current cockpit standards except for the global "**RUNWAY INCURSION**" callout for warnings, which has to be supplemented by a key word indicating the presence of conflicting runway traffic for reactive Surface Movement Alerting.

8.7 Discussion

8.7.1 Airport Moving Map

The airport moving map in itself was considered a mature function and highly appreciated by pilots, because it increases situational awareness and can thus help to prevent disorientation on the airport surface. Since this is a common precursor of Runway Incursions, most pilots were of the opinion that an introduction of AMM technology would eventually result in a higher level of safety.
Pilots' key criticism regarding the AMM related to the positioning of taxiway labels and particularly the occasionally missing taxiway designations on the AMM. Another point that was criticized was the lack of distinction between CAT I and CAT II/III stop bars, which were represented with identical symbols, a straight amber line. Consequently, all taxiways need to be labelled unambiguously for an operationally useful AMM. Accordingly, both the real-time labelling algorithm and the symbology for the display of stop bars need to be redesigned taking into account the results of the separate PhD thesis dedicated exclusively to labelling that was conducted largely in parallel to this thesis [Psc08].

Although some pilots expressed concerns about potentially increased head-down times and potential distraction from important real world visual cues, the evaluation campaign discussed in this document was not intended to yield any conclusive results on this issue; other experiments by Biella et al. [Bie04] with eye-tracking equipment have shown, however, that the main effect of the AMM in this context is the shift of attentional resources from the conventional paper map to the display. Besides, almost all pilots suggested to introduce panning or slew functionality enabling a detailed preview of the assigned taxi route and for locating gates or parking positions. Apart from minor details to be improved, therefore, the AMM can be regarded as valid onboard means of preventing Runway Incursions.

8.7.2 Traffic Presentation on AMM

The potential of visualising traffic on the AMM was also acknowledged by pilots, but usability and user acceptance depend on the completeness of the traffic picture presented. In fact, the central human factors aspect is the completeness of the traffic surveillance picture presented, i.e. the issue of whether all relevant surrounding traffic must be presented to achieve benefits in terms of situational awareness and safety, or whether a partial representation is already beneficial with appropriated training. Pilots had diverging opinions on this issue.

For both the case of an incomplete traffic surveillance picture and the issue of airport vehicles not covered by the display policy, it seems that the solution of choice might be to suppress the display of traffic except in case of alerts, i.e. to use the traffic surveillance information for the creation of alerts only. The rationale for this is not to present a potentially misleading traffic picture while simultaneously retaining the possibility of presenting clearly identified traffic conflicts based on an incomplete surveillance picture, i.e. not to give up the opportunity to use what is already there to improve flight safety.

Another important issue is symbol scaling. Particularly at large ranges, the display of generic traffic symbols with constant size does not allow pilots to judge the precise location of the aircraft with respect to the holding positions or stop bars. There is, unfortunately, no simple solution to this issue.

8.7.3 Information on Operational Environment

Enhancing the AMM with information on the operational status of runways, such as the presentation of closed runways and other NOTAM, was generally considered as operationally important and relevant by participants. Concerning the presentation of runway closures, all except two pilots confirmed the operational need, resulting in an average rating of 80%. Nevertheless, even the pilots dissenting did not raise any objections against the presentation, which is also reflected by the fact that the chosen symbology received a mean rating of 95%. The distinction of closure levels (82%) and the colour concept (86%) were in general also acknowledged by pilots. It is noteworthy that both symbology and colour were rated substantially better than in the validation campaign with the Navigation Test Vehicle, which indicates that the design has gained maturity. Nevertheless, a few pilots reported that they were somewhat irritated by the use of white crosses to visualise runways or runway segments usable for taxiing only, because painted white crosses are sometimes also used to mark completely closed sections in reality.

Although the MCDU pages for manual back-up entry and modification of runway closure information were generally considered acceptable, most pilots would have preferred direct interaction with the AMM or a more intuitive, graphically oriented interface, operated by a Cursor Control Device (CCD) in both cases.

Regarding the highlighting of the FMS-selected take-off or landing runway on the AMM, both the operational relevance (95%) and the particular HMI design choice made (78%) were confirmed by the pilots. The same applies to the visualisation of the active runway (93%). Due to concerns regarding conspicuity, the HMI solution itself received a slightly lower average rating of 80%. In conclusion, these results confirm both the necessity and scope of presenting information on the operational environment on the AMM as well as the particular implementation chosen.

8.7.4 ATC Instructions and Clearances

Likewise, the visualisation of ATC instructions and clearances on the AMM was received very well by pilots. A presentation of the assigned taxi route is a feature which pilots unanimously desire. With an average rating of 98%, it is the SMAAS element with the highest level of appraisal in this evaluation campaign. The representation chosen also exclusively received very positive feedback (96%). However, there is a clear need to investigate potential effects of cognitive tunnelling in future experiments, since several pilots commented that they sometimes just blindly followed the presented route and did not double-check and keep track of navigation as usual.

Due to concerns about the party line effect and the timeliness of CPDLC, the level of agreement with respect to the visualisation take-off and landing clearances is slightly lower than for taxi instructions, but may still be considered highly relevant from an

operational perspective with an average rating of 81%. The HMI realisation was appreciated as well in terms of symbology (83%) and colour (87%).
A further noteworthy evaluation result is pilots' immediate acceptance and appreciation of using data link and conventional R/T in parallel, particularly in the domain of runway-related ATC instructions and clearances. There seems substantial reluctance to give up the party line effect with respect to runway operations.

8.7.5 Surface Movement Alerting

The preventive Runway Incursion alerting functions were accepted with respect to both scope and alert level. Particularly when pilots are at risk of causing a Runway Incursion, the presented caution and warning alerts were considered as operationally highly desirable by all participants, resulting in a mean rating of 95%, while the perceived contribution to safety was rated even slightly higher on average (97%). Although the visualisation of the assigned taxi route and runway-related clearances as well as the airport moving map itself drastically reduce the risk of an inadvertent runway entry in pilots' perception, this does not eliminate the need for alerting, which is also reflected in feedback on the alerts intended to prevent impending infringement of completely closed runways. With a mean rating of 96% on operational desirability, these received an even higher level of agreement than Runway Incursion alerting in general, whereas the impact on flight safety was considered substantially lower (85%) in this case. Likewise, the warnings when attempting to take off from a runway not selected in the FMS or a taxiway were also considered highly useful by participants, and incidentally achieved the same average rating of 90%. In conclusion, the simulator experiment reconfirmed that preventive Surface Movement Alerting is perceived as capable of mitigating the risk of ownship Runway Incursions.
Pilot feedback clearly indicates that alerts when encountering conflicting traffic in the aerodrome environment are considered as operationally highly relevant; the mean rating of 84% can be attributed to concerns regarding potential nuisance alerts outside the runways, although participants' opinions as to whether alerting should be limited to conflicting traffic in the runway environment diverge. Nevertheless, a majority of pilots disagrees that they could detect traffic conflicts themselves based on the visualisation of traffic only.
The alerting HMI was deemed intuitive and acceptable by most of the participants. Nonetheless, the reactions of the pilots clearly show that the general "RUNWAY INCURSION" callout in case of a warning level alert requires additional clarification regarding the event causing the alert to re-integrate pilots in the loop and to induce the desired pilot reaction.

8.7.6 Summary

In conclusion, the airport moving map has been proven a suitable basis for conveying information – by means of additional symbology – on both the operational status and configuration of the aerodrome, as well as ATC instructions and clearances. Furthermore, the presented alerting concept was appreciated by all pilots in terms of scope and implementation; only the callouts associated with warning alerts require refinement.

8.8 Comparison of Results from the Two Validation Campaigns

The evaluation of SMAAS consistently yielded positive pilot feedback concerning both operational relevance of the presented functionality and the particular implementation chosen in both the field trials with the Navigation Test Vehicle as well as during the experiments using the Institute's Research Flight Simulator. This section compares questionnaire results for both validation campaigns and attempts to elucidate potentially significant differences and discusses the possibly underlying reasons. Since questionnaire feedback in both campaigns sometimes exhibited a highly significant deviation from a normal distribution, a conservative approach was taken, and the comparison of the results of field and simulator trials was conducted using the Mann-Whitney U-Test as distribution-free, non-parametric method [Bor05].

With respect to the basic airport moving map, the corresponding comparison yields that both the overall operational support provided and design aspects were consistently rated significantly better during the field trials with the Navigation Test Vehicle. However, this should not necessarily be taken as evidence that the design of the prototypic A380 OANS used in these trials is substantially better than that of TUD's AMM, all the more as both designs share many similarities. In view of pilots' comments, the main reason for the difference is most likely to be found in the issues with taxiway identifiers and the missing panning function for the prototypic AMM used during the simulator campaign. Besides, potential inter-individual aspects due to the different participants in both experiments cannot be excluded with certainty, either.

Conversely, there is no statistically significant difference in the perceived additional support provided by the presentation of the surrounding traffic in relation to the AMM. The same applies to pilots' trust in the displayed traffic, although the level of confidence in what is presented was on average lower during the field trials. The observed unreliability of the real ADS-B data used during the sessions, as described previously, is the most probable explanation.
However, the traffic symbology used during the simulator trials, as described in Section 5.2.2, received a significantly better rating than the alternative set used during the field tests. Again, the interpretation of these results appears comparatively easy, because the 0° default heading used for this exclusively directional symbology confused and misled the participating pilots, as discussed in Section 7.6.2.

Concerning the Operational Awareness, Clearance Awareness functions and alerting, there are no significant differences between both campaigns. Nevertheless, there were some minor differences. Compared to the field trials, the necessity of highlighting the FMS-selected runway on the AMM was rated slightly higher during the simulator campaign, whereas symbology and colour received somewhat lower appraisal. It is noteworthy that in both experiments, the colour coding consistently achieved slightly better ratings than the symbology itself.
Nonetheless, the absence of significant differences is an important result, because this provides clear evidence that any AMM can be extended by the proposed SMAAS features, and that the associated HMI design is sufficiently generic and independent of a particular AMM basis.

9 Conclusion and Outlook

9.1 Conclusion

Runway Incursions have resulted in numerous fatal accidents within the last three decades, among them the Tenerife disaster with 583 fatalities [ICA80], which is still the worst airplane accident in history. There is consensus in the world of aviation that Runway Incursions constitute a substantial threat to flight safety, and a growing or stagnating number of incidents clearly indicates that current measures to get the problem of Runway Incursions under control are insufficient, cf. [NTS07].

In an analysis of 40 selected incidents and accidents, it could be shown that from a flight crew perspective, all Runway Incursions can be attributed to at least one of the following five core causal factors: disorientation, undetected traffic conflicts, insufficient airport information, communication deficits, and errors by ATC. Besides, it was found that current flight deck instrumentation does not provide pilots with adequate support in any of these domains.

Ground-based measures to prevent Runway Incursions, e.g. enhanced airport markings, typically lack either robustness against weather influences, such as rain and snow, or worldwide applicability. By contrast, commercially available onboard solutions such as the airport moving map or RAAS only address individual aspects of the problem of Runway Incursions. A holistic onboard approach is still missing, although all the technologies required as cornerstones of a corresponding solution are either already available or can be expected to enter service in the near future. Since an onboard solution has numerous advantages over ground-based measures, among others a consistent level of flight crew support throughout the world, it was decided to pursue an onboard solution in this thesis, while bearing in mind the required interfaces with installations on the ground.

Subsequently, this thesis developed the concept for a surveillance-type onboard Surface Movement Awareness and Alerting System (SMAAS), which is intended to address the deficiencies in current flight deck instrumentation by supplying pilots with the operationally necessary information to mitigate the risk of Runway Incursions at different levels, ranging from the mere presentation of information to warning level alerts. Based on an airport moving map addressing the issue of disorientation by improved positional awareness, SMAAS is capable of visualising the surrounding traffic, pertinent short-term or temporary information on aerodrome operational status, as well as ATC instructions and clearances. These three additional layers of information are envisaged to increase flight crew situational awareness, thus enabling pilots to detect potential traffic conflicts proactively and to access e.g. NOTAM or ATIS information in an intuitive, integrated fashion. Besides, the visualisation of ATC instructions and clearances based on a CPDLC data link will make these continuously accessible to pilots, while simultaneously reflecting controller intentions in an unambiguous fashion, which is believed to resolve most current communication issues.
In case a mere presentation of this information is not sufficient to eliminate hazardous situations, various advisories as well as caution and warning alerts are provided.

In particular, potentially conflicting traffic in the runway environment is detected based on an analysis of the compatibility with the manoeuvre intended by ownship. This does not only provide protection against Runway Incursions caused by other traffic or controller error, but also offers protection against potentially inadvertent runway entry even when runway-related ATC instructions and clearances are not available in machine-readable form via CPDLC.

To validate SMAAS both in a real environment and a representative operational context, two evaluation campaigns were conducted. The evaluation results obtained for the Surface Movement Awareness and Alerting System (SMAAS) both in field trials and in the simulator clearly demonstrate that the proposed onboard surveillance system has the potential to prevent Runway Incursions.
Virtually all pilots were very positive about the overall SMAAS concept, which was in line with their expectations concerning an onboard surveillance system. Apart from minor points to be improved, the basic airport moving map was highly appreciated and deemed mature by all participants in both experiments. Most pilots could recall a recent operational situation in which an airport moving map would have supported them far better than current paper charts.

According to pilots, the usefulness of the traffic display is also very high, but at the same time strongly coupled to the percentage of cooperative traffic in the airport environment. Several pilots had concerns about a partial representation of the surrounding traffic in case the traffic surveillance picture obtained via ADS-B, TIS-B or other means is incomplete. Concerning the scope of the traffic presentation, an indiscriminate visualisation of all airport vehicles is clearly not desired by participants. Only vehicles operating on taxiways and runways should always be shown, whereas others could be displayed only when causing a conflict and a corresponding alert.

Likewise, the display of the assigned taxi instructions was unanimously praised as a highly useful feature, and an introduction of this feature can be recommended without prejudice. By contrast, due to the associated loss of the so-called 'party line effect', using CPDLC as sole means for runway-related clearances was considered unacceptable by most of the participants. Conversely, the simultaneous use of CPLDC and voice, which violates current ICAO regulations, cf. [ICA01a], found a surprisingly high acceptance among participants, probably because there is already similar redundancy in runway-related ATC instructions at airports equipped with stop bars. Accordingly, most pilots were in favour of presenting take-off and landing clearances on the airport moving map, and acknowledged the proposed HMI.

Concerning the presentation of information on the aerodrome's operational configuration typically contained in ATIS broadcasts and pertinent short-term or temporary limitations conveyed via NOTAM, pilots generally also provided very affirmative feedback on both operational relevance and the particular HMI design. With respect to the presentation of active runways and the FMS-selected runway, several participants expressed slight concerns regarding the conspicuity of the chosen visualisation. Consequently, results obtained during both field test and the simulator trials suggest that a presentation of the FMS-selected runway would make a valuable addition to

the basic AMM. Since all data required to support this feature are available aboard the aircraft, it could be realised as a mere software upgrade on those transport category or business aircraft already capable of displaying an AMM. Its near-term introduction into existing AMM products is therefore strongly recommended.
Furthermore, the need to present information on closed runways could also be established, since this feature received very positive ratings in terms of operational relevance and safety impact. In the domain of symbology, both the representation chosen and the distinction of closure levels can be regarded as validated, all the more since distinguishing completely closed runways or runway segments from those still usable for taxi operations in the simulator campaign resulted in a marked increase in pilot assent on symbology and colours, compared to the field trials. It should be noted, though, that the operational benefit gained from a corresponding presentation strongly depends on the currency and integrity of the underlying NOTAM data.
Some special cases, such as temporary RWY length restrictions, need to be evaluated by future studies. Besides, while the MCDU pages for manual back-up entry and modification of runway closure information were generally considered acceptable, most pilots would have preferred direct interaction with the AMM using a Cursor Control Device (CCD), or alternatively a more intuitive, graphically oriented interface typically found on multi-functional displays or an Electronic Flight Back (EFB).

Overall pilot feedback on Surface Movement Alerting leaves hardly any doubts concerning necessity and desirability from an operational perspective. Scope, the distinction between advisories, caution or warning alerts and the definition of the trigger conditions for the preventive alerts addressing the hazard of ownship actively causing a Runway Incursion were confirmed by pilots, although some saw the need for limited fine-tuning with respect to the timing of the alerts. Nevertheless, there were no complaints about nuisance alerts.
The same applies to the possibility to alert flight crews of Runway Incursions caused by other aircraft and vehicles or controller errors, both of which manifest themselves in the form of conflicting runway traffic. Again both trigger conditions and timing of the alerts were generally accepted, and the choice not to provide conflict resolution guidance along with the alerts seems valid. Although the HMI and the overall cockpit integration were liked, the choice of aural alert messages was criticised by most pilots, who wanted a greater diversification of Runway Incursion aural warnings, containing more information as to the reason for the alert. In particular, pilots desire a different callout for all warnings when conflicting traffic is involved.

In conclusion, an onboard surveillance system such as the prototypic SMAAS devised in the frame of this thesis emerges as the solution of choice to mitigate the risk of Runway Incursions by providing pilots with operational information absent or inaccessible on current flight decks, supplemented by alerting in case of potentially hazardous situations. In this context, the fact that the evaluation results on the SMAAS concept are consistent for both evaluation campaigns although the assessment took place with two distinct AMM applications <u>and</u> in two very different environments deserves particular appraisal. It demonstrates the independence of SMAAS concerning the particular AMM implementation chosen, and may furthermore serve as evidence that the SMAAS concept is valid irrespective of a particular HMI design.

9.2 Potential Impact on Products

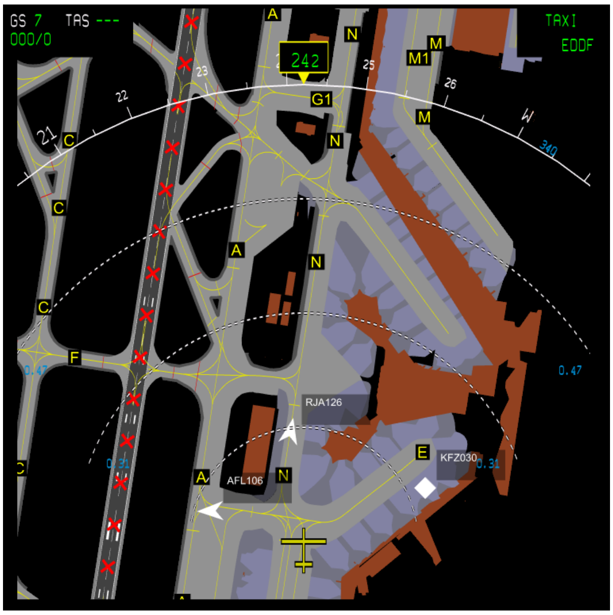

Figure 220: SMAAS Prototype (2007) [Ver07]

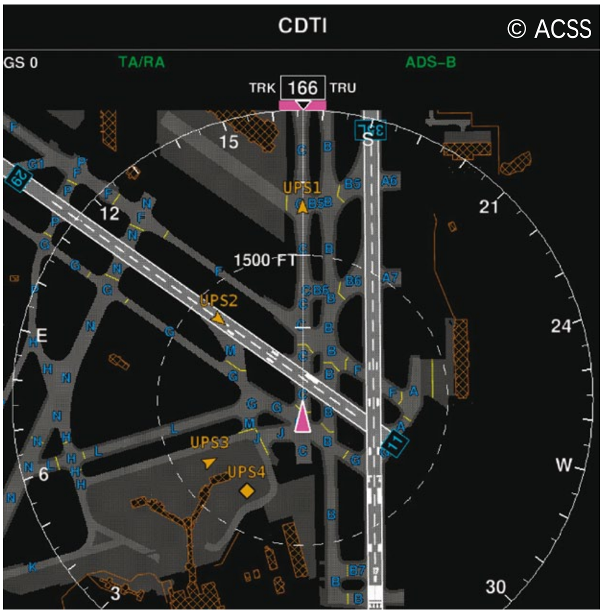

Figure 221: SafeRoute (2008)

As mentioned already in Section 3.1.3, the Human-Machine Interface (HMI) of SafeRoute has evolved considerably from the initial design presented in Figure 240 to the current product shown in Figure 221. There is a remarkable resemblance between the current SafeRoute HMI and an intermediate version of the SMAAS HMI design that was presented in several publications in 2006 and 2007, cf. [Ver06, Ver06a, Ver07]. Figure 220 shows a SMAAS screenshot taken from a paper presented at the International Symposium on Enhanced Solutions for Aircraft and Vehicle Surveillance (ESAVS 2007) organised by German Institute of Navigation (DGON), cf. [Ver07].
When comparing Figure 220 and Figure 221, the most striking resemblance is the use of the TCAS proximate traffic symbol in conjunction with an identification label for traffic that is apparently (in the case of UPS4 parked at the gate in Figure 221) not supplying a valid heading via ADS-B. Additionally, the following further similarities can be observed:

- a clear distinction of apron taxiways and other apron areas,
- the colour chosen for the buildings,
- the visualisation of touchdown zone markings and painted runway identifiers on the airport moving map for a comparable range setting, and
- a darkened representation of taxiway shoulders in relation to taxiway pavements.

Furthermore, the runway labels used in Figure 221 are virtually identical to those used by SMAAS, except for the blue colour. None of these features is present in the original SafeRoute design, cf. Figure 240. It is left to the reader to judge whether these similarities are coincidence, or whether the present SafeRoute HMI was partially inspired by SMAAS. In either case, since SafeRoute is a certified product, the resemblance of HMI design features may be taken as further evidence for the validity of the SMAAS design presented in this thesis.

9.3 Outlook and Next Steps

With respect to the market perspective of a SMAAS product, it must be noted that the economic and operational success of onboard surveillance systems such as ACAS and TAWS is not based on the cost savings they deliver to airlines, but rather on the fact that aviation legislation has made equipage with these systems mandatory. This is an important aspect to consider for any SMAAS-like product. There are of course factors that make systems like RAAS and EFB-based AMMs marketable; safety-minded airlines are likely to buy such tools, particularly if they are packaged, as in the case of SafeRoute, with other functionality that creates operational benefits, such as an airborne merging application.

SMAAS itself is also modular and could be introduced in increments. Furthermore, while the full SMAAS concept requires an airport moving map, a large part of the alerting logic could be implemented as a purely callout-based system in current generation airliners to avoid costly upgrades to the cockpit display system avionics. As an example, an extension of the existing take-off configuration warning system to the external unsafe conditions discussed in this thesis might be a suitable option instead of an additional surveillance system like SMAAS, provided that dedicated callouts can be made available. First of all, the alerting concept developed for the prevention of an inadvertent take-off from a runway other than the FMS-selected one or a taxiway can be implemented in any GPS-equipped aircraft as a largely software-based add-on, and would certainly even in this basic configuration have prevented the Taipei and Lexington accidents as well as the taxiway take-off incidents at Anchorage. This functionality would then only require a reduced set of AMDB data.
Likewise, provided that a complete AMDB and traffic data are available to the SMAAS logic, these sources could be used to generated aural alerts for conflicting traffic in the runway environment even without an airport moving map. Certainly, in Munich incident and the Paris accident, aural alerts of conflicting traffic might have prevented the crews involved from entering the runway. It must be pointed out, however, that these solutions would only provide last resort conflict alerting, but not enhanced situation awareness.

Due to the need to limit experiment sessions to one day, only a limited part of the SMAAS features described in this thesis could be fully evaluated. Particularly with respect to the Operational Awareness Functionality, further assessments are necessary to validate the more advanced concepts described, in particular the proposed notification concepts. Besides, constraints concerning the simulation environment prevented the evaluation of a realistic interaction with CPDLC clearances, which is nevertheless highly relevant from a usability perspective.
Future work will also have to address the fine-tuning of alerting algorithms and callouts. This necessitates trials with real ADS-B data or fused traffic data representative of current traffic computer output. In this context, it might be worthwhile to develop and assess intelligent de-cluttering algorithms for traffic visualisation at airports as well, and to evaluate the concepts for vehicle traffic display set forth in this thesis. Likewise, several aspects of cockpit integration, particularly concerning the flight warning system and the ECAM/EICAS or equivalent functions, require a detailed

assessment that was beyond the scope of the initial evaluation described in this thesis. The same applies to a coupling of SMAAS to other systems providing support in the aerodrome environment, such as the Brake-to-Vacate function available on Airbus aircraft.

Last but not least, coordination between SMAAS-equipped aircraft and interoperability with similar onboard systems aboard other aircraft should be studied, since this might pave the way towards conflict resolution guidance: as with TCAS, conflict avoidance manoeuvres could be coordinated, which might be realised by an extension of existing TCAS coordination messages, by utilizing spare fields in existing Extended Squitter messages, or by additional Extended Squitter messages. At non-towered airports or in areas with insufficient ATC coverage, equipped aircraft could additionally form a cooperative network, exchanging safety-relevant and operational information via data link and VHF Unicom procedures. This way, taxi routes or departure sequences might be exchanged or negotiated. Today, this exchange between aircraft is limited to radio telephony. Additionally, as for TCAS, where down-linking of resolution advisories is presently studied [Eur06a], and a corresponding flag in the ADS-B Aircraft Operational Status Message is foreseen [RTC03], alert information could be down-linked to the ground, which might be employed as part of a system to alert controllers of potential Runway Incursion hazards.

Appendix I: Detailed Accident Analysis

I-1 Worst Accident in Civil Aviation: Tenerife, March 27th, 1977

During take-off from RWY 30 at Tenerife's Los Rodeos Airport in dense fog around 17:06 h (UTC) on March 27th, 1977, a Boeing 747-200 (PH-BUF) operated by KLM as Flight 4805 from Amsterdam to Las Palmas, Gran Canaria, collided with a Boeing 747-100 (N736PA) backtracking the same runway, operated by PanAm as Flight PAA 1736 from Los Angeles via New York to the same destination. Both aircraft were destroyed by the impact forces and a subsequent fire. All 248 persons aboard the KLM aircraft were killed, and only 70 of the 396 people onboard the PanAm aircraft, among them 7 crew members, were saved. However, nine of the surviving passengers later succumbed to their injuries, raising the overall death toll to 583 fatalities.

I-1.1 Sequence of events

This worst accident in civil aviation to date was preceded by a terrorist attack and a resulting mass diversion of aircraft. While flights KLM 4805 and PAA 1736 were en route to their original destination, Las Palmas, a bomb exploded in the terminal building of this airport at 12:30. As a result, the passenger terminal was evacuated, and because there was a warning of a potential second bomb, the airport was closed. Like most other traffic bound for Las Palmas, KLM 4805 diverted to Los Rodeos Airport, where it arrived at 13:38 (UTC). PAA 1736 landed at Los Rodeos, its alternate airport, for the same reason at 14:15. The KLM passengers disembarked their aircraft approximately 20 minutes after landing, and were ferried to the terminal, while the PanAm flight's passengers remained on board all the time.

Due to the large number of flights diverted to Tenerife, the airport was congested, and the two Boeing 747s had to be parked on a taxiway leading to RWY 12 with three other airplanes. Once Las Palmas Airport had been re-opened around 15:00, the flight crew of PAA 1736 prepared to proceed to their original destination, but when requesting permission to start up the engines, the tower told them that the direct entry to the runway might be blocked by the KLM Boeing 747, and that taxiing to the runway via an alternative route was also impossible due to aircraft congestion on the main apron, since Los Rodeos had never been designed for the amount of traffic it was forced to handle that day. The PanAm first officer and flight engineer therefore left the aircraft and determined there was indeed insufficient clearance to pass by. Consequently, the PanAm flight was forced to wait until the KLM aircraft had left, while there was apparently enough room for the three other aircraft parked on the taxiway, a Douglas DC-8, a Boeing 727 and a Boeing 737, to bypass the KLM Boeing.

When the KLM passengers (except one) had re-boarded, the aircraft was refuelled with 55,500 l while passengers remained on board, which took approximately 30 minutes. Eventually, KLM 4805 called the tower at 16:56 requesting permission to taxi, and upon authorisation, at 16:58 requested to back-track on RWY 12 for take-off on RWY 30. Initially, the controller had planned to have the KLM flight taxi to the holding position for RWY 30 via the main runway, then taking the third taxiway (C-3) to the left (see Figure 222), to follow the parallel taxiway B-7 to the holding position. However, the controller then amended this clearance, permitting KLM 4805 to back-track over the full length of RWY 12 and making a 180° degree turn at the end.

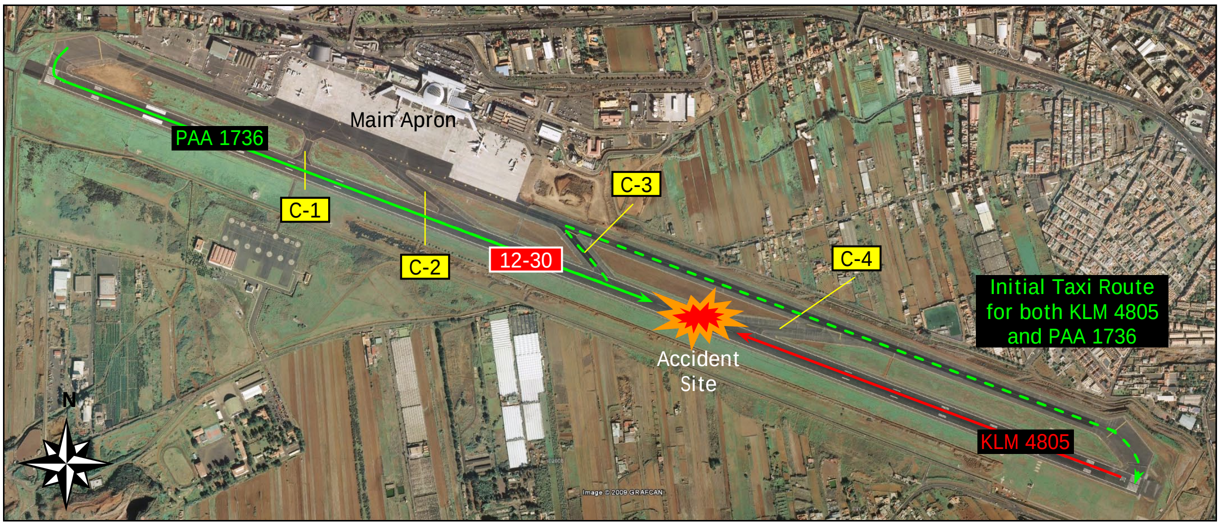

Figure 222: Overview of Tenerife's Los Rodeos Airport

Three minutes later, PanAm 1736 was cleared to follow the KLM aircraft. The PanAm crew was also instructed to leave the runway at the third taxiway and to report upon leaving the runway.

KLM 4805 had, in the meantime, reached take-off position around 17:05:27, after completing a 180° degree turn at the end of the runway, and the first officer finalised the take-off checklist only seconds later, at 17:05:36.

The flight crew reported ready for take-off at 17:05:44 and was given instructions for a Papa beacon departure, "KLM eight seven zero five [sic!] - uh - you are ***cleared*** to the Papa Beacon, climb to and maintain flight level nine zero ... right turn after ***take-off*** proceed with heading zero four zero until intercepting the three two five radial from Las Palmas VOR." The KLM 4805 first officer read back these instructions and added, "We are now at take-off", while the captain commenced the take-off roll.

Tenerife tower, aware that Pan Am 1736 was still taxiing down the runway replied, "OK ...... Stand by for take-off, I will call you." Unfortunately, the part of the message following the "OK…" after a pause of approximately two seconds coincided with the PanAm crew's transmission, "No ... uh we're still taxiing down the runway, the Clipper 1736". These communications caused a shrill noise in the KLM cockpit for approximately 3.7 seconds, rendering both transmissions unintelligible.

Tenerife tower instructed PAA 1736 to report when they were clear of the runway, whereupon the PanAm crew replied: "OK, will report when we're clear". This transmission caused some concerns with the KLM flight engineer, who asked his captain: "Is hij er niet af dan?[144]" After he had repeated the question, the captain answered emphatically, "Jawel[145]."

A number of seconds before the impact, the KLM crew saw the PanAm Boeing still taxiing down the runway. In a desperate attempt to climb away, they became airborne after 22 m of tail drag in an excessive rotation. Likewise, to avoid a collision, the PanAm crew immediately turned the aircraft to the left and applied full power. The KLM aircraft was airborne, but the fuselage skidded over the PanAm's aft fuselage, destroying it and shearing off the tail. The KLM aircraft flew on and crashed out of control 150 m further on, sliding another 300 m bursting into flames [ICA80].

[144] Is he not clear then?
[145] The official report translated this as "Oh, yes." By meaning, it is closer to "Of course (he is)."

I-1.2 Analysis

What is particularly noteworthy about this accident is that the critical communications and events that turned KLM 4805 and PAA 1736 from non-routine flights into the world's worst air disaster occurred within less than two minutes, between 17:05:27 and 17:06:50, and concerned the take-off clearance as the virtually last procedural safety barrier. Consequently, a significant part of accident investigation was devoted to the factors making the KLM flight crew, and particularly the captain, believe that the flight was indeed cleared for take-off.

In parallel to the official investigation, the Airline Pilots' Association (ALPA) studied the Human Factors aspects of the accident, and concluded that throughout the events leading to the accident, it was evident that language difficulties, including accent and idiomatic usage, degraded information transfer [ALP78]. Therefore, this section commences with a detailed analysis of the communications and the likely interpretation by the recipients.

Five seconds after the completion of the take-off checklist at 17:05:36, the captain slightly opened the throttle, which was, according to Dutch sources, standard procedure to check the engines [ICA80], but has also been interpreted as an indication that the captain was under pressure to take off [ALP78]. At this point, anyhow, the KLM first officer reminded the captain that they did not have an ATC clearance yet. The captain closed the throttles and replied, "Nee, dat weet ik, vraag maar[146]." The way in which the first officer then reported ready for take-off and asked for the ATC clearance implied, according to common practice at the time, a request for both the take-off and the initial en-route ATC clearances.

However, the controller's response, as cited in the previous section, was intended only as ATC clearance, but the KLM captain interpreted this as take-off clearance and advanced the throttles while the first officer was still reading back the ATC clearance, adding "We are, uh, taking off" or "We are at take-off"[147]. The fact that the ATC clearance contained the word 'take-off' may have reinforced the captains erroneous conclusion that clearance had been given.

Likewise, the controller understood from the first officer's last statement that the KLM flight was holding at the take-off position, but the crucial part of the following transmission by the controller that made it clear that he had only replied to the ATC clearance request and deferred the take-off clearance, his "standby for take-off ... I will call you", coincided with the PAA 1737's transmission that they were still taxiing down the runway, causing the whistling noise in the KLM cockpit. However, since this squeal was only audible in the KLM cockpit, neither the PanAm flight crew nor the controller were aware that their respective messages had not been intelligible to the intended recipient(s). It is important to note that the controller did not ask KLM 4805 for confirmation of his important instruction to stand by for take-off.

[146] No, I know that, go ahead ask.

[147] After several hours of replaying the CVR tapes, investigators were unable to determine the precise statement made by the first officer.

Even worse, with the controller's transmission effectively truncated to "OK", it may have had an affirmative character with respect to the KLM first officer's comment that they were taking off that had never been intended.

Consequently, due to this technical perturbation of radio communication, the crew of KLM 4805 understood neither of these critical messages, and commenced take-off in the absolute conviction that they were cleared for it and that the PanAm Boeing 747 had already vacated the runway. Due to the prevailing fog, they had no chance of visually acquiring the PanAm aircraft until it was too late, cf. [ICA80].

In fact, the KLM captain's emphatic response to the flight engineer's somewhat hesitant question whether the PanAm aircraft was probably not clear of the runway shows how firmly the crew believed the runway to be clear. Unfortunately, the KLM flight engineer's emerging concerns that the runway might not be clear were not substantial enough (yet) for him to call for a rejected take-off.
The KLM flight crew's erroneous perception that the runway was clear may have resulted from a misinterpretation of the PanAm's request to the controller to confirm that he wanted them to take the third exit. According to the ALPA report, the KLM crew most probably concluded from this statement that the PanAm had already arrived at the exit and was asking for final confirmation before initiating the turn-off, whereas the PanAm was actually not sure whether they had just missed the exit.
In fact, the PanAm crew passed the third taxiway on the left (C-3) in poor visibility while concentrating on the ATC clearance being given to the KLM. Given the size of the Boeing 747, the geometry of C-3 in relation to the runway must have made it an unlikely candidate for the assigned exit in the PanAm crew's perception, if the rapidly changing visibility was sufficient for them to visually acquire it at all at the time.

The investigation considered a number of other factors influencing the KLM flight crew's mindset that might have induced them, particularly the captain, to take off.
The official report heavily dwells on the hypothesis that the captain was under pressure to take off because the flight crew was approaching a rigid duty time limit, which was likely to result in a termination of the flight in Las Palmas, with all the unpleasant organisational and economic consequences, if he could not leave Tenerife soon. This hypothesis is mainly based on an earlier discussion in the KLM cockpit on the recently tightened Dutch duty time regulations, which were so complicated that the flight crew themselves were virtually unable to calculate their current duty time. Furthermore, it was no longer possible for flight crews to extend the limit at their own discretion in order to complete a delayed service. As a result, the captain even consulted a company official in Amsterdam on potential duty time implications while on the ground in Tenerife.
This allegedly created stress and anxiety for the Dutch crew, an atmosphere that the investigators felt reflected in the Cockpit Voice Recorder (CVR) tapes in a subtle fashion. Interestingly, it can be inferred from intra-cockpit communication that the PanAm flight crew may also have had the impression that the KLM crew was "anxious", epitomised by the statement of the PanAm first officer referring to the KLM flight, "[…] after he held us up for an hour and a half […] now he's in a rush."

It must be noted, however, that the KLM flight crew adhered to all checklists and procedures, i.e. there were no observable lapses that might serve as additional factual evidence they were in haste. The only indication that the captain was not fully attentive to controller instructions all the time was that he asked twice at which taxiway they would have to turn off the runway, although the ATC instruction had already been amended to a full back-track. But since he might have been busy with checklists, reviewing charts or other operational matters at the time the controller revised the original instruction, this is not necessarily an indication of "absent-mindedness", as the official report claims, cf. [ICA80].

Additionally, the investigation discussed the potential impact of the KLM captain's role and reputation as a head of the KLM Flight Training Department on the events, particularly his function as training captain. The ALPA report claims that there is a natural subtle tension in the cockpit atmosphere whenever upper management captains fly line trips that is not found between regular line crew members [ALP78]. Combined with the KLM captain's role in training and proficiency checks, this implies that the situation might have fostered a larger than usual hesitancy to voice concerns [ICA80]. Along these lines, investigators interpreted the KLM first officer's ambiguous and somewhat hurried statement that they were "at take-off" or "taking of" as an indication that he was surprised by the captain commencing take-off, felt concern that this decision was not correct, and therefore tried to alert everybody on the frequency that they were taking off with his statement [ALP78]. However, the hurriedness might also be an indication that he wanted to finish the read-back as soon as possible to focus his attention on the take-off run as required.

