Safety Requirements and Distribution of Functions for Automated Valet Parking

Vom Fachbereich Maschinenbau an der
Technischen Universität Darmstadt
zur Erlangung des Grades eines
Doktor-Ingenieurs (Dr.-Ing.)
genehmigte

Dissertation

vorgelegt von

Valerij Schönemann, M.Sc.
aus Dmitrijewka

Berichterstatter:	Prof. Dr. rer. nat. Hermann Winner
Mitberichterstatter:	Prof. Dr.-Ing. Uwe Klingauf
Tag der Einreichung:	24.07.2019
Tag der mündlichen Prüfung:	15.10.2019

Darmstadt 2019

D 17

Schönemann, Valerij: Safety Requirements and Distribution of Functions for Automated Valet Parking
Darmstadt, Technische Universität Darmstadt,
Jahr der Veröffentlichung der Dissertation auf TUprints: 2019
URN: urn:nbn:de:tuda-tuprints-92386
Tag der mündlichen Prüfung: 15.10.2019

Vorwort

Die vorliegende Arbeit entstand während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Fachgebiet Fahrzeugtechnik (FZD) der Technischen Universität Darmstadt. Die Inhalte dieser Dissertation resultieren aus dem Forschungsprojekt ENABLE-S3.

Meinen besonderen Dank möchte ich zuerst an meinem Doktorvater, Prof. Dr. rer. nat. Hermann Winner, aussprechen, der mir die Möglichkeit der Promotion in Aussicht stellte. Die wertvollen Anregungen sowie die kritischen Auseinandersetzungen mit den Inhalten dieser Arbeit haben maßgeblich zu dieser Arbeit beigetragen. Das in mich gesetzte Vertrauen und die mir gewährten gestalterischen Freiheiten und Pflichten als wissenschaftlicher Mitarbeiter seines Fachgebiets haben meine persönliche Entwicklung stark geprägt.

Bei Herrn Prof. Dr.-Ing. Uwe Klingauf, Leiter des Fachgebiets für Flugsysteme und Regelungstechnik der Technischen Universität Darmstadt, möchte ich mich herzlich für die Übernahme des Korreferats und sein Interesse an dieser Forschungsarbeit bedanken.

Danken möchte ich allen Mitarbeiterinnen und Mitarbeitern des Fachgebiets Fahrzeugtechnik einschließlich des Sekretariats. Die Atmosphäre, sowie die Vielfältigkeit und das freundschaftliche Miteinander werde ich in guter Erinnerung behalten. Mein Dank gilt auch den zahlreichen von mir betreuten Studenten, die im Rahmen studentischer Arbeiten und als wissenschaftliche Hilfskräfte zum Erfolg dieser Arbeit beigetragen haben.

Ein ganz besonderer Dank geht an meine Familie, die mich in jeder Lebenslage stets unterstützt hat, die mir mit Rat und Tat zur Seite stand und mir ermöglicht hat, mein Leben nach eigenen Wünschen und Entscheidungen zu gestalten. Für den Rückhalt möchte ich mich bei meinen Eltern und Geschwistern bedanken.

Mein liebster Dank geht an meine Frau, mit der ich Hand in Hand durch das Leben gehe.

Valerij Schönemann   Darmstadt, Juli 2019

List of Contents

Abbreviations

Abbreviation	Description
ADAS	Advance Driver Assistance Systems
ASIL	Automotive Safety Integrity Level
AVP	Automated Valet Parking
C2C	Car-to-Car
C2I	Car-to-Infrastructure
BASt	Bundesanstalt für Straßenwesen
DARPA	Defense Advanced Research Projects Agency
DGPS	Differential Global Positioning System
EKF	Extended Kalman Filter
ENABLE-S3	European Initiative to Enable the Validation of highly Automated Safe and Secure Systems
FMEA	Failure Mode and Effects Analysis
FSR	Functional Safety Requirement
FTA	Fault Tree Analysis
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GT	Ground Truth
GUI	Graphical User Interface
HARA	Hazard Analysis and Risk Assessment
HMI	Human-Machine Interface
HIL	Hardware in the Loop
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LIDAR	Light Detection and Ranging
MRP	Minimum Required Perception
MRS	Minimum Required Safety
NHTSA	National Highway Traffic Safety Administration
PAM	Parking Area Management
PEGASUS	Project for Establishing Generally Accepted quality criteria, tools and methods as well as Scenarios And Situations for approval of highly automated driving functions
RADAR	Radio Detection and Ranging
RO	Research Objective
RQ	Research Question
RSS	Responsive-Sensitive Safety
SAE	Society of Automotive Engineering
SG	Safety Goal
SLAM	Simultaneous Localization And Mapping
SOTIF	Safety of the intended Functionality

Abbreviation	**Description**
SUT	System Under Test
SIL	Software in the Loop
VDA	Verband der Automobilindustrie
VTD	Virtual Test Drive
WLAN	Wireless Local Area Network
XML	Extensible Markup Language

Symbols and Indices

Symbol	Unit	Description
a	m/s²	acceleration
A	m²	area
D	m/s²	deceleration
d	m	distance
g	m/s²	gravity constant
i	-	index
j	-	index
ℓ	m	length
n	-	number
t	s	time
v	m/s	velocity
w	m	width
μ	-	friction coefficient
τ	s	time durations

Index	**Description**
B,lag	brake lagging time
ego	ego-vehicle
egoF	ego in forward direction
egoR	ego in reverse direction
func	functions
obj	object
occ	occupied
ODD	operational design domain
man	maneuvering
max	maximum
min	minimum
P	parking Space
R,ad	response time of the automated vehicle
req	required
R,md	reaction time of the manually driven vehicle
RSS	Responsibility-Sensitive Safety
stop	stopping
tol	tolerance
V	vehicle
x	x-direction (longitudinal vehicle direction)
y	y-direction (lateral vehicle direction)

Kurzzusammenfassung

Automatisiertes Valet-Parken (AVP) ist ein Dienst, welcher das Potential besitzt den Fahrer von der Last des manuellen Parkens zu befreien und ihm wertvolle Zeit zu ersparen. Die Einführung eines AVP-Systems in schon bestehende Parkhäuser kann zum Mischverkehr zwischen manuell geführten und automatisierten Fahrzeugen führen. Hierbei können Funktionsmodule zur Ausführung des AVP-Dienstes im Fahrzeug und/ oder in der Infrastruktur untergebracht werden. Zwei, in diesem Szenario bis dato ungelöste Forschungsfragen, sind die Definition von notwendigen Mindestkriterien an einen sicheren AVP-Dienst und die Verteilung von Funktionen zwischen der Infrastruktur und dem automatisierten Fahrzeug. Insbesondere die Definition von Mindestkriterien ist erforderlich, um die notwendige Sicherheitsauslegung in der frühen Systementwicklungsphase zu gewährleisten. Diese Arbeit spezifiziert solche Mindestkriterien für AVP-Systeme, um das Risiko von Gefährdungen zukünftig eingesetzter AVP-Systeme zu reduzieren. Die notwendige Sicherheitsauslegung wird für verschiedene Parkhaustopologien bei Berücksichtigung der benötigten Kooperation zwischen Infrastruktur und automatisiertem Fahrzeug hergeleitet. Im ersten Schritt wird das Fehlen von Mindestkriterien und möglicher AVP-Konfigurationen im Stand der Technik identifiziert. Die Methodik zur Identifikation der Mindestkriterien ist dabei in drei Teile gegliedert: *Mindestsicherheitsanforderungen,* eine *mindestens erforderliche Wahrnehmungszone* und *funktionale Anforderungen. Mindestsicherheitsanforderungen* definieren die notwendig zu bestimmenden Parameter und zugehörige Schwellenwerte. Sie verhindern, dass das AVP-System potenzielle Gefahren und kritische Situationen verursacht. Eine *mindestens erforderliche Wahrnehmungs-* und *Sicherheitszone* beschreibt technologieunabhängige, geometrisch basierte und minimal sicherheitsrelevante Bereiche um das Ego-Fahrzeug. Die Bestimmung notwendiger Parameter für das kollisionsfreie Anhalten wird in dieser mindestens erforderlichen Wahrnehmungszone gefordert. Zusätzlich wurden aus definierten Szenarien *funktionale Anforderungen* an das AVP System abgeleitet. Diese funktionalen Anforderungen werden Funktionsmodulen zugeordnet und bilden als Systembausteine eine modulare AVP-Systemarchitektur. Die Mindestsicherheitsanforderungen, die mindestens erforderliche Wahrnehmungszone und die funktionalen Anforderungen bilden die Mindestkriterien für die in dieser Arbeit erarbeitete Checkliste. Im Rahmen dieser Arbeit dienen Mindestkriterien und Einflussfaktoren auf Kosten, Zeiteffizienz, Sicherheit und Verfügbarkeit als Grundlage für die Ableitung benötigter AVP-Konfigurationen. Dabei besteht ein Zielkonflikt zwischen den Gesamtkosten, der Zeiteffizienz, der Sicherheit und Verfügbarkeit von AVP-Systemen mit heutigen Fahrzeugen. AVP Konfigurationen und Mindestkriterien erleichtern die Migration von AVP-Systemen in existierende und neu errichtete Parkhäuser. Mindestkriterien legen die Grundlage für die Entwicklung einer notwendigen Sicherheitsauslegung.

Summary

Automated valet parking (AVP) is a service which potentially releases the driver from the burden of parking the vehicle manually and saves his valuable time. However, the integration of AVP systems into today's parking facilities may result in a mixed traffic of manually driven and automated vehicles. Thereby, function modules to execute the AVP Service can be placed inside the vehicle and/ or inside the infrastructure. The two yet unresolved research questions in such a scenario are the definition of necessary minimum criteria for a safe AVP service and the distribution of functions between the infrastructure and the automated vehicle. In particular, the definition of minimum criteria is required to ensure the necessary safety by design in the early system development phase. This thesis specifies such minimum criteria for AVP systems to minimize the risks of harm for future deployed AVP systems. The necessary safety design is derived for different topologies of parking garages by considering the needed cooperation between the infrastructure and the automated vehicle.