Since the KLM captain was heavily involved in simulator training, and had not performed any airline flights in the 12 weeks prior to the accident, ALPA investigators speculated that the borders between simulator training and airline flights might have become blurry momentarily ("training syndrome"). One of the arguments given by both the ALPA and the official investigation report was that in the simulator, the instructor virtually always also acts as controller, typically issuing the take-off clearance as the take-off checklist is completed, and usually responding affirmatively to all pilot requests, driven by the need to fit the maximum amount of training into the available simulator time. Likewise, training flights are usually much shorter than normal line flights, and usually do not encounter operational delays.

While all of these psycho-social factors may have played an important role in the sequence of events leading to the accident and should not be easily dismissed, they remain somewhat speculative, since unambiguous evidence substantiating the presence of hurriedness or a "training syndrome" is missing. After 9:21 h of duty, fatigue could have played a role as well.

On the ATC side, the unexpectedly large traffic volume caused high workload, and with the main apron crammed by diverted aircraft, controllers were facing significant challenges. Besides, there was some confusion, because the two controllers were operating three frequencies, and clearances were not always given consistently with the function of the associated ATC unit – some aircraft received their start-up clearances on the tower frequency [ALP78]. Additionally, as the Dutch comments on the final report point out, the background noises in the tower transmissions suggest that the controllers were listening to (or watching) a football match, which would have been a significant distraction.

There is some evidence of either high workload and/or distraction in the communication of the controller. When addressing the KLM flight with the ATC clearance, he used an incorrect callsign, “KLM 8705”, but without effect on the effectiveness of communication. However, upon requesting the PanAm crew to report when they had vacated the runway, the controller – for the only time – addressed the PanAm as “Papa Alpha” instead of using the familiar “Clipper” normally used to address PanAm aircraft. While the PanAm crew replied immediately, it is likely that this was a missed opportunity to raise the KLM crew’s attention, which was already focussed on the take-off run, to the no longer expected presence of the PanAm aircraft. In fact, the KLM flight engineer raised his concerns when he overheard the PanAm crew’s response to that controller instruction.

I-1.3 Probable Cause

The official investigation report concludes that the probable cause of the accident was the KLM captain’s decision to take off as soon as he heard the ATC clearance, and the failure to comply with the controller’s instruction to stand by for take-off. In addition, the report claims that the captain should have aborted take-off when the PanAm flight reported they were still on the runway, instead of dismissing the flight engineer’s doubts as to whether the other Boeing 747 had vacated the runway.

The investigation report offers a growing feeling of tension resulting from the potential duty time limitations, the rapidly changing weather situation and the associated prospect of having to terminate the flight as a result of these constraints if not leaving Tenerife very soon as primary explanation for the captain’s behaviour, whereas the fact that two radio transmissions occurred simultaneously is only mentioned as contributory factor. However, this position was disputed by the Dutch authorities, which, as well as the ALPA report, draw a slightly different and more balanced picture from a Human Factors perspective. Essentially, the cause of the accident was a misunderstanding between the flight crew of KLM 4805 and Tenerife tower, due to ambiguities in the ATC phraseology in use at the time of the accident. The misunderstanding was aggravated by the fact that a crucial part of the transmission from Tenerife tower, which might have made the intention of the controller more clear and prevented the misunderstanding, was rendered unintelligible due to a perturbation on the frequency caused by the simultaneous transmission of PAA 1736. There were no serious operational errors involved.

With respect to the refuelling, the investigation found that the captain had probably chosen to refuel in Tenerife to save time in Las Palmas, the KLM Boeing 747 had sufficient fuel for this flight, and could even have returned to Amsterdam without refuelling. In conjunction with the operationally perfectly valid decision to take off at reduced power, this nonetheless raises the obvious question whether, some 50 tons lighter and at full take-off thrust, the KLM Boeing 747 would have succeeded in climbing free of the PanAm aircraft. However, it must be stressed that refuelling and de-rated take-off thrust were not contributing factors, but in retrospect at best missed opportunities to mitigate the outcome.

I-1.4 Flight Deck Instrumentation Aspects & Conclusion

The investigation reports explicitly concede that both flight crews suffered from inadequate visual information due to low visibility. Consequently, the following can be deduced with respect to flight deck instrumentation and situational awareness:

KLM 4805

- The flight crew of KLM 4805 was at all times aware of their position on the aerodrome surface. There was no disorientation involved.
- The flight crew of KLM 4805 was erroneously convinced that the PanAm flight had already vacated the runway, and thus unaware of its true position on the aerodrome. Consequently, a method of presenting the surrounding traffic in relation to the airport layout might have helped the crew to establish and maintain adequate traffic awareness.
- There was a breakdown of communication between the flight crew of KLM 4805 and the controller. While the controller had intended to relay only the ATC clearance, the captain of the KLM aircraft believed that the flight had simultaneously also been cleared for take-off. Unambiguous information on the take-off clearance could have prevented the KLM 747 from taking off.
- In the presence of either better traffic or clearance information, it is unlikely that the KLM flight crew would have started the take-off roll.

PAA 1736

- The flight crew was, due to the limited visibility, not fully aware of their location with respect to the runway exit C-3 and subsequently missed it. A means of indication their position with respect to the airport layout would have been beneficial.
- In parallel, information on the assigned taxi route might have been useful.
- The flight crew of PAA 1736 was concerned, but not positively sure that KLM 4805 was going to take off or had already commenced its take-off run. Information on traffic activities in the runway environment, independent of visibility conditions, could have confirmed their suspicion, leaving more time for an evasive manoeuvre.

As a result of the investigation findings, and in line with ALPA and Dutch recommendations, procedures and phraseology were changed considerably to disambiguate the assignment of clearances. Among the recommendations realised was e.g. that an ATC clearance should never contain the word take-off, and further measures were taken to prevent confusion of ATC and take-off clearances. Today the initial en-route clearance is transmitted to the flight crew before they start taxiing, and the word "cleared" is reserved for take-off and landing authorisation. By contrast, lining up or crossing a runway is instructed using the word "approved". While virtually all procedural issues revealed by the accident investigation have been addressed, the ALPA recommendation to provide a redundant means of conforming take-off clearances at all airports remains to be realised even more than 30 years later.
Last but not least, the ALPA's recommendation to commission research by an appropriate institution to "*determine optimum crew member interaction to minimize the probability of human error*" can be seen as one of the key milestones leading to the development of Crew Resource Management (CRM).

I-2 Disorientation in the Fog I: Madrid, December 7th, 1983

During its take-off run on RWY 01 at Madrid-Barajas Airport (LEMB) on December 7th, 1983, an Iberia Airlines Boeing B-727 (EC-CFJ) bound for Rome collided with an Aviaco DC-9 (EC-CGS) bound for Santander, which had inadvertently entered the runway in dense fog.
As a result of the impact and the rapidly developing subsequent fire, all 37 passengers and 5 crew members of the DC-9 perished. The B-727, which was travelling down the runway approximately at V_1 when the collision occurred, lost its left wing and main gear as a result of the impact, and continued to slide down the runway for another 460 m. The massive fuel spillage resulted in an almost immediate fire, and 50 of the 84 passengers on board and one assistant crew member died. Eight crew members survived [CIA84].

I-2.1 Sequence of events

The DC-9 aircraft which was to carry out Aviaco Flight 134 to Santander was located at Parking 8 in the Northern Area of the airport. The flight was 33 min behind schedule due to the weather conditions (fog) and requested start-up at 08:29:10. In response, start-up was approved and the ATC en-route clearance was given at 08:30:15. At 08:33:20, Aviaco Flight 134 requested taxi instructions and was instructed to proceed to "holding point RWY 01 through outer taxiway and [to] inform when leaving Northern Area and entering the taxiway".

The Aviaco flight crew read back this instruction and confirmed leaving the Northern Area at 08:36:26, upon which ATC instructed the flight "to call entering segment Oscar 5, please".
Some time after this instruction had been confirmed, the controller asked the Aviaco flight crew to confirm their position at 08:39:08, upon which they replied, "Look, we cannot see Oscar 5 indicators on the ground, we are taxiing with… heading zero, with heading zero nineteen, with heading one hundred and ninety, sorry, and apparently, we are entering the segment." The collision occurred immediately after the end of this transmission at 08:39:29.

In parallel, preparations for Iberia Flight 350 to Rome-Fiumicino had been completed. The B-727 was parked at Parking Number 56 at the International Terminal of Madrid-Barajas airport. IB 350 requested start-up at 08:21:36, but due to the delay situation, was not given permission to start the engines until 08:26:20. After taxiing to the holding position of RWY 01 and the transfer to the tower frequency, upon which the flight crew immediately reported ready, IB 350 was cleared for take-off at 08:38:32. Around 08:38:45, the B-727 commenced its take-off roll. 44 s into the take-off roll, immediately after the V_1 callout of the first officer, the aircraft collided with the Aviaco DC-9 [CIA84].

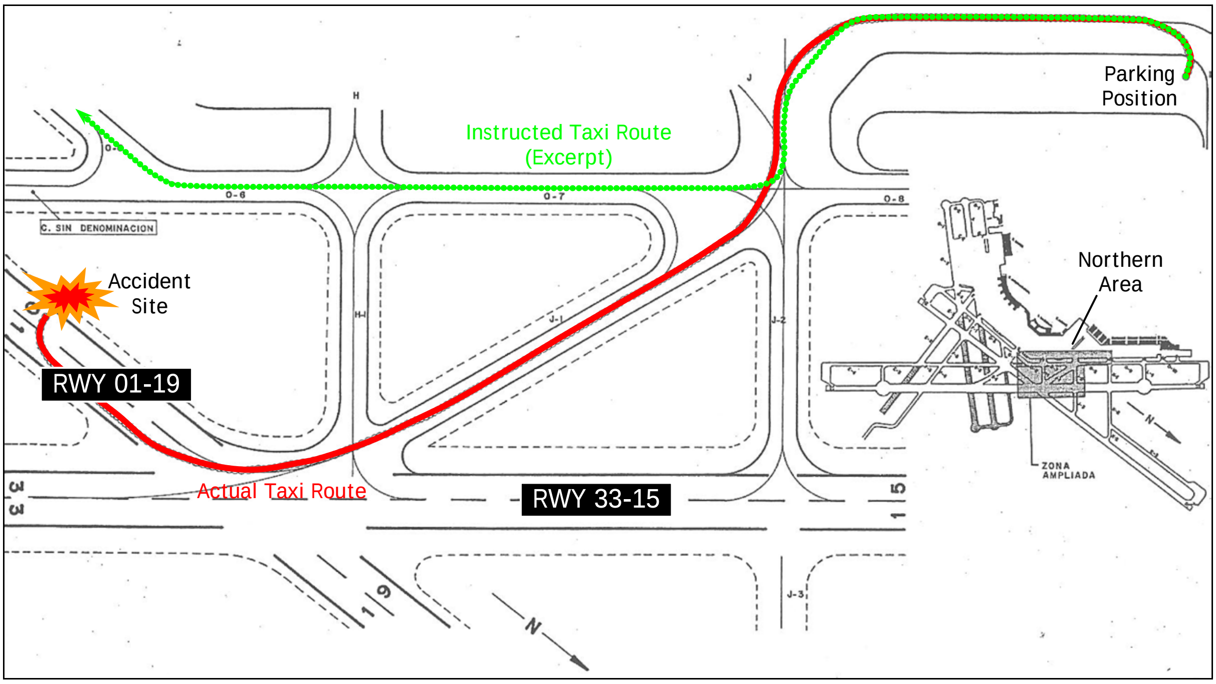

Figure 223: Instructed and actual taxi route of Aviaco Flight 134 (after [CIA84])

I-2.2 Analysis

The reconstruction of the Aviaco DC-9's actual taxi route from the parking position to the location approximately 230 m south of the intersection of RWY 01/19 and RWY 15/33 where the collision occurred was very difficult, since the FDR was badly damaged by fire, limiting the amount of usable data that could be extracted, and because the DC-9 was not fitted with a CVR, which was not compulsory when aircraft was manufactured in 1975.

Consequently, the accident investigation performed extensive tests based on the salvaged FDR content to determine a likely trajectory for the DC-9. After several post-accident ground tests with another DC-9, the actual taxi route of Aviaco Flight 134 could eventually be reconstructed, as presented in Figure 223 (red line). It shows that the flight crew opted for a left turn when leaving Parking 8 and eventually exited the Northern Area via taxiway J, which was perfectly consistent with the somewhat sparse taxi instructions that they had received. Given the fact that both pilots had logged in excess of 10,000 flight hours and that Aviaco routinely operated from this part of the airport, the controller seems to have referred to an – albeit unwritten – "standard" taxi route. Some 37 m prior to reaching the centreline of taxiway Oscar, the flight crew reported that they were leaving the Northern Area at 08:36:26, which indicates that the flight crew were still well aware of their position despite the fog.

However, at the shallow-angle intersection of taxiways O-7, J-1 and J-2, the aircraft did not make a sufficiently strong right turn to enter into O-7, but eventually crossed taxiway Oscar and continued taxiing on J-1.

According to official measurements at 8:30, visibility (determined by direct observation) was 100 m, and the Runway Visual Range (RVR) for RWY 01, measured by a transmissometer, was 300 m. The report concludes, however, that effective visibility could easily have been as low as 20…30 m in the area where the Aviaco DC-9 was taxiing [CIA84].

The investigation later found that the line connecting J and O-7 had not been repainted, and was thus somewhat faint, most likely not providing sufficient contrast to be clearly perceivable when the pavement was wet, as on the day of the accident. Given a visibility of only 20…30 m, it is likely that the flight crew was not able to see the lateral limits of the taxiway, and thus unable to realise that while they followed the only visible taxiway guidance line, they nonetheless ended up on the wrong taxiway.

The actual taxi route in Figure 223 is consistent with the hypothesis that the Aviaco flight crew mistook J-1 for O-7, because they passed taxiway H-1, possibly regarding it as the O-7/H intersection, and then made a right turn onto RWY 01/19, taxiing towards the threshold of RWY 01, which corresponds to the bend in O-6.
That the flight crew had difficulties to see the taxiway edge and any potential signs placed there is consistent with the observation that the captain later taxied the aircraft off the centreline and close to the left edge of RWY01, allegedly to ensure that he did not miss any signs confirming they were indeed on O-6, because the flight crew apparently had not seen any signs after entering J-1, according to their exchange with ATC at 08:39:08.

It seems that it must have dawned on the flight crew that they had inadvertently entered an active runway approximately eight seconds before this ATC call, because the captain initiated a right turn on RWY 01/19, cf. Figure 223. The investigation report speculates that the flight crew might have thought they had entered the runway via the unnamed taxiway, and were now desperately trying to vacate the runway via the area where taxiways G1 and G3 intersect RWY 01/19. Furthermore, at the time of the impact, the DC-9 had a true heading of 274°, which is consistent with this hypothesis. The fact that the flight crew had realised that something was amiss regarding their position would also explain the somewhat erratic and imprecise reply of the first officer to the ATC request at 08:39:08 to confirm position – he needed three attempts to report heading correctly. However, the flight crew failed to communicate any considerations on their actual position and the reason for the manoeuvre the captain had obviously initiated to ATC.

I-2.3 Probable Cause

The undetected incursion of Aviaco Flight 134 onto RWY 01/19 was identified as cause of this accident by the investigation board, and bad visibility is cited as potential reason for the surface navigation error of the Aviaco flight crew.
Furthermore, the board noted that there were no dedicated low-visibility taxi procedures. The investigation board also criticized that the communication between ATC and Aviaco Flight 134 was minimalist, that the flight crew did not reply punctually and that the controller did not request clarification. Besides, the flight crew's decision to take action, i.e. to initiate a turn on the runway, without informing ATC about the considerations leading to this decision, was disapproved by the board [CIA84].

I-2.4 Flight Deck Instrumentation Aspects & Conclusion

AO 134

From the preceding analysis, it is obvious that flight crew disorientation due to limited visibility eventually lead to this Runway Incursion. Disorientation was potentially facilitated by a faded taxiway guidance line on wet pavement at the taxiway junction where the flight crew took a wrong turn. Since the DC-9 was not equipped with a CVR, it is not possible to determine the precise reasons for the disorientation and potential other crew-related factors (distraction, deficiencies in CRM, …) that may have influenced decision making. Likewise, any statements on the impact of potentially unserviceable airport lights would be highly speculative, because the actual status of airport lighting at the time of the accident is unknown.

This accident shows how conventional airport navigation techniques fail under adverse visibility conditions, even if the flight crew is familiar with an airport, which can be assumed for the Aviaco flight crew due to their background and due to the fact that they did not request any clarification of the minimalist taxi instructions they received. It is also noteworthy that the heading discrepancy between J-1 and O-7 was apparently not sufficiently large to catch the flight crew’s attention. On the runway itself, which is parallel to the second part of O-6, no heading discrepancy would be observable.

Irrespective of the previous, an independent source of information on the aircraft’s position with respect to the airport layout could have supported the DC-9’s flight crew in airport navigation and prevented the inadvertent runway entry.
In addition, a presentation of the assigned taxi route might have made the emerging discrepancy between the instructed and the actual taxi route more palpable. Last but not least, information or alerting that the runway they were approaching as a result of their navigation error was used by another aircraft might have beneficial.

IB 350

By contrast, the Iberia flight crew succeeded in taxiing their aircraft to the threshold of RWY01 without incident despite the fog, there was no disorientation involved. Nevertheless, due to the huge local variations in visibility that may occur in fog, it is possible that IB 350 taxied in visibility conditions still allowing them to maintain adequate external visual references to complete the surface navigation task successfully.

However, the Iberia flight crew – like the controller – had no means of determining the presence of the Aviaco DC-9 on the runway. Consequently, a method of presenting the surrounding traffic in relation to the airport layout, potentially supplemented by traffic alerts, might have helped the crew to maintain adequate traffic awareness, and could have given them ample time to reject take-off and to prevent a collision.

I-3 Disorientation in Fog II: Anchorage, December 23rd, 1983

While erroneously attempting to take off from RWY 24R at Anchorage International Airport on December 23rd, 1983, Korean Air Lines Flight 084, a scheduled cargo flight to Los Angeles, collided head-on with Southcentral Air Flight 59, a scheduled commuter flight to Kenai, Alaska, at 14:06 local time in IMC conditions, with fog prevailing. Both aircraft, the Korean Air Lines DC-10 (HL7339) and the Southcentral Air Piper PA-31-350 (N35206), were destroyed, but there were no fatalities [NTS84].

I-3.1 Sequence of events

At 13:39, the pilot of SCA 59, whose flight had been delayed for over an hour due to the weather conditions, requested taxi because the RVR had begun to improve. Given the choice between RWY 6L and 6R, the pilot elected the longer runway, 6L. At 13:44, the pilot of SCA 59 reported that he was holding short of RWY 6L on W-3 (see Figure 224) and ready for departure as soon as the RVR had improved to the required 1,800 ft (550 m). In reply, the local controller promised that he would advise as soon as this condition was fulfilled.

The flight crew of KAL 084 was also given a choice between two runways, RWY 6R or RWY 32, and the captain opted for the latter. At 13:57, KAL 084 was instructed to taxi to RWY 32. Since the ground controller could not observe KAL 084 taxiing due to the fog, he requested the flight to report entering the East-West taxiway, which the flight crew did at 14:01. The ground controller then advised KAL 084 to hold short of RWY 32 and to change to the local control frequency.

At 14:03:36, the captain of KAL 084 reported to the local controller that he was taxiing on the East-West taxiway and ready for departure, and was instructed to line up on RWY 32. Shortly thereafter, at 14:03:39, the local controller confirmed with the SCA 59 pilot that he was holding at W-3. After this communication, the local controller cleared KAL 084 for take-off on RWY 32 at 14:04, which the captain acknowledged. One minute and 28 seconds later, SCA 59 was instructed to line up on RWY 6R by the local controller, who reported that the RVR had risen to 1,800 ft. At 14:06:18, the captain of KAL 084 transmitted that he was starting the take-off roll.

Shortly thereafter, the captain of KAL 084, who had erroneously commenced take-off on RWY 24R, sighted the Piper aircraft lined up on RWY 6L and tried to evade it by rotating and applying left rudder. However, the centre and left main landing gear of the DC-10 hit the Piper, pushing it rearward on the runway and shearing off both of its wings. The DC-10 continued off the departure end of RWY 24R, demolished several approach lights and rushed through a wooded area, down a gully and was destroyed by an immediate fire when it finally came to a rest.

The accident, which resulted in no fatalities, occurred around 14:06:40 during the hours of daylight.

I-3.2 Analysis

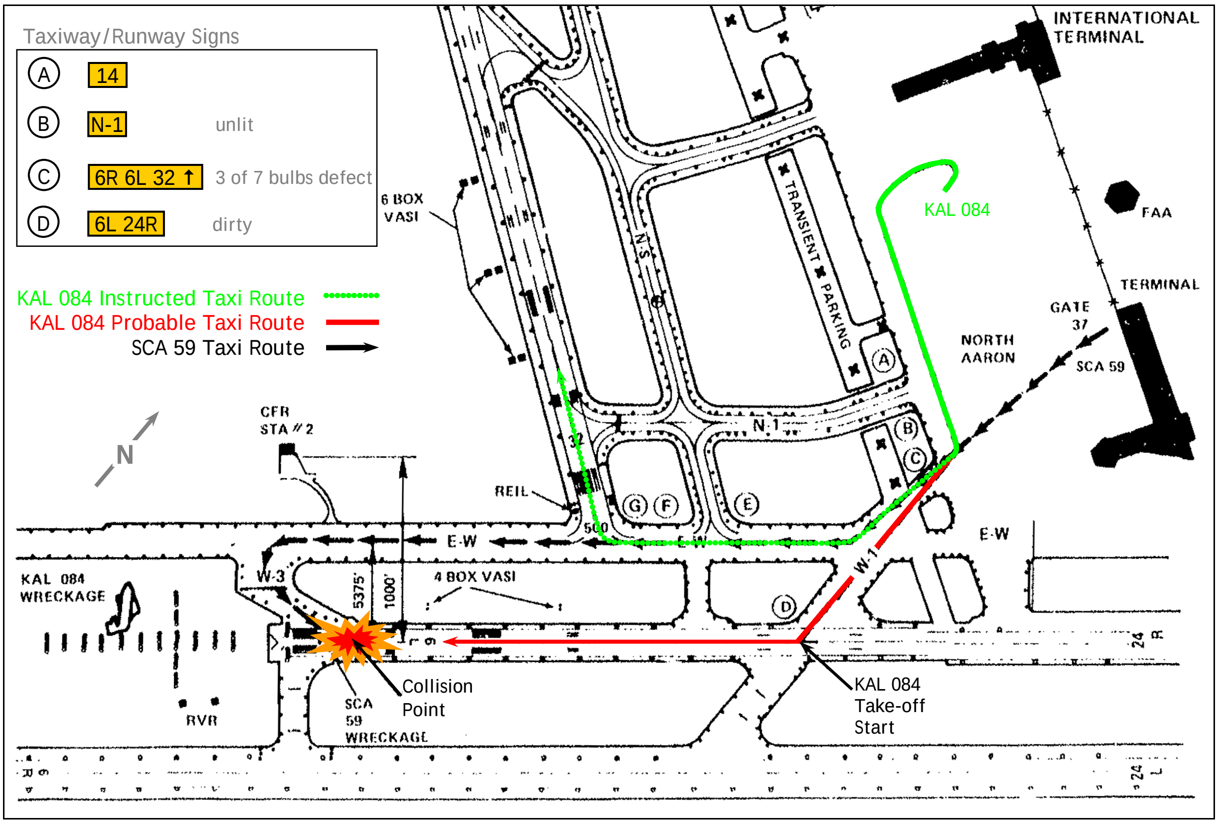

Figure 224: Assigned taxi route and actual track of KAL 084 (after [NTS84])

In a post-accident interview, the pilot of SCA 59 told investigators that due to his familiarity with the airport and the slow taxi speed, he had not experienced any undue difficulties taxiing his aircraft in spite of the fog. Interestingly, however, other aircraft were encountering orientation problems: a Japan Airlines aircraft had erroneously started to enter W-3 while SCA 59 was holding there, mistaking it for W-4, the entrance to RWY 6R, but realised the error in time and turned back.

Since the captain of KAL 084 had logged 73 take-offs and 78 landings at Anchorage International Airport in the 8½ years preceding the accident, he was by no means unfamiliar with it. However, due to the heavy ice fog, he experienced significant difficulties in tracking the taxiway centreline and in seeing the markings. When lining up on what he thought was RWY 32, the captain was unsure whether he was on the correct runway, and looked for identification markings, but could not see any. The first officer, however, felt confident that they were on the correct runway, and after 3 to 4 minutes of discussion, the captain eventually decided to request clearance and to take off.
After the accident, the first officer, who had accomplished 66 take-offs and landings at Anchorage within the previous 3¾ years, stated that he apparently lost his sense of direction in the dense fog and confused the East-West taxiway with the North-South taxiway. Accordingly, the DC-10 passed the intersection of W-1 and the East-West taxiway, with the crew erroneously believing that they were already on the East-West taxiway, while they were in fact on W-1.

The accident investigation revealed that both taxiways W-1, W-2 and N-1 and RWY 6L/24R were covered with a thin layer of snow, ice and frost at the time of the accident, rendering most of the markings unreadable. Additionally, the sign designating RWY 06L/24R ("D" in Figure 224) was found to be dirty, reducing the contrast between its background and lettering. Further deficiencies of the airport signage were that there was neither a sign designating W-1 nor a specific indication for the East-West taxiway. Last but not least, one of the taxiway signs along the taxi route of KAL 084 was unlit, and another sign was only partly lit due to deficient bulbs. Essentially, therefore the KAL 084 flight crew operated without external information to assist them while taxiing.

With outside visual cues thus degraded and given the size of their aircraft, the Safety Board concluded that it was likely that the flight crew could not correctly perceive the difference between the 60° turn they actually made onto W-1 and the 100° turn required to turn onto the East-West taxiway as instructed. However, the flight crew failed to use their heading indicators to orient themselves. In this context, it is particularly surprising that they did not confirm their heading in the course of their discussion as to whether they were on the correct runway or not, which is a widely accepted method of accomplishing the procedurally required pre-take-off runway confirmation. The board was unable to obtain an explanation for this error and the poor decision making of the captain, who commenced take-off although he was not sure whether he was on the correct runway. In doing so, the captain failed to recognise that his familiarity with the airport was not sufficient to compensate for the limitations in other sources of information. However, the investigation acknowledged that the obscuration of taxiway and runway markings at the airport may have had adverse effects on the performance of the Korean Airlines flight crew by forcing them to give disproportionate attention to the location of runway markings.
The Safety Board also acknowledged that the evasive manoeuvre performed by the captain of KAL 084 prevented extensive damage to the fuselage of the other aircraft and thus potentially fatal injuries to the occupants of both aircraft.

I-3.3 Probable Cause

The NTSB determined that the probable cause of the accident was the failure of the KAL 084 flight crew to follow accepted procedures during taxi. As a result, they became disoriented while selecting the runway, but failed to use the compass to confirm their position, and decided to take off although they were not sure whether their aircraft was positioned on the correct runway. The disorientation itself was largely caused by the fog, which reduced visibility to a point where the pilots could not ascertain their position visually, and the control tower personnel could not assist them. A further contributing factor was a lack of legible taxiway and runway signs at several intersections passed by KAL 084 while taxiing [NTS84].

It is also noteworthy that, at the time of the accident, taxiway and runway signs were identical in both basic and lettering colour, and accordingly, the Safety Board recommended using a different set of colour for signs designating runways to increase the conspicuity of runway-related signs.

I-3.4 Flight Deck Instrumentation Aspects & Conclusion

Korean Air Lines Flight 084

An independent source of aerodrome mapping information, indicating their aircraft's position in relation to the aerodrome, would almost certainly have prevented the disorientation by compensating for the lack of visual information due to visibility restrictions and deficiencies with airport signage or markings.

Additionally, redundant information on the assigned taxi route, potentially including an advisory or alert upon deviation, might have been helpful in preventing this accident. Last but not least, both indications and an alert that the flight crew was commencing take-off on a runway other than the one assigned by ATC could have offered a last-resort opportunity to avoid this accident. While certainly helpful, additional information on the surrounding traffic would not have prevented an accident of KAL 084, since the available take-off distance on the erroneously chosen runway segment (2400 ft/730 m from the W-1 intersection to the departure end of RWY 24R) was much shorter than the 8150 ft (2500 m) required for a successful take-off.

Southcentral Air Flight 59

The flight crew of Southcentral Air Flight 59 successfully managed to taxi to the assigned runway in spite of the fog, there was no disorientation involved. However, an independent source of traffic information might have helped them to detect the intrusion of the Korean Airlines DC-10 onto the runway for which they were expected to receive a take-off clearance very soon, which would certainly have caused them to contact the controller. This, in turn, might have provided all parties involved with more margin to avert the emerging collision hazard.

I-4 Controller Coordination: Minneapolis, March 31st, 1985

On March 31st, 1985, two Northwest Airlines DC-10's nearly collided at the Minneapolis-St. Paul International Airport in Minnesota. This incident is particularly noteworthy, since it spawned a special investigation on Runway Incursions by the NTSB after reported near-collisions had been on the rise for two years. The results of the special investigation are published in ref. [NTS86].

At around 21:04 (CST), Northwest Airlines Flight 51 (NW51) was cleared for take-off on RWY 29L by the local controller. About the same time, Northwest Airlines Flight 65 (NW65) was instructed to cross RWY 29L at taxiway C, some 6,000 ft (1,830 m) from the approach end of the runway, by the ground controller. Both controllers failed to recognize the hazardous situation in time to take corrective action. NW51 was in its take-off roll when the captain saw the other DC-10 crossing RWY 29L. The captain of NW51 averted a collision by rotating to a take-off attitude below the recommended rotation speed, lifting off prematurely and overflying NW65. Because of poor braking conditions and too little distance to stop his aircraft, he had no alternative. According to the captain's estimate, NW51 cleared the other DC-10 by 50 to 75 feet (15 to 23 m).
In total, there were 501 persons aboard the two airplanes. There were no reported injuries, and neither airplane was damaged. At the time of the incident, as many as 13 other air carrier aircraft were operating within 500 ft (150 m) of the intersection of RWY 29L and taxiway C [NTS86]. This illustrates the severity of this incident, which could easily have lead to a catastrophe surpassing the Tenerife disaster in the number of casualties.

I-4.1 Sequence of events

At the time of the incident, a recent snowstorm had passed through the Minneapolis area and left 14 inches (36 cm) of wet snow on the airport, and RWY 29R and several taxiways were still closed for snow removal. While RWY 4 was used for departures, NW51 requested departure from the longer RWY 29L, then in use for arrivals. Visibility was 20 statute miles (32 km), there were a few clouds, and the braking action on RWY 29L had been reported as "fair" and "fair-to-poor"; for taxiway D, it had been classified as "nil".

At 20:50, NW65 had contacted the ground controller and been given instructions to taxi to RWY 4 and to hold short of RWY 29L. The crew acknowledged, and NW65 was holding short of RWY 29L on taxiway C at 21:02, waiting to cross behind two other flights. NW51 was instructed to line up and wait on RWY 29L at 21:02:03 by the local controller. Almost simultaneously, the ground controller authorised NW755 and Republic Airways Flight 79 to cross RWY 29L at taxiway C, and then NW65 some 30 s later. Because the captain of NW65 was concerned that another landing airplane, NW815, might slide into his aircraft due to the poor braking conditions, he delayed crossing an additional 30 s while waiting for NW815 to clear the runway, but did not advise the ground controller he had done so.

At 21:03:43, the local controller transmitted to NW51, "NW51 heavy, RWY 29L, there's traffic crossing downfield, fly the runway heading, cleared for take-off." After NW755 and the Republic Airlines flight had crossed the runway, NW51 commenced its take-off roll. At the same time, NW65 started its delayed runway crossing.
The captain of NW65 later stated that it appeared to him that another aircraft was holding on RWY 29L as his aircraft was entering the runway, and that he attempted to expedite the crossing when the second officer alerted him that that the other airplane was taking off.

I-4.2 Analysis

Safety Board investigators interviewed the controllers and determined that the coordination between ground controller and local controller had failed due to incomplete or misunderstood communication regarding the runway crossing of NW65. The ground controller could neither recall the phraseology used nor whether he conveyed the number of airplanes he wanted to cross. The local controller stated that he thought that only two airplanes were approved to cross, but could not remember any phraseology or specific reason why he believed this. The Safety Board found that there were no written procedures for the coordination between controllers at the airport.
The local controller realised the conflict when NW51 was already 500 to 2,000 ft (450 to 600 m) into its take-off roll, when the ground controller gestured and yelled wildly, "Are you rolling?" However, no warning transmission to either aircraft was made.

I-4.3 Probable Cause

The incident was caused by the failure of the ground controller and the local controller to coordinate the runway crossing of NW65 properly; the Safety Board does not mention any flight deck-related causal factors in its analysis of this incident.
Controller workload may have been an issue, since traffic had been "steady, heavy and complex" for several hours due to weather-related delays, according to the local controller, and the ground controller stated he was "nearing the peak of what he could do." In addition to his controller duties, the local controller also performed supervisory functions as Controller in Command (CIC), and as such was responsible to request snow removal from the taxiways. At the time of the incident, two other controllers on duty were permitted to have a break in spite of the high traffic volume. For this reason and, among others, because he failed to have a critical taxiway cleared from snow, the Safety Board concluded that the Local Controller made poor decisions in his CIC role.
As a result of its investigation, the Safety Board issued safety recommendations, requesting the FAA to develop and implement specific procedures and standards for coordination between controllers regarding approval to cross active runways.

I-4.4 Flight Deck Instrumentation Aspects & Conclusion

Disorientation was not a factor in this incident. However, this incident highlights once more the hazards associated with insufficient traffic awareness both in the cockpit and the tower. Furthermore, it shows that even compliance with ATC instructions may result in an extremely safety-critical situation, since the risk of a controller error can never be fully excluded.

NW 51

Due to the prevailing night VMC conditions at the time of the incident, the flight crew of NW51 had no chance of visually detecting the other DC-10 sufficiently early to abort take-off.

Present flight deck instrumentation does not offer reliable information on other traffic on the runway. Consequently, an indication or an alert advising the flight crew of the presence of other traffic on the runway would have compensated for this deficiency in traffic awareness, allowing the flight crew of NW51 to reject take-off much earlier and with more margin to resolve the situation, thus avoiding a potentially hazardous early rotation manoeuvre.

NW 65

The analysis on traffic situational awareness for NW51 generally also applies to NW65. When its flight crew first visually acquired the other DC-10, they could not positively determine whether the aircraft was lined up for take-off or had already commenced its take-off run. An indication or an alert attracting the flight crew's attention to the other traffic taking off on the runway they were just entering or crossing might have allowed NW65 to expedite vacating RWY 29L earlier on.

I-5 Disorientation in the Fog III: Detroit, December 3rd, 1990

On December 3rd, 1990, at 13:45 EST, Northwest Airlines (NWA) Flight 1482, a McDonnell Douglas DC-9, collided with NWA Flight 299, a Boeing 727, near the intersection of runways 09/27 and 03C/21C in dense fog at Detroit Metropolitan/Wayne County Airport (KDTW). The B-727 was on its take-off roll on RWY 3C, bound for Memphis, Tennessee, when it collided with the DC-9, which had inadvertently entered the runway when taxiing to departure for Pittsburgh, Pennsylvania. Although the B-727 sustained substantial damage, none its 146 passengers and 8 crew members were injured, but the DC-9 was destroyed by the collision and subsequent fire. Seven of its 40 passengers and one of its four crew members, a flight attendant, were fatally injured [NTS91].

I-5.1 Sequence of events

Due to an aircraft change, Flight 299 could not depart as scheduled at 12:10, but was delayed until 13:31, when pushback from Gate F11 commenced. The flight was initially instructed to taxi to RWY 3C via right turn from the gate, and to hold short of O-7, a taxiway short of the C concourse. Visibility was initially ¾ mile (1,200 m), but started deteriorating as the flight commenced taxiing. After transfer to the east ground controller near O-9, Flight 299 was instructed to taxi to RWY 3C via O-6 and Foxtrot, and to advise the controller when crossing RWY 9/27 (see Figure 225). Since the deteriorating weather was a concern, the flight crew checked the take-off minimum for RWY 3C, which was ¼ mile (400 m) and thus coincided with the updated visibility information from ATIS Information Echo. While taxiing through the O-6 area, they observed an NWA DC-9 taxiing eastbound on the Outer Taxiway toward O-4, which seemed to disappear into an area of even lower visibility. Shortly thereafter, they heard a discussion on their frequency concerning a taxiing aircraft missing the O-6 intersection. After crossing RWY 9/27 and reporting to the ground controller, the B-727 continued on taxiway Foxtrot and started the No. 3 engine. Upon turning on taxiway X-Ray, ground control requested their position and transferred Flight 299 to the local controller. At this time, the captain noted that he could see the end of the apron of RWY 3C, which was located approximately at a distance of 1,800 ft (550 m). Simultaneously, the second officer commented that the weather was deteriorating significantly. The B-727 then stopped at the hold line for RWY 3C and reported ready for take-off at 13:44:08, for which they were cleared 7 seconds later.

Since the Automatic Terminal Information Service (ATIS) reported the required visibility and the captain had adequate visual reference of the runway centreline, the captain believed it was the correct decision to take off, and power was advanced at 13:45:03, 48 s after the receipt of the take-off clearance. Five seconds into the take-off roll, the first officer remarked that visibility was definitely lower than a quarter mile. According to the flight crew, the aircraft entered an area of reduced visibility approximately as it accelerated through 100 knots. Suddenly, the DC-9 appeared on the right side of the runway ahead of the right wing of the B-727, and the captain forced the yoke to the left and slightly aft in a desperate attempt to avoid the collision. After the impact at 13:45:40, Flight 299 rejected take-off and stopped the aircraft with maximum braking. The collision occurred 1:20 min after the tower had cleared the B-727 for take-off, and 32 seconds into the take-off roll.

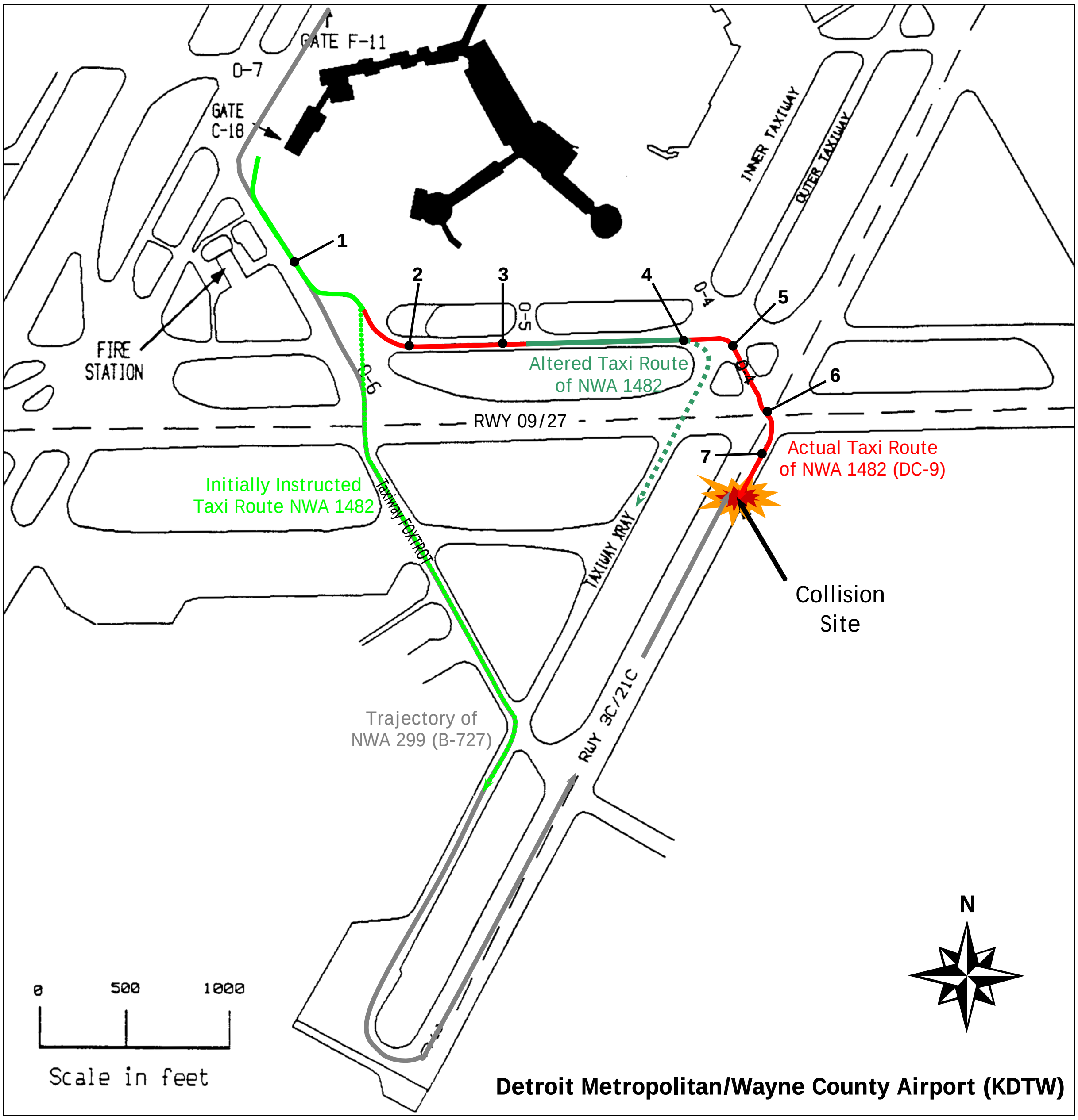

Figure 225: Instructed and actual taxi route of Northwest Airlines 1482 (after [NTS91])

The DC-9's captain had been off duty for an extended period of time due to medical reasons, and the accident flight was his first without supervision. After completing pre-start activities 40 minutes before the scheduled departure, the flight crew discussed their aviation backgrounds, expected flight duties and briefed for take-off.

At 13:35:31, the DC-9, which was parked at Gate C18, was instructed to taxi to RWY 3C, exiting the ramp at Oscar 6 (O-6). Like the B-727 flight crew, the DC-9's pilots also experienced a further deterioration of visibility as they started to taxi. According to a statement by the first officer, visibility was very close to zero-zero, but the crew were able to intercept the taxiway centreline and to identify that they were abeam the fire station when ground control requested their position. At this point, the ground controller issued the following additional taxi instruction: "Roger, Northwest 1482, taxi Inner, Oscar 6, Fox, report making the, ah, right turn on X-Ray". As the green dashed line in Figure 225 shows, NWA 1482 was thus instructed to take essentially the same route to the runway as NWA 299.

Approximately 30 seconds later, the first officer advised the captain to make a left turn (see "1" in Figure 225), but although the captain expressed some doubts, the aircraft made a swerve to the left to intercept the Inner Taxiway. The flight crew, at 13:39:22, configured flaps for take-off and read the first six items of the take-off checklist (2).

At some point, however, the DC-9's flight crew became increasingly uncertain of their position and eventually realised they had missed taxiway O-6 when the first officer saw a sign pointing to O-6 behind him. From the subsequent communication with ATC, it is obvious that there was disorientation, since the first officer stated (3) that they "… see a sign here that says, a, the arrows to Oscar 5. I think we are on Foxtrot now." The controller replied, "Northwest 1482, ah, you just approach[ed] Oscar 5 and you are on the Outer?", which the first officer confirmed. Ground control then amended the original taxi route and instructed Northwest 1482 to continue to Oscar 4 and to make a right turn on X-Ray. Taxiing very slowly, the captain then continued to taxi eastbound on the Outer TWY in a visibility of approximately 500 … 600 ft. As the airplane was nearing the Outer/Oscar 4 intersection around 13:42, the conversation between the flight crew reveals that they were increasingly confused about their position (4). Eventually, somewhat misled by the directions of the first officer, the captain did not turn right onto X-Ray, but ended up on O-4 instead. With doubts about their position, the captain of the DC-9 eventually set the parking brake (5) and told the first officer at 13:43:35 to contact the ground controller, "Give him a call and tell him that, ah, we can't see nothin' out here." However, the first officer failed to comply with this request, and reported that he believed they were holding short of RWY 9/27 on taxiway X-Ray when the controller asked the flight to confirm its position 10 seconds later. In spite of the positional uncertainty, the crew continued taxiing and eventually intruded into the runway intersection inadvertently, confused where RWY 9/27 they were supposed to cross actually was and where they actually were, but the first officer did not react to a second request of the captain to tell the controller they were stuck, either (6).
When the captain observed a white light to his left, he realised that they might be on an active runway, taxied the aircraft to the left edge of the runway, and decided to call the ground controller himself at 13:44:47, approximately 17 seconds before the other aircraft started its take-off run. After an unsuccessful first attempt, the captain related his concern that they might be on RWY 21C, but were not sure due to the fog, to the ground controller (7), who instructed them to vacate the runway immediately at 13:45:33, seven seconds prior to the collision. Simultaneously, by checking the heading indicator, the first officer realised that they were indeed on RWY 21C, and made affirmative statements while the captain talked to the ground controller.

I-5.2 Analysis

Given the actual visibility conditions, which were below minimums, the Boeing 727 (NWA 299) should not have taken off. The fact that the visibility was actually lower than specified in the ATIS was independently observed by both an off-duty controller and the B-727's first officer. Due to her observation, the off-duty controller asked the local controller whether he wanted to change the visibility. The local controller, however, who had made his observation without the required reference chart, refused. Likewise, five seconds after the take-off roll had begun, the first officer remarked, "Definitely not a quarter mile, but ah, at least they're callin' it." In fact, the NTSB investigation revealed that visibility was varying and partially as low as 100 ft (30 m).

Along with low visibility, inadequate signage and markings significantly contributed to the DC-9 flight crew's disorientation. The taxiway centreline of the Inner Taxiway was observed to be "*very faded*" to "*not visible*" in the Oscar 6 (O-6) area by the investigation even in daytime VFR conditions. Likewise, on the Outer Taxiway, the centreline was also faded between O-6 and O-4, and due to recent pavement works, 50 ft (15 m) were entirely missing in the vicinity of O-5; it turned out that repainting only took place twice a year. Nonetheless, the first officer's remark that he believed they were on taxiway F shows serious deficiencies in his familiarity with the airport layout, because there is no intersection of F and O-5; a close look at the airport diagram would have told him so. In this context, the Safety Board argued that the pilots could have studied the airport diagram more thoroughly prior to taxi.
Unfortunately, the ground controller's instruction to continue to O-4 and to make a right turn on X-Ray was imprecise and thus potentially confusing to the already somewhat disorientated DC-9 flight crew, because it was not necessary to proceed up to the centreline of O-4 to accomplish the right turn onto X-Ray. Moreover, it would have been more prudent of the ground controller, given the visibility and the apparent orientation problems of the flight crew, to keep the DC-9 away from the O-4 area, which was known as a Runway Incursion hotspot. In fact, as a result of the accident, the part of O-4 between the Outer Taxiway and the runway intersection was permanently removed in September 1991.
Near O-4, in the area where the critical disorientation leading to the accident occurred, even the investigators were unable to agree on the precise taxiway segment identifications after reading the available signs in daytime VFR conditions and in the absence of any time pressure. Furthermore, since the so-called wig-wag, a pair of alternating lights on the edge of the taxiway at the runway holding position, was unserviceable, it could not serve as a warning to the DC-9's flight crew that they were about to enter an active runway. Additionally, the large spacing of RWY 3C/21C edge lights - 584 ft (178 m) near the runway intersection with O-4 - and the fact that centreline lights were not illuminated at the time of the accident initially prevented the DC-9's flight crew from realising they had intruded an active runway.
In conclusion, compliance with the controller's instruction to proceed to O-4 almost necessarily lead the DC-9's flight crew to the runway intersection. However, both the captain and the first officer consistently failed to cross-check their aircraft's heading with the headings of their taxiway routing. Consequently, neither pilot realised that their heading of 160° could only mean they were on O-4, heading for the runway intersection, and not on X-Ray.

Potentially due to his long absence, the captain overly relied on the first officer, which eventually led to a de-facto roll reversal and a breakdown of CRM. The first officer encouraged this reversal by misleading the captain regarding his familiarity with the airport, and by somewhat exaggerating his accomplishments during his

previous career as a military pilot. While he had been an experienced B-52 commander and instructor, his claims that he had ejected from airplanes twice and retired from the Air Force as a Lieutenant Colonel could not be substantiated by his military records, which showed that he retired in the rank of a Major.
Additionally, he failed to follow the captain's instructions three times. As an example, when the captain started asking the first officer, noticing the latter's uncertainty about their position, to tell ATC that they were not sure where they were (5), the first officer simply interrupted him with additional directions and did not comply. This non-compliance of the first officer with the captain's requests possibly prevented timely controller action to advise the Boeing 727 to abort its take-off run. Likewise, although the first officer was not sure of their position, he did not advise the captain of his concerns, but rather continued giving directions to the captain, thus suggesting that he knew what he was doing.
On the other hand, the captain could have realised particularly from the aforementioned statement on taxiway Foxtrot that they were lost, and stopped the aircraft to request detailed and progressive taxi instructions. But the captain was probably fully occupied steering the aircraft, maintaining the centreline and looking for airport signs. The Safety Board believes that the flight crew eventually totally relied on the airport signage, and made no further attempt to consult the airport diagram. Although the captain had a Jeppesen airport diagram on his left side panel, it was difficult or impossible for him to consult it in this sub-optimum location while using the nose wheel tiller to steer the airplane.

Visibility was so poor at the runway intersection that neither airplane had a chance to visually acquire and avoid the other prior to the collision. But although the DC-9's captain questioned his position a full 53 seconds before the collision, i.e. several seconds before the other aircraft initiated its take-off roll, neither he or the first officer advised the ground controller of their uncertainty.
Likewise, the ground controller missed several options to resolved the flight crew's confusion, and did not take timely action to alert his colleagues once he had realised the DC-9 might have taxied onto the active runway. When the ground controller issued his warning that there was probably an aircraft on the active runway, the local controller decided not to issue a warning because he (erroneously) assumed that the B-727 was already airborne. The Safety Board also concluded that the presence of advanced surface radar might have prevented the accident.

I-5.3 Probable Cause

The NTSB determined that the probable cause of the accident was a lack of proper crew coordination, including a virtual role reversal by the DC-9 pilots, which led to their failure to stop taxiing their airplane and alert the ground controller of their positional uncertainty in a timely manner, both before and after intruding onto the active runway. Deficiencies in ATC services were cited as contributory factors, such as inadequate visibility observations, the failure to use progressive taxi instructions in a low-visibility environment, the issuance of inappropriate and confusing taxi instructions, and the ground controller's failure to advise the local controller of the potential Runway Incursion in a timely fashion. Furthermore, deficiencies in surface markings,

signs and lightings as well as the absence of CRM training at Northwest Airlines contributed to the accident. In particular, the Safety Board concluded that the placement of taxiway signs, the conspicuity of taxiway markings and runway lighting were inadequate at the time of the accident, particularly at the intersection of O-4 and the two runways, which had been recognised as a danger before.
In the wake of the accident, the NTSB issued several safety recommendations in the domain of airport markings and lighting, crew resource management and the more widespread use of progressive taxi instructions. Among others, the NTSB recommended the use of reflective paint for all airport markings and a better designation of complex runway intersections.

I-5.4 Flight Deck Instrumentation Aspects & Conclusion

NWA 1482
Deficient signage in the area where the DC-9 eventually entered the active runway deprived the flight crew of essential information required to detect their incursion and to regain position awareness. An unserviceable wig-wag, a gap in RWY edge lighting and a non-illuminated RWY centreline made it virtually impossible for the flight crew to detect their error on time.
Although the controller noticed very early that the DC-9's flight crew had difficulties in finding their way under these foggy conditions, he complicated the already disoriented crew's surface navigation task by routing them through one of the most complex intersections of the airport, instead of attempting to find a more simple routing. Of course, the deficiencies in Crew Resource Management (CRM) and the role reversion between the captain and the first officer were significant factors facilitating disorientation.
Irrespective of the previous, an independent source of aerodrome mapping information could have supported the DC-9's flight crew in airport navigation and prevented the inadvertent runway entry. Additionally, information on the assigned taxi route and potential deviations from it might have been helpful. Last but not least, an advisory or alert of some form indicating that another aircraft was taking off on the runway they had just entered could potentially have contributed to preventing the collision by giving the DC-9's flight crew more time to vacate the runway.

NWA 299
The flight crew of the B727 succeeded in maintaining awareness of their position despite the visibility at all times, but in the prevailing conditions had no chance of detecting the presence of the DC-9 early enough to avert a collision.
A function providing them with information on other traffic, indicating the presence of the disoriented DC-9 on the runway they intended to use for take-off, would most certainly have lead to a different decision whether to commence take-off or not.
Essentially, this accident is exemplary of how conventional surface navigation and traffic acquisition are prone to failure once external references are no longer available due to visibility limitations. This accident also serves as a reminder that visibility in fog is not homogeneous, but may show significant variations over relatively small distances.

I-6 Fatal Controller Error: Los Angeles, February 1st, 1991

While landing on RWY 24L at Los Angeles International Airport (KLAX) on February 1st, 1991, USAir Flight 1493 from Columbus/Ohio, a Boeing 737-300 (N388US), collided with Skywest Flight 5569 to Palmdale/California, a Fairchild Metroliner (N683AV), which was lined up on the same runway at the intersection with taxiway 45, waiting for its take-off clearance. The accident occurred in night VMC conditions at 18:07 local time, and killed all 12 persons aboard the Metroliner. Moreover, the captain, a flight attendant and 20 of the 89 passengers aboard the Boeing 737 sustained fatal injuries. Both aircraft were destroyed by the impact forces and a post-crash fire [NTS91a].

I-6.1 Sequence of events

Upon arrival into the Los Angeles area after an uneventful flight, USA 1493 was cleared for the CIVET Two Profile Descent to KLAX, and, while descending on this profile, instructed to perform an Instrument Landing System (ILS) approach to RWY 24R at 17:57:28. When, at 17:59, ATC inquired whether they had the airport in sight, the captain confirmed. Both flight crew members were able to distinguish the airport environment and some runways from a distance of approximately 25 miles (40 km). At 17:59:06, therefore, the approach radar controller cleared USA 1493 for a visual approach to RWY 24L. The captain acknowledged and, at 17:59:57, asked ATC to reconfirm that "the visual approach for USA 1493 is to 24L." Using the ILS of RWY 24R for vertical flight path guidance, the first officer then performed the visual approach to RWY 24L, for which neither Visual Approach Slope Indicator (VASI) nor ILS were available at the time. At 18:03:05, when approximately 10 km from the threshold of RWY 24L, USA 1493 was transferred to Los Angeles tower.
Approximately 5 minutes earlier, around 17:58, Skywest Flight 5569 had commenced taxiing from Gate 32 at Terminal 6 to RWY 24L, as shown in Figure 226. At 18:03:38, SKW 5569 contacted Los Angeles Tower to request take-off on RWY 24L from the intersection with taxiway 45. Intersection take-offs were commonly used by commuter aircraft at KLAX, and the local controller advised the flight to "taxi up to and hold short of two four left." SKW 5569 acknowledged and proceeded to the hold-short line.

Less than a minute later, at 18:04:33, the captain of USA 1493 initiated radio communication with the tower and reported the flight's position. His transmission, although received, was not acknowledged by the local controller, who at 18:04:44 approved the Skywest flight to line up and wait, "Skywest five sixty nine taxi into position and hold RWY 24L, traffic will cross downfield." The Skywest flight crew acknowledged and complied with this instruction.
The traffic the local controller was referring to was Wings West 5006, which was waiting for approval to cross RWY 24L at taxiway 52, but the flight crew had unintentionally departed from the tower frequency, resulting in a delay to the planned crossing until the Wings West crew had discovered their error and returned to the tower frequency. Wings West 5006 was eventually approved to cross RWY 24L at 18:05:16.

At 18:05:29, the captain of USA 1493 made a second radio call to the local controller. After an exchange with Skywest Flight 246, which had just taken off, the controller confirmed with Southwest Flight 725 that they were still holding short off RWY 24L, before she eventually cleared USA 1493 to land on RWY 24L at 18:05:53. Two seconds later, the USAir captain acknowledged. At this time, Skywest Flight 5569 was still waiting for its take-off clearance on RWY 24L. The local controller, however, diverted her attention to another landing US Airways flight (USA 2858), the Southwest B-737 (SWA 725) and Wings West Flight 5072 (see Figure 226), which had reported ready for take-off at 18:06:08. By error, the controller had received no flight progress strip for WW 5072, requiring her to communicate with both WW 5072 and her supervisor to resolve the issue.

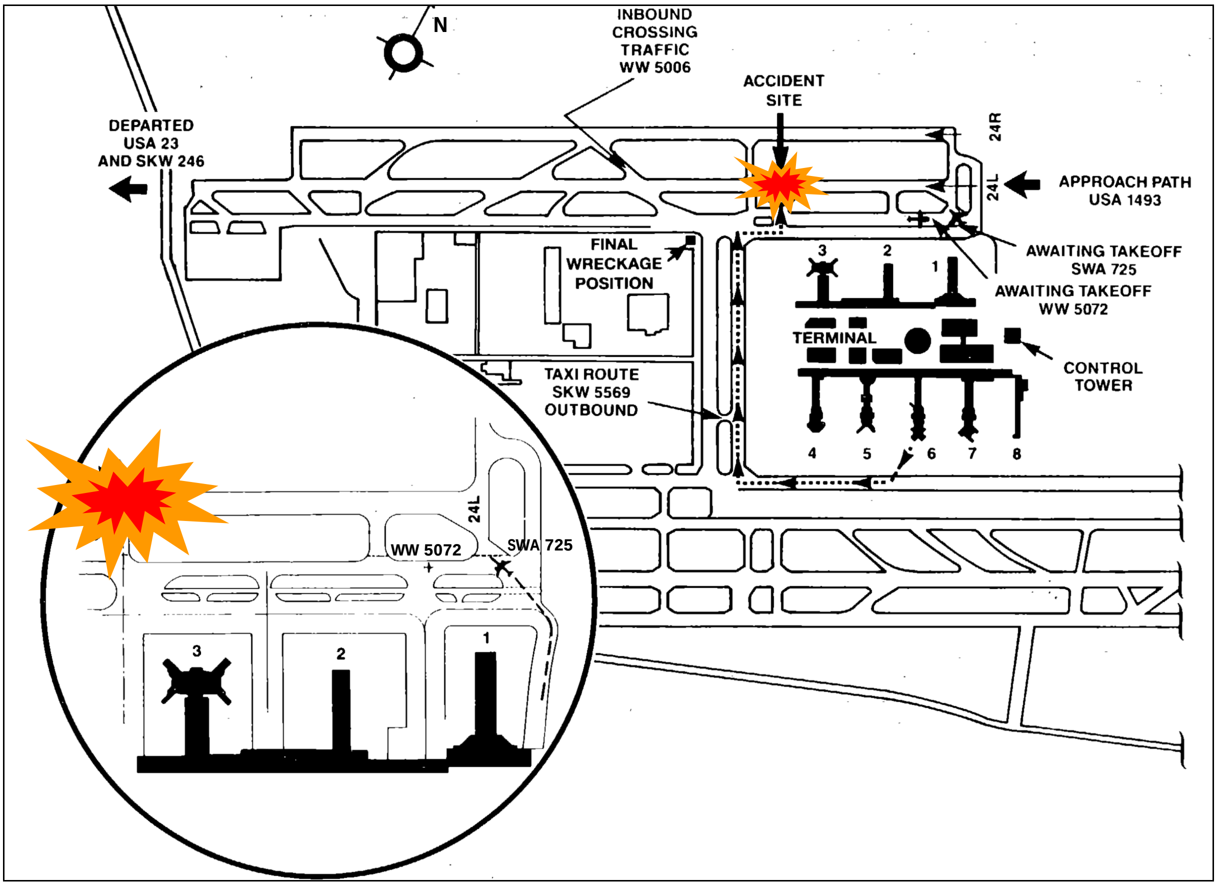

Figure 226: Location of the accident site at Los Angeles Airport [NTS91a]

In the meantime, the first officer had landed USA 1493 on RWY 24L, and while deploying thrust reversers and slowly de-rotating, he suddenly observed another aircraft on the runway immediately in front of and below him. There was insufficient time for evasive action, and although he immediately applied the brakes, his B-737 collided with the Metroliner when its nose wheel made contact with the runway, resulting in an immediate explosion and fire upon impact.

After the collision, the Boeing 737 and the part of the Metroliner that had been crushed beneath the left side of the B-737 slid 600 ft (180 m) down the runway before veering left, off the runway and across a taxiway, eventually impacting an unoccupied fire station, approximately 1,200 ft (365 m) from the collision site. The collision with the building destroyed the left side of the Boeing's cockpit, killing the captain.

I-6.2 Analysis

At the time of the accident, the local controller had seven aircraft on her frequency, resulting, according to herself, in a light to moderate traffic workload and complexity. However, the repeated attempts of the controller to re-establish contact with Wings West 5006 created additional workload, and subsequent unnecessary communication with the flight was apparently distracting. The Safety Board concluded that the controller became preoccupied during communication with Wings West 5006 and forgot that the Skywest Metroliner was still waiting for the take-off clearance. From the controller's communication with Wings West 5072, which called for take-off at 18:06:08, it is apparent that she confused this other Metroliner with Skywest Flight 5569, because she immediately asked the Wings West flight crew whether they were "at forty-seven or full length." Due to the misidentification of Wings West 5072, and the reconfirmation with Southwest Flight 725 that they were still holding short, the local controller believed RWY 24L was clear, and the search for the flight strip of WW 5072 she initiated resulted in further distraction from scanning the runway.

Besides, because the corresponding indicator at her position was out of service, the Airport Surface Detection Equipment (ASDE) radar system was not available to the local controller, although the FAA Air Traffic Service had mandated in 1986 that ASDE – where available – should be used between sunset and sunrise, irrespective of visibility conditions. The investigation revealed, however, that the ASDE at KLAX had been plagued by several prolonged outages due to the spare parts and support situation in the year prior to the accident. Furthermore, visibility of the collision site from the tower cab was impaired due to light pollution from Terminal 2 light fixtures producing glare.

While the NTSB investigation was unable to determine whether ASDE availability would have prevented the accident, the facility procedures in place at Los Angeles International Airport at the time of the accident were severely criticised, because they "*did not allow for lapses in judgement and decision making and removed human performance redundancies*," resulting in a situation with compelling distractions that was "*abnormally burdensome*." As an example, the procedures in effect at the time of the accident allowed taxiing aircraft to communicate randomly with the local controller on the tower frequency, precluding prior notification from the ground controller. The local controller would then have to select the flight strip of the calling aircraft and to determine its position.

I-6.3 Probable Cause

In determining the probable cause, the Safety Board was driven by the spirit that designers and operators of complex systems who fail to fully implement required design features and operating procedures, thus allowing a single individual to assume the full burden for safety-critical operations, must share responsibility for occasional human performance errors.

Consequently, the NTSB determined that the probable cause of the accident was the failure of the Los Angeles Air Traffic Facility Management to implement procedures providing redundancy as required by the applicable U.S. standards. Combined with additional organisational deficiencies, this created an environment in the tower that ultimately led to the failure of the local controller to maintain awareness of the traffic situation, "*culminating in the inappropriate clearances and the subsequent collision of the USAir and Skywest aircraft*."

I-6.4 Flight Deck Instrumentation Aspects & Conclusion

There was no disorientation involved in this accident, and airport familiarity was not an issue for either flight crew, because both crews routinely flew to Los Angeles Airport. The most important conclusion to be drawn with respect to flight crew human factors and flight deck instrumentation concerns aircraft conspicuity. Post-accident aircraft lighting tests performed on RWY 24L with an identical Metroliner revealed that the aircraft's white tail navigation light blended with the runway centreline lighting, and that the red anti-collision beacon was not as conspicuous as anticipated. Due to variety of lights on the airport surface, combined with the runway lights, aircraft and runway lights tended to blend together perceptually, making the aircraft virtually indistinguishable particularly from directly behind and above, i.e. another approaching aircraft. Consequently, the USAir flight crew had virtually no chance of detecting the other aircraft through visual observation.

The investigation found that aircraft external lighting standards are primarily driven by and tailored to in-flight conspicuity needs, and that no effort had been made by the FAA to address aircraft conspicuity on airport surfaces. Therefore, the NTSB recommended to study potential aircraft conspicuity enhancements, such as the general use of high-intensity strobe and logo lighting [NTS91a]. However, although the Metroliner was not equipped with the high-energy strobes used in most air carrier aircraft, which might have increased its conspicuity, it must be noted that strobes may be turned off when their reflections are deemed disturbing, e.g. particularly in fog.

Therefore, a method of providing independent information on traffic in the runway environment, potentially supplemented by alerting, might have prevented this accident. Likewise, a traffic awareness or advisory device might have enabled the Metroliner flight crew to realise that another aircraft was on the approach to the same runway they were lined up on.

A procedural change after the accident, forbidding intersection take-offs between sunset and sunrise, or whenever the intersection is not visible from tower, may help to prevent copycat accidents, but does not resolve the aircraft conspicuity and associated traffic awareness issue.

Another aspect relates to the use of phraseology. The Safety Board found that several of the pilot transmissions at Los Angeles International Airport around the time of the accident lacked the specificity required, and voiced a concern that the use of non-standard words and conversational phraseology precipitates misunderstanding between pilots and controllers. In this context, the NTSB also observed a lack of standard phraseology for requesting and instructing intersection take-offs in the corresponding standards.

I-7 On the Wrong Runway: St. Louis, November 22nd, 1994

In a clear night on November 22nd, 1994, at 22:03 local time, Trans World Airlines (TWA) Flight 427, a McDonnell Douglas DC-9-82 (MD-82), registered N954U, collided with a Cessna 441, N441KM, at the intersection of RWY 30R and taxiway R at the Lambert-St. Louis International Airport (KSTL) in Bridgeton, Missouri. While all 132 passengers and eight flight crew members aboard the MD-82 survived and only eight passengers incurred minor injuries during the evacuation after the accident, both occupants aboard the Cessna, the commercial pilot and a colleague of his in the co-pilot seat, who was rated as a private pilot, sustained fatal traumatic injuries.

I-7.1 Sequence of events

The MD-82 was scheduled to depart St. Louis for Denver at 21:34, but due to a small delay at the gate, the airplane was pushed back approximately 15 minutes late. Otherwise ground operations were routine, and the flight crew received instructions to taxi to RWY 30R for departure. At 22:01, while the MD-82 was taxiing southeast on taxiway P (see Figure 227), the first officer advised local controller that they were ready for take-off on RWY 30R. Shortly thereafter, at 22:01:23, the local controller cleared the MD-82 for take-off on RWY 30R, with instructions to fly a heading of 335°. The TWA first officer confirmed the assigned heading, and the airplane lined up on RWY 30R.

The Cessna had arrived from Iron Mountain with a single revenue passenger around 21:40 on RWY 30R, and after dropping her off at Midcoast on the General Aviation ramp and preparing the repositioning flight back to Iron Mountain, the Cessna pilot reported ready for taxi at 21:58. The ground controller instructed him to "back-taxi into position hold RWY 31" and to advise on the ground control frequency when ready for departure, which the pilot acknowledged. At 22:02:29, the Cessna pilot advised the local controller that he was ready for departure "on the right side" without specifying a runway.

About the same time, the MD-82 began its take-off roll with the first officer at the controls. Approximately 2-3 seconds after the captain had made the 80-knot callout, an additional crew member occupying the jumpseat yelled, "There's an airplane!" Both the captain and the first officer later stated that they saw the aircraft on the runway in front of them at almost the same instant that the additional crew member alerted them, and applied brakes. Additionally, the captain applied the rudder to steer the airplane to the left in a last-resort attempt to avoid the Cessna 441. However, another 2-3 seconds after spotting the other aircraft, they felt an impact on the right side and aborted take-off [NTS95].

I-7.2 Analysis

According to the three flight crew members aboard the MD-82, they did not observe the other airplane or its position lights at any point during their take-off roll. Rather, they first saw the Cessna when it was illuminated by the lights from their aircraft. In accordance with normal procedures, the MD-82 had all external lighting on at the time of the accident. Runway lighting was normal for RWY 30R at STL, and included runway edge, centreline, and touchdown zone lighting.

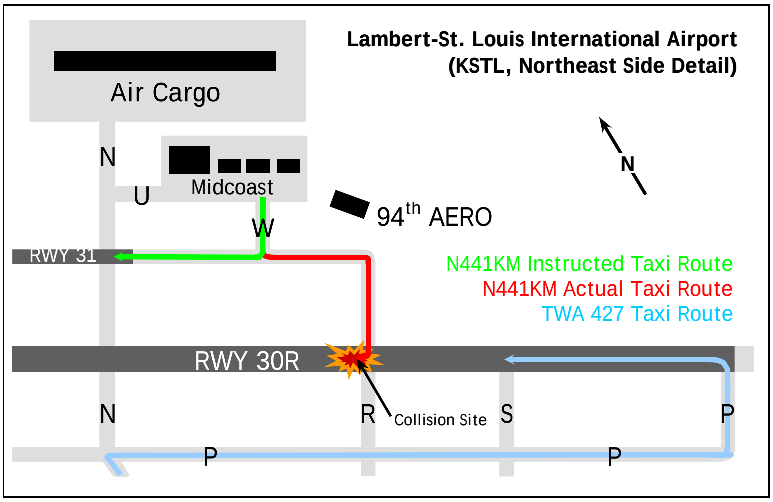

Figure 227: Taxi routes of TWA 427 and N441KM

Ground scars and physical evidence indicated that the Cessna 441 was located almost directly on the runway centreline, whereas the MD-82 had veered slightly to its left when the collision occurred. The right wing of the MD-82 struck the tail cone and fuselage structure of the Cessna 441, separating the horizontal and vertical stabilizers, and shearing off the top of cockpit and fuselage.

Airplane conspicuity tests performed as part of the investigation revealed that both aircraft navigation and taxi lights often blended with other airport lights, rendering visual acquisition difficult. Only the wing-mounted high-energy anticollision/strobe lights were effective at improving airplane conspicuity. Likewise, the landing lights were found to be effective for visibility in any situation. However, when these were turned off, even observers who knew its approximate position had difficulties in visually acquiring it.

Nonetheless, the key question in this accident is why the Cessna pilot taxied to RWY 30R instead of RWY 31 as instructed, all the more as the pilot was described as conscientious and safety-oriented.

Therefore, the Safety Board studied various scenarios why the Cessna pilot eventually intruded into RWY 30R. While the late time of the day and his expressed desire to go home may have played a role, the board dismissed the idea that the Cessna pilot was disoriented, because he had been to the airport once before, in January 1994 during a daytime flight. Additionally, the revenue passenger, who had flown with the pilot several times, reported that the pilot always taxied with an airport diagram and stopped his aircraft when uncertain of his position. Consequently, according to the NTSB, the pilot was probably rather pre-occupied by the idea that he would depart from RWY 30R, the runway he had landed on, than disoriented.

Factors that may have encouraged this belief include that the ATIS broadcast at the time of the accident did not contain any reference to the occasional usage of RWY 31 for departures. Additionally, all aircraft taking off or landing during the brief turnaround of the Cessna used either RWY 30L or RWY 30R. Since RWY 13/31 was actually a converted taxiway and still mainly used for that purpose, and only occasionally used as a "reliever" runway for General Aviation and commuter operations, it had the same width as the taxiways, and its lighting was dimmed compared to RWY 30L and RWY 30R. When he taxied to the Midcoast facilities after arrival on RWY 30R, the Cessna pilot did not receive any approval to cross RWY 31, which was, unlike the other runways, typically under the ground controller's responsibility until an aircraft required a take-off clearance. Furthermore, the investigation revealed that the displayed threshold markings of RWY 31 could have misled the pilot.

All of this may have fostered the Cessna pilot's erroneous impression that he was supposed to take off from RWY 30R. However, since he had neither requested nor been advised of an intersection take-off, the NTSB believes that he should not have entered RWY 30R at the intersection without confirming with the controller.

A further aspect is that the ground controller used non-standard phraseology when instructing the Cessna pilot to taxi to RWY 31, thus potentially allowing for ambiguities. Nonetheless, he clearly mentioned RWY 31 in two transmissions. Although the Cessna pilot failed to read back the assigned runway both times, he did not give any indication of uncertainty, thus creating an illusion of effective communication, when in fact he had apparently misunderstood the ground controller's intentions and acted on the preconceived idea that he was to take off from RWY 30R.

The investigation determined that an operational ground radar would have given the local controller an opportunity to detect the Cessna near the intersection of RWY 30R and R before issuing a take-off clearance to the TWA flight and might thus have prevented the accident by compensation for the Cessna's poor visual conspicuity.

I-7.3 Probable Cause

The NTSB dismissed the idea that the Cessna pilot was disoriented and thus determined that the probable cause of this accident was the Cessna 441 pilot's mistaken belief that RWY 30R was his assigned departure runway, which eventually resulted in his undetected intrusion onto that runway while the MD-82 was taking off.

Contributing to the accident was the lack of ATIS and other ATC information regarding the occasional use of RWY 31 for departure.

I-7.4 Flight Deck Instrumentation Aspects & Conclusion

While disorientation cannot be fully excluded in this accident, it is rather improbable that it played a substantial role. Traffic visual detectability and traffic awareness, ATC intentions and operational configuration of the aerodrome are the essential flight-deck related factors in this accident.

TWA 427

- The TWA flight crew was fully aware of their position on the airport and the assigned taxi route.
- The TWA flight crew had only minimal chances to detect the Cessna on the runway due to the relative intensities of aircraft and runway lighting as well as the low cross-section of the Cessna when viewed from behind along the runway axis.
- Consequently, a presentation of runway traffic in the cockpit and/or an alerting system indicating the presence of traffic on the runway would most likely have prevented the TWA crew from commencing take-off.

N441KM

- A way of conveying information on the intended take-off runway from the controller to the pilot in an intuitive, unambiguous fashion could have prevented this accident; the present method failed in this case, eventually causing the accident.
- An indication and/or alert that another aircraft was attempting take-off from the same runway might potentially have prompted the pilot to vacate the runway on time to avoid a collision.

I-8 Communication Problems: Paris CDG, May 25th, 2000

While lining up for an intersection take-off on RWY 27 at Paris Charles-de-Gaulle Airport (LFPG) in night visual meteorological conditions, a Streamline Aviation Shorts 330 (G-SSWN) operating on a mail flight to Luton collided with an Air Liberté McDonnell Douglas MD-83 (F-GHED), which was in its take-off roll as Flight 8807 to Madrid. At 0:52, at a speed of about 155 knots, the left wing of MD-83 slashed through the cockpit of the Shorts plane, immediately killing first officer and injuring the captain. After the collision, the MD-83 successfully rejected take-off; none of its 6 crew members or 151 passengers were injured. The left wingtip of the MD-83 was damaged; the cockpit of the Shorts 330 was partially destroyed [BEA01].

I-8.1 Sequence of events

The MD-83, call sign Liberté 8807, left its parking stand Y4 at Terminal 1 and was instructed to taxi to holding point RWY 27 at 0:12:40 (UTC). However, a technical problem resulting in the loss of auto-throttle forced the flight crew to wait on taxiway Q.

While the MD-83's crew was attempting to solve its problem, the Shorts 330, callsign Streamline 200, was departing cargo stand N51 and instructed to proceed to RWY 27 at 0:38:25. Six minutes later, the ground controller asked the Shorts flight crew whether they wished to perform an intersection take-off. The crew requested taxiway 16, which was granted and noted on the appropriate flight strip, but the ground controller did not verbally coordinate this with the local controller, an ENAC[148] instructor re-familiarizing himself with LFPG operations to maintain proficiency.

With the technical problem under control, the Air Liberté flight was instructed to contact the local controller at 0:47:10, while the aircraft was taxiing down taxiway Q towards the threshold of RWY 27. After several exchanges with the local controller regarding the departure to be used, the Liberté 8807 was approved to line up and wait on RWY 27 after a Boeing 737 (AEA 941) on final approach at 0:48:37. Three seconds later, Streamline 200 was also transferred to the tower frequency.

Shortly after, at 0:50:45, the B-737 vacated RWY 27 via taxiway 10, thus passing in front of the Shorts 330. At 0:50:52 the tower controller cleared the MD-83 for take-off in French, "Liberté 8807, autorisé au décollage 27, 230, 10 à 15 kts." Immediately afterwards, at 0:50:57, the Shorts 330 received the instruction to line up on RWY 27, "Stream Line 200, line up RWY 27 and wait, number two."

The Streamline crew taxied onto the runway, looking for "number 1" just as the MD-83 was approaching. Shortly before impact, the Shorts 330 Captain noticed the other aircraft's beacon lights and braked. Approximately two seconds before the impact, the Air Liberté crew also noticed the Shorts 330 on the edge of the runway as the aircraft was passing V_R. At 0:52:01, the left wing of the MD-83 collided with the right propeller and subsequently cut through the Shorts 330 cockpit. Aborting take-off, the Air Liberté flight informed ATC that they had just hit another aircraft.

148 École Nationale de l'Aviation Civile, a national French aviation academy offering, among others, basic training courses for ATC controllers.