In the first step, the lack of minimum criteria and the lack of possible AVP configurations is identified in the state-of-the-art. The methodology to identify minimum criteria is divided in three parts: *minimum safety requirements*, *minimum required perception zone* and *minimum functional requirements*. *Minimum safety requirements* define the parameters and corresponding thresholds that are required to be investigated. They prevent the AVP-system to cause potential hazards and critical situations. A *minimum required perception* and *safety zone* describe technology-independent, geometric-based and minimum safety-relevant areas around the ego-vehicle. The determination of necessary parameters for a collision-free stop is required in the minimum required perception zone. Additionally, *minimum functional requirements* are derived from defined scenarios. The functional requirements are assigned to function modules and form as system building blocks modular AVP system architecture. *Minimum safety requirements*, the *minimum required perception zone* and *minimum functional requirements* form the minimum criteria for the elaborated checklist.

In the scope of this work, minimum criteria and impacts on costs, time efficiency, safety as well as availability serve as a justification to derive needed AVP configurations. Distributed functions range from the perception to the execution. A tradeoff exists between overall costs, time efficiency, safety and availability of AVP systems with today's vehicles. AVP configurations and minimum criteria ease the migration of AVP systems in today's existing and in newly constructed parking garages. Minimum criteria lay the foundation for the development of a necessary safety design.

1 Introduction

The continuous urbanization and the increasing number of registered vehicles results in an increasing shortage of parking space in big cities[1]. Additionally, today's aerodynamic design of the bodywork decreases the driver's field of view.[2] As a consequence, the parking process becomes more complicated. Parking assistance systems are already integrated in series to support the driver with this increasingly demanding task. While early parking assistance systems provided informing signals based on ultrasonic technology, other systems such as fully automatic parking assistance systems take over longitudinal and lateral control of the vehicle and park the vehicle supervised automatically. The driver is monitoring the environment and is always keeping a dead man's switch activated.[3] More recent parking assistance systems provide a remote control for initiating the parking process.[4] The driver may monitor the parking process from outside the vehicle. Autonomous parking pilots which do not require the driver's presence are under research and development.[5] Automated valet parking (AVP) is a service which releases the driver from the burden of parking manually and potentially saves his valuable time. Thereby, the driver parks the vehicle at the entrance of a parking facility in the handover zone and initiates the AVP process via a terminal. Thereafter, the AVP system consisting of automated vehicle and the infrastructure (Parking Area Management, PAM) system takes over the responsibility for the driving mission. The driving tasks of perception and planning can be accomplished cooperatively by sharing required AVP functions. Once the vehicle is parked properly, the user can instruct a hand back request to continue his journey.

[1] Zixiong, J.: Report shows extreme shortage of parking spaces in China's megacities (2017).

[2] Bartlett, J. S.: Best and Worst Cars and SUVs for Visibility (2019).

[3] Gotzig, H.: Parking Assistance (2016).

[4] Daimler AG: Remote Parking Pilot: Remote parking with the smartphone app (2015).

[5] Banzhaf, H. et al.: The future of parking: A survey on AVP with an outlook on high density parking (2017).

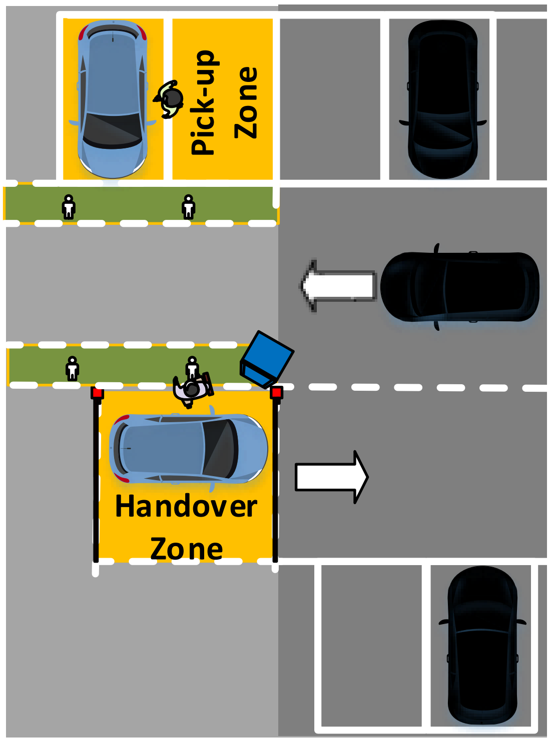


Figure 1–1: Automated valet parking starts at the entrance of the parking garage. The vehicle is dropped off at the handover zone for driverless automated parking. The parking pilot parks the vehicle at a parking spot and waits in standby for a driver's back request. Once the user initiates a hand-back request, the vehicle is parked at the pick-up zone.

1.1 Motivation

Today's parking facilities mainly target the provision of parking spaces for manually driven vehicles. The introduction of automated valet parking in these parking facilities may lead to a mixed traffic in which manually driven and automated vehicles are operating. The involvement of pedestrians and manually driven vehicles raises the issue of safety for life and health. The integration of AVP systems shall avoid additional risk in comparison to a manually operated parking garage. However, challenges lie in the release of safe automated driving systems. A major problem is the test coverage of the rapidly expanding parameter space to validate the safety of the automated system.[6,7] The Non-Traffic Surveillance (NTS) recordings from 2012 to 2014 show that around 5,700 people were killed and 277,000 were injured in the United States in non-traffic crashes such as on private roads, two-vehicle crashes in parking facilities, or collisions with pedestrians in driveways.[8] AVP systems could potentially decrease accidents in such non-traffic scenarios. However, just as a human driver proved his

[6] Amersbach, C.; Winner, H.: Functional decomposition: An approach to reduce the approval effort (2017).

[7] Wachenfeld, W. H.: How Stochastic can Help to Introduce Automated Driving (2017).

[8] Singh, S.: Non-traffic surveillance: fatality and injury statistics in non-traffic crashes, 2012 to 2014 (2016).

capability by passing a driving license test it would be beneficial to define criteria for the use case automated valet parking to standardize required capabilities of AVP systems and to provide consistency through the diverse development and implementation processes before automated systems are seriously deployed.[9] Minimum criteria have to be defined to provide a subset of minimum capabilities for automated driving in parking garages. The investigation of the state-of-the-art shows that existing minimum criteria for AVP are high-level (cf. chapter 2). Standard and guidelines provide an abstract definition of the system's capabilities for automated driving systems.[10,11] On the other hand the race of developing AVP systems is already taking place.[12] Sensing, planning and execution modules are developed and improved. However, still those AVP systems lack a definition for a required performance. Since manufacturers are trying to win the battle of introduction and release the first parking pilot in series, the need for definite test criteria of developed AVP systems becomes crucial. The consideration of the developed AVP systems for further release tests needs definite criteria. Manufacturers and suppliers require minimum criteria to design safe AVP system's in the concept phase. Minimum criteria shall minimize the risks of harm possibly caused by AVP systems. The integration of minimum criteria in the early system development process shall ease the design of safe AVP systems. Minimum criteria serve as a basis for *safety by design*[13]. Hereby, diverse topologies of parking garages exist.[14] A major issue is to find the necessary safety design for different topologies of parking garages by considering the needed cooperation between the infrastructure and the automated vehicle. The allocation of responsibilities between infrastructure and automated vehicle for the required safety design is challenging. A major problem is to specify justified thresholds which are applicable to diverse AVP implementations for different parking garage topologies.

When considering automation in parking facilities another yet unresolved research question is the distribution of functions between the vehicle and the parking facility. Functions hereby refer to sensing, planning and acting capabilities which can be taken over by the automated vehicle or by the infrastructure or shared between both entities. Thereby, there are two extremes: the functions can be implemented only inside the vehicle (vehicle-based AVP[15]) or placed inside the PAM system (infrastructure-based AVP[16]). Both extremes provide their benefits in terms of costs, time-efficiency, safety, availability, and early introduction. The

[9] Grubmüller, S. et al.: Automated Driving from the View of Technical Standards (2016). p. 38

[10] SAE International Standard J3016: Taxonomy for Automated Driving Systems (2014).

[11] ISO: ISO 26262: Road vehicles - Functional safety (2018).

[12] Banzhaf, H. et al.: The future of parking: A survey on AVP with an outlook on high density parking (2017).

[13] van de Poel, I.; Robaey, Z.: Safe-by-Design: from Safety to Responsibility (2017).

[14] Pech, A. et al.: Parkhäuser - Garagen (2009). pp. 375 – 410.

[15] Jeevan, P. et al.: Realizing autonomous valet parking with automotive grade sensors (2010).

[16] Daimler AG: Daimler and Bosch jointly premiere automated valet parking in China (2018).

extremes raise the question how functions can be distributed between infrastructure and automated vehicle and based on which kind of criteria this should be decided. Today's AVP configurations[17] vary in their technical realizations and approaches, but similarities lie in the preferred selection of a specific AVP configuration. The minimum criteria cover the sensing, planning and execution phase. The issue remains whether a vehicle-based or infrastructure-based AVP system is able to provide the identified minimum criteria standalone and which intermediate configuration is more beneficial. A distribution which is optimal in terms of costs, time efficiency, safety and availability is hereby desirable but may be a tradeoff. The description of different AVP configurations allows the parking garage operator and manufacturers to choose the desired degree of infrastructure support according their preferences. Some configurations are more beneficial in terms of time efficiency and early introduction whereas others can be preferred in terms of costs or availability. It is up to the parking garage operators and the manufacturers to decide which distribution of functions they find more beneficial. One of the configurations can be chosen due to its more appropriate suitability for certain parking facilities.