I-8.2 Analysis

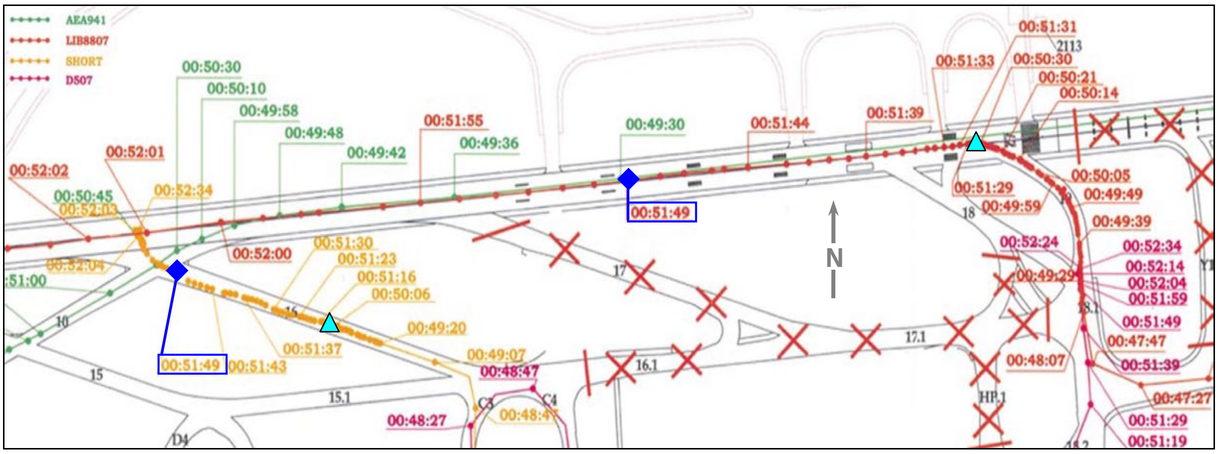

Figure 228: Radar-derived trajectories of Shorts 330 and MD-83 (after [BEA01])

As a result of the incomplete coordination between controllers, the local controller developed an erroneous mental picture of the traffic situation, and believed that Streamline 200 was somewhere behind the Air Liberté flight, assuming Streamline 200 would line up behind - instead of in front of - the MD-83 upon his instruction.

Figure 228 shows the radar-derived trajectories of the aircraft operating in the RWY 27 environment at the time of the accident. Due to the ongoing airport expansion, several taxiways in the vicinity of RWY 27 were closed (marked by red crosses). Additional lighting in the construction area to enable work at night, as well as approximately ten construction vehicles, all equipped with orange rotating lights, created light pollution that, according to investigators, made it difficult for the MD-83 flight crew to observe the Shorts 330 on taxiway 16, if not specifically looking for it. The cyan triangles in Figure 228, corresponding to the approximate positions of the aircraft at the time the take-off clearance, confirm this. When the Air Liberté flight crew had completed take-off preparations, which were more demanding due to the loss of auto-throttle, and initiated the take-off roll, the runway was clear of traffic [BEA01].
The trajectories presented in Figure 228 also enable a reconstruction of the accident dynamics. As is evident from the blue diamonds, corresponding to the positions of both aircraft at 0:51:49, the Shorts 330 was still clear of the runway 12 seconds prior to the collision. According to FDR information, the MD-83 had already passed 100 kts at this time. The fact that both aircraft were converging, unaware of each other, made the collision almost unavoidable.

Although the Shorts 330 cockpit offers a field of view of 120° on each side, the shallow angle of the high-speed taxiway 16 with RWY 27 made it physically impossible to acquire the approaching MD-83 visually before entering the runway surface.
Since the take-off clearance to the MD-83 was in French, the crew of the Shorts did not realise that there was an aircraft taking off, and entered the runway while still trying to identify the "number one" aircraft, and eventually apparently believed that the controller had referred to the landing Boeing 737. Given the circumstances, the flight crew of the MD-83 saw the Shorts too late to initiate any manoeuvre to prevent a collision [BEA01].

I-8.3 Probable Cause

The BEA concluded that the probable cause of the accident was the local controller's erroneous perception of the position of the aircraft, which led him to approve the Shorts 330 to line up on the runway. The inadequacy of systematic ATC verification procedures made it impossible to detect and correct the error, which had its origin in the lack of coordination between the ground and the local controller.

Furthermore, the Shorts 300 flight crew was criticised for not fully dispelling the doubts they had as to the position of the "number one" aircraft mentioned in their conditional clearance before commencing line-up.

Contributory factors were light pollution in the area of RWY 27 and **the use of two languages for radio communications, with the result that the Shorts crew were not conscious that the MD-83 was going to take off**. In addition, the angle between taxiway 16 and the runway made it impossible for the Shorts crew to perform a visual check before entering the runway. As a consequence of the accident, the high-speed exits are no longer used for intersection take-offs. Last but not least, there were issues with availability and readability of the radar for the controller [BEA01].

I-8.4 Flight Deck Instrumentation Aspects & Conclusion

Neither flight crew experienced difficulties with surface navigation, since visibility was sufficient for paper charts and visual observation to be successful. However, the accident clearly demonstrates that, apart from weather-related degradation of visibility, view restrictions resulting from either airport or cockpit geometry – or a combination of both, as for the Shorts 330 flight crew – can also lead to the breakdown of collision avoidance by "see and avoid" through visual observation.

Likewise, light pollution from the construction area and Terminal 1, aggravated by wet ground, once more raises the issue of aircraft conspicuity in a night-time airport environment, particularly for smaller airplanes. Accordingly, the BEA report concludes that it was very difficult for the Air Liberté flight crew, if not impossible, to detect the Shorts 330 moving on the taxiway if not specifically looking for it. However, given the conversation on the tower frequency, the MD-83's flight could only get the impression that the other aircraft was waiting somewhere behind them, and had thus no reason to suspect that another aircraft would attempt lining up in front of them.

In summary, this accident illustrates the need for better information on the surrounding traffic. They dynamics of the situation, along with the fact that both crews were busy performing check-lists and finalizing take-off preparations, thus limiting the share of attention available for traffic surveillance, suggests that not only traffic information, but also alerting might be required to prevent accidents like this.

The use of two different ATC languages had the effect that the Shorts' flight crew, not capable of understanding French, had no chance of realising that a take-off clearance had been issued to another aircraft on RWY 27, thus providing them cues to identify the "number one" in their line-up approval they were searching. While the use of different languages is mainly an ATC organisational issue, it emphasises the vulnerability of runway-related ATC instructions and clearances to a breakdown of communication. In consequence, additional and readily accessible information on clearances certainly has the potential to prevent misunderstanding.

I-9 Take-off from a Closed Runway: Taipei, October 31st, 2000

On October 31st, 2000, at 23:17 Taiwan time (15:17 UTC), Singapore Airlines Flight SQ006, a Boeing 747-400 with the Singapore registration 9V-SPK, crashed while taking off from a partially closed runway at Chiang Kai-Shek (CKS) International Airport, Taiwan.
Instead of taking off from RWY 05L for a night flight to Los Angeles as scheduled, the flight crew of SQ006 inadvertently lined up on the parallel RWY 05R, which was only available for taxiing due to a construction area between taxiways N4 and N5 some 1200 m from the threshold. The airplane was destroyed by its collision with construction equipment on Runway 05R and a subsequent fire caused by the impact.
There were a total of 179 people aboard the aircraft, including 159 passengers, 3 flight crew members and 17 cabin attendants. The accident resulted in 83 fatalities, among them four cabin crew members, and 39 serious injuries, including four flight attendants. The remaining cabin crew, one of the pilots and 22 passengers incurred minor injuries. Heavy rain and strong winds from typhoon "Xangsane" prevailed at the time of the accident [ASC02].

I-9.1 Sequence of events

The pilots reported for duty at 21:53 to collect their dispatch documents and to prepare the flight. The pre-flight briefing was a self-briefing conducted in the corridor leading to the aircraft's parking bay B5. Nonetheless, the EVA dispatcher[149] was present in case the crew might have had any questions. During the briefing, the pilots also reviewed the NOTAM on the partial closure of RWY 05R between N4 and N5 and on the closure of the section of the northern ramp between and behind parking bays A1 and A2 (see Figure 229).

Flight preparations in the cockpit were without incident, although the approaching typhoon "Xangsane", centred approximately 360 km south of the airport at the time and closing in, required particular focus on the weather situation, including the frequent re-calculation of crosswind components with the latest wind data. The flight crew received their ATC enroute clearance at 22:57. After pushback, at 23:05:57, the first officer requested taxi, and ATC instructed, "Singapore 6, taxi to runway six, via taxiway, correction, runway zero five left, via taxiway Sierra Sierra, West Cross and November Papa." After acknowledging the assigned route, the crew started to taxi.
During taxi, the weather situation was again in the focus of the flight crew's attention. They engaged in a brief discussion on the designated alternate airport because both Kaohsiung and Hong Kong had closed. Around 23:10, the relief crew member (CM-3) made a statement to the effect that the typhoon was coming in and that it would be worse with increasing delay. However, the captain only responded that he was going to taxi very slowly because of the wet and potentially slippery pavement. Shortly after the aircraft had turned left onto taxiway NP, the flight crew was instructed to transfer to the tower frequency at 23:12:58.

[149] At Taipei, Singapore Airlines (SIA) operates a station in charge of passenger handling, cargo loading, catering services and gate checking, using SIA personnel. Flight operation aspects, which include flight dispatch, flight planning, fuel, and freighter loading, are handled by EVA Airways, while engineering and maintenance are provided by China Airlines.

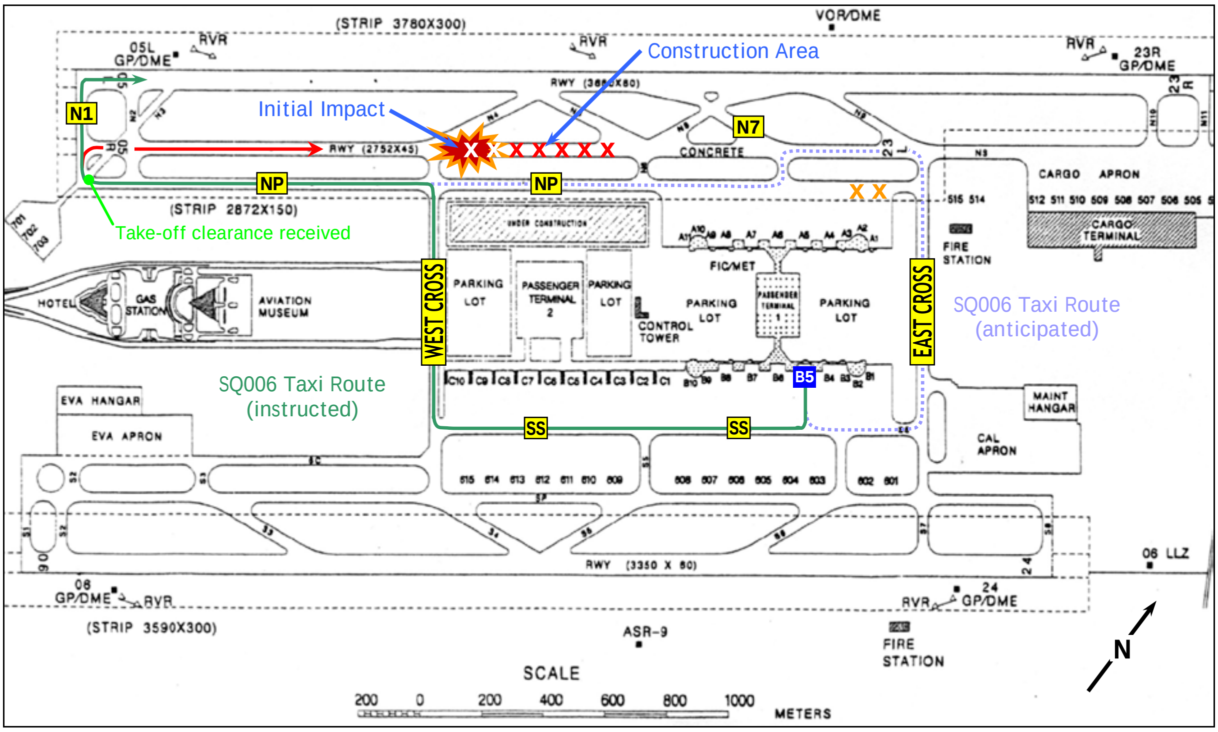

Figure 229: Chiang Kai-Shek International Airport with SQ006 taxi route (after [ASC02])

While SQ006 was still proceeding along taxiway NP, the first officer (CM-2) stated at 23:14:41, "Next one is November one." The captain cordially reminded him of the potential ambiguities associated with "next", stating that it was more precise to say "second right". Immediately afterwards, at 23:14:58, the captain instructed the first officer to tell ATC that they were ready for take-off. The controller initially approved line-up on RWY 05L, then shortly thereafter cleared the flight for take-off while the aircraft was approaching the south-western end of taxiway NP (see Figure 229), "Singapore six, **runway zero five left**, wind zero two zero at two eight, gust to five zero, cleared for take-off." According to FDR data, the aircraft turned from taxiway NP onto N1, but then did not completely pass the threshold marking area of RWY 05R to continue to RWY 05L as instructed, but entered RWY 05R in a continuous turn, apparently following the only visible green guidance lights in the pavement.

At 23:16:07, the first officer noticed that the Para-Visual Display (PVD) [150] had not yet become active (cf. Figure 230). Both the captain and the relief crew member attributed the shuttered PVD to the fact that they had not yet fully lined up with the runway. However, at 23:16:23, when line-up was complete, the PVD still had not activated, and captain remarked, "… not on yet er PVD huh **never mind we can see the runway**." After the captain had set the windscreen wipers to "high", the Boeing 747-400 erroneously commenced its take-off roll on RWY 05R at 23:16:44 in heavy rain, strong crosswinds and with only approximately 450 m RVR. It hit a first concrete barrier at the construction site approximately 33 seconds later at a ground speed of 131 kts. The aircraft subsequently collided with excavators, a bulldozer and other construction equipment, and was destroyed by impact forces and fire.

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150 The PVD is an optional glareshield-mounted indicator using the ILS localizer signal. It is used as an aid to tracking and maintaining the runway centreline in low visibility take-offs (CAT III). The PVD is normally shuttered and only reveals the actual indicator, a cylindrical barber-pole as shown in the inset, when it is active and acquiring a valid localizer signal. If the aircraft diverges from the centreline, the indicator is rotated such that it exhibits a lateral motion cue (left/right) to guide the aircraft back to the centreline.

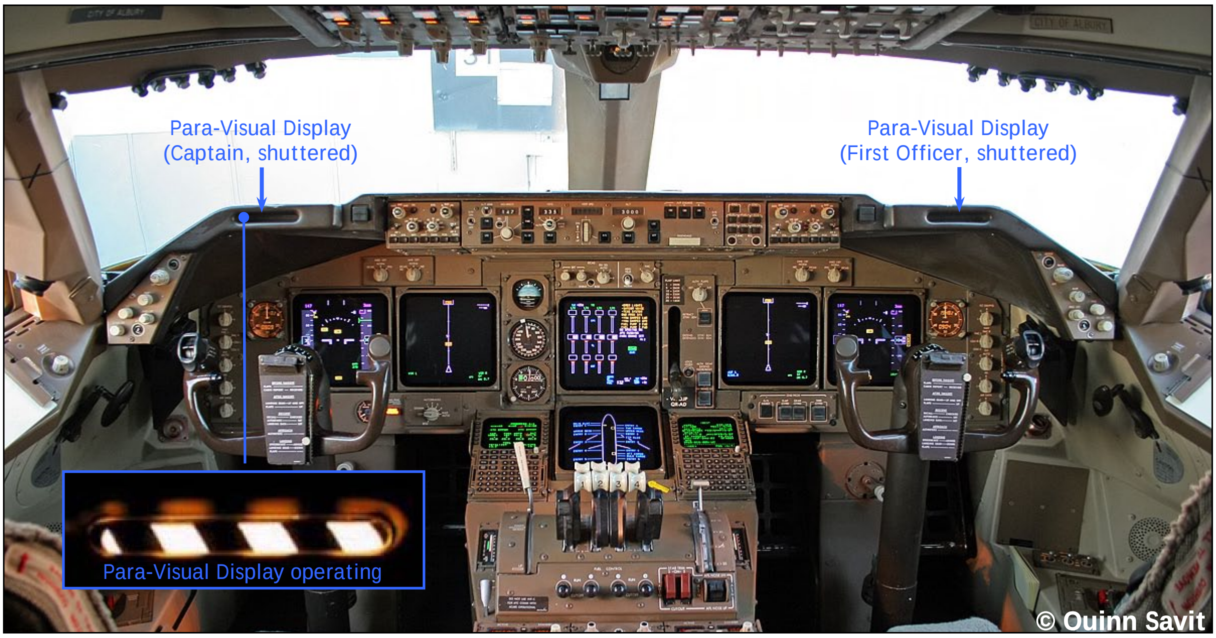

Figure 230: Boeing 747-400 flight deck with Para-Visual Display (PVD)

I-9.2 Analysis

The flight crew took off from the partially closed RWY 05R in the absolute conviction that they were on the correct runway. According to the official accident investigation, all crew members were well-rested, thus rendering fatigue an unlikely factor. Furthermore, there were neither behavioural, physiological nor medical anomalies that could have impaired crew performance.
The captain of the flight was very experienced and had logged a total flying time of 11,235 hours; he taxied the aircraft and was also to assume the role of the pilot flying (PF). The first officer had only accumulated 2,442 hours, whereas the relief first officer was more experienced with 5,508 hours and had of all crew members by far the greatest experience with the Boeing B747-400 (4,518 hours)[151]. Generally, the crew members were regarded as average to above average pilots. This analysis therefore focuses on the factors misleading all three flight crew members in the cockpit into believing they were on the assigned runway.

After the accident, the three members of the flight crew of SQ006, all of whom survived the accident, stated they had been fully aware that Runway 05R was partially closed due to ongoing construction work, and that the remainder of the runway was only available for taxiing, since they had reviewed the corresponding NOTAM along with their dispatch documents. The investigation determined that the crew had sufficient time to complete the checklists and to prepare for the departure. According to the captain, he had felt no time pressure, and advised the other crew members to be diligent with their checks.

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[151] Generally, SIA employs up to two flight crews for relief, depending on the distance and duration of the flight. However, there are no defined roles or duties for the relief crew when they are in the cockpit and not occupying a control seat. Rather, the precise role of relief crew will at the discretion of the PIC for the trip. The investigation report was unable to establish the influence of a SIA relief crewmember on decision making. Rather, an interview with a senior company pilot indicated that "*the effective interaction and use of resources on the flight deck between relief crewmembers and the primary crew may depend upon the individual aircraft commanders*."

The captain also reported that his focus was mainly on the strong cross winds and the low visibility. He wanted to determine if these were within company limits and therefore performed calculations with the other two pilots. This is confirmed by the CVR transcript, which reveals that the pilots were occupied with weather-related tasks, such as the calculation of cross winds and corresponding discussion, and considerations on alternate airports during taxi.

At Taipei, Singapore Airlines flights commonly use RWY 06, since this runway is closer to the parking positions typically used by the company. On the evening of the accident, however, with the RVR limited, the captain had chosen RWY 05L, because it may be used for CAT II operations and thus permits a lower visibility minimum. Besides, RWY 05L is longer and therefore provided better margins for the prevailing wet runway conditions. However, while the captain had been in Taipei roughly 2-3 weeks prior to the accident, **he had not used RWY 05L for about 2-3 years.** The first officer had not been to the airport recently. Since he was concerned about how he would support the captain, the first officer already familiarised himself with the airport layout in the hotel the night before the flight.

While still at the gate, the captain anticipated and briefed an expected taxi route via East Cross, as indicated by the dashed line in Figure 229, including a small section of back-tracking on RWY 05R due to the closure in the ramp area between bays A1 and A2. During this taxi route briefing, the first officer initially thought that RWY 05R was completely closed, but the relief crew member clarified. It is important to note that the actually assigned taxi route coincided with this expected taxi route in the critical last part where the runway confusion occurred, but was otherwise different. Therefore, the fact that neither N1 nor the crossing of RWY 05R were explicitly mentioned in the ATC taxi instructions to SQ006 was probably of little significance for the sequence of events.

Initially, both the first officer and the relief crew member, who took a spare copy of the Taipei Airport chart, monitored the progress along the taxi route. When approaching the N2 turn while on taxiway NP, the first officer had to attend to radio communication for the ATC line-up and take-off clearance. Likewise, upon receipt of the latest wind information via ATIS, the relief crew member put the taxi chart aside as the aircraft approached taxiways N1 and N2 to calculate the crosswind component for take-off, thus relocating his mental focus inside the aircraft. Captain and first officer then completed the take-off checklist. Effectively, therefore, the flight crew did not appropriately monitor the taxi route by using the available paper charts in the final stage of taxiing.

Irrespective of the previous, deficient airport lighting played a major role in the resulting disorientation which eventually caused the line-up on the wrong runway. Apparently, the flight crew was mislead by the compelling taxiway centreline lighting that guided them onto RWY 05R. From taxiway N1, lights with a spacing of 7.5 m continued into RWY 05R. In contrast to this, the green centreline lights straight ahead on N1 across the threshold towards RWY 05L were unevenly spaced at 30, 55, 116 and 138 m from the point of tangency with the lights leading into RWY 05R.

At the time of the accident, the minimum permissible RVR for RWY 05L was 200 m, and ICAO Annex 14 prescribes that on taxiways intended to be used for operations below 350 m RVR, centreline lights on straight segments should not be spaced by more than 15 m [ICA04b]. Additionally, the FAA recommends that alternating green and yellow lights should be used for taxiway centreline lighting across runways.

Consequently, the lighting along the critical part where the disorientation occurred did not meet ICAO standards or FAA recommendations. In addition to the inappropriately large spacing, the on-site investigation revealed that the second taxiway centreline light on the straight segment towards RWY 05L was unserviceable, and that the third was substantially reduced in its intensity. Last but not least, RWY 05L was not equipped with either runway guard lights (also referred to as wig-wag) or stop bar lighting as appropriate for a CAT II runway, which could have served as another cue to the flight crew that RWY 05L was still ahead of them. Furthermore, on N1, the taxiway centreline straight across RWY 05R towards was RWY 05L missing, but given the night conditions, this was probably without impact.

While the investigation determined that there were no physical restrictions to the visibility of taxiway and runway signs, several crew members remarked in their post-accident statements that because of rain and visibility, they were unable to see taxiway and runway signage. According to the relief first officer, the rain was very heavy, but the wipers were able to clear the windshield. Nonetheless, the visibility from the side windows was substantially degraded, forcing the crew to rely solely on the lighting. In line with the above findings, the crew reported not observing any taxiway centreline lights across RWY 05R on N1, but only the curved lights directly leading onto RWY 05R, which they then believed to be RWY05L.

The Taiwanese Air Safety Council, which conducted the investigation, explains this apparent contradiction by the fact that the flight crew's attentional resources were probably expended by pre-occupation with the take-off checklist and taxiing the aircraft on a slippery pavement. Consequently, the captain was attracted by salient visual cues, i.e. the more prominent lights leading onto RWY 05R. The investigation also revealed that the crew had not received training on low-visibility taxi procedures, which may serve as an explanation why they did not distribute tasks and their attentional resources more efficiently, particularly with a third crew member present.

Another explanation for the strong reliance on taxiway centreline lighting offered by the Safety Council relates to the surface guidance system employed by the flight crew's home base, Changi. The airport features a "follow the greens" system, i.e. taxiway centreline lights are illuminated along the assigned taxi route and dimmed, switched off or "blocked" by stop bars elsewhere. Given the additional workload induced by the meteorological conditions, the crew could have been susceptible to the latent misconception that they would automatically be guided to the correct take-off runway just by following the green centreline. In this context, however, it is surprising that the fact that they had not passed the partially closed parallel runway apparently did not alert the flight crew.

After erroneously lining up on RWY 05R, the flight crew also failed to correctly interpret the available visual cues that they were on the wrong runway. RWY 05R, originally conceived as a taxiway, was scheduled to be re-designated as taxiway NC. Due to its origins, it had green centreline lighting, but white edge lights and was only 45 m wide, whereas the other two runways featured a width of 60 m. At the time of the accident, the RWY edge lights were off. But neither this fact, the green centreline lighting, the absence of touchdown zone lighting nor the small width raised any concern with the flight crew. Apparently, the visual cues were strong enough that the flight crew erroneously believed they were on the active RWY 05L. This impression was facilitated by the fact the runway identifier could not be observed from the cockpit of a Boeing 747 lined up on RWY 05R, and that the lighted concrete jersey barricades delineating the construction area down the runway were not visible from the threshold even in VFR conditions during a re-enactment after the accident.
Indeed, an MD-11 captain departing from RWY 05L eight days prior to the accident confirmed that RWY 05R looked compelling with centreline and, on this day, also edge lights illuminated. However, in contrast to the accident flight crew, this particular pilot was able to resolve the conflicting visual information because of the missing touchdown zone lighting, the narrowness and the green centreline.

Unfortunately, the pre-occupation with pre-take-off tasks and crosswind calculations may have impeded the SQ006 flight crew's processing of runway configuration information, all the more since there was no immediate and salient indication that the runway in front of them was closed. All crew members unanimously stated in post-accident interviews that they were expecting a closed RWY 05R to be "black", i.e. to have an unlit centreline, and to feature warning signs or markings indicating the closure. Consequently, the centreline lighting on RWY 05R, contrary to crew expectations for a closed runway, proved to be deceptive for the flight crew, creating the illusion of an active runway. This misconception was aggravated by the fact that no signs of the obstruction down the runway were visible. Accordingly, the investigation concluded that lack of adequate closure warnings at the entrance of RWY 05R resulted in a failure to provide a potential last defence.

Apart from the misinterpretation of external cues, the flight was not alerted by indications on the flight deck that might have given rise to doubts as to whether they were on the correct runway or not, either.
The fact that the PVD, which was usually a very reliable instrument, had not unshuttered, was an indication that something might be inconsistent. However, since the PVD was not required because the visibility was sufficient for a visual take-off, and its check therefore not required, this was a missed opportunity to realise the mistake rather than a procedural oversight. From the captain's statement, it is clear that he gave priority to the visual information, and the runway picture seemed correct.
Likewise, on the head-down displays, the ILS indication on the PFD and an accordingly shifted "rising runway symbol" or misalignment of the aircraft symbol and the runway symbol on the ND in low range settings were subtle cues indicating the choice of the wrong runway. But again, this was merely a missed opportunity to catch the error, in contrast to the procedurally required external visual cues and cross-checks for positive confirmation that the crew was on the correct runway.

A psychological phenomenon known as 'confirmation bias' may have affected the flight crew's decision making, in that they were directing their attention towards information confirming their expectations and assumptions, and rejecting conflicting information. This bias facilitates errors in the search for information.
Another aspect was the timing of ATC instructions. For some reason, the captain appeared to have the wrong impression that the aircraft was visible from the tower, and that it was already very close to the take-off runway when they received the take-off clearance.

I-9.3 Probable Cause

The probable cause of this accident was a lack of flight crew situational awareness resulting in disorientation and a take-off from the wrong runway. The Safety Council concluded that the flight crew did not review the taxi route in a manner sufficient to ensure they all understood that the route to RWY 05L included the need to cross RWY 05R, and that in particular none of the flight crew members verified the taxi route when the aircraft turned from taxiway NP onto N1 and eventually RWY 05R. Likewise, none of the pilots orally confirmed which runway they had entered. Furthermore, the Safety Council believes that moderate time pressure to take off before the typhoon closed in, the concern about the strong crosswinds, low visibility and the slippery runway subtly influenced the flight crew's ability in decision-making and maintaining situational awareness [ASC02].

It is interesting to note that the identified deficiencies of the airport infrastructure are not listed as contributing factors, but merely as "findings related to risk", i.e. as issues potentially compromising aviation safety, but without proven impact on the sequence of events. While the potential confusion caused by sub-standard airport lighting is documented at least by flight crew statements, there is only ambiguous evidence concerning the purported time pressure. When the relief crew member mentioned the potentially deteriorating weather situation, the captain acknowledged but immediately commented that he would taxi very slowly nonetheless.

Further risks identified were the fact that Singapore Airlines had neither low visibility taxi procedures nor corresponding crew training for its Boeing 747-400 flight crews. Given the precipitation at the time of the accident and the resulting signal attenuation, the Safety Council was also unable to determine whether a surface radar, not yet installed at Taipei at the time of the accident because of a lengthy acquisition process, would have been able to aid controllers in detecting the erroneous line-up.

Last but not least, it is noteworthy that the Aviation Safety Council, inspired by a NTSB comment on the draft report, suggested to consider incorporating cockpit surface guidance and navigation technologies, such as an electronic moving map display for use during airport surface movement, in commercial airliners as a recommendation to both ICAO, IATA and Boeing.

I-9.4 Flight Deck Instrumentation Aspects & Conclusion

From the post-accident statements of the crew, it is obvious that their main concern during taxiing was the developing wind situation. Although part of the weather monitoring part had been delegated to the relief crew member, this secondary task provided a considerable distraction, shifting attentional resources from airport navigation. Position awareness was also made difficult by the fact that visibility was significantly impaired by the heavy rain. Additionally, the erroneous line-up was catalysed by the deficient and thus deceptive taxiway centreline lighting on taxiway N1 near RWY 05R. Likewise, insufficient familiarity with the airport environment in the area where the critical disorientation occurred may have played a crucial role in the accident, although this is not explicitly stated by the official accident investigation report.

This leads to the important conclusion that familiarity and currency with a certain aerodrome environment may very well be limited to certain areas of that airport, i.e. the parts commonly used by a certain airline.

Due to the nature of the runway closure and the way the construction area was barricaded and marked, the flight crew was deprived of any chance to acquire the construction area visually, and could therefore not employ their awareness of the partial runway closure of RWY 05R to ascertain they were on the wrong runway.

In conclusion, an independent source of information on their position at the airport would almost with certainty have enabled the flight crew to realise that they had lined up on the wrong runway, if not prevented them from being mislead by the deficient airport lighting on taxiway N1 in the first place. Likewise, an adequate indication of pertinent runway closures on the flight deck would have supported the flight crew's awareness of the precise nature and location of the closure irrespective of the presence of real-world markings, signs and barricades, thus serving as an additional information that their choice of runway was not correct.

Additionally, given the shift of attention away from the paper charts to weather and ATC communication that occurred in the cockpit of SQ006, an alert that the flight crew was commencing take-off on runway closed for take-off operations might have mitigated the outcome of the events considerably by permitting the flight crew to abort take-off in a timely fashion. Even in the absence of runway closure information, an indication and/or alert regarding an attempt to take off from a runway other than the pre-planned one would have served the same purpose.

I-10 Take-off from a Closed Runway II: Denver, September 2001

On September 25, 2001, around 03:48 local time, a United Parcel Service (UPS) cargo flight bound for Reno, Nevada, took off from the closed RWY 8 at Denver International Airport in Colorado, USA.
UPS Flight 896, a Boeing 757 with two crew members aboard, eventually passed within 32 feet (~ 10 m) of a temporary light fixture near the adjacent taxiway R7, which was undergoing construction. At the time of the incident, night visual meteorological conditions prevailed. Fortunately, no injuries were reported, neither on the ground nor aboard the airplane, and the flight continued uneventfully to its destination.
RWY 8 had been closed at 22:00 local time on the previous day because of construction work on taxiway R7. The construction area on taxiway R7 was clearly marked, lighted, and barricaded. However, RWY 8 and the runway entrances (other than those at R7) were not marked as closed or obstructed in any way, and the lights on RWY 8 were illuminated.

I-10.1 Sequence of events

The flight crew of UPS flight 896 contacted the Denver tower local controller for taxi instructions around 03:40, advising that they had arrival ATIS information "Hotel."[152] At the time of flight 896's departure, information Hotel was the current arrival ATIS and information Victor was the current departure ATIS. Both stated that RWY 8 was closed. About 03:42, the tower controller acknowledged that departure ATIS information "Victor" was current. At 03:42:16, the tower controller instructed the flight crew to taxi to RWY 35L and to advise her when it was ready for departure. At 03:43:57, the pilots requested a change to RWY 8 because they did not have the necessary departure data aboard to use RWY 35L. The tower controller responded, "UPS 896 no problem, continue northbound to RWY 8."
According to post-incident statements provided by the crewmembers of flight 896, they noticed construction activity on taxiway R7 as they approached RWY 8 and estimated that it was about 5,000 feet (1,500 m) away. While the aircraft was lining up, the captain asked the first officer "what all the lights were about." At 03:47:45, the flight crew reported ready to depart at RWY 8, and the tower controller erroneously cleared the flight for take-off[153].

The crewmembers indicated that the runway appeared to be clear, so they proceeded with the take-off. They reported that the aircraft passed through a cloud of dust next to the construction area but that the take-off was otherwise normal. Both crewmembers remained unaware that the runway was closed until the next day when UPS notified them that the aircraft had nearly struck a barricade. The captain stated that he did not recall if the runway closure information was on the ATIS broadcast.

[152] ATIS is the continuous broadcast of recorded non-control information in selected terminal areas. Each broadcast has a coded identifier that is used to confirm that flight crews have the correct ATIS data. Pilots are responsible for obtaining the appropriate ATIS information; controllers are responsible for either verifying pilots have done so or providing the information.

[153] Authorising UPS flight 896 to depart on a closed runway was contrary to Federal Aviation Administration (FAA) procedures.

About 03:51, a person identifying himself as "Engineering 567"[154] transmitted, "Engineering 567, 8-26 is believed closed?" The tower controller responded, "Agent air 526 [sic] affirmative." She then transmitted, "Oh!" At 03:51:51, Engineering 567 asked, "why did a plane take off from 8-26?" The controller did not respond. After the construction crew had notified airport management of the incident, it terminated construction activity for the night.

According to Denver airport management and local Federal Aviation Administration (FAA) air traffic management, the runway closure was coordinated with the tower and was part of a construction project that spanned several nights. However, a notice to airmen (NOTAM) about the closure was not issued because the communications system connecting the Denver airport operations office and the FAA's Denver automated flight service station (FSS) failed.
Although a NOTAM was transmitted from the airport operations office to the FSS, no acknowledgement of the transmitted NOTAM message was received, and the operations office did not follow up. However, the tower was notified directly by airport operations personnel when the closure went into effect [NTS03].

I-10.2 Flight Deck Instrumentation Aspects & Conclusion

The flight crew was aware of their position on the airport at all times, and had no difficulties in following the instructions of the controller. Other traffic was not a factor. However, an indication of the runways-in-use and, on the other hand, closed runways on the flight deck might have prevented this incident.

[154] Engineering 567 was a member of the construction crew at taxiway R7.

I-11 Disorientation in the Fog IV: Milano-Linate, 2001

During its take-off run at 8:10 local time (6:10 UTC) on October 8th, 2001, a McDonnell Douglas MD-87 (SE-DMA) operated by Scandinavian Airline System (SAS) as flight SK 686 from Milano-Linate (LIML) to Copenhagen-Kastrup (EKCH) collided with a Cessna Citation 525-A (D-IEVX) which had, in dense fog, inadvertently taxied into the active runway from the West Apron designated for General Aviation. After the collision, the MD-87 continued travelling down the runway, became airborne for a short time, but then fell back to the ground where it impacted a baggage handling building after an uncontrolled slide. It was destroyed by impact forces and fire. The Cessna was destroyed on the runway by a post-impact fire.
All 104 passengers and 6 crew aboard the MD-87, all four people aboard the Cessna and four people of the ground staff working in the baggage handling building suffered fatal injuries. Four more persons on the ground suffered injuries and burns of various degrees [ANS04].

I-11.1 Sequence of events

Earlier on the morning of the accident, the privately owned Cessna Citation 525-A had arrived from Cologne (EDDK) and landed on RWY 36R at 04:59. It then taxied to the West Apron via taxiway R6 to pick up two passengers, the first an employee of Cessna Aircraft and the second a potential Citation 525-A customer, for a demonstration flight to Paris-Le Bourget (LFBP).
SAS fight SK 686 was scheduled to depart from Milano-Linate at 5:35 with destination Copenhagen-Kastrup. When the boarding of the 104 passengers had been completed, the flight crew requested approval to start the engines, which was granted with the remark that their departure slot was at 6:16. At 5:54, the flight crew requested taxi, and was instructed to taxi to the ILS CAT III holding position of RWY 36R and to advise when entering the main taxiway (see Figure 231). Subsequently, when passing the fire station, it was transferred to the tower frequency at 5:59 as number four in the departure sequence.
In the meantime, at 5:58, the Cessna flight crew contacted the ground controller for engine start-up. Their request was approved and they were advised of their departure slot at 6:19. At 6:05:44, the pilots of the Cessna received their taxi instructions, "Delta Victor X-Ray, taxi **north** via Romeo 5, QNH 1013, call me back at the stop bar of the … main runway extension." Immediately afterwards, the ground controller instructed another aircraft in Italian to follow the Cessna on the same taxiway.
When leaving its parking position on the West Apron, the Cessna made two left turns and eventually reached a position where the taxi line splits into R5 and R6. Contrary to the instructions, the Cessna followed the southeast-bound taxiway R6. On this taxiway, the aircraft successively reached two holding positions designated S5 and S4. At the latter, at 6:08:23, the pilot reported, "D-IEVX is approaching S4." The controller asked the flight to confirm its position, which the Cessna flight crew did, and then instructed crew to maintain its position.
After confirming, again in Italian, position with an Air One flight, the ground controller returned to the Cessna at 6:09:09, "Delta Victor X-Ray, continue your taxi on the **main apron**, follow the Alpha line." The Cessna flight crew acknowledged and proceeded through a third stopping area 180 m short of RWY 36R, including a white

"STOP" marking painted on the asphalt, another yellow holding position marking and red stop bar lights accompanied by a CAT III sign. Eventually, it passed the last holding yellow holding position marking on R6 and entered the runway, following the green centreline lighting of R6 towards the runway centreline.

Simultaneously, at 6:09:28, the tower controller cleared the MD-87 for take-off, "Scandinavian 686 Linate, clear for take-off 36, the wind is calm, report rolling, when airborne squawk ident[155]." SK 686 promptly acknowledged and complied. The Cessna entered the runway when the MD-87 was already in its take-off run. At 6:10:21, while rotating at an indicated airspeed of 146 kts (270 km/h), the MD-87 collided with the Cessna, which had reached the middle of the runway by then. An exclamation on the MD-87's CVR and an additional nose-up elevator command on the FDR indicate that the Scandinavian flight crew spotted and attempted to avoid the Cessna within 1 s of the collision.

I-11.2 Analysis

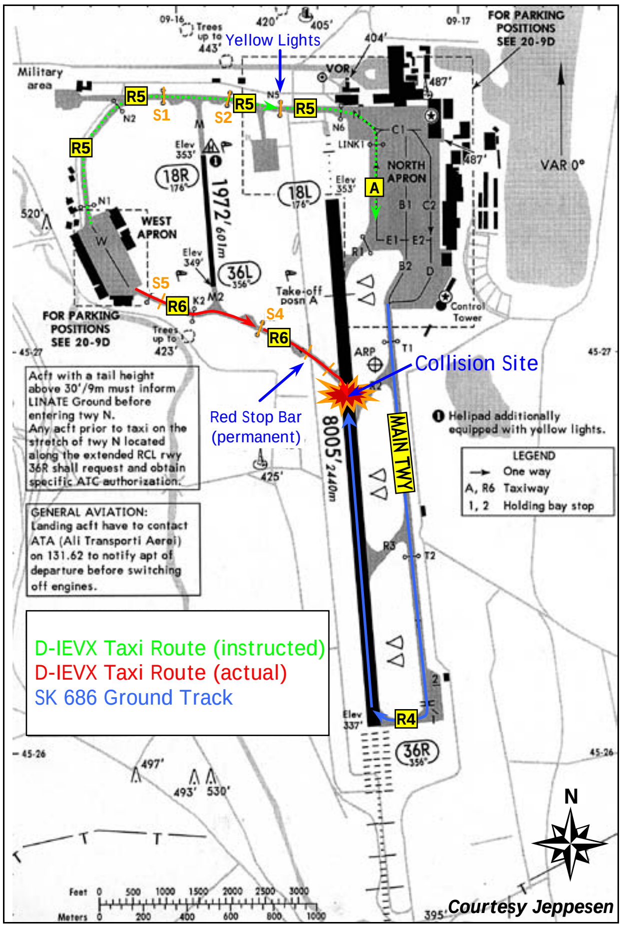

Figure 231: Accident at Milano-Linate

In the hour preceding the accident, ATC served 21 departing and three arriving aircraft. CAT III operations were in effect since 5:24, with visibility between 50 and 100 m and the RVR around 200 m with a minimum at 175 m. Since there were no technical aids, such as a ground radar, to monitor the position of aircraft, controller workload was high.

The accident investigation revealed that the Cessna flight crew was only qualified for CAT I operations, i.e. down to a minimum RVR of 550 m, and should, given the prevailing visibility conditions, not have initiated or been authorised to conduct the flight to Le Bourget in the first place.

The fact that the Cessna pilots were consequently not properly trained for low-visibility operations may serve as an explanation for their failure to comply with the assigned taxi route and to realise their error based on the sparse available visual cues. Nonetheless, since both pilots were professionals (one with more than 12,000 h experience) who had been to Milano-Linate several times before, it remains difficult to understand why they did not realise that they were going southeast rather than north as explicitly instructed, or ask the controller for clarification when they were approaching an active runway, which was inconsistent with their assigned taxi route. It is also possible that the Cessna pilots were preoccupied with the idea

[155] On the ATC transponder control panel in the cockpit, there is an IDENT button which, when pressed, will cause the aircraft thus "squawking ident" to be highlighted on the controller's radar screen.

that they would taxi back to departure using largely the same route they had used after landing. This might explain why they crossed the runway when instructed to proceed, although it must be noted that this crossing occurred without the controller's explicit approval, and involved passing a red stop bar. At any rate, since the Cessna was neither fitted with a CVR nor was required to have one, it is not possible to infer more about the reasons for its flight crew's behaviour.

However, the investigation revealed numerous deficiencies in the state of implementation and maintenance of airport standard signage, particularly in relation to taxiways R5 and R6, which may shed some light on this matter. On the West Apron, at the location where the taxiway centreline splits, yellow R5 and R6 markings were painted on the pavement to the left of the respective centrelines. However, the markings were worn, did not conform to any ICAO specification and could be easily confused. Apart from this surface-painted marking, there were no further signs or markings identifying taxiway R6 throughout its length until the intersection with RWY 18L/36R[156], thus depriving the Cessna pilots of any chance to realise their mistake based on airport signs. Additionally, there was a difference between the actual and the published taxi lines on the West Apron, and the holding markings S1, S2 on taxiway R5 and S4, S5 on taxiway R6 were not documented. In particular, the Linate controllers were not aware of their existence, and since they were not documented in the Aeronautical Information Publication (AIP), they were not published on the airport charts available at the time of the accident, either (cf. Figure 231[157]).

Furthermore, the stop bar associated with the CAT III holding position (but devoid of any runway identification) was permanently lit, because its controls had been deactivated three years prior to the accident, and an electronic device to detect runway intrusions at the intersection of RWY 18L/36R and taxiway R6 had been disconnected at the same time, also for unknown reasons. Likewise, runway guard lights had been removed in 1992. Last but not least, the old existing ground radar equipment had been decommissioned in 1999, with the replacement process still ongoing at the time of the accident.

On top of this, the documented ATC procedures were inconsistent both with the AIP information and operational practice at Linate. As an example, controllers used inaccurate phraseology and always employed the word “stop bar” irrespective of whether they referred to the yellow lights on R5 or the white “STOP” marking on R6. In his taxi instructions to the Cessna, the ground controller re-designated the “North Apron” as “Main Apron”. Moreover, pilots were routinely instructed to cross the permanently illuminated red stop bar on R6. The investigation also revealed issues with the training of ATC personnel. As an example, the supervisory controller had not received any recurrent training within the past 20 years.

The discrepancies between actual signage and markings, the available documentation and operational procedures resulted in a situation in which neither the Cessna flight crew nor the ground controller had sufficient information or visual cues for meaningful position reporting and monitoring. Consequently, because the controller

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[156] On taxiway R6, RWY 18L/36R was only indirectly identified through the “CAT III” sign, because it was the only CAT III runway at the airport.

[157] In this context, it must be noted that Figure 231 is based on a chart of the airport published in 2005. Taxiways are re-labelled as they were signed at the time of the accident, and the markings S1 to S5 were added by the author for clarification; there were no holding markings whatsoever in the chart current at the time of the accident.

was unaware of the existence of the S4 holding marking, he was unable to decode the Cessna flight crew's position report appropriately and realise their error, but he did not ask for clarification, either. Instead, he instructed the aircraft to proceed, unaware that compliance with this instruction would lead to a Runway Incursion.

I-11.3 Probable Cause

The accident occurred due to the unauthorised entry of the Cessna Citation into the active RWY 36R while the MD-87 was in its take-off roll. Among the imminent and systemic causes quoted by the official investigation were the low visibility of only 50…100 m, the lack of adequate visual aids, deficiencies in radio communications, inadequate operational procedures and a faulty and poorly documented airport layout at Milano-Linate. Additionally, there were "*blatant human errors*", such as the Cessna crew using the wrong taxiway and the failure of the authorities to check the qualification of the Cessna crew. Last but not least, the nature of the flight might have exerted a certain pressure on the Cessna crew to commence the flight despite the prevailing weather conditions.
Contributing factors were the high traffic volume, inadequate technical equipment, the use of both Italian and English in communications, and inappropriate training of ATC personnel. The combination of all these causal and contributing factors neutralized any possibility for corrective action and thus resulted in the accident [ANS04].

I-11.4 Flight Deck Instrumentation Aspects & Conclusion

D-IEVX

Low visibility, the lack of appropriate taxiway signage, markings and other visual aids resulted in a substantial disorientation of the Cessna flight crew, who was not qualified to conduct the flight under the prevailing meteorological conditions. An independent indication of their position with respect to the airport layout would certainly have supported them in realising they were on the wrong taxiway, and could have offered positive confirmation that they were approaching RWY 18L/36R. Additionally, information on the taxi route assigned to them could have dispelled any potential doubts about the controller's intention.
Due to the visibility conditions, the Cessna pilots had no chance of detecting that the MD-87 was in its take-off roll on the runway they were entering. An indication or alert that RWY 36R was used for take-off by another aircraft could have triggered remedial action on behalf of the Cessna crew.

SK 686

In spite of the low visibility, the Scandinavian Airlines flight crew did not experience any difficulties in airport navigation, and successfully taxied to the runway holding position. However, due to the visibility conditions, they did not have the slightest chance of acquiring the intruding Cessna aircraft sufficiently early to take successful remedial action. An indication of the surrounding traffic, potentially supplemented by an alert, might therefore have been beneficial in preventing a collision, or at least mitigating its consequences, by allowing the MD-87's flight crew to anticipate the incursion, and to reject take-off sufficiently early.

I-12 Wrong Runway Take-off: Lexington, August 27th, 2006

On August 27, 2006, at 06:07 Eastern Daylight Time (EDT), Comair Flight 5191 to Atlanta, a Bombardier CRJ-100 with the registration N431CA, crashed upon take-off from Blue Grass Airport in Lexington (KLEX), Kentucky, in night VMC conditions [NTS07].

While the flight had been instructed to taxi to RWY 22, the runway intended for departure, the crew erroneously lined up and eventually took off from the much shorter RWY 26, which is only half as long as RWY 22. Approximately 20 seconds after the take-off run had commenced, and immediately after the V_1 callout, the aircraft reached the end of RWY 26, but continued to traverse the grass beyond the runway's end until the landing gear hit an earth berm approximately 300 ft (90 m) behind the runway end. After becoming airborne briefly, the aircraft struck trees and descended, hitting more trees, and crashed into a meadow less than 2000 ft (600 m) from the end of the runway, where it was destroyed by impact forces and a significant post-crash fire. All of the 47 passengers aboard and two of the three crewmembers were killed. Only the first officer survived in critical condition [NTS07, ALP07].

I-12.1 Sequence of events

After collecting their flight release documents, the pilots proceeded to the air carrier ramp, where two Comair CRJ 200s were parked. A ramp agent performing the security check of the accident aircraft noted the flight crew boarding the wrong aircraft. When advised that they were on the wrong plane, the pilots shut down the already started Auxiliary Power Unit (APU) and went to the correct airplane [NTS07].

At the time of the accident, Lexington Tower was operating with a single FAA air traffic controller on duty, who was responsible for performing clearance delivery, ground control, local control, and departure control duties. While finishing flight preparations in the cockpit, the flight crew received their ATC en-route clearance at 5:49, and reported ready for taxi at 6:02. The controller then instructed the flight, "Comair one ninety one, taxi to RWY 22," which implicitly included approval to cross the non-active RWY 26.
However, at 06:04:33, the captain brought the aircraft to a stop at the holding position for RWY 26 (see Figure 232). Afterward, the first officer made a welcome address to the passengers and completed the before take-off checklist. With the aircraft still holding, the first officer reported to the controller at 6:05:15 that, at his leisure, "Comair one twenty one [sic]" was "ready to go."
The controller responded immediately and cleared the flight for take-off two seconds later, "Comair one ninety one, Lexington uh, tower, fly runway heading, cleared for take-off." After a brief exchange with another flight, the controller turned his back on the departing aircraft and proceeded to administrative duties. Subsequently, the captain erroneously lined up the aircraft on RWY 26 and transferred the flight controls to the first officer for take-off at 06:05:57. Approximately 43 seconds after receiving the take-off clearance, Comair 5191 began its fatal take-off roll on RWY 26 [ALP07, NTS07].

I-12.2 Analysis

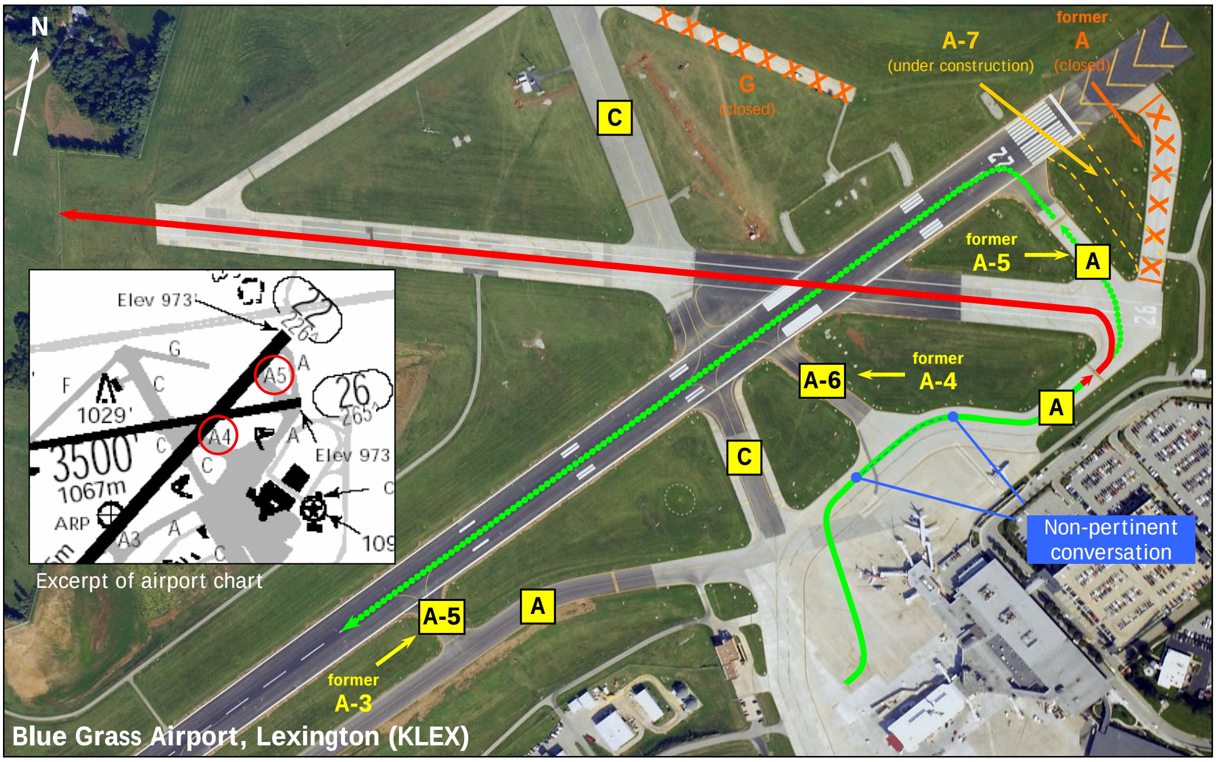

Figure 232: Lexington Blue Grass Airport with Comair 5191 ground track

At the time of the accident, Blue Grass Airport was approaching the end of a major five-year construction phase aimed at extending the non-standard 100 ft (30 m) runway safety area of RWY 4/22 to the required 1,000 ft (300 m). To achieve this, the threshold of RWY 22 was shifted by 325 ft (99 m) to the southwest. Simultaneously, the previously two taxiways north of RWY 8/26, A-5 and A, were to be eliminated in favour of a single new taxiway A-7 [ALP07, NTS07]. The consequences of these construction activities are depicted in Figure 232: the former taxiways A-3 and A-4 had already been re-designated as A-5 and A-6, respectively, in accordance with the new airport layout. Furthermore, to enable the construction of taxiway A-7, taxiway A had been closed and barricaded north of RWY 26. As an interim solution until the completion of A-7, the original taxiway A-5 was signed as taxiway A to avoid having duplicate taxiway names[158].

In June 2006, the airport construction plan was modified one day before changes had to be submitted to the National Flight Data Center (NFDC), which forms a central part of the FAA's Aeronautical Information Services Division. Due to the time pressure, Lexington's airport authority eventually decided to submit charting information reflecting the final airport configuration **after** construction to the NFDC, and to cover any discrepancies by NOTAM in the meantime [ALP07].
However, due to a limitation of an automatic change notification software at Jeppesen, the company supplying airport charts to Comair, the NFDC information on the chart revision for Lexington, which arrived after office hours on a Friday, went unno-

[158] As a convention, in REF _Ref233026697 Figure 232, the rectangular taxiway designator signs reflect the actual signage situation at the time of the accident, whereas the original situation is indicated by the "former ...." text labels.

ticed. As a result, the Jeppesen airport diagram current at the time of the accident (cf. inset in Figure 232) reflected the situation before the shift of RWY 22, whereas charts produced by the National Aeronautical Charting Office (NACO) reflected the final airport configuration after the shift. This left Blue Grass Airport in the uncomfortable situation of having to correct two sets of airport charts inaccurate in different ways by NOTAM.
As an example, NOTAM A-1682 stated that taxiway A was closed north of RWY 8/26. For unknown reasons, this NOTAM was neither part of the Comair 5191 dispatch documents (like three further relevant NOTAM) nor on the ATIS on the day of the accident, whereas it had been broadcast during the six previous days [ALP07]. It is worth mentioning that the NOTAM itself was problematic, since it could only be decoded with the Jeppesen chart. Irrespective of the chart used, however, the NOTAM was inconsistent with the actual airport signage, because there was an open segment of taxiway A north of RWY 8/26 due to the re-designation of taxiway A-5.

In conclusion, the pilots of Comair 5191 were provided inaccurate charts, incomplete NOTAM and consequently confusing signage. Numerous changes to the airport layout were not accurately presented on the charts, and some of the NOTAM advising of construction activities and reflecting the changes to the airport were not available; all of this may adversely have affected their situational awareness and eventually fuelled disorientation [ALP07]. In view of the above facts, it is not surprising that several other flight crews interviewed by the investigators also experienced confusion while taxiing to RWY 22 in August 2006, particularly during hours of darkness, mainly due to the airport charting discrepancies and because of a rapidly changing airport environment as a result of the construction activities.

There are no indications that the flight crew was rushed; all pre-flight checklists and briefings were conducted. From a flight crew performance perspective, however, there were nonetheless some deficiencies. When the first officer read the checklists, a number of minor inconsequential lapses occurred, most of them undetected. This may be taken as an indication that the first officer was mildly fatigued. Additionally, the flight crew made two procedural errors, which investigators believe to be relevant for the events. First of all, the first officer did the taxi briefing in lieu of the captain, and the briefing was not a full one as required, but abbreviated and omitted the crucial fact that crossing of RWY 8/26 was required to reach RWY 22. Furthermore, when taxiing the first officer engaged in non-pertinent conversation with the captain, continuing an earlier discussion at the gate and thus violating the FAA's regulations on the sterile cockpit procedure during critical flight phases.
Seen by themselves, neither the fact that the crew initially entered the wrong aircraft (although the correct tailsign was in their documents), nor the minor lapses during checklist reading, the use of an incorrect callsign (121 instead of 191) when reporting ready for take-off or the brief non-pertinent conversation seem to be particularly significant. However, when combined, these events create the impression that the pilots were, for whatever reason, not as attentive as required for a safe conduct of the flight. Fatigue is a potential explanation, but a slightly too relaxed attitude, evidenced most prominently by the non-pertinent conversation, is also plausible. Due to the missing

NOTAM information, the crew was largely unaware of the challenges resulting from the construction activities, and probably anticipated a brief and easy taxi out.
The Comair flight crew commenced take-off on RWY 26 in the firm belief that they were on the correct runway, RWY 22 [NTS07]. This can be inferred from the fact that the aircraft was brought to a stop at the holding position of RWY 26, the finalisation of checklists, the welcome address to the passengers and reporting ready for take-off to ATC. There is no indication of any positional uncertainty on the CVR transcript. If the flight crew had any serious doubts as to their location, they would certainly not have made the passenger announcement and reported ready for take-off.

In conclusion, therefore, this accident was caused by disorientation, but the accident investigation was unable to determine why and how precisely the situational awareness disconnect occurred. It can only be said that the disorientation occurred sometime before the aircraft was brought to a stop at the holding position of RWY 26 (in the belief that it was RWY 22). During the short taxi out, the first officer was mainly head-down performing checklist duties, reducing possibilities for him to keep track of the aircraft's position on the airport surface [ALP07, NTS07]. It is entirely plausible that on passing the taxiway signed as A-6, which was still designated as A-4 on his chart, the flight crew got the erroneous impression that they were already north of RWY26 and approaching RWY 22 – according to the taxiway naming logic at Lexington, A-6 could only be north of the taxiway A-5 depicted on the flight crew's charts. Consequently, it is legitimate to assume that the charting inaccuracies contributed to the disorientation. Additionally, the fact that the controller cleared the flight for take-off may have had an affirmative character for the flight crew that they were indeed holding short of their take-off runway. However, there is no conclusive objective evidence that this is indeed what happened.

Additionally, ineffective mitigation strategies allowed this misconception to persist, most notably the flight crew's failure to check aircraft heading for consistency with direction of the desired take-off runway after line-up, a slight misinterpretation of the NOTAM concerning the lighting system of RWY 22, and a generally similar appearance of RWY 22 and RWY 26 when viewed from the threshold. RWY 22 was sloped with a bulge in the middle, and therefore not visible full length. When viewed from the threshold, this visually shortened it, creating similarities with RWY 26.
When the first officer flew into Lexington on the day before the accident, most of the runway lighting of RWY 22 had been out of service due to construction work, an apparently impressive experience that the first officer related to the captain during the take-off briefing with the words that "the other night it was like lights are out all over the place." But only runway centreline and touchdown zone lights of RWY 22 were still out of service on August 27th, whereas runway edge lights were available again, and the NOTAM concerning the edge lights had been cancelled and was not part of the dispatch documents. Nonetheless, the first officer's personal experience of landing on the partially unlit RWY 22 the night before was an important factor, because it formed the flight crew's expectations what their take-off runway should look like, and thus made it acceptable to them to commence take-off on an runway without lighting. Consequently, there was apparently insufficient visual stimulus for the flight crew to question their position on the airport, and thus their decision to take

off, since they expected a largely unlit RWY 22, and thus the actually unlit RWY 26 did not raise any suspicions, and the erroneous line-up remained undetected.
Again, it appears that the behavioural phenomenon known as confirmation bias in psychology and cognitive science played a major role.
The hypothetical V_1 speed for RWY 26 was approximately 103 knots. It was reached shortly after the crossing of RWY 22, the runway actually intended for take-off, and several seconds after the first officer's statement, "It's weird with no light!", which most NTSB board members believe was made with an inflection in the voice indicating that it eventually dawned upon the speaker that something was wrong [NTS07].

At the time of the accident, the tower at Blue Grass Airport operated at less than the required staffing due to budget and personnel constraints. Because the controller proceeded to administrative paperwork after issuing the take-off clearance to Comair Flight 5191, ATC did not notice the flight crew's error, and thus had no chance to warn the crew. Apart from workload issues, diverting the controller's attention away from his primary task of controlling traffic, scheduling rotations had also prevented the controller from maintaining adequate rest, and he was therefore fatigued after only 2h of sleep when the accident happened.
The controller was legally not required to monitor the flight until take-off, but the NTSB found that delaying the take-off clearance until confirming that an airplane had crossed all intersecting runways to a departure runway could reduce the risk of erroneous take-offs from the wrong runway.

I-12.3 Probable Cause

The official NTSB investigation, which consumed approximately 13,000 hours, encountered difficulties in determining the probable cause of the accident because of the human performance issues involved.
Eventually, the Safety Board determined that the probable cause of the accident was the flight crew's failure to use available cues and aids to identify the airplane's location on the airport surface during taxi and their failure to cross-check and verify that the airplane was on the correct runway before take-off.
Since it was, according to the Safety Board, likely that the 40 seconds of non-pertinent conversation led to "*a loss of positional awareness*" [sic], the flight crew's non-pertinent conversation and the Federal Aviation Administration's failure to require that all runway crossings be authorised by specific ATC clearances were given as the two factors contributing to the accident. Safety Board Member Hersman, who led the investigation, filed a concurring statement on the investigation report, but criticised the narrow focus of the findings on crew performance [NTS07].
The NTSB also concluded that the implementation of cockpit moving map displays or cockpit runway alerting systems on air carrier aircraft "*would enhance flight safety by providing pilots with additional awareness about the runway and taxiway environment.*"
Consequently, one of the safety recommendations made by the NTSB to the FAA was that air carrier aircraft should be fitted with cockpit moving map displays or an automatic system alerting pilots "*when take-off is attempted on a taxiway or a runway other than the one intended.*" In addition, the board recommended enhanced taxiway centreline markings near holding positions and procedural changes, most notably a

crew procedure for positive confirmation and cross-checking an airplane's location at the assigned departure runway. On the ATC side, the board recommended prohibiting performing administrative duties for controllers while aircraft are moving in their area of responsibility, and issuing take-off clearances to taxiing aircraft before the aircraft has crossed all intersecting runways.

I-12.4 Flight Deck Instrumentation Aspects & Conclusion

In this accident, at first glance human error seems so egregious that it appears to offer an easy explanation of the events [ALP07]. For a meaningful conclusion with respect to flight deck instrumentation, however, it is essential to understand why the perceptions and decisions of the flight crew appeared to make sense at the time (local rationality), and what prevented the flight crew from maintaining adequate situational awareness. Therefore, based on the investigation results, the analysis section has attempted to reveal the complexity of the situation and the potentially conflicting information that eventually mislead the Comair flight crew into believing they were on the correct runway.

Doubtlessly, non-pertinent conversation is a distraction and may thus be detrimental to maintaining adequate situational awareness. However, there are no indications that pilots were completely absorbed by this conversation, which occurred on a virtually straight segment of taxiway A while passing the intersection with the taxiway signed as A-6 (see Figure 232), and the NTSB does not provide any detailed explanation on how the non-pertinent conversation contributed to disorientation, or why this should be given any more weight than the apparent airport charting and NOTAM deficiencies. Of course, a potential scenario is that the non-pertinent discussion initiated by the first officer disturbed the captain in resolving the apparent conflict resulting from the fact that this taxiway was not documented on their charts, and thus fostered disorientation. But even then, inaccurate airport charting information would still be at the root of disorientation.
In summary, there is no conclusive factual evidence to what extent the non-pertinent conversation was a factor leading to the erroneous line-up on RWY 26, and it is therefore not fully satisfactory as main explanation for the disorientation. Besides, the fact that other flight crews experienced confusion at Lexington as well may serve as an indication that this accident is less related to individual flight crew performance, but more to systemic issues such as inaccurate airport charting and inadequate NOTAM information.

Another concern with respect to non-pertinent conversation as a key factor leading to disorientation is that maintaining a cockpit environment completely free of distractions or parallel tasks is virtually impossible. Surprisingly, performing checklist activities, which kept the first officer head-down for most of the taxiing, is not even mentioned in the findings of the NTSB investigation. Besides, there are several further valid operational reasons, such as cabin readiness, slot discussions with ATC, weather concerns or technical problems that might equally divert a flight crew's attention during taxiing. In fact, distraction by weather-related considerations has also been identified as a potential reason for the disorientation in the Taipei accident (cf.

Appendix I-9). Therefore, the Lexington accident once more documents the vulnerability of an adequate level of situational awareness towards degradation in an airport environment under less than optimum circumstances.

Consequently, the main systemic issue is not the occurrence of distraction or disorientation, but the inadequacy of current flight deck instrumentation and procedures to reliably detect, manage and resolve surface navigation errors, irrespective of their cause, i.e. independent of whether they result from e.g. low visibility, operational distractions, non-pertinent conversation or erroneous aeronautical information. In conclusion, the underlying cause of the Lexington accident was not that distraction and disorientation occurred, but that this problem was not detected and corrected.

From a flight deck instrumentation perspective, it is unlikely that the flight crew of Comair Flight 5191 would have opted for take-off in the presence of a device providing them with continuously updated information on their current position on the airport, such as an airport moving map as recommended by the NTSB. Even if the flight crew had not paid any attention to this device, the accident could still have been prevented if the crew had been made aware of the fact that they were lined up and attempting take-off on the wrong runway by an alerting system of some kind.

An aspect not explicitly addressed by the NTSB recommendations is that an airport moving map display would have shown airport information based on largely the same sources of information as the conventional charts. Consequently, an airport moving map would not automatically have addressed the charting discrepancies or missing NOTAM information, which the author believes played a significant role in the disorientation causing this accident.
However, for the purpose of Runway Incursion avoidance, an airport moving map is believed to be more robust against taxiway charting discrepancies than paper charts, provided that it offers sufficient positional integrity and as long as the runway information presented is correct. Provided that the flight crew can trust the presented ownship position, this will probably enable pilots to detect the perceived inconsistencies as charting discrepancies, rather than attempting to fit the inconsistent information somehow in the perception of their position.

I-13 Erroneous Take-offs from a Taxiway

I-13.1 China Airlines Flight 011, Anchorage International Airport (1/25/2002)

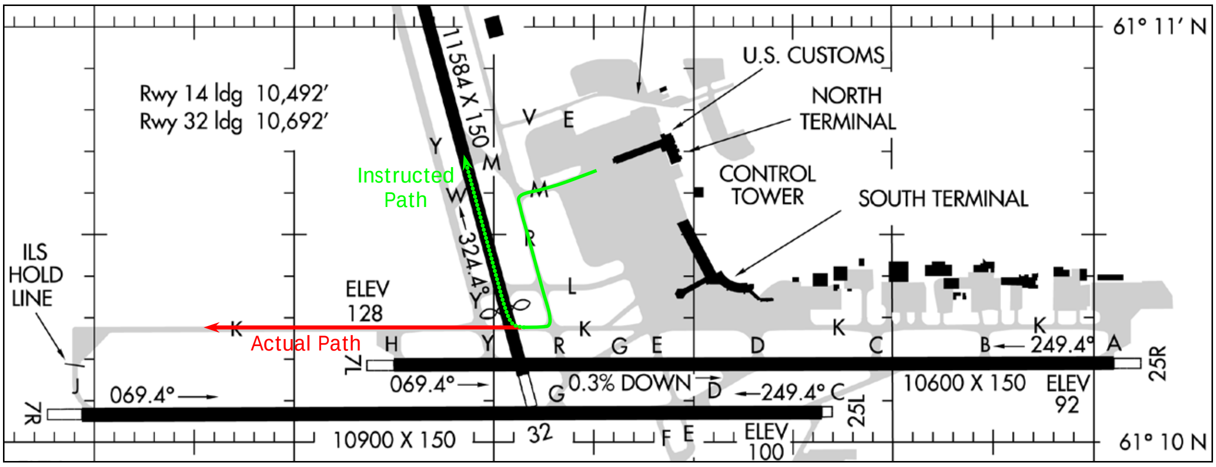

Figure 233: Instructed and actual path of Dynasty 011

On January 25th, 2002, at 02:43 local time, a China Airlines Airbus A340-300 (B-18805), callsign Dynasty 011, erroneously took off from taxiway K instead of RWY 32 at Ted Stevens Anchorage International Airport (PANC). None of the three flight crew members, 12 cabin crew members, and 237 passengers was injured, and the airplane, which was bound for Taipei (Taiwan) sustained no damage, and continued its flight uneventfully. At the time of the incident, dark night visual meteorological conditions prevailed.

After the Dynasty 011 had been pushed back from gate N4, the first officer contacted ATC for taxi instructions at 02:32. In return, the controller gave the following instruction, "Dynasty 011 heavy, taxi RWY 32 at Kilo, taxi via Mike, Romeo, Kilo." The incident airplane correctly followed the assigned route. As it was taxiing southbound on taxiway R and preparing for the right turn onto taxiway K at 02:40:06, the controller already cleared the flight for take-off on RWY 32. The flight crew acknowledged and, at 02:41:58, stopped the aircraft on taxiway K at the hold line, east of the extended portion of RWY 32. However, instead of turning right (north) onto RWY 32 to line up, Dynasty 011 began accelerating west on taxiway K at 02:42:10.
The controllers, upon noticing the mistake some 35 s later, did not instruct the flight crew to abort take-off, but activated the emergency phone to the airport fire brigade. However, the A340-300 managed to take off successfully, reporting airborne at 02:43. Members of the airport authority later discovered tyre impressions from the aircraft's main landing gear in a snow bank at the west end of taxiway K.
The subsequent investigation revealed that all three crew members had used Jeppesen airport diagrams during taxiing, and both captain and first officer used the Navigation Display (ND) in ARC mode and with a range of 10 NM, in which the runway symbol is visible. Although it had been the captain's first flight to Anchorage, the first officer and relief captain had been there before. Both captain and first officer recalled very bright centreline lights on TWY K, which they apparently mistook for runway lights. Specifically, the first officer stated that, while he initially (and more appropriately) thought the aircraft had only turned 100°, the bright centreline lights then made him think he was already on the runway when the captain transferred

control to him. Likewise, the relief captain, a China Airlines check airman occupying the jumpseat, described TWY K centreline lights as white, contrary to a previous visit, where he had clearly perceived them as green. Consequently, all three crew members, neither of whom checked the aircraft's heading, were in the firm belief they were indeed on RWY 32 when the first officer commenced take-off, apparently deceived by the airport lighting.
However, subsequent night taxi tests with another China Airlines A340 revealed no anomalies with taxiway K lighting in all three intensity settings; it thus remains unclear what caused the misperception and disorientation of the incident flight crew. As a result of this incident, China Airlines revised its Airbus A340 AOM to include verbalization and verification of the runway in use [NTS02].

I-13.2 EVA Air Flight BR635, Anchorage International Airport (11/05/2005)

On November 5th, 2005, EVA Air Flight BR635, a McDonnell-Douglas MD-11F, accidentally took off from taxiway Y at Anchorage International Airport (PANC) instead of the parallel RWY 32 for a cargo flight to Taipei. Although the taxiway is shorter than RWY 32, the aircraft managed to take off successfully and continued to Taipei without further incident.
This incident was reported in the news media in 2005, referencing an investigation by the FAA or the NTSB. However, neither the NTSB incident/accident database nor the Taiwanese Air Safety Council (ASC) list of investigated occurrences contain any reference to this incident.
It seems, however, that BR635 with a crew of three (including a relief captain) was initially cleared to RWY 32 via taxiway K. Subsequently, the flight crew was advised of a runway change, and instructed to taxi to RWY 07L via taxiway K, cf. Figure 233. Shortly afterwards, while still taxiing on taxiway K – and presumably after having crossed RWY 32 – ATC informed the flight crew of yet another runway change, and requested them to taxi to the extension of RWY 32 via RWY 07L. Upon line-up, all three flight crew members believed that they were on RWY 32, and commenced take-off. Apparently, though, there was some disorientation, and the aircraft had made a premature left turn, lining up and taking off on taxiway Y instead.
While Anchorage tower was unaware of any infringement of taxiway Y, a radar trace showed the aircraft departing from the taxiway, and the flight crew was eventually instructed to contact Anchorage ARTCC.
Neither the precise time of the incident nor the prevailing meteorological and visibility conditions are known, and there is – unfortunately – insufficient information available to draw any conclusions on the reasons why this apparent crew disorientation occurred. Since both the pilot-in-command and the relief captain had, within the previous 48 h, flown Anchorage – New York (KJFK) – Anchorage and effectively had only had 21 h of rest between November 3 and November 5, 2005, fatigue may have been an issue, although all three crew members met the minimum CAA rest requirements[159].

[159] The presentation of the event in this thesis is based on discussions in an EVA Air flight crew forum, http://nankantraz.org, incident information obtained via the Aviation Safety Network (http://www.aviation-safety.net) and the website of the Flight International magazine, http://www.flightglobal.com.

I-14 Runway Incursions Caused by Vehicles

I-14.1 Anchorage International Airport (12/19/1983)

A Japan Airlines Boeing 747-200F (J8151) sustained substantial damage when colliding with a pick-up truck during landing on RWY 6R shortly after midnight on December 19th, 1983. With the RVR between 600 and 800 ft, and the nose gear still in the air when the collision occurred, the flight crew stated that they did not see the vehicle. It turned out that the local controller, potentially due to workload issues, could not remember whether he had acknowledged the ground controller's request to cross the vehicle. The three flight crew members received minor injuries in the accident, whereas the driver was severely injured and lost both legs [NTS84].

I-14.2 Sioux Falls Airport (12/20/1983)

An Ozark Air Lines DC-9 struck a snow sweeper while landing on RWY 03 at Sioux Falls, Dakota. When clearing the aircraft to land, the controller did not advise the flight crew of the snow removal operation in progress on the runway. Thus, since the ATIS reported blowing snow but did not mention any snow removal, either, the flight crew attributed what they saw to the weather, and did not realise that they were actually perceiving the snow removal.
The collision destroyed the snow sweeper, killing its driver, and broke off the DC-9's right wing. None of the flight crew or the 77 passengers aboard the DC-9 were injured, and the impact fire extinguished itself as the airplane spun through 180° after the collision [NTS85].

I-14.3 Amsterdam Airport Schiphol (12/10/1998)

A Delta Airlines Boeing 767-300 (N193DN), operating as Flight DAL 39, aborted take-off on RWY 24 at Amsterdam Airport Schiphol when observing a KLM Boeing 747-400 being towed across the runway, accompanied by an airport authority van. The incident occurred at 10:32 local time in low visibility, with the RVR between 1600 and 1800 m. Due to a low cloud base, the visibility from the tower was close to zero.

Because of a misunderstanding when coordinating with the assistant controller handling the aircraft under tow, the controller clearing the Delta Boeing 767 for take-off was in a wrong mindset as to the direction in which the tow would cross, and therefore, based on the ground radar picture, considered the crossing complete before it had actually begun. Additionally, difficulties with stop bar operation and associated discussions in the tower created both distraction and confusion, delaying the runway crossing of the aircraft under tow.

The investigation concluded that a catastrophic accident was only prevented due to the quick and proficient action by the flight crew, which had sufficient visibility to acquire the conflicting traffic visually [RVT01]. Since the vehicles were handled on a different frequency, the Delta flight crew had no chance of noticing the emerging conflict in advance.

I-14.4 Denver International Airport (2/2/2007)

On February 2nd, 2007, at 17:38 local time, a United Airlines Boeing 737-500 (N928UA), operating as flight UAL1193, nearly collided with a snowplough while in its landing rollout on RWY 8. Visual meteorological conditions prevailed at the time of the incident.

The investigation revealed that the snowplough driver had proceeded across the runway without clearance from air traffic control or airport operations. The driver stated that he saw the landing airplane while crossing the runway and increased acceleration.
The flight crew had initially observed the snowplough holding short of a taxiway, but after landing, they suddenly observed the snowplough crossing the runway in front of them. Employing significant reverse thrust and brakes, they managed to bring the aircraft to a halt on the runway. The controller apparently did not see the snowplough; he was alerted to the Runway Incursion by the flight crew's report. While the Airport Movement Area Safety System (AMASS) was operational, no alarm had sounded [NTS07b].

I-15 Collisions on Taxiways

I-15.1 Newark Liberty International Airport (10/31/2006)

At 18:30 local time, a Lufthansa Boeing 747-400 (D-ABVY) operated as Flight DLH 403 to Frankfurt, Germany, incurred substantial damage when its left wing contacted the right wing of a Boeing 757-200 that was under tow, but stopped, at Newark Liberty International Airport (EWR), Newark, New Jersey. None of the 18 crewmembers and 294 passengers onboard the Boeing 747 was injured, and there was no one onboard the Boeing 757. The accident occurred in the vicinity of the intersection of taxiways A and S; night visual meteorological conditions prevailed at the time of the accident.
The investigation revealed that the B747 flight crew was not aware of the aircraft under tow. The captain reported that the accident occurred in an area where the B757 in tow was backlit by apron lights blinding him, and that the crew's attention was diverted to another B757 ahead that they had been instructed to follow. Furthermore, the B757 in tow had been taxiing ahead of the B747 prior to reaching the diverging taxiways, and had received its taxi instructions prior to the B747 crew being on the frequency [NTS07c].