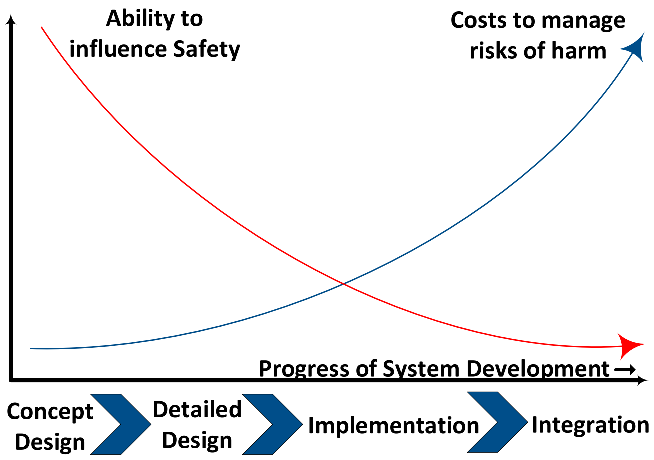


Figure 1–2: Since the race for AVP systems has already started[17] and a multitude of AVP systems is expected to be released by different manufacturers, safety by design[14] will become crucial before the deployment of such automated systems. Minimum criteria are elaborated by considering diverse topologies of parking garages and the cooperation between the infrastructure and the automated vehicle. Defined minimum criteria are integrated in the concept phase of the early development process to minimize the risks of potential harm (*safety by design*) and avoid larger costs after deployment. The figure is modified and taken from Szymberski[18].

[17] Banzhaf, H. et al.: The future of parking: A survey on AVP with an outlook on high density parking (2017).

[18] Szymberski, R.: Construction Project Safety Planning (1997).

1.2 Research Objectives

Following the motivation described in 1.1 two main research questions can be derived:

- *RQ1*: What is the essential subset of minimum criteria AVP configurations require to fulfill for safe operation?
- *RQ2*: Which degrees of infrastructure support are needed and what are their benefits?

Based on the two research questions the following research objectives (*RO*) are elaborated:

- *RO1*: The identification of minimum criteria valid for AVP configurations to minimize the risks of harm.
- *RO2*: A specification of the required infrastructure support for AVP to achieve a desired AVP performance.

Research objective *RO1* shall answer the research question *RQ1*. Minimum criteria for all degrees of infrastructure support have to be identified to minimize the risk of harm. Minimum criteria which are mandatory for AVP configurations in a mixed traffic are specified to avoid hazards and collisions. Minimum criteria can be used to identify whether a specific AVP configuration may suitable to execute a collision-free AVP process. Minimum criteria can be used in the early development phase for the design of safe AVP systems. However, completeness of requirements and sufficient specifications for all gathered criteria cannot be guaranteed. The elaborated set of minimum criteria shall target diverse topologies of parking garages and indicate the required support of the infrastructure. A subset of defined criteria may not be able to certify the AVP system or provide a safety approval for AVP systems. However, this thesis contributes to the minimization of possible harm which is potentially caused by safety-critical AVP systems. For that purpose, a mandatory checklist which defines required minimum criteria targeting the collision-free performance of the AVP service is presented. A minimum criteria-based capability checklist shall reduce the amount of safety-critical AVP deployed in future parking garages. The AVP system has to meet every single criterion to pass the checklist. The checklist provides potential for reduction of hazards before the deployment of AVP systems. The research question *RQ1* raises additional sub-questions concerning minimum safety requirements to prevent hazards and unreasonable risks, minimum areas required to be perceived to detect potential collision partners and minimum required functions to ensure the performance of an AVP service. This thesis focuses on these sub-questions addressed in Figure 1–3 and in the methodology:

- *RQ1-1*: Which parameters of the ego-vehicle's and object's state space does every AVP configuration have to determine and which situations have to be prevented to provide a safe AVP-service? (*Minimum safety requirements*)
- *RQ1-2*: In which minimum areas does the identified parameters require to be perceived? (*Minimum required perception zone*)

- *RQ1-3*: Which minimum functionalities does every AVP configuration have to provide in order to perform an automated parking pilot? (*Minimum functional requirements*)

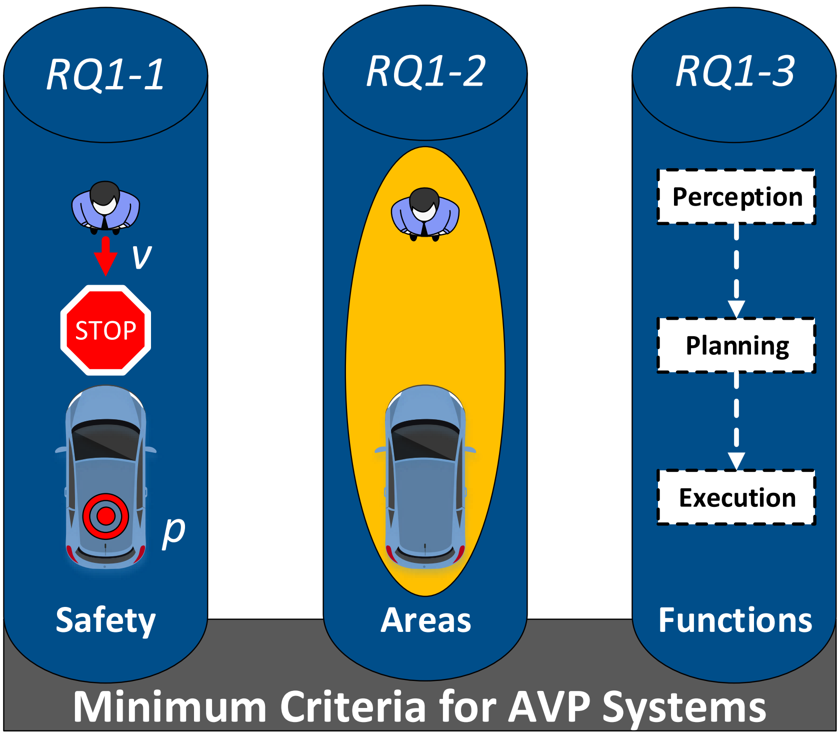


Figure 1–3: Minimum criteria is based on three main pillars. Minimum safety requirements prevent hazards and unreasonable risks (*RQ1-1*, left pillar), minimum areas required to be perceived contribute to the detection of potential collision partners (*RQ1-2*, middle pillar) and minimum required functions ensure the performance of an AVP service (*RQ1-3*, right pillar).

Research objective *RO2* shall answer the research question *RQ2*. The specification of the required infrastructure support shows to which degree today's parking facilities have to be adjusted to increase the performance of a valet parking service. More precisely, possible degrees of infrastructure-support can be described for cooperative AVP to optimize the parking process. Cooperative AVP in this context refers to the collaboration between automated vehicle and PAM infrastructure. The garage operator can adjust his parking facility according the desired degree of infrastructure-support to increase the performance of the parking garage. Thereby, the degree of infrastructure automation may vary between a complete vehicle-based AVP service or an automated vehicle which only executes instructions of an intelligent infrastructure. The allocation of modules between infrastructure and vehicle provides a recommendation how a specific AVP configuration can be designed. The required support of the infrastructure is evaluated by considering specified impacts on costs, time-efficiency, safety and availability. This thesis contributes hereby, by providing distributions of functions which should rather be executed by the infrastructure and/ or by the automated vehicle. In particular, the results of this work ease the migration of AVP system's in today's existing parking garages and in newly constructed parking facilities. Parking garage operators and manufacturers can select their preferred degree of infrastructure support. Both can choose between personally preferred version of AVP configurations based on the relevance of costs, time-efficiency, safety, availability and early introduction. Compared to existing literature on AVP systems, this thesis hereby contributes to identification of the necessary safety design for the individual parking garage and the needed infrastructure support.