I-16 Noteworthy Recent Incidents

I-16.1 Munich Franz-Josef-Strauß Airport (5/3/2004)

On May 3rd, 2004, at 21:39 local time, a Boeing 737-300 landing on RWY 08R at Munich Airport (EDDM) nearly collided with an ATR 42-500 lining up on the same runway from high-speed taxiway B4. A catastrophic accident was only prevented because the flight crew of the Boeing 737 visually acquired the other aircraft sufficiently early to initiate an evasive manoeuvre; they eventually passed the ATR 42-500 within metres at a speed of 110 kts (204 km/h).

Around 21:39, the ATR 42-500 was ready for take-off to its destination Villafranca (LIPX) with 25 passengers and four crew members. It was holding short of RWY 08R at the CAT I holding position on taxiway B4, which was designed as a high-speed exit for RWY 26L. About the same time, the Boeing 737 arriving from Amsterdam (EHAM) with 26 passengers and a crew of five was approximately two NM (3.7 km) from the threshold; its flight crew had contacted tower at 21:37:20 and been advised that landing clearance would be given on short final due to another departing aircraft, an Airbus A321 lined up on RWY 08R at the intersection with taxiway B2 near the runway threshold. It was cleared for take-off at 21:38:03 and commenced its take-off run 20 seconds later.

Shortly thereafter, the controller issued the following conditional clearance to the ATR flight crew, "[…] behind next landing short final line up 08 right behind." The ATR flight crew acknowledged, and commenced line-up after the departing A321 had passed the intersection B4 some 16 seconds later. Two seconds before the departing A321 lifted off, at 21:39:01, the Boeing 737 was cleared to land on RWY 08R, and crossed the threshold 11 seconds later. At this time, the ATR was moving very slowly and still 70 m from the runway centreline. During touchdown at 21:38, this distance had decreased to 40 m. Two seconds later, the flight crew aboard the Boeing 737 saw that there was another aircraft on the runway. They used the thrust reversers, maximum auto-brake and made a swerve to the right to avoid a collision with the ATR, which was approximately 10 m from the runway centreline when the Boeing 737 passed it at 21:39:26. Neither aircraft was damaged, and there were no injuries.

Post-incident interviews showed that the ATR flight crew had commenced line-up in the conviction that the A321 which had just passed on RWY 08R was the landing aircraft the controller was referring to in her conditional clearance. In fact, experiments conducted by the investigators revealed that in darkness, an aircraft passing B4 on RWY 08R could not unambiguously be identified as departing or landing. Due to the shallow angle (~ 30°) of B4 with RWY 08R, the approach sector could, contrary to the controller's assumption, not be surveyed visually by the ATR crew, who consequently had no chance of seeing the approaching Boeing 737 until it passed in front of them.

In conclusion, therefore, a fundamental pre-requisite for conditional clearances in ICAO Doc. 4444, that all of "*the aircraft or vehicles concerned are seen by the appropriate controller and pilot*" [ICA01a], was not fulfilled. Furthermore, the controller did not provide the ATR flight crew with required additional information, such as airline or aircraft type, that could have enabled them to positively identify the aircraft she was referring to. Merely using ‘next’ in the conditional clearance proved to be ambiguous.

In the 30 min preceding the incident, there were 24 movements, and 9 aircraft were on the controller’s frequency when the incident occurred. Due to the high traffic volume, the controller attended to other traffic immediately after clearing the Boeing 737 for landing, and therefore did not observe the emerging conflict situation visually or on the radar screen. It is particularly noteworthy that a so-called Runway Incursion Monitoring function based on surface movement radar data was available at Munich tower, but the system was not working properly, producing an unacceptable number of false and spurious alerts. Therefore, the controller had turned it off at her working position [BFU09].
In conclusion, this incident is remarkably similar to the accident in Paris in 2000 (cf. Appendix I-8), because line-up via a high-speed taxiway resulted in limited visibility of runway traffic, and there was also confusion about which aircraft a conditional clearance referred to.

I-16.2 Boston Logan International Airport (6/9/2005)

On June 9, 2005, about 19:40 local time, an Airbus A330-300 (EI-ORD) operated by Aer Lingus as Flight 132 (EIN132), and a Boeing 737-300, N394US, operated by US Airways as Flight 1170 (USA1170) were involved in a Runway Incursion at Boston Logan International Airport (KBOS) in daytime VMC conditions. There were neither injuries nor aircraft damage, and both airplanes proceeded to their respective destinations without further incident.

At the time of the incident, aircraft operating at KBOS were landing on runways 4R and 4L, and departing from runways 15R and 9. The KBOS Local East Controller (LCE) was responsible for aircraft operating on runways 4R and 9, and the KBOS Local West Controller (LCW) was responsible for aircraft operating on runways 15R and 4L. RWY 15R intersected three active runways: 4L, 4R, and 9. Because runways 4R and 9 were under the control of the LCE, the LCW was required to obtain a release from the LCE before authorising departures from RWY 15R.
At 1939:10, the LCW cleared EIN132 for take-off from RWY 15R. Five seconds later, the LCE cleared USA1170 for departure from RWY 9, although he had released RWY 15R for the Aer Lingus flight in an exchange with the LCW less than a minute before, and both aircraft commenced take-off.
Shortly after the V_1 callout, the first officer of USA1170 noticed the Aer Lingus A330 rotating just prior to the intersection of RWY 15R and RWY 9. Keeping their Boeing’s nose down by pushing the control column forward, the US Airways flight crew managed to prevent a collision with the Airbus A330, which passed overhead their aircraft with very little separation, and to lift off towards the end of the runway.

The subsequent investigation concluded that the probable cause of this Runway Incursion, which was classified as “Category A” according to the FAA severity scheme, was that the LCE had forgotten he had released RWY 15R for the Aer Lingus flight, most likely due to workload issues [NTS05].

I-16.3 Frankfurt/Main Airport (1/12/2006)

At 19:11 on January 12th, 2006, a Boeing 747-200B freighter that had arrived on RWY 07R from Beijing crossed RWY 07L while an Airbus A320 arriving from Dublin was landing on the same runway. The A320 was able to decelerate sufficiently to prevent a collision hazard. The incident, which occurred in night IMC conditions with visibility around 4,800 m, did not result in any damage or injuries.

During rollout on RWY 07R, the flight crew of the Boeing 747 had been instructed to "taxi Golf and hold short of runway 07L" at 19:08. However, since the readback, "Taxi Golf and Hotel eh hold short of runway 07L," was inaccurate with respect to the taxiways to be used, the controller repeated his instruction, "Yes on Golf **hold short of** runway 07L." Again, the flight crew's readback was incorrect, since they answered, "On Golf eh **cross** runway 07L." However, this breakdown of communication went unnoticed by the controller, who cleared the Irish Airbus A320 to land on RWY 07L immediately afterwards.
While decelerating after landing, and at a speed of approximately 100 kts (185 km/h), the flight crew aboard the Airbus observed a Boeing 747 entering and crossing the runway approximately 800 m downfield. The crew increased pressure on the brakes, immediately notified ATC at 19:11, and left the runway via taxiway G, thus following the Boeing 747 which had just crossed.

Since it corresponded to their expectations on the next instruction to be received from ATC, it appears that the Boeing 747 flight crew erroneously interpreted the controller's repeated instruction as new or updated, and therefore made a readback to the effect that they were approved to cross RWY 07L. The controller did not notice this error, and his landing clearance to another aircraft failed to raise any concern with the Boeing 747's flight crew, although this clearance was in contradiction to the instruction they believed to have received.

The controller did not observe the Runway Incursion. Although the surface movement radar at Frankfurt was supplemented by a Runway Incursion Monitoring function, it had been de-activated due to the frequent false alerts [BFU09a].

I-16.4 Newark Liberty International Airport (10/28/2006)

On October 28th, 2006, at 18:31 local time, a Continental Airlines Boeing 757-200 (N17105), inbound from Orlando as Flight 1883, erroneously landed on taxiway Z at Newark Liberty International Airport (KEWR) in night visual meteorological conditions after a circling approach to RWY 29. There were no injuries to the 154 persons aboard, and the aircraft was not damaged.

While inbound to Newark for a circling approach to RWY 29, ATC initially cleared Flight 1883 to the ILS approach of RWY 22L by default procedure. At an altitude of approximately 8,000 - 9,000 ft (2,700 - 2,400 m), the flight crew was then instructed to "circle to land on RWY29" as planned. The first officer, who had not performed a RWY 29 approach at Newark before, disconnected the autopilot at the glide slope intercept at an altitude of 3,000 feet (900 m), and manually flew the airplane to the outer marker on the ILS Runway 22L approach. At an altitude of 900 ft (270 m), the first officer turned the airplane onto the final approach for RWY 29, observing four white lights on the PAPI visible on the left when rolling level, and consequently pitching the airplane nose down to capture the proper glide path.

Apparently not remembering that the PAPI of RWY 29 was in a non-standard configuration on the right side of the runway (instead of the left), the flight crew believed they were established on the proper glide path, and had the runway centreline lights in view. As the airplane descended below 300 ft (90 m), it passed an intermittent rain shower, briefly reducing the flight crew's visibility of the runway. After clearing the rain shower, the flight crew confirmed final glide path alignment and noted that the PAPI appeared extremely bright compared to other lights. Moreover, lighting that appeared to be runway centreline lights were in view, and green high-speed turnoff lights were observed further down the “runway”. The airplane touched down on taxiway Z, near the intersection with R, at about 140 kts with a normal sink rate. When the first officer deployed the thrust reversers, the captain realised they had landed on taxiway Z, took control of the aircraft, and taxied to the gate without incident. Both the intensity of RWY 29 and taxiway Z lighting could be controlled in five steps. Interestingly, the runway lights were only on step 1, with the taxiway lights set to step 3; lighting procedures were later changed to have runway lighting always one step brighter than taxiway lights [NTS07d].

This incident indicates that erroneous landings on airport surfaces other than runways must be considered in the context of incursion avoidance, since non-standard approach aids – even if they are properly described by available airport information - may easily deceive even highly experienced flight crews – the captain of the incident flight had accumulated approximately 24,000 flight hours, and the first officer 6,202 h. Once more, this incident demonstrates how easily airport lighting can be misperceived under less than ideal visibility conditions.

I-16.5 Denver International Airport (1/5/2007)

A Swearingen Metroliner (N425MA), operating as Key Lime Air (LYM) Flight 4216 and a Frontier Airbus A319 (N915FR), Flight 297, were involved in a Runway Incursion at Denver International Airport (KDEN), on January 5th, 2007, at 07:28 local time.

LYM4216 had been instructed to taxi to RWY 34 from taxiway SC, via M and AA. According to the Metroliner pilot, however, blowing snow reduced his visibility, and taxiway SC was covered with snow, preventing him from seeing the centreline lighting. While attempting to find the centreline lighting, he saw blue taxiway edge lights and followed them. Instead of turning left onto taxiway M as intended, this brought him further straight ahead on taxiway M-2, and he eventually turned left onto RWY 35L at 07:27:06. At 07:28:10, the ground controller asked LYM4216 to confirm is location. Upon this question, the pilot noticed that he was on a runway.

In the meantime, FFT297 had been cleared to land on RWY 35L, and broke out of the clouds around 600 ft (180 m). Both pilots perceived the runway as clear at the time, and did not see the other aircraft, which was then approximately 2,000 ft (600 m) or more down the runway, until they were about 100 to 50 feet (30 to 15 m) above the runway. The first officer immediately commenced a go-around, missing the other aircraft by roughly 50 ft (15 m). Blowing snow and winds combined with the propeller wash from the Metroliner had obscured the aircraft from the Frontier flight crew. After the FFT297 flight crew initiated a go-around upon seeing the Metroliner, the Airport Movement Area Safety System (AMASS) activated at 07:28:17, and 4 seconds later, the tower controller instructed FFT297 to "go around" [NTS07e].

Two aspects of this incident are particularly noteworthy. The first is that snow may easily cover airport lights and markings, rendering them virtually unusable for airport navigation. Besides, blowing snow, irrespective of whether it is of natural origin or originating from jet or propeller wash, can easily create whiteout-like conditions, making visual acquisition of both airport features and other traffic exceedingly difficult. The second aspect is the timeliness of AMASS alerts, which apparently need fine-tuning although the system is already operational at many US airports. Given that both aircraft missed each other by only 15 m, and that the go-around instruction based on the AMASS alert reached the flight crew several seconds after they had already initiated it by themselves, it is somewhat questionable whether AMASS would have prevented an accident in this particular situation.

I-16.6 Almost a Runway Incursion?

On a night in November 2005, around 20:50 UTC, a Bombardier CRJ 700 was approaching Toulouse airport in night VMC. As visibility was excellent and the weather was calm, the captain turned of the autopilot and intercepted the ILS of RWY 14R manually. Between 3000 and 2000 ft, the crew asked ATC whether they could use RWY 14L, which has no centreline lighting, instead. The controller replied positively and immediately added "cleared to land RWY 14L". However, as the aircraft continued its descend, another aircraft which had apparently landed on RWY 14R could be seen taxiing slowly towards a RWY 14L. Around 500 ft radio altitude, it was obvious that the other aircraft was going to cross RWY 14L, which it had accomplished roughly at 400 ft radio altitude. At the same time, the controller asked the CRJ 700 to confirm that they were on final. When the crew confirmed, the controller said again "cleared to land RWY 14L", which the CRJ pilot non-flying acknowledged by replying "we were already cleared to land". The controller chose not to comment on this[160].

Although the situation was perfectly safe at all times, this incident was technically a Runway Incursion, because the controller cleared two aircraft for the runway at the same time without being fully aware of this situation, apparently. According to [ICA01a], section §7.9.3, an aircraft can be cleared to land provided there is "*reasonable assurance that the separation […] will exist when the aircraft crosses the runway threshold*." But in the context of the sequence of events, the double clearance seems unusual and suggests that the controller was probably in the wrong mindset, obviously still expecting the CRJ 700 on RWY 14R.

[160] The sequence of events is reported based on a credible personal account available to the author.

I-17 Further Incidents and Accidents

The following Runway Incursion incidents and accidents were also analysed for this thesis, but are not presented in detail, because they do not provide any significantly new aspects and insights with respect to crew human factors and flight deck instrumentation, compared to those already discussed in the previous sections:

- **Chicago O'Hare International Airport (2/15/1979):** The ground controller cleared a Delta Boeing 727-200 across RWY 9R because he overlooked an approaching Flying Tiger Boeing 747-F on the radar screen. To avoid a collision, the B-747 veered off the runway and was substantially damaged. According to the Safety Board, both the controller's error and a lack of vigilance of the Delta flight crew for approaching traffic were causal factors in this accident. However, due to a fog bank at the approach end of the runway and a restricted field of view from the cockpit, the Delta crew could not have seen the B-747 until 4 s prior to the near-collision [NTS79].
- **Minneapolis-St. Paul International Airport (3/31/1985):** Earlier on the day of the incident described in Appendix I-4, another local controller failed to provide sufficient separation and to promptly recognise that an Eastern Airlines DC-9 had rejected take-off on RWY 29L due to an engine failure, and cleared another aircraft to land on the same runway [NTS86].
- **Philadelphia International Airport (5/8/1985):** Lufthansa Flight 403, a McDonnell Douglas DC-10, successfully rejected take-off from RWY 27R when the flight crew observed a DC-9 crossing the runway. This Runway Incursion was again the result of a coordination breakdown between local and ground controller [NTS86].
- **Minneapolis-St. Paul International Airport (6/12/1985):** A Learjet taxied across RWY 29R while a Bemidji Airlines Beech 80 was in its take-off roll after an error in coordination between the local controller and the ground controller; the Bemidji aircraft continued take-off and eventually crossed the Learjet at an altitude of 200 ft (60 m) [NTS86].
- **Chicago Midway Airport (7/3/1985):** The ground controller forgot to instruct a B-737 to hold short of RWY 13, which was occasionally being used for take-off and landing, but not listed as active runway on the ATIS. As a result, the B-737 taxied across RWY 13 while a DC-9 was taking off from the same runway, eventually overflying the B-737 at an altitude of 200 ft (60 m) [NTS86].
- **Dallas-Fort Worth International Airport (2/27/1995):** In night VMC conditions, the local controller erroneously instructed a Swearingen SA227 (N355AE) to line up and wait on RWY 35L only seven seconds after clearing an American Airlines MD-11 (N1763) to land on the same runway. The supervisor, subsequently noticing the conflict, alerted the local controller. Because he did not remember the precise callsign of the American Airlines flight, and since the identification of aircraft on his radar screen had failed, the local controller issued emergency go-around instructions to the non-existing flights AA1251 and AA1261. Eventually, the MD-11 passed the other aircraft with 35 ft (11 m) vertical clearance [NTS95a]; the scenario resembles the Los Angeles Accident (Appendix I-6).

- **Atlanta-Hartsfield International Airport (1/18/ 1990):** An Eastern Airlines Boeing 727-200 (N8867E) landing on RWY 26R crashed into a Beechcraft King Air A100 (N44UE), which had landed on RWY 26R shortly before and was turning off the runway. While the pilot of the King Air was killed and his co-pilot severely injured, none of the 149 passengers and 8 crew members aboard the B-727 were harmed. The accident, which occurred around 19:04 local time in average traffic density and night IMC conditions, i.e. three miles (4828 m) visibility with haze, left the King Air totally destroyed and the Boeing 727 substantially damaged. The Eastern Airlines flight crew only saw the other airplane when their landing lights illuminated it, and although they attempted an evasive manoeuvre, it was too late, and the right wing of the B-727 hit the King Air. The investigation revealed that some of the King Air's strobes and red anti-collision lights had been inoperative, making it virtually impossible for the Eastern Airlines crew to see the other aircraft. It is particularly noteworthy that the NTSB determined "*the failure of the Federal Aviation Administration to provide air traffic control procedures that adequately take into consideration human performance factors such as those which resulted in the failure of the north local controller to detect the developing conflict between N44UE and EA 111*" as the first of two probable cause items, the second being the failure of the controller to ensure separation [NTS91b].
- **Paris Charles-de-Gaulle Airport (10/6/1998):** In a scenario remarkably similar to the accident in 2000 (cf. Appendix I-8), Streamline Flight 200 to Luton, a Shorts 330, erroneously lined up from a high-speed taxiway on the then single southern RWY 10 (now RWY 08L) while an Air France Boeing 747-400, bound for Tokyo, had been cleared for take-off from the threshold of the same runway. The Streamline flight crew, when requesting line-up, had neither specified its position nor requested an intersection take-off before, and the controller – erroneously believing the Shorts 330 was behind the Air France Boeing 747 as instructed, approved line-up. When the Shorts 330 entered the runway, the Air France crew saw the other aircraft, delayed initiating its take-off roll, and reported the incursion to ATC for clarification [BEA01].
- **Paris Charles-de-Gaulle Airport (9/26/2000):** At 19:50, a Lufthansa flight erroneously taxied onto RWY 26R via taxiway W7 in front of a FedEx flight, which had lined up via W10. DLH 4177 entered the runway at the same moment as FDX8A was cleared for take-off. According to the Lufthansa flight crew and other surrounding aircraft, the stop bar on W7 was not illuminated [BEA01].
- **Dallas-Fort Worth International Airport (8/16/2001):** During their take-off run on RWY 18L, the flight crew of Delta Airlines Flight 1521 observed another aircraft, a Continental Airlines Boeing 737, taxiing across the runway. They succeeded in avoiding a collision by applying full power and rotating early, but their aircraft sustained minor damage due to a slight tailstrike. The incident occurred in daytime VMC conditions. The NTSB investigation revealed that the controller had erroneously approved Continental Airlines Flight 1487 to cross RWY 18L although he had previously cleared Delta Airlines Flight 1521 for take-off on the same runway. When initiating the runway crossing, the Continental flight crew had perceived the other aircraft waiting lined up on the runway [NTS01].

For a number of further incidents, the available data does not provide sufficient detail to analyse Human Factors aspects involved and associated causal factors:

- **Newark Liberty International Airport (2/11/1993):** In night VMC conditions, the captain of a Continental Airlines Boeing B-727 became disoriented as to whether he was on the inner or outer taxiway, and made a wrong turn towards RWY 4L. Upon recognizing the runway edge lights, he realised his error and turned around in time to avoid collision with a departing Boeing B-737 [NTS93].
- **Chicago O'Hare International Airport (4/1/1999):** Shortly after 2 a.m., Korean Air Flight 36 and Air China 9018, both Boeing 747s, nearly collided on RWY 14R. Air China had just landed and was rolling out on RWY 14R when the tower controller instructed Korean Air to line up and wait. After Air China exited the runway at taxiway T10, the tower controller instructed the flight to turn left on taxiway K and cross RWY 27L, and then cleared KAL36 for take-off. As the airplane was rolling down the runway, Air China erroneously taxied onto RWY 14R. The Korean Air captain saw the 747 taxiing on to the runway, but since it was too late to abort, he lifted off earlier than normal and banked left to avoid striking Air China. The two aircraft, carrying 382 people, missed colliding by about 80 ft (24 m)[161].
- **Hamburg Airport (1/29/2004):** In CAT I conditions, after landing on RWY 23, a Fokker F50 crossed RWY 33 without authorisation while an Airbus A319 was on its take-off run on the same runway. Since the Fokker flight crew had already switched to the ground control frequency by its own initiative, it could not hear the controller's repeated warnings to hold short of RWY 33, and the A319 had to reject take-off at a speed of approximately 60 kts [BFU04b].
- **Seattle-Tacoma International Airport (10/30/2006):** Alaska Airlines Flight 61, a Boeing 737-200 (N740AS) took off from RWY 34R instead of the assigned RWY 34C. There were neither injuries to the 71 passengers or 5 crew members nor damage to the airplane, which continued uneventfully to its destination of Juneau International Airport, Juneau, Alaska [NTS07f].
- **Fort Lauderdale-Hollywood Airport (7/11/2007):** UAL1544, an Airbus A320, missed a turn onto taxiway B, instructed as part of the taxi route, for unknown reasons and consequently headed for RWY 9L, on which a Delta Airlines Boeing B-757 was cleared to land. The controllers noticed and resolved the Runway Incursion by instructing the United flight to stop immediately and the Delta aircraft to go around. The incident occurred in daytime VMC [NTS07g].
- **Los Angeles International Airport (8/16/2007):** When visually acquiring West Jet Flight 900 after landing, the responsible ground controller failed to recognize that the flight was north of RWY 24L and needed to cross the active runway to taxi to the gate. The West Jet flight crew proceeded to cross RWY 24L without explicit approval, and stopped beyond the holding line only when they noticed other traffic (NWA180) taking off [NTS07h].

[161] As sole reference, an animation of the incident is available on the NTSB website.

Appendix II: Visual Aids to Surface Navigation

Airport signs, markings and lights convey information that is essential for surface navigation. The following sections give a brief introduction to the most important signs, markings and lights as detailed by ICAO Annex 14 [ICA04b].

II-1 Airport Signs

The perhaps most concise overview of airport signs can be found in the FAA's *Pilot's Handbook of Aeronautical Knowledge* [FAA08a], as shown in Figure 234. Although it reflects the application of the ICAO standard in the United States rather than the standard itself, it is shown here for its brevity and clarity, and to illustrate diversity of airport signs due to both airport and national specifics.

Airport signs fall in two general categories. Signs with white text on a red background are referred to as Mandatory Instruction Signs, cf. Figure 235. They are used to identify a location beyond which an aircraft taxiing or vehicle must not proceed unless authorised by the aerodrome control tower, or not at all, as in the case of the 'NO ENTRY' sign.
The most important Mandatory Instruction Sign is the so-called runway holding position sign, which is located at holding positions on taxiways where they lead onto or cross a runway, and on intersecting runways. The signs contain the designation of the intersecting runway as shown in Figure 234 and Figure 235. The arrangement of runway numbers on the sign reflects the relative location of the corresponding runway threshold. As an example, "25-07" indicates that the threshold for Runway 25 is to the left and the threshold for Runway 07 is to the right.

Type of Sign	Action or Purpose	Type of Sign	Action or Purpose
4-22	**Taxiway/Runway Hold Position:** Hold short of runway on taxiway		**Runway Safety Area/Obstacle Free Zone Boundary:** Exit boundary of runway protected areas
26-8	**Runway/Runway Hold Position:** Hold short of intersecting runway		**ILS Critical Area Boundary:** Exit boundary of ILS critical area
8-APCH	**Runway Approach Hold Position:** Hold short of aircraft on approach	J →	**Taxiway Direction:** Defines direction & designation of intersecting taxiway(s)
ILS	**ILS Critical Area Hold Position:** Hold short of ILS approach critical area	↙ L	**Runway Exit:** Defines direction & designation of exit taxiway from runway
⊖	**No Entry:** Identifies paved areas where aircraft entry is prohibited	22 ↑	**Outbound Destination:** Defines directions to takeoff runways
B	**Taxiway Location:** Identifies taxiway on which aircraft is located	↖ MIL	**Inbound Destination:** Defines directions for arriving aircraft
22	**Runway Location:** Identifies runway on which aircraft is located		**Taxiway Ending Marker:** Indicates taxiway does not continue
4	**Runway Distance Remaining:** Provides remaining runway length in 1,000 feet increments	↙A G L →	**Direction Sign Array:** Identifies location in conjunction with multiple intersecting taxiways

Figure 234: Overview of the most important airport signs [FAA08a]

Where taxiways intersect runways close to the threshold, only the designation of the corresponding take-off runway may appear on the sign as shown in Figure 235 c, while all other signs typically feature the designation of both runway directions.

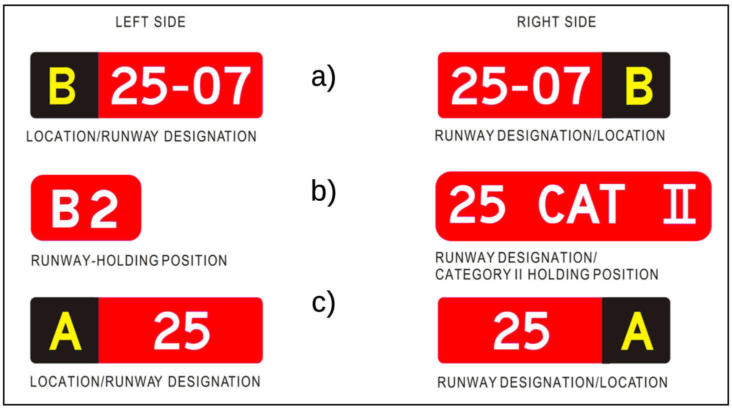

Figure 235: Mandatory Instruction Signs [ICA04b]

Mandatory Instruction Signs are also used in case it is necessary to hold aircraft on a taxiway at a location other than the previously described holding position to prevent interference with the Instrument Landing System (ILS) or with approach operations in general. The so-called ILS critical area is marked by a simple "ILS" sign or a reference to the corresponding approach category, i.e. by Category I, II or III holding position signs (cf. Figure 235), as appropriate [ICA04b]. Where basic geometrical considerations necessitate an additional holding position, "APCH" is used [FAA09]. Due to the criticality of the information they convey, holding position signs are placed on each side of the taxiway at intersections with runways.

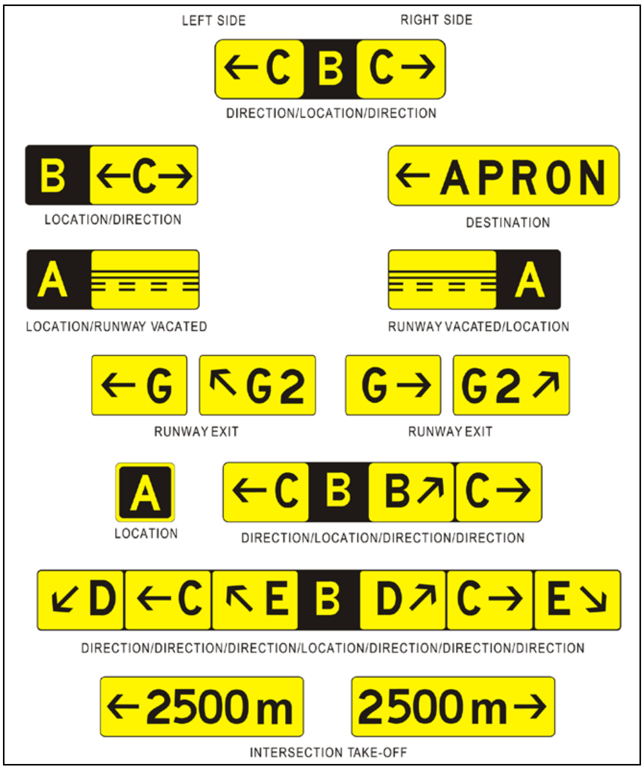

Figure 236: Information Signs [ICA04b]

The second category encompasses the so-called Information Signs, which use a black and yellow colour coding, cf. Figure 236.

Location signs identify the taxiway or runway the aircraft is currently located on by a yellow designator on a black background. Runway exit signs identify taxiways suitable to vacate the runway and exhibit the corresponding designator in black on a yellow background. Where runway exit taxiways do not feature centreline lighting, location signs are accompanied by signs indicating that the runway or the ILS critical area have been vacated; these signs mirror the corresponding surface marking. Direction signs also feature a yellow background with a black inscription identifying the designation(s) of the intersecting taxiway(s), accompanied by an arrow indicating the direction of the turn. Destination signs look like direction signs, but guide aircraft to specific airport destinations or facilities, such as terminals or the cargo area.

Information signs are typically placed at least 60 m ahead of the intersection; for certain taxiway-taxiway intersections, this may be reduced to 40 m. Direction and destination signs are placed to the left or to the right of location signs. All signs indicating left turns are located left of the location sign, all others on the opposite side, where the inner right side is reserved for directions/destinations straight ahead (where applicable) [ICA04b]. Most airport signs are lighted at night.

II-2 Airport Markings

Runway markings, which have priority over any other airport markings, are painted in white, whereas the colour for taxiway markings is yellow. Typically, reflective paint is used for airport markings to enhance their conspicuity during nighttime.

As a minimum, runway markings on paved runways consist of a dashed centreline marking and a painted two-digit runway designator (see Figure 237), which is supplemented by 'L' (left), 'C' (centre) or 'R' (right) for multiple parallel runways where required. These markings are generally sufficient for a runway intended for visual operations. However, additional markings are required for non-precision or precision instrument runways. Both require the white-striped threshold markings sometimes referred to as 'piano keys', which are also mandatory for visual runways used for international air transport. The number of stripes is used to code the runway width.

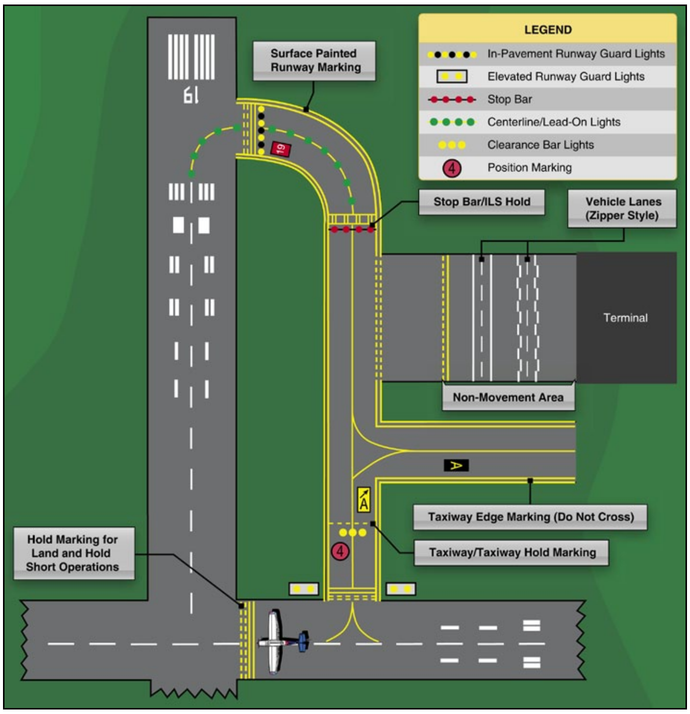

Figure 237: Sample application of airport markings in the United States [FAA08]

Additionally, rectangular aiming point markings located between 150 and 400 m from the threshold are required for instrument runways and visual runways either longer than 1,200 m or used by jet aircraft. Depending on runway length and width, these markings are between 30 and 60 m long and 4 to 10 m wide [ICA04b].

A continuous side stripe marking outlining the runway edge is mandatory for precision instrument runways or whenever there is a lack of contrast between the runway edges and the shoulders or the surrounding terrain. Precision instrument runways also require touchdown zone markings consisting of up to six pairs of rectangular bars symmetrically arranged about the runway centreline to identify the touchdown zone for landing operations. The number of pairs is related to the landing distance available and codes distance information in 150 m increments. The basic pattern consists of single bars, but alternatively, groups three, two and then single bars are used, as shown in Figure 237.

Continuous taxiway centreline markings are required on all paved taxiways, de-icing facilities and aprons to provide continuous guidance between the runway centreline and aircraft stands, except where the centreline intersects with a runway-holding position marking or an intermediate holding position marking as shown in Figure 238. At an intersection of a taxiway and a runway, the centreline of a taxiway serving as runway exit should be curved into the runway centreline marking as shown in Figure 237 and be extended parallel to the runway centreline marking for a distance of at least 30…60 m beyond the point of tangency. Taxiway centreline markings have to be at least 15 cm wide [ICA04b]. Taxiway edge markings are used when the taxiway edge does not correspond with the edge of the pavement [FAA09].

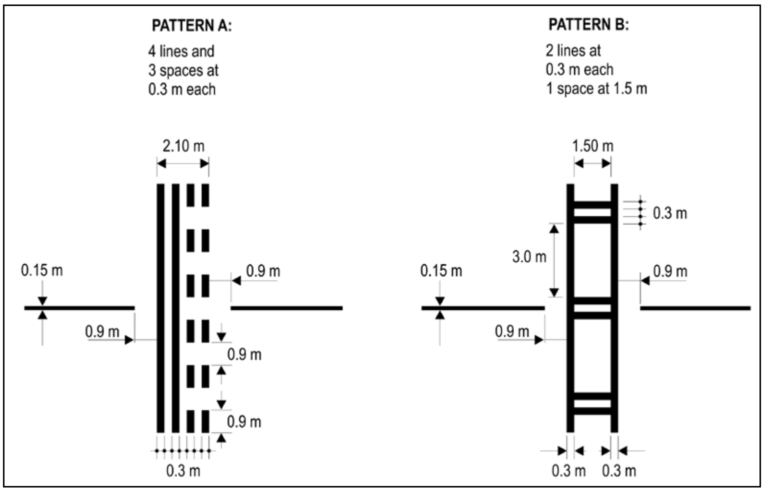

Figure 238: Runway holding position markings [ICA04b]

Runway holding positions are established at the intersection of a taxiway and a runway and at the intersection of two runways, if one runway is part of a standard taxi-route. Additional runway holding positions are necessary if the location or alignment of the taxiway is such that a taxiing aircraft or vehicle can infringe an obstacle limitation surface or interfere with the operation of radio navigation aids.

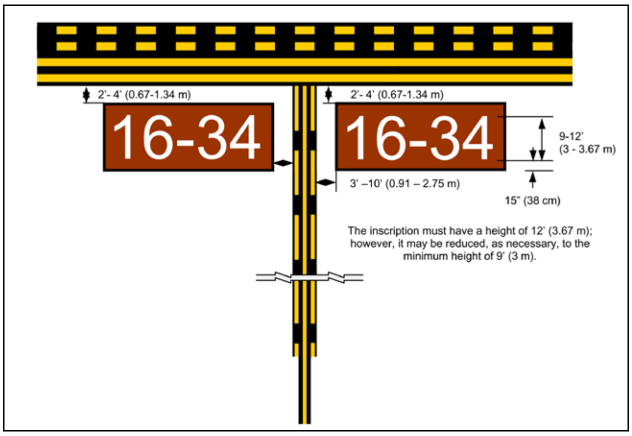

Figure 239: Enhanced taxiway holding position markings proposed by the FAA [FAA05a]

For non-precision approaches and take-off operations, runway holding positions are typically located 75 m from the centreline of the runway types commonly used for air transport operations. Whenever a taxiway and a non-instrument, non-precision approach or take-off runway intersect, the runway holding position marking shown in Figure 238, Pattern A, is used.

If the intersecting runway is a precision approach Category I, II or III runway, two or three runway holding positions at least 90 or 107.5 m from the runway centreline may be necessary, depending on the precise geometry and elevation of the intersection[162]. In this case, the runway holding position marking closest to the runway is always painted as shown in Figure 238, Pattern A, whereas the markings farther

[162] The distance may be decreased if the holding position is lower than the runway and has to be increased by 5 m for every metre that the holding position is above the threshold elevation. Additionally, airfield elevation may necessitate an additional increase of the distance, e.g. by one metre for every 100 m above 700 m for airports at elevations up to 2,000 m. For aerodromes located at elevations of 4,000 m or higher, a supplement of 43 m plus two metres for every 100 m above 4,000 m is required [ICA04b].

from the runway correspond to Pattern B [ICA04b]. To enhance the conspicuity of holding position markings in an effort to reduce the number of Runway Incursions, the FAA has proposed to supplement the Pattern A holding position markings by painted runway designators and an enhanced taxiway centreline as shown in Figure 239, which is now part of the standards for aerodrome markings [FAA05a].

II-2.1 Designation and Marking of Closed Runways

According to ICAO Annex 14, "*a closed marking shall be displayed on a runway or taxiway, or portion thereof, which is permanently closed to the use of all aircraft*" [ICA04b]. The same applies to temporarily closed runways (and taxiways) as well; markings may only be omitted if the closure is of short duration and adequate warning is provided by air traffic services[163]. The markings to be used are specified in detail by Annex 14. Closed runways have to be marked by a cross resembling a capital "X" of 36 m length and 14.5 m width that must be positioned on the runway centreline. The lines of the X should have a width of 1.8 m. Likewise, closed taxiways must be marked with a smaller, quadratic cross of 9 m in size, painted with a line width of 1.5 m; see Figure 240 for details[164]. The aerial photo inset shows an exemplary application of the ICAO guidelines at Vienna International Airport (LOWW).