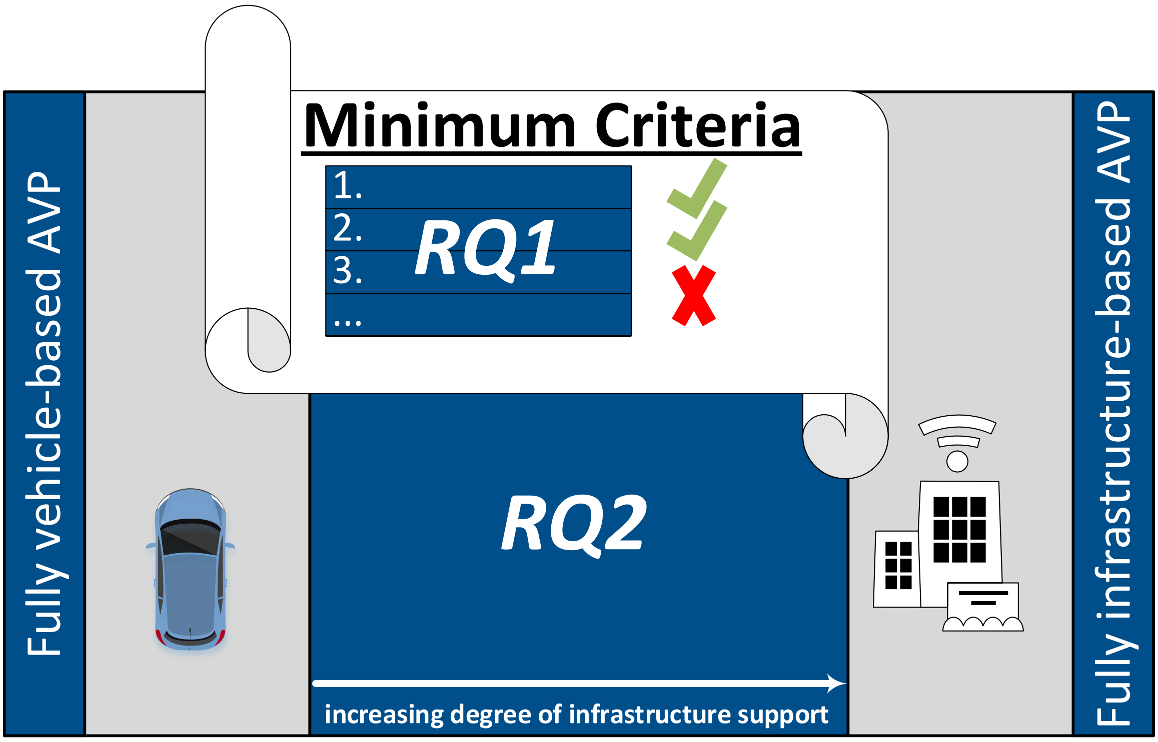


Figure 1–4: Functions which are required to be performed during the AVP service can be allocated to the automated vehicle and/ or to the intelligent infrastructure. This raises the research question which possible degrees of infrastructure support do exist for AVP. Furthermore, a definition of minimum criteria summarized in a checklist minimizes the risks of harm throughout the early safety design process. The two yet unresolved research questions are the definition of minimum criteria and the distribution of functions between the infrastructure and the automated vehicle.

1.3 Research Methodology

The overall methodology developed in this thesis contains the three pillars to determine minimum criteria for automated valet parking, namely, minimum safety requirements, minimum required perception zone and the minimum functional requirements. The *minimum safety requirements*, *minimum required perception zone* and *minimum functional requirements* form hereby together the minimum criteria as a foundation for the safety by design (*RQ1, RO1)*. If a specific AVP implementation does not fulfill the minimum criteria, the system is potentially safety-critical and may require modification. In particular, this thesis introduces a checklist of minimum criteria to minimize risks of harm already in the early concept phase. However, considering the overall automated driving system is fairly complex. A broad range of parameters concerning the system's behavior and environment renders definition of requirements infeasible extensive. If the overall system is considered, the number of occurring situations might be unlimited.[19] An abstraction of the system's behavior is necessary to limit the excessive number of existent parameters. Therefore, this thesis introduces a split of the overall automated driving system into a manageable amount of functional scenarios in order to provide a functional description of the system. The system's functional behavior is decomposed into functional scenarios according to Ulbrich et al.[20]. An abstraction of the system's behavior is proposed in functional scenarios which occur during the AVP service.[21] A scenario describes snapshots of the environment and the interaction of entities while time is progressing. The decomposition in scenarios is in compliance with the item definition of ISO 26262[22]. The ISO 26262 is an international standard for functional safety of E/E systems in road vehicles which provides a systematic approach to prevent unreasonable risks. The approach suggests an item definition. The item definition describes the functionality, interfaces, and environmental conditions of the item. Identified functional scenarios introduced in this thesis provide the input for the analysis of *minimum safety requirements, a minimum required perception zone* and *minimum functional requirements.*

Minimum safety requirements (RQ1-1) are elaborated from a situational analysis in the way of a Hazard Analysis and Risk Assessment (HARA). An ISO 26262-compliant approach is used to assess hazards and elaborate safety requirements to risks and reduce them to acceptable levels. The objective of the HARA is the identification of potential malfunctions to determine related top-level safety requirements called safety goals. These safety goals can be further broken down into low-level safety requirements. Low-level safety requirements define the parameters that are required to be investigated and corresponding thresholds for parameter determination. Parameters are required to be perceived in specific areas of interest around the ego-vehicle.[23] The *minimum required perception zone (RQ1-2)* consists of safety-relevant areas around the ego-vehicle. Areas of interest are derived from occurring maneuvers in the parking garage. Each functional scenario is examined according to specific maneuvers that are instructed by the automation system. Additionally, maneuvers are extracted from layouts of car parks.[24] Worst case constraints for the operational domain and serve as an input for each maneuver to specify a minimum required areas for collision avoidance. The superposition of relevant areas forms the minimum zone around the ego-vehicle.[25] The AVP system can be safe, but may not provide the minimum functional performance. *Minimum functional requirements (RQ1-3)* that every AVP configuration has to fulfill are therefore derived from the item definition by investigating the required functional behavior for

[19] Amersbach, C.; Winner, H.: Defining Required and Feasible Test Coverage for HAV (2019).

[20] Ulbrich, S. et al.: Defining and Substantiating the Terms Scene, Situation, and Scenario for AD (2015).

[21] cf. Schönemann, V. et al.: Scenario-based functional Safety for AD on the Example of AVP (2018).

[22] ISO: ISO 26262: Road vehicles - Functional safety (2018).

[23] cf. Schönemann, V. et al.: Fault Tree-based Derivation of Safety Requirements for AVP (2019).

[24] Pech, A. et al.: Parkhäuser - Garagen (2009). pp. 375 – 408.

[25] cf. Schönemann, V. et al.: Maneuver-based adaptive Safety Zone for infrastructure-supported AVP (2019).

each functional scenario. Functional requirements are building functional modules that AVP system have to provide. The system building blocks can be assigned to the vehicle or to the infrastructure.

Minimum criteria and impacts are used to specify degrees of infrastructure support for AVP to achieve a desired AVP performance (*RQ2, RO2)*. This thesis introduces a set of possible function distributions between infrastructure and automated vehicle. functions range from the perception to the control of actuators. Thereby, the following impact factors are considered for the arbitration of modules:

- *Costs*: Characterizes additional efforts and expenses that have to be made to implement the described functionality apart from today's state-of-the-art parking garages or vehicles.
- *Time efficiency*: Describes a quick handover, parking and pickup process to increase the vehicle throughput in a parking garage and decrease congestion.
- *Safety*: Refers to a collision-free AVP process and the avoidance of critical scenarios.
- *Availability*: Specifies the impact if the function cannot be performed anymore. The degree may vary from a single AVP vehicle in standstill to a complete breakdown of the parking facility operation.

Figure 1–5 illustrates the described methodology as introduced in this thesis. The research questions *RQ1* and *RQ2* as defined in section 1.2 are hereby assigned to corresponding blocks.

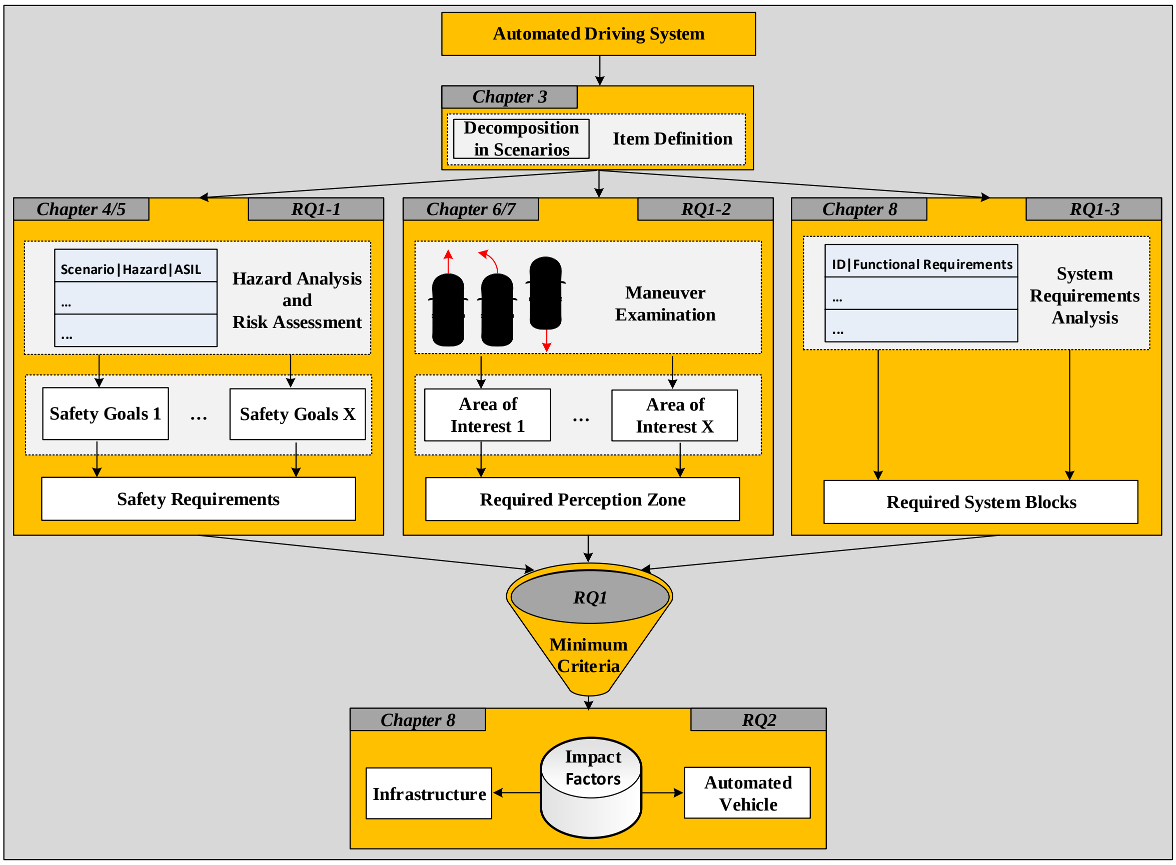


Figure 1–5: The overall methodology developed in this thesis. Decomposition of the automated driving system in functional scenarios which serve as input for the following steps: hazard identification and derivation of safety requirements from safety goals (left), maneuver-based specification of areas of interest (middle), analysis of system requirements (right) to achieve minimum criteria for AVP and characterize possible degrees of infrastructure support

The main contribution of this thesis is hereby the definition of minimum criteria for AVP systems (*RQ1*) and a detailed analysis for the distribution of functions between the automated vehicle and the parking facility (*RQ2*), which has not been fully provided in the state-of-the-art before. In order to contribute to the research questions *RQ1* and *RQ2* this work is structured as follows:

- Chapter 2 summarizes the state-of-the-art of today's standards, future valet parking systems and research projects to investigate if minimum criteria were targeted yet. Furthermore, it is described which AVP configurations are present in the state-of-the-art
- Chapter 3 describes the functionality, interfaces, and environmental conditions of the item. The sections provide a system description which serves as a basis for the further safety and functional analysis.
- Chapter 4 identifies hazards and assesses risks based on the item definition to derive top-level safety requirements (safety goals).
- Chapter 5 breaks down top-level safety requirements into low level-safety requirements to determine minimum thresholds valid for all AVP configuration in all parking facilities.

- Chapter 6 specifies minimal areas of interest around the ego-vehicle for specific maneuvers in a parking garage. The superposition of maneuver-based zones leads to a minimal area for which the defined minimum criteria are valid.
- Chapter 7 illustrates the implementation of an adaptive safety zone which characterizes the least point for initiating a deceleration. The chapter describes used software tools and the interaction of the components to avoid collisions.
- Chapter 8 identifies functional system blocks based on the item definition. The system modules are distributed according the impacts on costs, time-efficiency, safety and availability between vehicle and infrastructure to derive possible AVP configurations.
- Chapter 9 summarizes the key insights, contributions and limitations of this work and provides an overview about possible directions for future research.

2 State-of-the-art

Future AVP systems[26] raise the research question whether developed AVP systems are sufficient to provide a safe automated valet parking service or whether modifications would be necessary before the release of such systems. In the following sections, the state-of-the-art of AVP is investigated to clarify to which extent answers exists for these issues. First of all, standards and guidelines are summarized to find out whether recommendations and restrictions are specified for automation systems. Subsequently, the associated minimum capabilities for automated valet parking systems are described. Finally, the design process for functional safe road vehicles and for the safety of the intended functionality as introduced in literature to date is illustrated. Finally, related to the contributions of this thesis selected research projects for scenario-based testing, verification and validation of automated driving functions are presented. A mathematical model, called Responsibility-Sensitive Safety (RSS), is introduced to describe main differences between the results in RSS and the contributions of this thesis.

2.1 Standards and Guidelines

The diversity of actual and potential automated driving systems gives need for standardized approaches for the assessment and categorization of different levels of automation. Such standards may contribute to a general consensus of minimum criteria for automated driving systems. Different organizations have already targeted the definition of automation levels and assigned system capabilities to each automation level. These entities are the Society of Automotive Engineering (SAE), the National Highway Traffic Safety Administration (NHTSA), the German Federal Highway Research Institute (BASt) and the German Association of the Automotive Industry (VDA).

The SAE International[27] provides a taxonomy for the six levels of driving automation ranging from no driving automation (level 0) to full driving automation (level 5). The international standard categorizes automated valet parking as a level 4 automated driving system. Thereby, the automation system shall perform both the longitudinal and the lateral vehicle motion control tasks of the dynamic driving task. The automation system shall monitor the driving environment (detecting, recognizing and classifying objects and events) and respond to such events as required to execute the dynamic driving task and/ or the fallback. The automated driving system does not operate outside of its operational design domain unless a

[26] Banzhaf, H. et al.: The future of parking: A survey on AVP with an outlook on high density parking (2017).

[27] SAE International Standard J3016: Taxonomy for Automated Driving Systems (2014). p. 23

conventional driver takes over the dynamic driving task. The automated driving system performs the fallback and is required to achieve a minimal risk condition in case of performance-relevant system failure or upon exit of the operational design domain. The fallback-ready user does not have to be receptive to a fallback request.

The National Highway Traffic Safety Administration[28] (NHTSA) released a preliminary statement of policy concerning automated vehicles. NHTSA distinguishes between 5 levels of automation starting with level 0 to 4. A level 4 system involves automation of two primary control functions such as lateral and longitudinal control. The automation system performs all safety-critical driving functions and monitors the roadway conditions for an entire trip. The driver is not responsible for the monitoring of the roadway or safe operation anymore. The driver does not have to be physically present inside the vehicle, but has to activate the automated vehicle system. The regain of manual control with an appropriate amount of transition time (fallback) is not expected and therefore safe performance is solely based on the automated system.

The German Federal Highway Research Institute[29,30] (BASt) provided definitions for automation which range from driver only to full automation. The level *full automation* requires the system to take over lateral and longitudinal control completely and permanently within the individual specification of the application. Before the system's limits are reached, a takeover request needs to be initiated with a sufficient time buffer. A takeover request does not have to be performed by the driver. In absence of driver control after a takeover request, the system has to establish a minimal risk condition in all situations. The driver is no longer required for monitoring purposes.

Similarly, the German Association of the Automotive Industry[31] (VDA) categorizes valet parking as a level 4 automation system. The driver can hand over the entire driving task to the system in a specific use case which are characterized by the type of road, the speed range and the environmental conditions. The system requires to recognize its limits and shall perform longitudinal and lateral driving actions within the defined use case. The system must execute the monitoring at all times and the driver does not have to resume the dynamic driving task within the use case. The VDA assumes the introduction of automated valet parking around 2020 as shown in Figure 2–1.

As a first legal basis the Vienna Convention on road transport[32] allows since 2015 the influence of automated systems only if they can be overruled or turned off at any time by the driver. Therefore, the Vienna Conventions still requires that each vehicle must have a driver.

[28] NHTSA: Preliminary Statement of Policy Concerning Automated Vehicles (2013).

[29] Gasser, T. M. et al.: Rechtsfolgen zunehmender Fahrzeugautomatisierung (2012). pp. 8-12

[30] Gasser, T. M.; Westhoff, D.: BASt-study: Definitions of automation and legal issues in Germany (2012).

[31] VDA: Automation: From Driver Assistance Systems to Automated Driving (2015).

[32] United Nations: Vienna Convention on Road Traffic (1968).

The operation of driverless vehicles is not possible in the current situation on public roads. However, there is an on-going discussion for a novel convention of driverless vehicles.

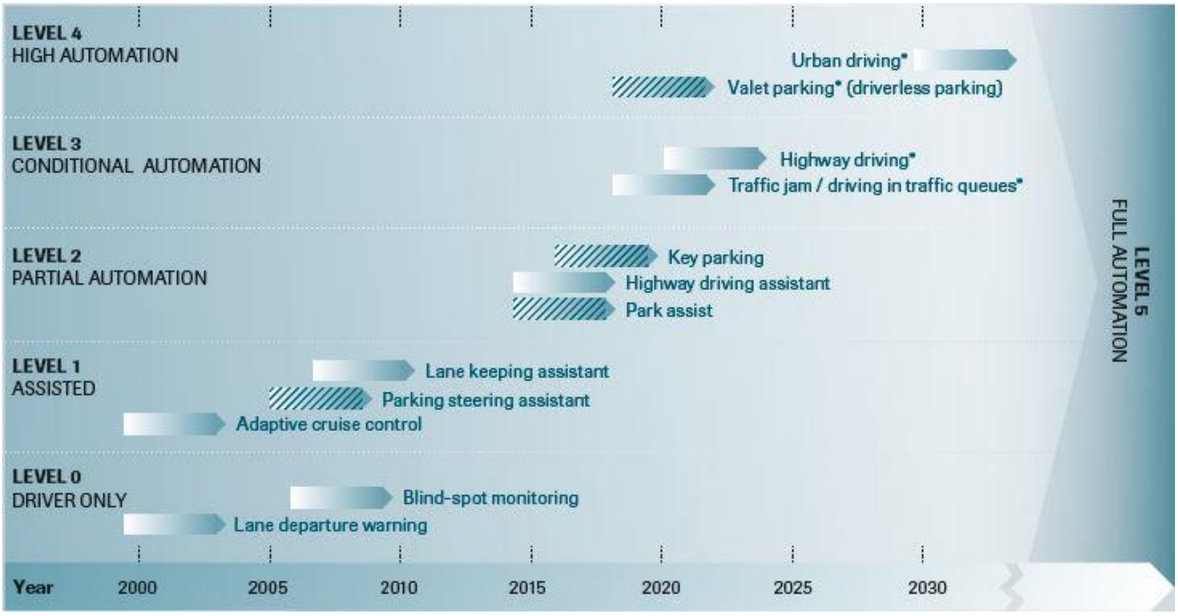


Figure 2–1: Former and expected periods of introduction for assisting and automated driving functions according to the German Association of the Automotive Industry (VDA)[31]. The VDA assumes the introduction of automated valet parking around 2020.

Considering the various definitions of the automated driving levels, the following minimum capabilities can be deduced for automated valet parking. The criteria are summarized in Table 2–1:

- Automated valet parking shall perform both the longitudinal and the lateral vehicle motion control tasks of the dynamic driving task simultaneously and permanently.
- The automation system shall monitor the driving environment and respond to such events as required to execute the dynamic driving task and/ or the driver fallback.
- The automated driving system by design shall not operate outside of its operational design domain unless a conventional driver takes over the dynamic driving task.
- The automated driving system shall be capable of performing the fallback and achieving a minimal risk condition in case of performance-relevant system failure or upon exit of the operational design domain. It may allow the user to perform the fallback.