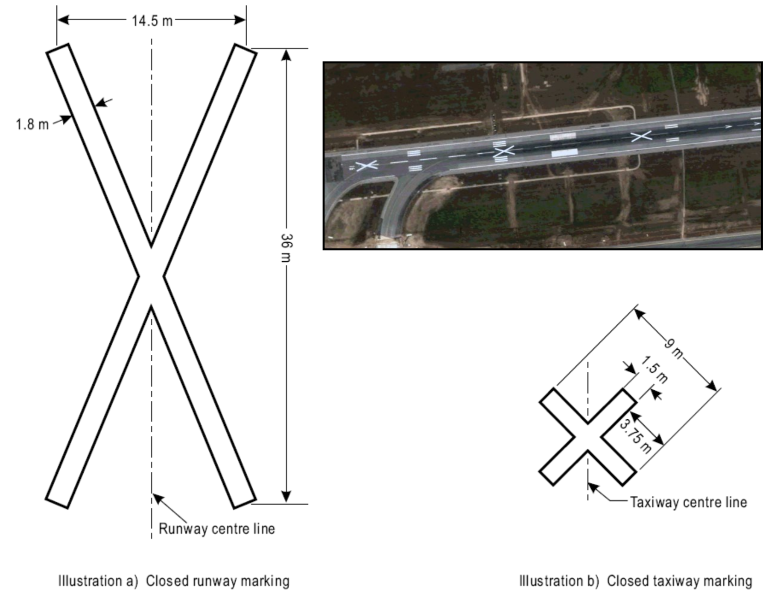

Figure 240: ICAO runway and taxiway closure markings [ICA04b]

The closure marking must be placed at each end of a closed runway or runway segment. Additional markings have to be placed in between, and the maximum permis-

[163] After the incident described in [NTS03], the NTSB questioned the practice of leaving the decision to omit temporary closure markings to the airport operator in a Safety Recommendation to the FAA, but the paragraph in question was not changed in the new version of AC 150/5340-1 [FAA05a], which gives guidance on airport markings.

[164] In the Unites States, alternatively, closed runways may be marked with a quadratic cross twice the size of the ICAO closed taxiway marking shown in Figure 240. Likewise, closed taxiways may alternatively be indicated by an elongated cross half the size of the ICAO closed runway marking [FAA05a].

sible interval between markings is 300 m. On closed taxiways, markings shall be placed at least at each end of the closed taxiway or taxiway segment.
Regarding the colour of the markings, ICAO prescribes that runway closure markings must be white, while those for taxiways have to be painted in yellow, i.e. the closure markings are painted in the predominant marking colours of runways and taxiways, respectively. In the United States, both closure markings are applied in yellow [FAA05a].
For permanently closed runways or taxiways, ICAO mandates additionally that the normal markings should be obliterated, which is a requirement that cannot be fulfilled for temporary closures, all the more as frangible barriers or markings utilizing materials other than paint or "*other suitable means*" may be used to identify the closed area in this case. For temporary closures, often only one cross is placed on each threshold on top of the runway designation markings [FAA05], and some airports reportedly use electrically lighted, X-shaped markers placed on the threshold.
Any other lighting on a closed runway, closed taxiway or any portion thereof should not be operated, except for maintenance purposes. During Low Visibility Operations, such lighting should not be operated under any circumstances [ICA08].

II-3 Airport Lights

II-3.1 Runway Lights

Runway edge lights are used to outline the edges of runways during periods of darkness or restricted visibility conditions. They are required for night operations or on precision approach runways, and should be provided whenever take-off operations in RVR conditions of less than 800 m are performed. Runway edge lights are generally white, but on instrument runways, yellow may replace white on the last 600 m or within the last third of the runway, whichever is less, to form a caution zone for landings. For instrument runways, spacing should not exceed 60 m. The threshold lights at the end of the runway emit red light toward the runway to indicate the end of runway, whereas green light is emitted outward from the runway in the direction of the approach to indicate the threshold to landing aircraft.

Runway centreline lights are required for Category II/III approach operations and take-off in RVR conditions below 400 m, but installed with a spacing of 15 m on most precision approach runways to facilitate landing under adverse visibility conditions. From the landing threshold, runway centreline lights are white until the last 900 m of the runway. The white lights begin to alternate with red for the next 600 m, and for the last 300 m of the runway, all centreline lights are red.

Touchdown zone lights are required for Category II/III approach operations and are available on many precision approach runways, consisting of two rows of transverse white light bars disposed symmetrically about the runway centreline, extending 900 m beyond the landing threshold or to the midpoint of the runway, whichever is less.

Taxiway centreline lead-off lights provide visual guidance to aircraft or vehicles exiting the runway. They are colour-coded to warn pilots and vehicle drivers that they are within the runway environment or landing system critical area, whichever is more restrictive. Alternate green and yellow lights are installed, beginning with green, from the runway centreline to the perimeter of the ILS/MLS critical or sensitive area. In the opposite direction, the same lights serve as lead-on lights with the same intention, cf. Figure 237. On runways approved for Land and Hold Short Operations (LAHSO), **Land and hold short lights** indicate the hold short point by a row of pulsing white lights across the runway when LAHSO is in effect.

A description of the various approach lighting systems is beyond the scope of this thesis; details can be found in ICAO Annex 14 [ICA04b] or the FAA Aeronautical Information Manual (AIM) [FAA09].

II-3.2 Taxiway Lights

To facilitate operations at night and under low visibility conditions, **taxiway centreline lights** are illuminated in green, whereas **taxiway edge lights** outline the edges of taxiways by blue lights. Taxiway centreline lights with 15 m spacing are required for operations below 350 m RVR; 30 m spacing is sufficient in most other cases. At holding positions on taxiways, yellow clearance bar or intermediate holding position lights are installed to increase the conspicuity of the holding position during periods of darkness or in low visibility (see Figure 237).

At the intersection of taxiways and runways, two alternately flashing yellow **Runway Guard Lights** are installed to enhance the conspicuity of the taxiway/runway intersection. While originally intended for low visibility conditions, they are typically operated regardless of the meteorological conditions [ICA04b].

Stop bar lights are typically required below 350 m RVR and used to confirm the ATC clearance to enter or cross the active runway in low visibility conditions. A stop bar consists of a row of red, unidirectional, in-pavement lights installed across the entire taxiway at the runway holding position, and elevated red lights on each side. A controlled stop bar is operated in conjunction with the taxiway centreline lead-on lights, which are extinguished for at least 90 m behind a lighted stop bar. Following the ATC clearance to proceed, the stop bar is turned off and the lead-on lights are turned on. Typically, the stop bar and lead-on lights are automatically reset by a sensor or backup timer. Pilots should never cross a red illuminated stop bar, even if an ATC clearance has been given to proceed onto or across the runway [ICA04b, FAA09].

Appendix III: MCDU Pages

III-1 MCDU Pages for ePIB

Figure 241: ePIB Main page (MCDU), first design

Figure 241 illustrates the initial design proposal for the ePIB main menu, implemented as a MCDU page. The first line specifies the flight number/flight plan callsign, the ePIB creation date (in most cases this will be identical with the flight date) and the time at which the current bulletin was produced. By pressing the keys adjacent to ORIGIN, DESTINATION, ALTERNATE and ENROUTE, the crew can review the PIB content for the respective airport or flight segment on dedicated pages, with examples given in Figure 244/Figure 245. The link to the LOAD page may be used to upload a different ePIB, e.g. if AOCC sends an update while still on the ground. By default, any available ePIB is always loaded in the most recent version as soon as the appropriate flight number or callsign has been entered on the INIT page. Touching the key next to REQUEST will open a new menu page on which the crew can request updated NOTAM information from AOCC. Depending on the available means of communication with AOCC, this might be a shortcut to the corresponding ACARS page. In the future, this function could be extended by requests directly to the AIS provider. As usual, the RETURN key will re-call the previous page.
As it should be beneficial from an operational point of view to visualize the selections for origin, destination and alternate airport as a reminder, the menu was rearranged slightly in the first implementation for the FLYSAFE project (in cooperation with NLR) to enable a display of the corresponding ICAO identifiers adjacent to the respective items, as shown in Figure 242. Data are from an actual Lufthansa Cargo flight from Tselinograd/Aqmola (UACC) in Kazakhstan to Frankfurt/Main (EDDF), with Frankfurt-Hahn (EDFH) set as a destination alternate [DLH06a]. Nevertheless, since it is not desirable that the crew can alter selections already made on the INIT page, this layout should be improved further, all the more as it requires to merge the LOAD/REQUEST item and does not leave any room for potential future extensions.

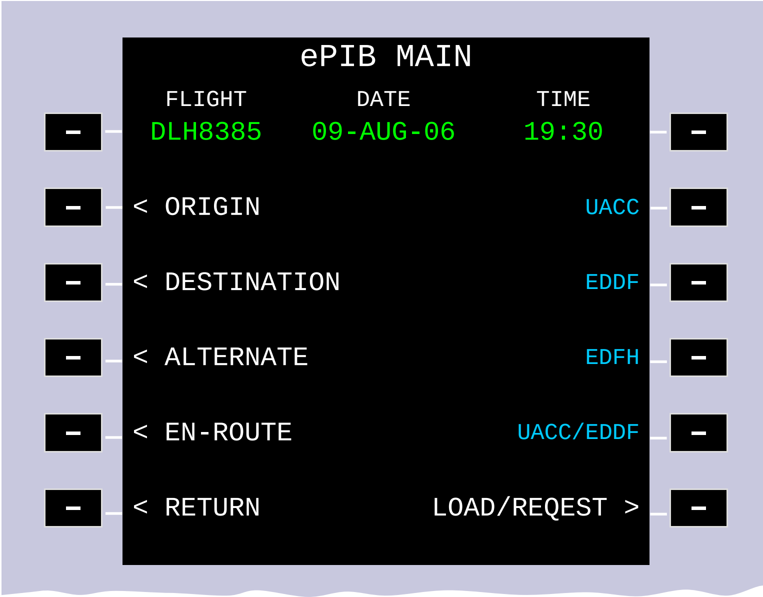

Figure 242: Alternative ePIB Main page (MCDU)

Figure 243 presents a combination of both solutions, which uses the structure of the initial design from Figure 241, but indicates the current airport selections as fixed data below the corresponding menu items to address the issues mentioned above.

Figure 243: Final ePIB Main page (MCDU)

Any PIB is created for a specific combination of origin and destination. However, since information on several alternate airports is usually contained as well, and thus also in the corresponding ePIB, any change of destination or alternate airport on the INIT page could automatically be reflected on the ePIB Main page as long as the corresponding data are available. If the original ePIB package does not contain information on a selected airport, its ICAO identifier will change to amber. If no flight number has been entered yet, amber dashes in lieu of flight number, date, time and airport identifiers will indicate this.

An amber flight number and the removal of all menu options except RETURN and LOAD, along with a text message such as "LOADING FAILURE" (also in amber) will announce an ePIB failure.
From a usability perspective, flight crews may not want to go back to the INIT page and change the alternate airport just to review NOTAM information for a different alternate airport. This aspect is addressed by the design of the respective ePIB NOTAM page shown in Figure 244, which is called for the respective airport if the line select keys adjacent to ORIGIN, DESTINATION or ALTERNATE in Figure 243 are pressed. Below the airport name and its ICAO identifier, this ePIB NOTAM page lists the NOTAMs contained in the ePIB for this airport. Furthermore, there is a direct link to the Airport Menu (see next section) of the respective airport.

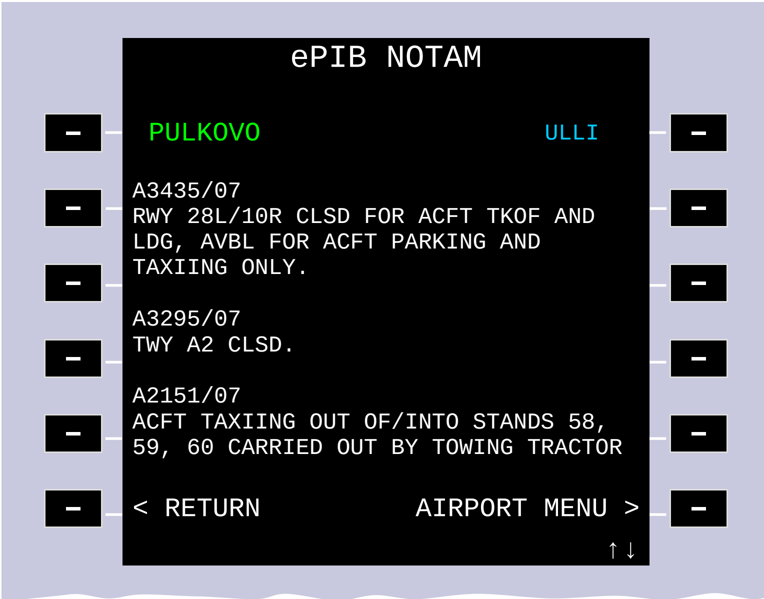

Figure 244: ePIB NOTAM page (MCDU) for airports

By entering a different ICAO identifier using the 1R key, the flight crew can review NOTAM information for any other airport contained in the ePIB, which gives quick access to NOTAM for different (alternate) airports. "NO CURRENT NOTAM" will be displayed in white for any airport covered by the ePIB which does not have any current NOTAMs. By contrast, "NO DATA AVAILABLE" will be indicated in amber for any airport not covered by the ePIB, and likewise, "NOT IN DATABASE", also in amber, will be shown for any airport not covered by the current navigation database of the aircraft.

Any NOTAM which has expired during the flight will be displayed in amber to reflect the fact that it is no longer active, and moved to the end of the active NOTAM list. Furthermore, NOTAM information that is applicable only for a certain period of time during the day will be presented in yellow outside the hours in which it is applicable. To determine this, depending on the distance and the type of NOTAM, either local time or the estimated time of arrival (ETA) are used, potentially combined with a hysteresis of several minutes, as discussed in Section 5.3.4.1.

If an airport is not covered by the ePIB of the current flight, but NOTAM files from previous ePIBs for a different flight are still available and valid, these might be shown as well, but with an amber reminder like “NOT IN CURRENT EPIB” on the ePIB NOTAM page to indicate that the information shown may not be complete.
While the design shown in Figure 244 might give quick access to all NOTAM information, it could become increasingly inefficient with a growing number of applicable NOTAM. Figure 245 shows an alternative approach permitting a more structured review of NOTAM information based on the categories used in conventional PIBs issued by Lufthansa Systems, cf. [DLH06a]. However, this requires an additional pilot selection by pilots before individual NOTAM can be reviewed. However, this solution might be complementary to the solution above, and could e.g. be employed only if the ePIB contains the corresponding structure, which the latter would by default in case there are e.g. 10+ applicable NOTAM for an airport. This might allow the flight crew to access the information of interest in a more structured way.

Figure 245: ePIB NOTAM page (MCDU) for airports, alternative design

A potential further drawback of the scrollable plain-text presentation of NOTAM information in Figure 244 is the lack of a possibility to interact with individual NOTAM. However, it is difficult to find a suitable approach to interactivity. With NOTAM serial numbers, which are virtually meaningless to pilots, as sole menu items, the flight crew would successively have to call up several NOTAM to locate the information they are looking for, which does not seem desirable. A way of avoiding this drawback could be listing the first couple of characters below the corresponding identifier for each NOTAM, as shown in Figure 246. In this approach, the full NOTAM text and further details could be accessed through the line-select keys adjacent to the NOTAM number where required. For the NOTAM relating to the runway closures at Frankfurt Airport, A1977/06 and A1970/06, the main information is already visible on this summary page. The colour-coding of the text indicates that these two NOTAM are currently not applicable, since the estimated ETA is outside the time of daily validity, as discussed above.

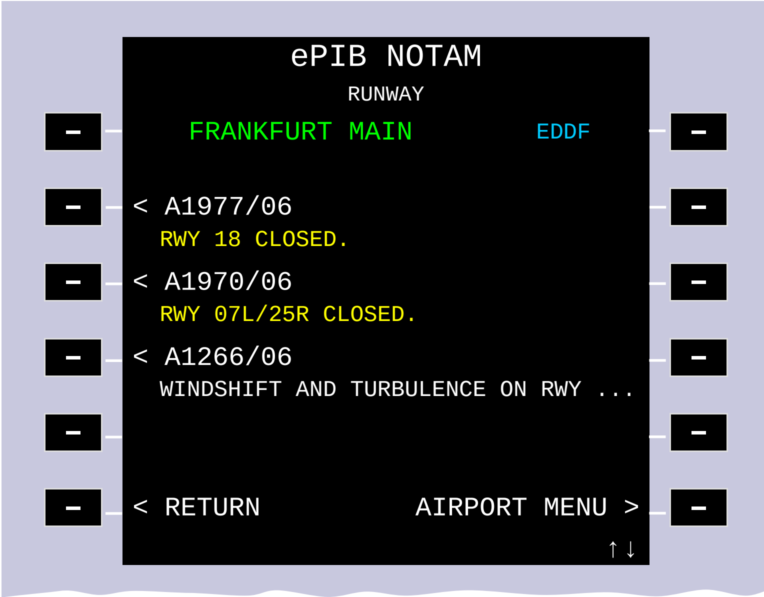

Figure 246: ePIB MCDU page for runway-related NOTAM

For NOTAM A1266/06, three dots at the end of the line indicate that more text is available. Figure 247 presents the review page for an individual NOTAM, which is titled with the NOTAM number and, once more, the airport or FIR name and the corresponding ICAO identifier, which takes into account that NOTAM numbers are not unique; cf. [ICA04].

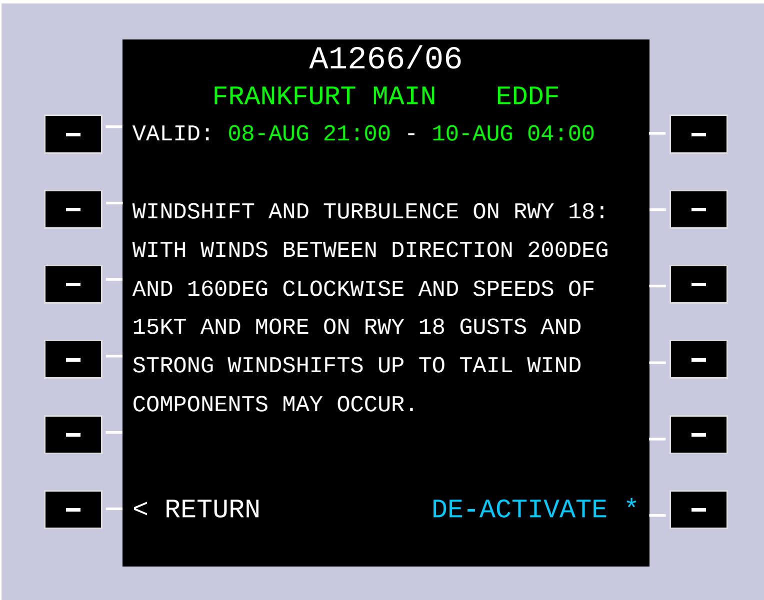

Figure 247: ePIB NOTAM review page

Immediately below the airport/FIR name, the period of validity is given. The remainder of the page is dedicated to a display of the plain-text information contained in the corresponding NOTAM file. In case the crew learns via radio or other means that a NOTAM has been cancelled, they can manually de-activate the corresponding NOTAM. This will not only change the text to amber, but more importantly discontinue the use of the machine-readable part of the NOTAM by any other avionics system. Thus, if a runway closure NOTAM is manually de-activated, the closure crosses will be removed from the corresponding runway on the airport moving map, and there will be no longer any alerting related to runway closure on that particular runway. Likewise, the inverse process should also be possible at least for expired NOTAM having only an estimated end of validity. These could be re-activated using this same page, for which the 6R line caption would then change to "RE-ACTIVATE".

Figure 248: ePIB NOTAM review page with highlight function

Daily limitations of validity should also be indicated for any NOTAM containing a corresponding restriction, as illustrated by Figure 248. For NOTAM referring to an AMDB or navigation database element or any other item with a defined geographical location, such as a temporary obstacle, the corresponding features could be highlighted on the ND if the "HIGHLIGHT" function is activated. The operational value of this highlighting feature will, however, have to be evaluated by further studies.

III-2 MCDU Pages for SMAAS

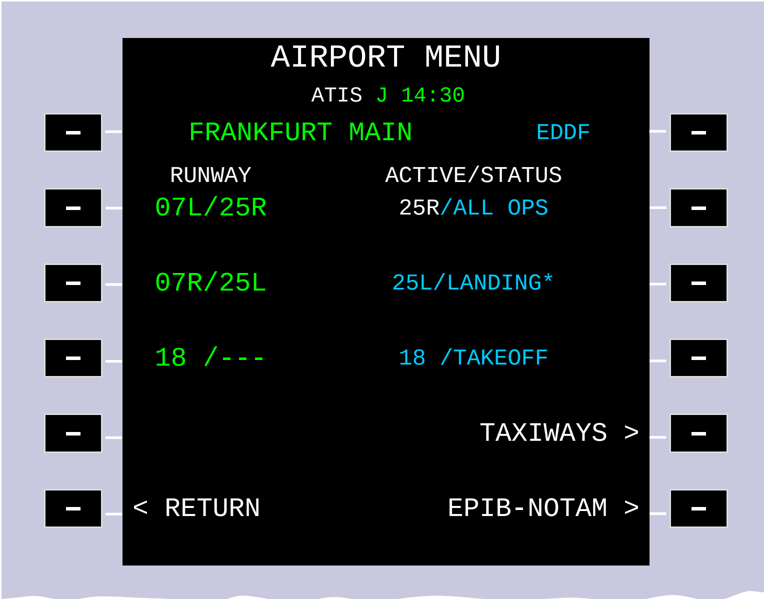

Figure 249: Airport Menu, the main SMAAS MCDU page

The proposed MCDU Airport Menu (Figure 249) provides a synoptic overview of the runways available at a certain airport and their status. This enables the flight crew to review, complete and amend ePIB and D-ATIS information regarding the operational status of the runways for any given airport.
The official name of the airport and its ICAO identifier are displayed adjacent to the 1L and 1R key, respectively. This is required for an unambiguous identification of the aerodrome concerned. Otherwise, there is a risk of confusing airports with similar ICAO identifiers and identical runway designators. As an example, both Munich (EDDM) and Berlin-Tegel (EDDT) have two parallel runways named 08L/26R and 08R/26L, respectively. Using the 1R key, the crew can retrieve data for a different airport by entering its ICAO identifier. Airport name and available runways are extracted from the ARINC 424 FMS Navigation Database [ARI02], or alternatively as back-up, the Airport Database (ADB), for each airport.
Since a possibility to indicate both the runway-in-use (if applicable) and the general runway status is required, the runways available at the corresponding airport are displayed adjacent to the left hand side LSKs 2L to 4L. Like for any other fix information that may not be modified, a green font colour is used. As shown in the figure, runway identifiers are presented with the lower magnetic runway heading first, and listed by increasing runway heading. For parallel runways, the sequence is Left, Centre, Right. Runway status information is partially obtained from the ePIB, partially from D-ATIS, which is used to retrieve active runway information. To indicate on which ATIS transmission the information presented is based, ATIS code letter and the associated release time are indicated. The FMS-selected runway will always be indicated in white, irrespective of whether active runway information is available. If the status of the FMS-selected runway is not compatible with the desired type of operation, it is presented in amber, as shown in Figure 250.
If there are specific restrictions to a runway, e.g. regarding the available length, the corresponding status indication is supplemented by an asterisk, as shown for RWY

25L in Figure 249. Detailed runway information, with a possibility to review and manually adapt restriction information, could then be accessed by pressing the line-select keys on the left adjacent to the corresponding runway designators.
Apart from the default RETURN option, the Airport Menu features a direct link to the ePIB NOTAM page (see previous section) for the corresponding airport, which the crew can use to obtain more detailed information, e.g. on the reasons for a runway closure, and for a review of other pertinent airport information.

Since pilots might want to preview the airport moving map for a specific airport in flight, e.g. during the approach briefing or when considering a diversion to an alternate airport, it is envisaged that the MCDU Airport Menu can also be used to select any airport contained in the ADB for display on the ND screens. By slewing the position reference to the ARP of the airport currently entered on the MCDU Airport Menu, the corresponding airport moving map is shown on the ND irrespective of ownship position[165], provided that the Airport Menu is the active MCDU page and that the ND on the same cockpit side is in PLAN mode (and has a suitable range setting).

Future studies will have to reveal whether a dedicated page for the review and potential amendment of taxiway closures and limitations, as indicated by the caption TAXIWAYS (5R) in Figure 249, is required or desirable. It is likely, though, that a synoptic overview will not be necessary, since taxiway closures and restrictions are neither as time- nor safety critical as those of runways. At any rate, the absence of the TAXIWAY menu item will provide more room to review runway information for complex airports.

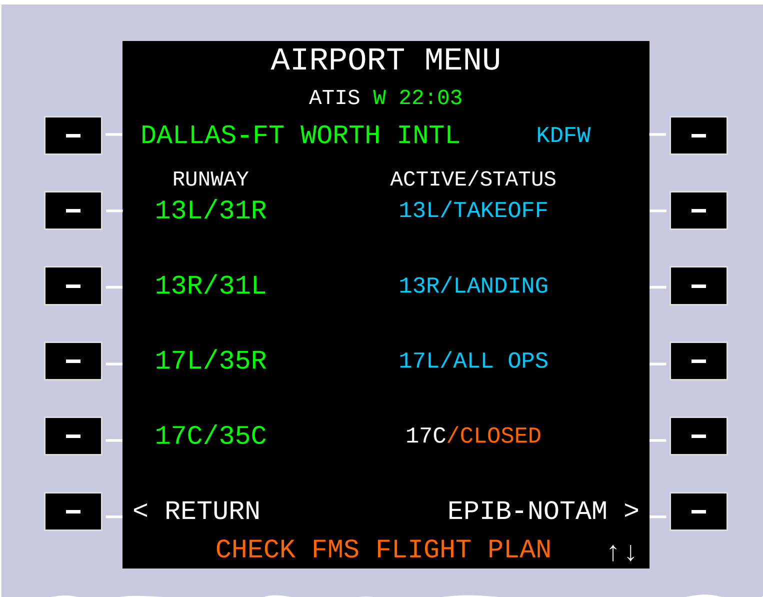

Figure 250: Airport Menu for Dallas-Fort Worth International (KDFW), Part A

[165] It should be noted, however, that although the airport selection influences only the EFIS on the CPT or FO side, respectively, any amendments made to the runway status data will affect the overall system.

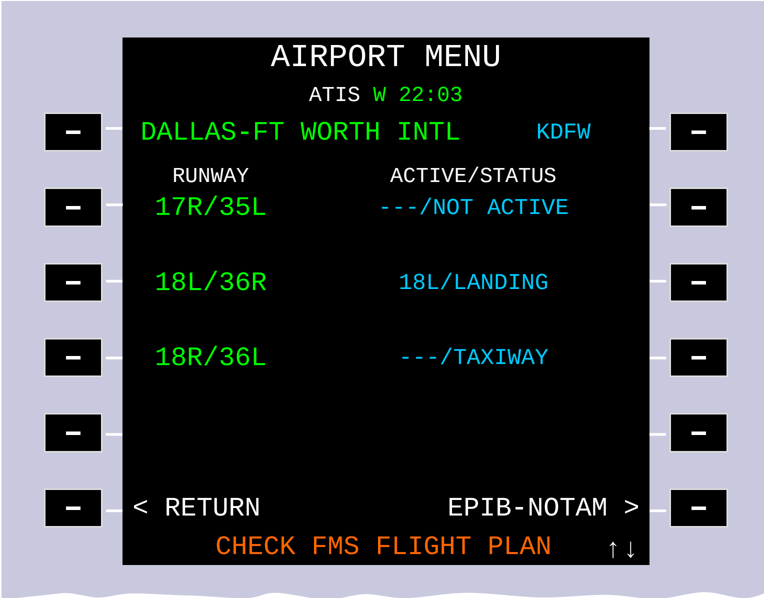

Figure 251: Airport Menu for Dallas-Fort Worth International (KDFW), Part B

Figure 250 and Figure 251 illustrate the behaviour of the Airport Menu for airports with more than four runways, such as Dallas-Fort Worth International Airport (KDFW), which has seven runways. In this special case, the crew has to use the vertical slew keys (↑ and ↓, cf. Figure 59) to scroll through all the runway information available. At the same time, this example is used to demonstrate further envisaged features of the Airport Menu. In Figure 250, the crew has selected RWY 17C as take-off or landing runway in the FMS flight plan. However, since the runway is closed according to ePIB information, the status is displayed in amber instead of blue. Additionally, a message “CHECK FMS FLIGHT PLAN” in the scratchpad advises pilots of this inconsistency, which might result in a dangerous situation if not resolved. As Figure 251 indicates, the message is shown irrespective of whether the corresponding runway is in view on the screen or not. In this example, RWY 17R/35L is neither active nor closed, which is indicated by the dashes and the “NOT ACTIVE”. Technically, the crew could request this runway for take-off or landing, provided there are significant operational reasons [ICA01a]. By contrast, RWY 18R/36L is closed and may only be used as a taxiway, and depending on the precise nature of the closure, it may not be possible for the airport authority to make this runway available on flight crew request, however valid the operational reason might be.

Figure 252 once more uses the example of Frankfurt/Main Airport (EDDF). It is assumed that the ePIB for the flight contains the NOTAM A1970/06 already shown in Figure 246, which effects a daily closure of RWY 07R/25L between 20:30h – 04:00h. Consider the following scenario: A cargo flight taxiing out for departure on taxiway S from the south apron at 03:45h learns from ATC that the runway is already open again, and might elect to use RWY 07R instead of the planned RWY 07L because of the shorter taxi route. In this case, the existing runway status information must be amended. One way of achieving this would be to search and deactivate the corresponding NOTAM as described in the previous section. It appears more convenient, however, to amend runway status information manually.

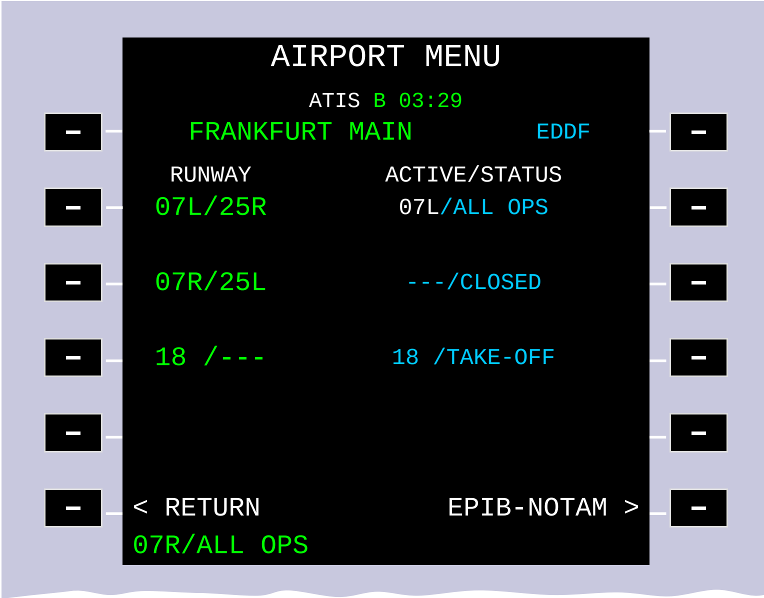

Figure 252: Airport Menu page with runway closure

Therefore, the flight crew has entered "07R/ ALL OPS" in the MCDU scratchpad. The result of inserting this information using the 3R key is shown in Figure 253. Manually amended status and active runway information are shown in a larger font to reflect the manual revision, cf. [Tha05]. Since this updated information does not reflect a specific ATIS information any longer, the corresponding indication is removed.

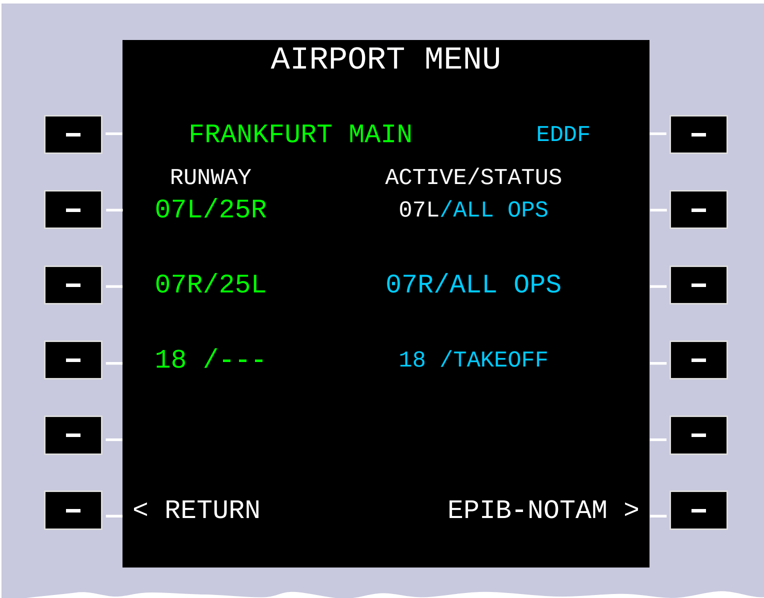

Figure 253: Airport Menu page with manual revision of runway status

Figure 254 shows the Airport Menu page for a manually selected airport (ICAO identifier in large font) for which no ePIB or D-ATIS information is available. Information on active runways and runway status can be entered manually. Of course, a full entry of all runway-related data by hand is not desirable, since it puts extra workload on the crew in the flight preparation phase.

Figure 254: Airport Menu page for manually selected airport without ePIB and D-ATIS

In principle, the crew could limit manual entries to any runway closures known to them. It should be stressed once more that the basic runway closure display and alerting functions do not require active runway and status information for all runways; one entry for a single closed runway is sufficient.
Figure 255 illustrates the behaviour of the Airport Menu page for airports for which, for whatever reason, no runway data is available. In the example below, the airfield in question, Fuldatal Heliport (EDVZ), is obviously used for helicopters only. The same behaviour could be applied to all minor airfields that do not have paved runways. By contrast, for an airport not in the customized navigation database of an aircraft, or an incorrect ICAO identifier, the airport name in the above example will remain blank, with just three amber dashes, and the third line will show "NOT IN DATABASE" in amber.

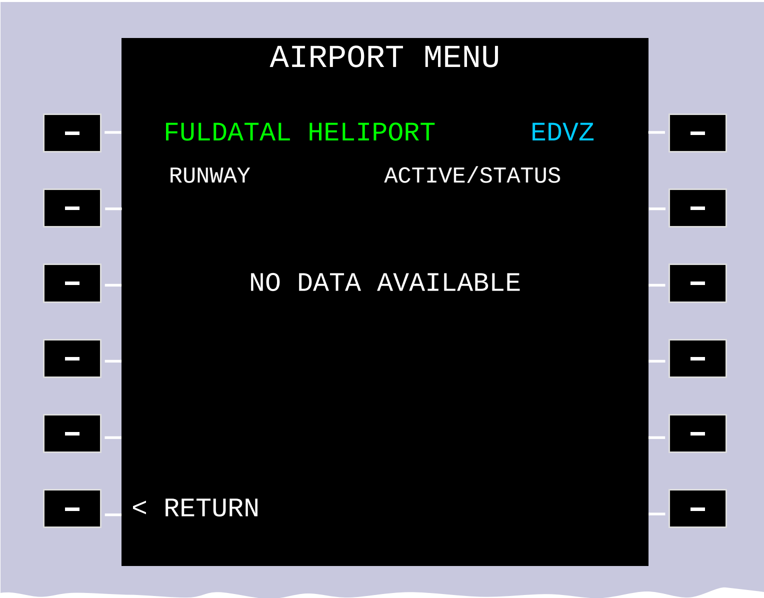

Figure 255: Airport Menu page in case of airport data unavailability

References

[AAI06] AIR ACCIDENT INVESTIGATION & AVIATION SAFETY BOARD (AAIASB): *Aircraft Accident Report: Helios Airways Flight HCY522, Boeing 737-31S, at Grammatiko, Hellas, on August 14 2005*, Accident Investigation Report 11/2006, Ministry of Transport and Communications, Hellenic Republic, Athens 2006

[AAU09] AIR ACCIDENT INVESTIGATION UNIT: *Final Report on the Accident Occurred on 25 May 2008 at Brussels Airport on a Boeing B747-209F Registered N704CK*, Ref. AAIU-2008-13, Brussels 2009

[ACS05] ACSS, *ACSS Joins with UPS to Develop SafeRoute*, Press Release, June 15, 2005, Le Bourget, 2005

[ACS07] ACSS, *ACSS Receives STC & TSOA on SafeRoute for B757*, Press Release, July 23, 2007, Phoenix, 2007

[Air03] AIRBUS S.A.S.: *Global Market Forecast 2003-2022*, Toulouse-Blagnac 2003

[Air04] AIRBUS S.A.S.: *Global Market Forecast 2004-2023*, Toulouse-Blagnac 2004

[Air04a] AIRBUS CUSTOMER SERVICES: *Getting to Grips with Datalink*, Flight Operations Support & Line Assistance, Toulouse-Blagnac 2004

[Air04b] AIRBUS CUSTOMER SERVICES: *Getting to Grips with FANS*, Flight Operations Support & Line Assistance, Toulouse-Blagnac 2004

[Air05] AIRBUS S.A.S.: *Airbus A320 Flight Crew Operating Manual, Vol. 1, Systems Description*, Revision 37, Toulouse-Blagnac 2005

[Air05a] AIRBUS CUSTOMER SERVICES: *Takeoff and Departure Operations: Revisiting the "Stop or Go" Decision*, Flight Operations Briefing Notes, Toulouse-Blagnac 2005

[Air06] AIRBUS S.A.S.: *Global Market Forecast: The Future of Flying, 2006-2025*, Toulouse-Blagnac 2006

[Air07] AIRBUS S.A.S.: *Global Market Forecast: Flying by Nature, 2007-2026*, Toulouse-Blagnac 2007

[Air08] Sophie DE CUENDIAS: *The Future Air Navigation System FANS B: Air traffic communications enhancement for the A320 Family*, Airbus FAST Magazine No. 44, Tolouse-Blagnac 2008

[Air09] AIRBUS S.A.S.: *Airbus A380 Airplane Characteristics*, Revision No. 8, Toulouse-Blagnac 2009

[Air10] AIRBUS S.A.S.: *Airbus A340-500/-600 Airplane Characteristics*, Revision No. 8, Toulouse-Blagnac 2010

[AIU03] AIR ACCIDENT INVESTIGATION UNIT (AAIU): *AAIU Formal Report No: 2003/010*, AAIU File No: 2002/0050, Department of Transport, Republic of Ireland, Dublin 2003

[ALP78] Airline Pilots' Association (ALPA): *Human Factors Report on the Tenerife Accident*, Engineering and Air Safety Division, Washington D.C. 1978

[ALP07] Airline Pilots' Association (ALPA): *Comair MEC Analysis on Flight 5191 Accident for NTSB*, 2007

[And95] A. D. ANDRE: *Information requirements for low-visibility taxi operations: What pilots say.* In: R.S. Jensen & L.A. Rakovan (Eds.): *Proceedings of the Eighth International Symposium on Aviation Psychology*, Columbus 1995

[ANS04] AGENZIA NAZIONALE PER LA SICUREZZA DEL VOLO (ANSV): *Final Report, Accident involved aircraft Boeing MD-87, registration SE-DMA, and Cessna 525-A, registration D-IEVX, Milano Linate airport, October 8, 2001,* Rome 2004

[ARI89] AERONAUTICAL RADIO INCORPORATED (ARINC): *ARINC Specification 718-4, Mark 3 Air Traffic Control Transponder (ATCRBS/MODE S)*, Annapolis 1989

[ARI01] AERONAUTICAL RADIO INCORPORATED (ARINC): *ARINC Specification 429, Mark 33 Digital Information Transfer System*, Annapolis 2001

[ARI02] AERONAUTICAL RADIO INCORPORATED (ARINC): *ARINC Specification 424-16, Navigation System Database*, Annapolis 2002

[ARI02a] AERONAUTICAL RADIO INCORPORATED (ARINC): *ARINC Specification 661, Cockpit Display System Interfaces to User Systems*, Annapolis 2002

[ARI05] AERONAUTICAL RADIO INCORPORATED (ARINC): *ARINC Specification 768, Integrated Surveillance System (ISS)*, Annapolis 2005

[ARI06] AERONAUTICAL RADIO INCORPORATED (ARINC): *ARINC Specification 816, Embedded Interchange Format for Airport Mapping Database*, Annapolis 2006

[ASC02] AIR SAFETY COUNCIL (ASC): *Aircraft Accident Report: Crashed on a Partially Closed Runway during Takeoff, Singapore Airlines Flight 006, Boeing 747-400, 9V-SPK, CKS Airport, Taoyuan, Taiwan, October 31, 2000*, Taipei 2002

[BAO00] Vernol BATTISTE, Rose ASHFORD and Baltazar Oscar OLMOS: *Initial Evaluation of CDTI/ADS-B for Commercial Carriers: CAA's Ohio Valley Operational Evaluation*, AIAA World Aviation Conference, San Diego 2000.