Table 2–1: Minimum criteria for AVP assigned by today's standards

VDA Level	Narrative Definition	Lateral and longitudinal motion control	Monitoring	Fallback	Operational design domain
4	Performance of the dynamic driving task in the operational design domain and fallback even if the user is not receptive to a fallback request.	System	System	System	Limited

Such a high-level definition of minimum criteria ensures the suitability and applicability for all use cases in the automated driving domain. After a parking request the valet parking is performed without presence of a human driver. Therefore, the driver will not be involved in a potential fallback situation. The self-driving system requires safety mechanisms to transfer the system into a minimal risk condition at any point in time. Beside the categorization of automated driving levels, standards exist which target the functional safety of road vehicles.

The International Organization for Standardization (ISO) released the ISO 26262 as an automotive adaptation of the International Electrotechnical Commission (IEC) 61508[33]. ISO 26262 specifies a development process for functional safety of electrical and/ or electronic (E/E) systems within road vehicles. The standard is based upon a V-model for the different phases of product development and aims to identify hazards caused by malfunctioning behavior. In the first step, ISO 26262 suggests an item definition in which a system description has to be performed. The objective of the item definition is to support an understanding of the item by listing the functionalities, behavior, interfaces and environmental conditions to perform subsequent phases. One of the subsequent phases is a hazard analysis and risk assessment (HARA) in which potential risks are identified to formulate safety goals in order to prevent or mitigate unreasonable risk. Safety goals are assigned a risk level called automotive safety integrity level (ASIL) determined by the severity, exposure and controllability of the hazardous event. It is crucial that safety mechanisms[34] are evaluated during the HARA and are not assumed prior to the analysis. Functional safety requirements are derived from safety goals and has to be allocated to architectural elements. Functional safety requirements are derived from the associated safety goal. The derivation can be supported by established methods e.g. Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis, and Hazard and Operability (HAZOP). The application of ISO 26262 is not mandatory. However, the international standard provides a standardized methodology which is generally-acknowledged as state-of-the-art. Hazards may be caused not only by faults addressed in the ISO 26262, but also by lack of the intended functionality or by misuse. The safety of the intended

[33] IEC SC 65A: Functional safety of electrical/electronic/programmable electronic safety-related systems (2010).

[34] cf. 6.4.1.2. ISO: ISO 26262-3: Road vehicles - Functional safety - Part 3: Concept phase (2018).

functionality (SOTIF) is addressed in the ISO/PAS 21448[35] and defines methods to achieve the absence of unreasonable risk for these types of hazards in compliance with ISO 26262. The aim is to minimize hazards that are unsafe and known by either improving the function or by restricting its use or performance. Unsafe and unknown risks shall be reduced with an acceptable level of effort. In the verification phase, the system is proved to behave as expected to avoid known hazards and it is examined if its components are covered sufficiently by sensor, decision-algorithm and actuator tests. In the validation step, system functions performed by sensors, decision-algorithms and actuators are analyzed for causation of unreasonable risk in real-life situations such as field experiences, long-term vehicle test or worst-case scenarios. This can be achieved by applying the process indicated in Figure 2–2 and by considering performance limitations of the intended functionality. Figure 2–2 shows the V-model methodology proposed by ISO 26262 and SOTIF.

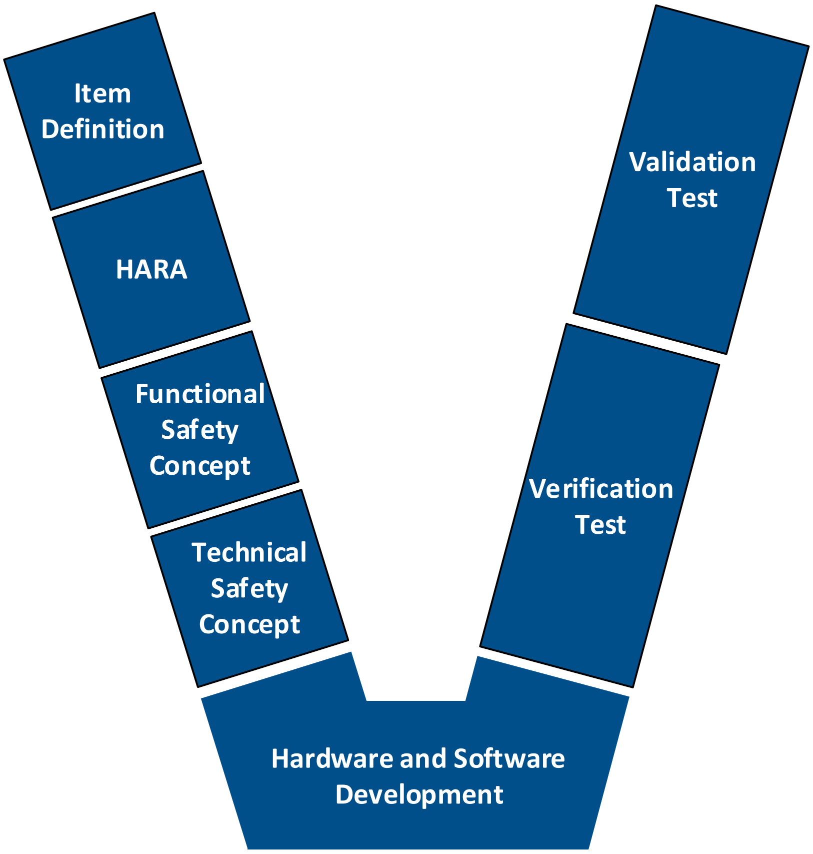


Figure 2–2: V-model methodology according to ISO 26262 and SOTIF[35]. The item definition describes the system behavior, its interfaces and the interaction with the environment. The hazard analysis and risk assessment (HARA) aims to identify top level safety requirements called safety goals which can be used to derive low level safety requirements for a functional and technical safety concept. The safety concept is implemented in hardware and software and requires verification and validation.

[35] International Organization for Standardization: ISO/PAS 21448: Road vehicles - SOTIF (2019).

The described standards and guidelines are targeting automated driving systems in general. However, to the best of the author's knowledge specific minimum criteria for AVP are not specified in today's standards.

2.2 Automated Valet Parking

The following sections summarize the state-of-the-art of the scientific and the practical perspective on automated valet parking. It is investigated which limitations exists and which parameters require a specification of minimum criteria. Furthermore, this section describes how the distribution of AVP functions between infrastructure and vehicle is implemented in the state-of-the-art. Existing research results are taken into account for the development of minimum criteria and for the identification of possible AVP configurations. Thereby, current valet parking systems are categorized according the distribution of functions between vehicle and infrastructure with the following definition:

- *Vehicle-based AVP*: The AVP service is executed by the automated vehicle standalone. No additional infrastructure support is required.
- *Cooperative AVP:* Automated vehicle and infrastructure are sharing the responsibility for the driving task. System modules can be allocated between the vehicle and the infrastructure.
- *Infrastructure-based AVP*: The entire process chain of perception and planning is managed by the infrastructure. The vehicle is only executing instructions via trajectory control.

2.2.1 Vehicle-based AVP

In 2007, the Defense Advanced Research Projects Agency (DARPA) announced the Urban Challenge which initiated the development of test vehicles in numerous research projects to tackle the challenges of automated driving.[36,37,38] Automated vehicles were designed to drive in urban environments in compliance with traffic rules. Beside a merging into a moving traffic, the driving on long and complex routes with stationary obstacles and intersections, the test consisted of an automated parking scenario. In this parking scenario, the vehicle had to navigate towards the parking spot, detect the free space and park. The DARPA challenge allowed to use the Global Positioning System (GPS), due to the line-of-sight in the test environment. The test vehicles were equipped with a broad variety of expensive sensors, e.g. the Chevrolet Tahoe called Boss which won the DARPA Urban Challenge was equipped

[36] Montemerlo, M. et al.: Junior: The stanford entry in the urban challenge (2008).

[37] Urmson, C. et al.: Autonomous Driving in Urban Environments: Boss and the Urban Challenge (2008).

[38] Rauskolb, F. et al.: Caroline: An Autonomously Driving Vehicle for Urban Environments (2008).

with a combination of sensors such as five radar, two camera and eleven lidar sensors. The Urban Challenge proved the feasibility of the demanded driving tasks in a closed test environment under controlled environmental conditions. However, for commercial use the sensor setup was too expensive and required heavy modifications of series vehicles.

Figure 2–3: Defense Advanced Research Projects Agency (DARPA) boosted the development of automated driving. One major task was an automated parking scenario. The Chevy Tahoe named Boss that won the DARPA Urban Challenge was equipped with an extensive sensor setup containing 11 lidar sensors, 5 radar sensors, 2 cameras and GPS[37]

Jeevan et al.[39] combined the learned lessons from the DARPA Urban Challenge to develop an automated valet parking system by using automotive grade sensors. The authors reused software modules from the Junior 3 test vehicle of the DARPA Urban Challenge and focused on a parking spot detector and a localization system in a GPS-denied environment such as a parking garage. The localization approach combines the visual-based landmark detection and odometry through a Kalman filter. The odometry serves complimentary for the prediction whereas the camera-based detection of artificial landmarks on the road surface provides the observation update. The landmarks are georeferenced offline and known in the map before entering the parking garage. Costs are kept at a minimum for the parking garage operator. The authors state that typical position inaccuracies are around 20 centimeters and heading accuracy are within 2°. Predominant factors are uneven road surface or sharp turns which causes inaccuracies in landmark detection. The vehicle uses only odometry during the parking maneuver. Therefore, errors accumulate over the course of the parking maneuver to 40 cm in lateral, 11 cm in longitudinal direction and 3.5° for the heading angle.

Chirca et al.[40] describes a valet parking system developed by Renault for private home residences without the need of infrastructure support. The vehicle stores the final parking position only if a manual driving procedure was performed once. While the driver is parking, the

[39] Jeevan, P. et al.: Realizing autonomous valet parking with automotive grade sensors (2010).