[BEA00] BUREAU D'ENQUETES ET D'ANALYSES POUR LA SECURITE DE L'AVIATION CIVILE (BEA): *Accident survenu le 25 juillet 2000 au lieu-dit La Patte d'Oie de Gonesse (95) au Concorde immatriculé F-BTSC exploité par Air France*, Rapport f-sc000725, Paris 2000.

[BB04] E. A. BUSTAMANTE and J. P. BLISS: *Effects of Varying the Threshold of Alarm Systems on Human Performance*. In: D. A. VINCENCI, M. MOULOUA, P. A. HANCKCOCK (Eds.): *Human Performance, Situation Awareness and Automation: Current Trends and Research*, Volume II, Mahwah 2004

[BEA01] BUREAU D'ENQUETES ET D'ANALYSES POUR LA SECURITE DE L'AVIATION CIVILE (BEA): *Accident survenu le 25 mai 2000 à Paris Charles de Gaulle (95) aux avions immatriculés F-GHED exploité par Air Liberté et G-SSWN exploité par Streamline Aviation*, Rapport f-ed000525, Paris 2001.

[Ber04] Philippe BERGE et al.: *EMMA Air-Ground Operational Service and Environmental Description (OSED)*, EMMA Deliverable D1.3.1, Toulouse 2004.

[BFU04] BUNDESSTELLE FÜR FLUGUNFALLUNTERSUCHUNGEN: *Jahresbericht 2003: Unfälle und schwere Störungen beim Betrieb ziviler Luftfahrzeuge*, Braunschweig 2004

[BFU04a] BUNDESSTELLE FÜR FLUGUNFALLUNTERSUCHUNGEN: *Investigation Report AX001-1-2/02*, Braunschweig 2004

[BFU04b] BUNDESSTELLE FÜR FLUGUNFALLUNTERSUCHUNGEN: *Bulletin: Unfälle und schwere Störungen beim Betrieb ziviler Luftfahrzeuge, Januar 2004*, Braunschweig 2004

[BFU05] BUNDESSTELLE FÜR FLUGUNFALLUNTERSUCHUNGEN: *Jahresbericht 2004: Unfälle und schwere Störungen beim Betrieb ziviler Luftfahrzeuge*, Braunschweig 2005

[BFU06] BUNDESSTELLE FÜR FLUGUNFALLUNTERSUCHUNGEN: *Jahresbericht 2005: Unfälle und schwere Störungen beim Betrieb ziviler Luftfahrzeuge*, Braunschweig 2006

[BFU07] BUNDESSTELLE FÜR FLUGUNFALLUNTERSUCHUNGEN: *Jahresbericht 2006: Unfälle und schwere Störungen beim Betrieb ziviler Luftfahrzeuge*, Braunschweig 2007

[BFU08] BUNDESSTELLE FÜR FLUGUNFALLUNTERSUCHUNGEN: *Jahresbericht 2007: Unfälle und schwere Störungen beim Betrieb ziviler Luftfahrzeuge*, Braunschweig 2008

[BFU09] BUNDESSTELLE FÜR FLUGUNFALLUNTERSUCHUNGEN: *Untersuchungsbericht EX006-1-2/04*, Braunschweig 2009

[BFU09a] BUNDESSTELLE FÜR FLUGUNFALLUNTERSUCHUNGEN: *Untersuchungsbericht EX001-1/2/06*, Braunschweig 2009

[Bie05] Marcus BIELLA: *Blickbewegung in kritischen Flug- und Rollphasen: Ergebnisse aus dem DLR-Projekt MOSES*, 6. Berliner Werkstatt Mensch-Maschine-Systeme, Berlin 2005

[Bil96] Charles E. BILLINGS: *Human-Centered Aviation Automation: Principles and Guidelines*, NASA Technical Memorandum No. 110381, Moffett Field 1996

[Boe04] BOEING COMMERCIAL AIRPLANES: *Current Market Outlook 2004*, Seattle 2004.

[Boe04a] BOEING COMMERCIAL AIRPLANES: *Statistical Summary of Commercial Jet Airplane Accidents, Worldwide Operations 1959 – 2003*, Seattle 2004.

[Boe05] BOEING COMMERCIAL AIRPLANES: *Current Market Outlook 2005*, Seattle 2005.

[Boe06] BOEING COMMERCIAL AIRPLANES: *Statistical Summary of Commercial Jet Airplane Accidents, Worldwide Operations 1959 – 2005*, Seattle 2006.

[Boe06a] BOEING COMMERCIAL AIRPLANES: *Current Market Outlook 2006*, Seattle 2006.

[Boe07] BOEING COMMERCIAL AIRPLANES: *Statistical Summary of Commercial Jet Airplane Accidents, Worldwide Operations 1959 – 2006*, Seattle 2007.

[Bom06] BOMBARDIER AEROSPACE: *Commercial Aircraft Market Forecast 2006-2025*, Montreal 2006

[Bor05] Jürgen BORTZ: *Statistik für Human- und Sozialwissenschaftler*, 6. Auflage, Heidelberg 2005

[BT05] C. BOUSMANNE, D. TONEA: *CASCADE Data Link Operational Terminal Information Service (D-OTIS), Operational Service and Environmental Description for D-OTIS Data Link Service*, Version 0.5, Brussels 2005

[Bus01] PHILIPPE BUSQUIN et al.: *European Aeronautics: A Vision for 2020*, European Commission for Research, Luxembourg 2001.

[Che05] Jean-Marie CHEVALLIER: *Paris – Charles de Gaulle: The need for increasing runway capacity*, Eurocontrol Wake Vortex Workshop, Brétigny 2005

[CIA84] Comisión de Investigación de Accidentes e Incidentes de Aviación Civil (CIAIAC): *Accident which occurred to Aircraft McDonnell Douglas DC-9 and Boeing B-727-200, Registration EC-CGS and EC-CFJ, in Madrid-Barajas Airport, Spain*, Technical Report, Madrid, 1984

[Dek06] Sidney DEKKER: *The Field Guide to Understanding Human Error*, Aldershot 2006

[DFS08] DEUTSCHE FLUGSICHERUNG GMBH: *Luftverkehr in Deutschland: Mobilitätsbericht 2008*, Langen 2008

[DLH97] DEUTSCHE LUFTHANSA AG: *Airplane Operations Manual AOM A320 Family, Vol. II, Chap. 0-7, Procedures & MEL,* Revision 34, Frankfurt 1997

[DLH06] DEUTSCHE LUFTHANSA AG: *Geschäftsbericht 2005*, Köln 2006

[DLH06a] DEUTSCHE LUFTHANSA AG: *NOTAM LH8385/09/TSE/FRA/*, Briefing-Unterlagen für den Lufthansa Cargo-Flug LH8385 am 9.8.2006, Frankfurt 2006

[EEC04] EUROCONTROL EXPERIMENTAL CENTRE (EEC): *Review of Root Causes of Accidents due to Design*, EEC Note No. 14/04, Brétigny-sur-Orge 2004

[EAS06] EUROPEAN AVIATION SAFETY AGENCY: *Certification Specifications for Large Aeroplanes, CS-25*, Cologne 2006

[Emb06] EMPRESA BRASILEIRA DE AERONÁUTICA S.A. (EMBRAER): *2006-2025 Embraer Market Outlook: A Long-Term View of the 30 to 120 Seat Commercial Jet Market*, 3rd Edition, São Paulo 2006

[EMM07] EMMA CONSORTIUM: *Moving Map and Surface Movement Alerting, Final Synthesis 1st Campaign*, EMMA Deliverable D2.2.3, Braunschweig 2007

[End95] Mica R. ENDSLEY: *Towards a theory of situation awareness*, Human Factors, 1995, 37(1), 32-64

[End99] Mica R. ENDSLEY: *Situation Awareness in Aviation Systems*, in D. J. GARLAND, J. A. WISE and V. D. HOPKIN (Eds.): *Handbook of Aviation Human Factors*, Mahwah, New Jersey 1999

[Eur01] EUROCONTROL/FEDERAL AVIATION ADMINISTRATION (FAA): *Principles of Operation for the Use of Airborne Separation Assurance Systems*, Version 7.1, Brussels & Washington D.C. 2001

[Eur02] EUROCONTROL: *CARE/ASAS Activity 5, Description of a first package of GS/AS applications*, Version 2.2, Brussels 2002

[Eur04] EUROCONTROL RUNWAY SAFETY OFFICE: *European Action Plan for the Prevention of Runway Incursions*, Release 1.1, Brussels 2004

[Eur04a] EUROCONTROL PERFORMANCE REVIEW COMMISSION: *Performance Review Report: An Assessment of Air Traffic Management in Europe during the Calendar Year 2003*, Brussels 2004.

[Eur06] EUROCONTROL RUNWAY SAFETY OFFICE: *European Action Plan for the Prevention of Runway Incursions*, Release 1.2, Brussels 2006

[Eur06a] EUROCONTROL: *FARADS - Technical Study of RA Downlink Methods*, Brussels 2006

[Eur07] EUROCONTROL: *European Operational Concept Validation Methodology (E-OCVM)*, Version 2.0, Brussels 2007

[Eur08] EUROCONTROL PERFORMANCE REVIEW COMMISSION: *PRR 2007: Performance Review Report: An Assessment of Air Traffic Management in Europe during the Calendar Year 2007*, Brussels 2008

[Eur08a] EUROCONTROL SAFETY REGULATION COMMISSION: *Annual Safety Report 2008*, Brussels 2008

[Eur08b] EUROCONTROL: *Notice of Proposed Rulemaking ENPRM/08-009, Laying down requirements for the Performance and Interoperability of Surveillance for the Single European Sky*, Brussels 2008

[Eur09] EUROCONTROL: *Flight Crew Data Link Operational Guidance for LINK 2000+ Services*, Edition 4.0, Brussels 2009

[FAA81] FEDERAL AVIATION ADMINISTRATION (FAA): *Visual Confirmation of Voice Takeoff Clearance (VICON) Operational Evaluation*, Volume I, Washington D.C. 1987

[FAA87] FEDERAL AVIATION ADMINISTRATION (FAA): *Advisory Circular 25-12, Airworthiness Criteria for the Approval of Airborne Windshear Warning Systems in Transport Category Airplanes*, Washington D.C. 1987

[FAA88] FEDERAL AVIATION ADMINISTRATION (FAA): *Advisory Circular 25.1309-1A, System Design and Analysis*, Washington D.C. 1988

[FAA93] FEDERAL AVIATION ADMINISTRATION (FAA): *Pilot Guide to Takeoff Safety*, Takeoff Safety Training Aid, Washington D.C. 1993

[FAA93a] FEDERAL AVIATION ADMINISTRATION (FAA): *Advisory Circular 25.703-1, Takeoff Configuration Warning Systems*, Washington D.C. 1993

[FAA96] FEDERAL AVIATION ADMINISTRATION: *Advisory Circular 120-50A, Guidelines for Operational Approval of Windshear Training Programs*, Washington D.C. 1996

[FAA96a] FEDERAL AVIATION ADMINISTRATION (FAA): *Technical Standard Order TSO-C117a, Airborne Windshear Warning and Escape Guidance Systems for Transport Airplanes*, Washington D.C. 1996

[FAA00] FEDERAL AVIATION ADMINISTRATION: *Introduction to TCAS II, Version 7*, Washington D.C. 2000

[FAA01] FAA RUNWAY SAFETY REPORT: *Runway Incursion Severity Trends at Towered Airports in the United States 1997 - 2000*, FAA Office of Runway Safety, Washington D.C. 2001

[FAA01a] FEDERAL AVIATION ADMINISTRATION: *Advisory Circular 120-55B, Air Carrier Operational Approval and Use of TCAS II*, Washington D.C. 2001

[FAA02] FAA RUNWAY SAFETY REPORT: *Runway Incursion Trends at Towered Airports in the United States CY 1998 – CY 2001*, FAA Office of Runway Safety, Washington D.C. 2003

[FAA02a] FEDERAL AVIATION ADMINISTRATION: *Aviation Safety Statistical Handbook*, Washington D.C. 2002

[FAA02b] FEDERAL AVIATION ADMINISTRATION: *Notice N 8110.98, Addressing Human Factors/Pilot Interface Issues of Complex, Integrated Avionics as Part of the Technical Standard Order (TSO) Process*, Washington D.C. 2002

[FAA02c] FEDERAL AVIATION ADMINISTRATION (FAA): *Technical Standard Order TSO-C151b, Terrain Awareness and Warning System*, Washington D.C. 2002

[FAA03] FAA RUNWAY SAFETY REPORT: *Runway Incursion Trends at Towered Airports in the United States FY 1999 – FY 2002*, FAA Office of Runway Safety, Washington D.C. 2003

[FAA03a] FEDERAL AVIATION ADMINISTRATION: *Advisory Circular 120-74A, Parts 91, 121, 125, and 135 Flightcrew Procedures during Taxi Operations*, Washington D.C. 2003

[FAA03b] FEDERAL AVIATION ADMINISTRATION: *Advisory Circular 120-76A, Guidelines for the Certification, Airworthiness, and Operational Approval of Electronic Flight Bag Computing Devices*, Washington D.C. 2003

[FAA03c] FEDERAL AVIATION ADMINISTRATION: *Technical Standard Order TSO-C165, Electronic Map Display Equipment for Graphical Depiction of Aircraft Position*, Washington D.C. 2003

[FAA04] FAA RUNWAY SAFETY REPORT: *Runway Incursion Trends and Initiatives at Towered Airports in the United States FY 2000 – FY 2003*, FAA Office of Runway Safety, Washington D.C. 2004

[FAA04a] FEDERAL AVIATION ADMINISTRATION (FAA): *Order 7110.65P, Air Traffic Control*, Washington D.C. 2004

[FAA05] FAA RUNWAY SAFETY REPORT: *Runway Incursion Trends and Initiatives at Towered Airports in the United States FY 2001 through FY 2004,* FAA Office of Runway Safety, Washington, D.C. 2005

[FAA05a] FEDERAL AVIATION ADMINISTRATION (FAA): *Advisory Circular 150/5340-1J, Standards for Airport Markings*, Washington D.C. 2005

[FAA07] FEDERAL AVIATION ADMINISTRATION: *FAA Runway Safety Report: Runway Incursion Trends and Initiatives at Towered Airports in the United States, FY 2003 through FY 2006*, FAA Air Traffic Organisation, Safety Services, Washington, D.C. 2007

[FAA07a] FEDERAL AVIATION ADMINISTRATION: *Advisory Circular 20-159, Obtaining Design and Production Approval of Airport Moving Map Display Applications Intended for Electronic Flight Bag Systems*, Washington D.C. 2007

[FAA07b] FEDERAL AVIATION ADMINISTRATION: *ADS-B Aviation Rulemaking Committee, Order 1110.147*, Washington, D.C. 2007

[FAA07c] FEDERAL AVIATION ADMINISTRATION: *FAA Needs To Improve ASDE-X Management Controls To Address Cost Growth, Schedule Delays, and Safety Risks*, Memorandum, Federal Aviation Administration Report Number AV-2008-004, Washington, D.C. 2007

[FAA08] FEDERAL AVIATION ADMINISTRATION: *FAA Runway Safety Report: Trends and Initiatives at Towered Airports in the United States, FY 2004 through FY 2007,* Washington, D.C. 2008

[FAA08a] FEDERAL AVIATION ADMINISTRATION: *Pilot's Handbook of Aeronautical Knowledge*, FAA-H-8083-25, Washington, D.C. 2008

[FAA09] FEDERAL AVIATION ADMINISTRATION: *Aeronautical Information Manual (AIM): Official Guide to Basic Flight Information and ATC Procedures*, Washington, D.C. 2009

[FAH05] D. C. FOYLE, , A. D. ANDRE & B. L. HOOEY: *Situation Awareness in an Augmented Reality Cockpit: Design, Viewpoints and Cognitive Glue*, in: Proceedings of the 11th International Conference on Human Computer Interaction, Las Vegas 2005

[FAN06] FANS INTEROPERABILITY TEAM: *FANS-1/A Operations Manual*, Version 4.0, September 2006

[FAR07] FEDERAL AVIATION REGULATIONS (FAR): *Part 25 – Airworthiness Standards: Transport Category Airplanes*, Washington D.C. 2007

[Fis75] Baruch FISCHHOFF: *Hindsight ≠ Foresight: The Effect of Outcome Knowledge on Judgment Under Uncertainty*, Journal of Experimental Psychology 1975, 288-299

[Fit51] PAUL M. FITTS (ED.): *Human Engineering for an Effective Air-Navigation and Traffic Control System*, National Research Council, Washington D.C. 1951

[Flt07] FLT TECH ONLINE: *L-3 Says ACSS SafeRoute System Set for Certification*, http://www.flttechonline.com/Current/L-3 Says ACCS SafeRoute System Set for Certification.htm, published 2007-06-20, retrieved 2009-08-12

[Fra07] FRAPORT AG: *Annual Report 2006. Managing capacity – securing growth*, Frankfurt 2007

[Fra07a] FRAPORT AG: *Facts and Figures 2007 for Frankfurt Airport*, Frankfurt 2007

[Fri08] Axel FRIEDRICH: *Evaluierung von Methoden zum Erstellen und Aktualisieren von sicherheitskritischen Flughafendatenbanken nach RTCA Do-272a*, Dissertation, Technische Universität Darmstadt 2008

[GA99] D. A. GRAEBER and A. D. ANDRE: *Assessing Visual Attention of Pilots while using Electronic Moving Maps for Taxiing*, in: R. S. JENSEN, B. COX, J. D. CALLISTER, & R. LAVIS (Eds.), *Proceedings of the Tenth Symposium on Aviation Psychology: 2, 791-796*, Columbus, Ohio, 1999

[Ger07] M. GERZANICS, *Runway Success*, in: Flight International, 21-27 August 2007

[Gre06] David F. GREEN, Jr.: *Runway Safety Monitor Algorithm for Single and Crossing Runway Incursion Detection and Alerting*, NASA/CR-2006-214275, Hampton 2006

[Gul10] GULFSTREAM AEROSPACE CORPORATION: *Gulfstream G550*, Product Brochure, Savannah 2010

[Har93] K. HARWOOD: *Defining human-centered system issues for verifying and validating air traffic control systems.* In: J. Wise, V. D. Hopkin and P. Stager (Eds.), *Verification and Validation of Complex and Integrated Human Machine Systems*, Berlin 1993

[Hon03] HONEYWELL INTERNATIONAL INC.: *Runway Awareness and Advisory System (RAAS), Product Description*, Redmond 2003

[HSL02] HAVARIKOMMISJONEN FOR SIVIL LUFTFART (HSL): *Rapport 33/2002*, Lillestrøm 2002

[IAT05] INTERNATIONAL AIR TRANSPORT ASSOCIATION (IATA): *Safety Report, 2004 Edition*, Montreal - Geneva 2005.

[ICA80] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): Circular 153-AN/98, *Aircraft Accident Digest No. 23*, Montreal 1980

[ICA86] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Manual of Surface Movement Guidance and Control Systems (SMGCS)*, Doc 9476, AN/927, 1st edition, Montreal 1986

[ICA90] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Annex 2 to the Convention on International Civil Aviation, Rules of the Air*, 9th edition, Montreal 1990

[ICA99] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Manual of Air Traffic Services Data Link Applications*, Doc 9694, AN/955, Montreal 1999

[ICA01] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Annex 11 to the Convention on International Civil Aviation, Aircraft Traffic Services*, Montreal 2001

[ICA01a] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Air Traffic Management*, Doc 4444, ATM/501, 14th ed., Montreal 2001

[ICA01b] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Annex 13 to the Convention on International Civil Aviation, Aircraft Accident and Incident Investigation*, Montreal 2001

[ICA01c] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Annex 6 to the Convention on International Civil Aviation, Operation of Aircraft, Part I: International Commercial Air Transport – Aeroplanes*, 8th ed., Montreal 2001

[ICA01d] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Annex 10 to the Convention on International Civil Aviation, Aeronautical Telecommunications, Volume II: Communication Procedures including those with PANS status*, 6th edition, Montreal 2002

[ICA01e] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Annex 4 to the Convention on International Civil Aviation, Aeronautical Charts*, Montreal 2001

[ICA02] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Economic Contribution of Civil Aviation*, Circular 292-AT/124, Montreal 2002

[ICA02a] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Annex 10 to the Convention on International Civil Aviation, Aeronautical Telecommunications, Volume IV: Surveillance Radar and Collision Avoidance Systems*, 3rd edition, Montreal 2002

[ICA04] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Annex 15 to the Convention on International Civil Aviation, Aeronautical Information Services*, Montreal 2004

[ICA04a] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Advanced Surface Movement Guidance and Control Systems (A-SMGCS) Manual*, Doc 9830, AN/452, 1st edition, Montreal 2004

[ICA04b] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Annex 14 to the Convention on International Civil Aviation, Aerodromes, Volume I: Aerodrome Design and Operations*, Montreal 2004

[ICA06] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Manual of Radiotelephony*, Doc 9432, AN/925, 3rd edition, Montreal 2006

[ICA07] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *Manual on the Prevention of Runway Incursions*, Doc 9870, AN/463, Montreal 2007

[ICA08] INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO): *European Guidance Material on Aerodome Operations under Limited Visibility Conditions*, EUR Doc 013, 3rd edition, Paris 2008

[IDW04] *Automobilindustrie - Vom Netzwerk profitieren*, in: Direkt – Presseinformationen aus dem Institut der Deutschen Wirschaft, Jg. 30, Nr. 68, Köln 2004

[Jep05] JEPPESEN: *Taxi Position Awareness – Enhanced Situational Awareness*, Product Brochure, Englewood 2005

[Jep08] JEPPESEN: *Jeppesen Airport Moving Map to Improve Runway Safety by Reducing Incursion Risk*, Press Release March 24, 2008, Englewood 2008

[Jon05] Denise R. JONES: *Runway incursion prevention system testing at the Wallops Flight Facility*, Proc. SPIE: Enhanced and Synthetic Vision, Vol. 5802, Orlando 2005

[Jur85] ADOLPH S. JURSA (ED.): *Handbook of Geophysics and the Space Environment*, United States Air Force Geophysics Laboratory, Hanscom 1985

[HHR01] J. HOEKSTRA, B. HEESBEEN and R. RUIGROK: *Traffic Manager User Manual, Version 5.1 & higher*, Amsterdam 2001

[HJK04] R. M. HOEFT, F. JENTSCH and J. A. KOCHAN: *Freeing NOTAMs From Teletype Technology*, in: Flight Safety Foundation, Flight Safety Digest 23(4), Alexandria 2004

[Kra04] Stefan KRANZ: *Ein Beitrag zur Lösung der Bodenverkehrsproblematik auf Großflughäfen*, Dissertation, Technische Universität Darmstadt 2004

[Kub99] W. KUBBAT, S. KRANZ, A. HELMETAG, P.M. LENHART, D. GIROUX and H. V. VIEBAHN: *A-SMGCS with Gate to Gate 4D Flight Guidance Displays*, Proceedings of the International Symposium on Advanced Surface Movement Guidance and Control System, Stuttgart, 21. – 24. Juni 1999

[Lou99] Lincoln LOUNSBURY: *Why a Little More Traffic Makes a Lot More Runway Incursions*, Air Line Pilot, May 1999

[NAV08] NAV CANADA: *Operational Performance Report April 2008*, Ottawa 2008

[NG01] Richard L. NEWMAN, Kevin W. GREELEY: *Cockpit Displays: Test and Evaluation*, Ashgate, Aldershot 2001

[NTS79] National Transportation Safety Board (NTSB): Aircraft Accident Report NTSB/AAR-79/11, *Delta Air Lines, Inc., Boeing 727-200, N467DA, and Flying Tiger, Inc., Boeing 747-F, N804FT, O'Hare International Airport, Chicago, Illinois, February 15, 1979*, Washington D.C. 1979

[NTS84] National Transportation Safety Board (NTSB): Aircraft Accident Report NTSB/AAR-84/10, *Korean Air Lines McDonnell Douglas DC-10-30, HL7339, Southcentral Air Piper PA-31-350, N35206, Anchorage, Alaska, December 23, 1983*, Washington D.C. 1984

[NTS85] National Transportation Safety Board (NTSB): Aircraft Accident Report NTSB/AAR-85/01/SUM, *Aircraft Accident/Incident Summary Reports*, Washington D.C. 1985

[NTS86] National Transportation Safety Board (NTSB): Special Investigation Report NTSB/SIR-86/01, *Runway Incursions at Controlled Airports in the United States*, Washington D.C. 1986

[NTS91] National Transportation Safety Board (NTSB): Aircraft Accident Report NTSB/AAR-91/05, *Northwest Airlines, Inc. Flight 1482 and 299 Runway Incursion and Collision, Detroit Metropolitan/Wayne County Airport, Romulus, Michigan, December 3, 1990*, Washington D.C. 1991

[NTS91a] National Transportation Safety Board (NTSB): Aircraft Accident Report NTSB/AAR-91/08, *Runway Collision of USAir Flight 1493, Boeing 737 and SkyWest Flight 5569 Fairchild Metroliner, Los Angeles International Airport, Los Angeles, California, February 1, 1991,* Washington D.C. 1991

[NTS91b] National Transportation Safety Board (NTSB): Aircraft Accident Report NTSB/AAR-91/03, *Runway Collision of Eastern Airlines Boeing 727, Flight 111, and EPPS Air Service Beechcraft King Air A100, Atlanta Hartsfield International Airport, Atlanta, Georgia, January 18, 1990,* Washington D.C. 1991

[NTS93] National Transportation Safety Board (NTSB): *Factual Report Aviation, NTSB Identification NYC93IA064*, Washington D.C. 1993

[NTS94] National Transportation Safety Board (NTSB): *Safety Recommendations A-94-208 through -210*, Washington D.C. 1994

[NTS95] National Transportation Safety Board (NTSB): Aircraft Accident Report NTSB/AAR-95/05, *Runway Collision Involving Trans World Airlines Flight 427 and Superior Aviation Cessna 441, Bridgetown, Missouri, November 22, 1994,* Washington D.C. 1995

[NTS95a] National Transportation Safety Board (NTSB): *Factual Report Aviation, NTSB Identification FTW95IA126A*, Washington D.C. 1995

[NTS01] National Transportation Safety Board (NTSB): *Factual Report Aviation, NTSB Identification FTW01IA183A*, Washington D.C. 2001

[NTS02] National Transportation Safety Board (NTSB): *Factual Report Aviation, NTSB Identification ANC02IA011*, Washington D.C. 2002

[NTS03] National Transportation Safety Board (NTSB): *Safety Recommendation A-03-05 and A-03-06*, Washington D.C. 2003

[NTS06] National Transportation Safety Board (NTSB): *Preliminary Report Aviation, NTSB ID: DCA06MA064*, Washington D.C. 2006

[NTS07] National Transportation Safety Board (NTSB): Aircraft Accident Report NTSB/AAR-07/05, *Attempted Takeoff From Wrong Runway, Comair Flight 5191, Bombardier CL-600-2B19, N431CA, Lexington, Kentucky, August 27, 2006*, Washington D.C. 2007

[NTS07a] National Transportation Safety Board (NTSB): *NTSB Most Wanted List: Transportation Safety Issues 2008, Critical changes needed to reduce transportation accidents and save lives*, Washington D.C. 2007

[NTS07b] National Transportation Safety Board (NTSB): *Factual Report Aviation, NTSB Identification DEN07IA058*, Washington D.C. 2007

[NTS07c] National Transportation Safety Board (NTSB): *Factual Report Aviation, NTSB Identification NYC07LA017*, Washington D.C. 2007

[NTS07d] National Transportation Safety Board (NTSB): *Factual Report Aviation, NTSB Identification NYC07IA015*, Washington D.C. 2007

[NTS07e] National Transportation Safety Board (NTSB): *Factual Report Aviation, NTSB Identification OPS07IA001B*, Washington D.C. 2007

[NTS07f] National Transportation Safety Board (NTSB): *Factual Report Aviation, NTSB Identification DCA07IA008*, Washington D.C. 2007

[NTS07g] National Transportation Safety Board (NTSB): *Factual Report Aviation, NTSB Identification OPS07IA006A*, Washington D.C. 2007

[NTS07h] National Transportation Safety Board (NTSB): *Factual Report Aviation, NTSB Identification OPS07IA009A*, Washington D.C. 2007

[Pen81] Donald C. PENNINGTON: *Being Wise After the Event: An Investigation of Hindsight Bias*, Current Psychological Research 1981, 271-282

[Psc08] Christian PSCHIERER: *Automatic Label Generation for Airport Charts*, Dissertation, Technische Universität Darmstadt 2008

[Rea90] James REASON: *Human Error*, Cambridge University Press, Cambridge 1990

[Rea00] James REASON: *Human error: models and management*, in: British Medical Journal 320 (7237): 768–770, London 2000

[RM01] W. ROUWHORST, A. MARSMAN: *ISAWARE DC 5.1.2, ISAS Flight Simulation Evaluation Results*, NLR-TR-2001-509, Amsterdam 2001

[RTC97] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-185A, Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II) Airborne Equipment*, Washington D.C. 1997

[RTC97a] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-239, Minimum Operational Performance Standards for Traffic Information Service (TIS) Data Link Communications*, Washington D.C. 1997

[RTC98] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-243, Guidance for Initial Implementation of Cockpit Display of Traffic Information*, Washington D.C. 1998

[RTC00] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-260, Minimum Operational Performance Standards for 1090 MHz Automatic Dependent Surveillance - Broadcast (ADS-B)*, Washington D.C. 2000

[RTC00a] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-259, Application Descriptions for Initial Cockpit Display of Traffic Information (CDTI) Applications*, Washington D.C. 2000

[RTC01] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-272, User Requirements for Aerodrome Mapping Information*, Washington D.C. 2001. Also published by EUROCAE as ED-99.

[RTC02] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-242A, Minimum Aviation System Performance Standards For Automatic Dependent Surveillance Broadcast (ADS-B)*, Washington D.C. 2002.

[RTC03] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-260A, Minimum Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependent Surveillance - Broadcast (ADS-B) and Traffic Information Service – Broadcast (TIS-B)*, Washington D.C. 2003

[RTC03a] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-257A, Minimum Operational Performance Standards for the Depiction of Navigational Information on Electronic Maps*, Washington D.C. 2003

[RTC04] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-291, Interchange Standards for Terrain, Obstacle, and Aerodrome Mapping Data*, Washington D.C. 2004. Also published by EUROCAE as ED-119.

[RTC05] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-272A, User Requirements for Aerodrome Mapping Information*, Washington D.C. 2005. Also published by EUROCAE as ED-99A.

[RTC06] RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA): *DO-242A, Minimum Aviation System Performance Standards For Automatic Dependent Surveillance Broadcast (ADS-B), Change 1*, Washington D.C. 2006.

[RVT01] RAAD VOOR DE TRANSPORTVEILIGHEID (RVTV): *Final Report 98-85/S-14, N 193 DN, Boeing 767, 10 December 1998, Amsterdam Airport Schiphol*, The Hague 2001

[RW02] Z. RADÓ and J. C. WAMBOLD: *Aircraft Braking Friction Prediction from Flight Data Recorder Data*, 2002 Federal Aviation Administration Technology Transfer Conference, Washington D.C. 2002

[SAE88] SOCIETY OF AUTOMOTIVE ENGINEERS (SAE): *ARP 4032, Human Engineering Considerations in the Application of Color to Electronic Aircraft Displays*, Warrendale, P.A., April 1988

[SAE88a] SOCIETY OF AUTOMOTIVE ENGINEERS (SAE): *ARP 4102/4 Flight Deck Alerting System*, Warrendale, P.A., July 1988

[SAE88b] SOCIETY OF AUTOMOTIVE ENGINEERS (SAE): *ARP 4102, Flight Deck Panels, Controls, and Displays*, Warrendale, P.A., July 1988

[SAE03] SOCIETY OF AUTOMOTIVE ENGINEERS (SAE): *ARP 5364, Human Factor Considerations in the Design of Multifunction Display Systems for Civil Aircraft*, Warrendale, P.A., July 2003

[Sch04] Christian SCHMALZ: *Generierung und Verifikation einer optimalen Referenztrajektorie zur Bewertung von Fahrzeugnavigationssystemen*, Dissertation, Technische Universität Darmstadt 2004

[Sen07] SENSIS CORPORATION: *Honeywell International and Sensis Corporation Demonstrate Runway Incursion Alerting to Cockpits*, Press Release, August 28, 2007, East Syracuse 2007

[She04] T. SHERIDAN: *Interpolation Method for Rating the Severity of Runway Incursions*, Proc. of the Symposium on Human Performance, Situation Awareness, and Automation, Daytona Beach, 23–25 March 2004

[StB06] STATISTISCHES BUNDESAMT: *2005: Geringste Zahl an Verkehrstoten seit über 50 Jahren*, Pressemitteilung vom 23. Februar 2006, Wiesbaden 2006

[TC00] TRANSPORT CANADA (TC): *National Civil Aviation Safety Committee, Sub-Committee on Runway Incursions, Final Report*, Ottawa 2000

[Tha04] THALES AVIONICS S.A.: *TAWS+: The Superior Strategic and Tactical Tool*, Product Brochure, Toulouse 2004

[Tha05] THALES AVIONICS S.A.: *A330/A340 New FM Pilot's Guide*, Revision 2, Toulouse 2005

[TSB07] TRANSPORTATION SAFETY BOARD OF CANADA: *Runway Overrun and Fire, Air France Airbus A340-313 F-GLZQ, Toronto/Lester B. Pearson International Airport, Ontario, 02 August 2005*, Aviation Investigation Report A05H0002, Ottawa 2007

[TUD06] TECHNISCHE UNIVERSITÄT DARMSTADT (TUD): *Study on the applicability of the xNOTAM concept for updating Airport Mapping Database (AMDB) applications, Results and Findings*, Darmstadt 2006

[Ver03] C. VERNALEKEN, M. HANDIG: *Junkers Ju 388 – Entwicklung, Erprobung und Fertigung des letzten Junkers-Höhenflugzeugs*, Oberhaching 2003

[Ver05] C. VERNALEKEN, A. V. ECKARTSBERG, L. MIHALIC, M. JIRSCH AND B. LANGER: *The European research project ISAWARE II: a more intuitive flight deck for future airliners*, Proc. SPIE, Enhanced and Synthetic Vision, Vol. 5802, Orlando 2005

[Ver06] C. VERNALEKEN, L. MIHALIC, M. GÜTTLER and U. KLINGAUF: *A fresh look at runway incursions: onboard surface movement awareness & alerting system based on SVS*, Proc. SPIE, Enhanced and Synthetic Vision, Vol. 6226, Orlando 2006

[Ver06a] C. VERNALEKEN, M. GÜTTLER, C. URVOY, AND U. KLINGAUF: *Runway Incursion Prevention: Concept for an Onboard Surface Movement Awareness & Alerting System*, in: DGLR Jahrbuch 2006, Band I+II, Bonn 2006

[Ver07] C. VERNALEKEN, C. URVOY, and U. KLINGAUF, *Runway Incursion Prevention by Enhanced Onboard Surveillance: Concept for a Surface Movement Awareness & Alerting System*, International Symposium Enhanced Solutions for Aircraft and Vehicle Surveillance (ESAVS 2007), 06-07 March 2007, Bonn 2007

[Ver08] C. VERNALEKEN, C. URVOY, and U. KLINGAUF, *Considerations on symbology, data requirements, and operational concept for integral NOTAM visualization on airport moving map displays*, Proc. SPIE, Enhanced and Synthetic Vision, Vol. 6957, Orlando 2008

[Vil09] Fabrice VILLAUMÉ: *Brake-to-Vacate system: The smart automatic braking system for enhanced surface operations*, Airbus FAST Magazine No. 44, Tolouse-Blagnac 2009

[VW05] Volkswagen AG: *Geschäftsbericht 2004*, Wolfsburg 2005

[WBH06] Drew WESTEN, Pavel S. BLAGOV, Keith HARENSKI, Clint KILTS and Stephan HAMANN: *The neural basis of motivated reasoning: An fMRI study of emotional constraints on political judgment during the U.S. Presidential election of 2004*, in: Journal of Cognitive Neuroscience, 18, 1947-1958, 2006

[Wag96] W. WAGNER: *Hugo Junkers, Pionier der Luftfahrt – seine Flugzeuge,* Die Deutsche Luftfahrt Vol. 24, Bernard & Graefe Verlag, Bonn 1996

[Wie93] E. L. WIENER: *Life in the second decade of the glass cockpit*, in: R. S. JENSEN and D. NEUMEISTER (Eds.): *Proceedings of the Seventh International Symposium on Aviation Psychology*, Ohio State University, Columbus 1993

[Wip05] Patrick WIPPLINGER: *Untersuchung des Pilotenverhaltens bei HALS/DTOP-Anflügen*, Dissertation, Technische Universität Darmstadt 2005

[Yeh04] Michelle YEH: *Human Factors Considerations in the Design and Evaluation of Moving Map Displays of Ownship on the Airport Surface*, Department of Transportation, John A. Volpe National Transportation Systems Center DOT/FAA/AR-04/39, Cambridge, M.A. 2004

[Zei93] CARL ZEISS: *Handbuch für Augenoptik*, Carl Zeiss, Oberkochen 2000.