[40] Chirca, M. et al.: Autonomous valet parking system architecture (2015).

AVP perceives the environment and stores the driven trajectory. Thereafter, the starting position can be adapted and the AVP system is still able to execute an AVP process. The test vehicle is equipped with sensors that exists in high volume series for Advance Driver Assistance Systems (ADAS). It contains a front and rear camera, four wheel odometer encoders, steering encoder, GPS and ultrasonic sensors. A Controller Area Network is used for data transmission. An occupancy map is computed with 12 ultrasonic sensors. Ultrasonic sensors are capable to detect objects in the range of 0.2 m to 4 m. Due to a high rate of false positives caused by echoes from the ground, a filtering system was added. Odometer sensors were fused with visual data for localization. The authors used Simultaneous Localization And Mapping (SLAM) based on an Extended Kalman Filter (EKF). Currently perceived images are continuously matched with key-images previously saved along the trajectory. Images are inspected against the current view to detect the pose. The maximum deviation was ±0.1 m for distances shorter than 500 m.

Continental[41] presented at the International Automobile Exhibition (IAA) an AVP system which finds a parking spot without the help of an infrastructure in the parking garage. No other efforts are required in the parking facility. The automated vehicle is able to navigate on the first floor of the parking garage. The environment is perceived via four surround-view cameras, four short range radar and a forward-facing mono camera. Pedestrians and other vehicles can be detected. The handling of ramps is expected to be possible by 2022.

2.2.2 Cooperative AVP

Beside the placement of functions inside the vehicle, a cooperation between the automated vehicle and the infrastructure is possible to accomplish the dynamic driving task. Different researchers targeted the interaction of both entities. Min and Choi[42,43] implemented an automated valet parking system divided in three modules. The system architecture consists of an AVP server, an AVP mobile and an AVP vehicle controller. Each module provides functionalities shown in Figure 2–4:

- *AVP mobile system*: Valet parking requires to be instructed via a human machine interface. The AVP service is requested and can be monitored via the user's mobile device. A parking area map is transmitted to the user's mobile device to assign a parking space. The computed parking trajectory is displayed and the user is notified if the vehicle is parked successfully.
- *AVP Server*: Environment data is provided by an AVP server which also generates a driving path and monitors the current state of the automated vehicle. Infrared sensors

[41] Continental AG: Pull Up and Have Your Car Parked for You (2017).

[42] Min, K.-W.; Choi, J.-D.: Design and implementation of autonomous vehicle valet parking system (2013).

[43] Min, K.; Choi, J.: A control system for autonomous vehicle valet parking.

detect static obstacles and generates an alternative trajectory. Additionally, the server assesses occupied parking spots and the geometry of the free parking space.

- *AVP Vehicle Controller*: A controller module is required to follow the computed trajectory. The control commands de-/accelerating, steering and gear shifting are performed in-vehicle to follow the trajectory transmitted from the AVP server. The vehicle contains lidar sensors to detect dynamic objects and to stop or to continue the valet parking process.

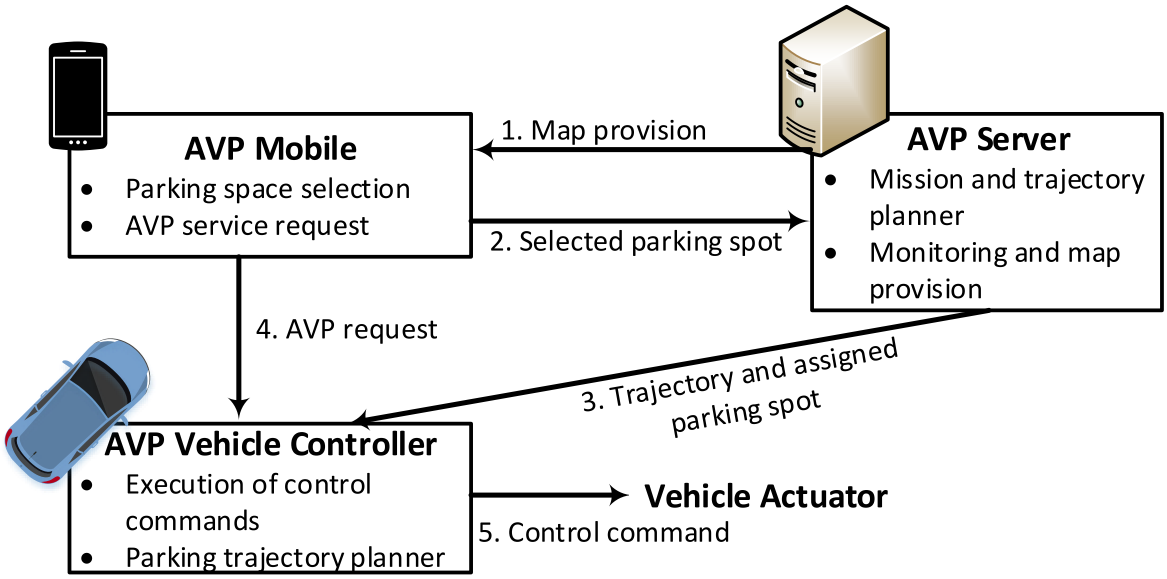


Figure 2–4: AVP System according to Min and Choi[42] based on an AVP server, an AVP mobile and an AVP vehicle controller. An AVP mobile ensures the selection of a parking spot for an AVP request. Thereafter, a corresponding trajectory is sent to the automated vehicle which executes the control commands. AVP Server and vehicle perceive the environment in cooperation.

Löper et al.[44] sees automated valet parking as an integrated travel assistance. An infrastructure camera that observes the parking area from a top view, detects free and occupied parking spaces. The infrastructure transmits the information to the vehicle using a communication device equipped with IEEE 802.11p standard. The information is incorporated in an occupancy grid framework. The remaining parts of the map are built by simultaneous localization and mapping (SLAM) with four IBEO LUX laser scanners. A highly accurate map and DGPS is used for the positioning task. The system is only able to handle static objects, dynamic objects were considered for future work. A smartphone displays the status, position and route of the automated vehicle and can be used for pickup and request purposes.

Schwesinger et al.[45] implemented in the European research project V-Charge an automated valet parking service using close-to market sensors cameras and ultrasonic sensors in a GPS-

[44] Löper, C. et al.: Automated valet parking as part of an integrated travel assistance (2013).

[45] Schwesinger, U. et al.: Automated valet parking and charging for e-mobility (2016).

denied parking garage for electric vehicles. According the authors electric vehicles will be one of the key factors to reduce CO_2 emissions. However, electric vehicles have two major disadvantages: reduced driving ranges and increased charging duration. Automated parking charging shall ease the traveler's transfer. Charging stations can be shared without human interaction by switching electric vehicles once the charging process has finished. Besides high density parking, AVP provides the possibility to reduce the number of required charging stations. The AVP procedure was shown in the low-speed range up to 10 km/h. The VW e-Golf platform is equipped with front- and rear facing stereo cameras with a horizontal field of view (FoV) of 45° and 120°. Additionally, four monocular fisheye cameras provide a 360° surround view. 12 ultrasonic sensors are used to detect close-range objects. All sensor data is fused in an occupancy grid map. The accuracy for both stereo sensors lies in the range of 11-21 centimeters.

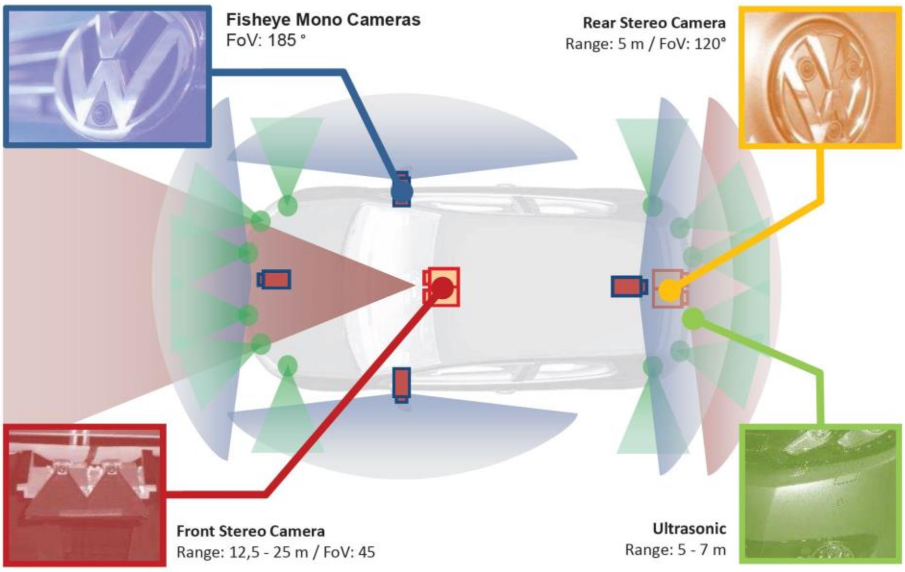


Figure 2–5: An automated valet parking service using close-to market sensors cameras and ultrasonic sensors in a gps-denied parking garage for electric vehicles. The sensor setup according to Schwesinger et al.[45] consists of two stereo cameras in front and to the rear, four fisheye monocular cameras and twelve ultrasonic sensors

Similarly, Klemm et al.[46] gives insights about the test vehicle which navigates to an assigned parking spot and is docked with a charging robot. The electric vehicle drives indoor in a multi-story building without external localization. According to the authors the infrastructure does not have to be heavily adapted: no sensors need to be installed and no other constructional changes are required. The infrastructure assigns a parking space and sends geometric and topological maps to the automated vehicle. The system provides a single charging robot to serve multiple parking spaces. The localization estimation is based on an Extended Kalman Filter (EKF) which fuses vehicle odometry, 2D laserscans with the geometric map

[46] Klemm, S. et al.: Autonomous multi-story navigation for valet parking (2016).

model. The authors claim that the accuracy is sufficient for parking and navigating within the parking facility. The mission control communicates the vehicle's current state to the user.

Friedl et al.[47] gives an overview about BMW's valet parking system that was presented at the Consumer Electronics Show (CES) 2015 in Las Vegas. BMW uses a smartwatch for the human machine interface to order instructions. The infrastructure transmits a digital map and assigns a free parking space. A priori map information contains the floor plan, the route network and semantic information. Thereafter, the automated vehicle navigates to the desired parking spot. A grid map is created based on lidar and ultrasonic sensor data combined with odometry. Perceived reference objects are matched with static map elements in an occupancy grid map. The estimation of the position is based on a Kalman filter. GPS data is not required. A major requirement was that maneuvering in unstructured environments should be possible since the destination is not always known at the starting point and the data correctness based solely on the stored map data cannot be assumed. The planning task is divided in submodules to accomplish the mission. A route planner determines a route towards the destination based on a route network by using the A* search algorithm. Maneuvers are planned to accomplish route segments. Occurring events are taken into account and a trajectory is computed in the trajectory planner from the current to the desired position. The automated vehicle is kept at the lane center to its destination via control actions determined in the trajectory controller. The hierarchical approach allows to plan complex maneuvers.

Even though a multitude of AVP systems tackle the technical challenges of automated driving in a parking environment, none of these focuses on the definition of minimum required criteria to show insufficiencies of AVP systems.

2.2.3 Infrastructure-based AVP

Bosch and Daimler[48,49] jointly implemented the first infrastructure-supported automated valet parking in a mixed traffic at the Mercedes-Benz Museum in Stuttgart. Bosch provides an intelligent parking garage which is equipped with a Wireless Local Area Network (WLAN) access points and lidar sensors to monitor the corridors and the vehicle's surrounding. In the next steps lidar sensors will be replaced by cheaper stereo cameras. A free parking space is assigned at the entrance of the parking garage. If the assigned parking space is occupied by a human driver, the system assigns another one. Daimler provides the vehicle technology. The transmitted control instructions are transmitted via WLAN and executed by the vehicle. In case of an object in the vehicle's trajectory, two types of braking are implemented: a distance-dependent soft and an emergency braking. The object can be a pedestrian, another vehicle or even an animal. The system accelerates once the obstacle is gone. The

[47] Friedl, M. et al.: Vollautomatisiertes Valet Parking: Funktions-und Planungsarchitektur (2015).

[48] Ebberg, J.: Bosch and Daimler demonstrate driverless parking in real-life conditions (2017).

[49] Pluta, W.: Lass das Parkhaus das Auto parken! (2017).

maximum allowed velocity is limited by 6 km/h. The system response time shall be short enough to remain within the legal framework. How short the latency time is, is not stated. The infrastructure-based AVP shortens the parking process and allows vehicles equipped with limited sensor setups to use the parking function. Instead of waiting until every vehicle is capable for automated driving, the transition phase is shortened by an infrastructure-based solution. Existing multi-storey car parks can be upgraded and used in a mixed traffic. If there is no need to open the door, additional 20% of vehicles can be parked in the available space. Environment perception and trajectory planning are performed by the infrastructure whereas the execution is realized by the vehicle. Reasons for the choice of an infrastructure-based configuration are not provided. Additional information which zones are perceived by the infrastructure to establish a safe service or which requirements overall system requires to fulfill are not mentioned.

Figure 2–6: Fully infrastructure-supported valet parking implemented by Bosch and Daimler[50]. The infrastructure provides the perception and planning for the automated vehicle. The vehicle executes the received control commands.

Ibisch et al.[51] propose a new approach on vehicle localization and tracking for infrastructure-embedded lidar sensors in a parking garage. A major benefit is that common vehicles can use the localization system and do not require specific equipment. The system is transferable into today's parking garages without the need of additional modifications. The authors use a 2D grid and estimate the occupation of a quadratic cell in a single time frame. The hypotheses provide the vehicle's center and its orientation based on the best traceable feature of the

[50] Robert Bosch GmbH: Die Infrastruktur kennt den Weg. (2018).

[51] Ibisch, A. et al.: Towards autonomous driving in a parking garage (2013).

vehicle: the well-known shape of the wheel. A rectangle contains the four wheels with a certain tolerance. The authors used the Random Sample Consensus (RANSAC) algorithm to eliminate outliers and an Extended Kalman filter for prediction. The sensor setup consists of six 2D SICK lidar LMS 500 distributed in the parking garage with a field of view of up to 190° and a range of 65 m. Test scenarios included the entrance area, a ramp and the parking area. Results were compared to human labeled data within unfiltered and raw recorded lidar data in every single timeframe. Differential GPS would have been more accurate compared to human labeled ground truth (GT) data, but was not used due to unavailability of DGPS hardware. The velocity error between the human labeled GT data and the prediction was 0.82 km/h and a standard deviation of ±0.6 km/h. The mean orientation error was 1.07° with a standard deviation of ±1.16°. The mean absolute lateral and longitudinal errors amount to 6.3 cm and 8.5 cm with a standard deviation of ±4.4 cm and ±5.6 cm. The authors adjusted all lidar sensors parallel to the ground plane which results in challenges in case of occlusion. Top-mounted infrastructure sensors may perceive occluded areas from the vehicle's view caused by dynamic objects.

Additional advances have been done in research projects which target the verification and validation of automated driving systems. Some of the research projects which are related to the contributions of this thesis shall be briefly described in the following.

2.3 Research Projects

Responsibility-Sensitive Safety (RSS) is a mathematical model introduced by Shalev-Shwartz et al.[52] which specifies safety-relevant distances for collision avoidance. A distance is considered safe if an accident is not possible. Worst-case scenarios are assumed to remove the need to estimate the traffic participant's intentions. A safe longitudinal distance is defined by the following situation: Two vehicles are driving towards each other with velocities $v_{x,\mathrm{ego}}$ and $v_{x,\mathrm{obj}}$, accelerate with maximum acceleration $a_{x,\max}$ during the system response time $\tau_{\mathrm{R,RSS}}$, and thereafter immediately brake with the always expected deceleration $D_{\mathrm{x},0}$ (the signs of the velocities are according to the definition of Shalev-Shwartz et al.[52]). The longitudinal safety distance is depicted in Figure 2–7 and is given by

$$d_{x,\mathrm{req}} = d_{x,\mathrm{reqEgo}} + d_{x,\mathrm{reqObj}} \tag{2–1}$$

$$d_{x,\mathrm{reqEgo}} = v_{x,\mathrm{ego}} \cdot \tau_{\mathrm{R,RSS}} + \frac{a_{x,\max} \cdot \tau_{\mathrm{R,RSS}}^2}{2} + \frac{\left(v_{x,\mathrm{ego}} + \tau_{\mathrm{R,RSS}} \cdot a_{x,\max}\right)^2}{2 \cdot D_{x,0}} \tag{2–2}$$

[52] Shalev-Shwartz, S. et al.: On a Formal Model of Safe and Scalable Self-driving Cars (2017).

$$d_{x,\mathrm{reqObj}} = |v_{x,\mathrm{obj}}| \cdot \tau_{\mathrm{R,RSS}} + \frac{a_{x,\max} \cdot \tau_{\mathrm{R,RSS}}^2}{2} + \frac{\left(|v_{x,\mathrm{obj}}| + \tau_{\mathrm{R,RSS}} \cdot a_{x,\max}\right)^2}{2 \cdot D_{x,0}} \tag{2–3}$$

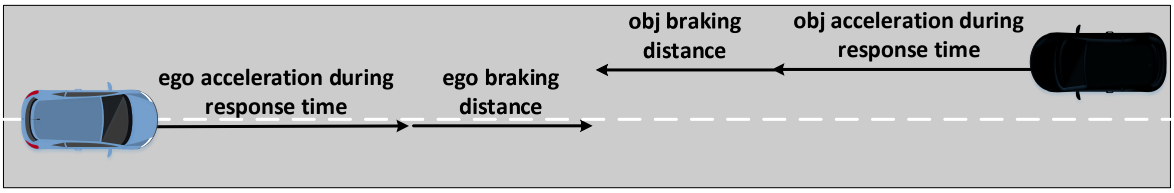


Figure 2–7: A safe longitudinal distance is specified according to Shalev-Shwartz et al.[52] as the sum of the ego-vehicle's and object's travelled distances when accelerating longitudinally during response time and thereafter immediately braking.

The safety distance between two vehicles in lateral direction is defined by a similar scenario in lateral direction. A lane-based coordinate system is used for lateral maneuvers. Figure 2–8 shows two vehicles applying lateral acceleration of $a_{y,\max}$ towards each other during the response time $\tau_{\mathrm{R,RSS}}$ and thereafter applying lateral deceleration of $D_{y,0}$ until the lateral velocity v_y is zero. The remaining distance between both vehicles is a safety margin d_{tol}. According to Shalev-Shwartz et al.[52], this is formalized by

$$d_{y,\mathrm{req}} = d_{\mathrm{tol}} + \left[d_{y,\mathrm{reqEgo}} + d_{y,\mathrm{reqObj}}\right]_+ \tag{2–4}$$

$$d_{y,\mathrm{reqEgo}} = v_{y,\mathrm{ego}} \cdot \tau_{\mathrm{R,RSS}} + \frac{a_{y,\max} \cdot \tau_{\mathrm{R,RSS}}^2}{2} + \frac{\left(v_{y,\mathrm{ego}} + \tau_{\mathrm{R,RSS}} \cdot a_{y,\max}\right)^2}{2 \cdot D_{y,0}} \tag{2–5}$$

$$d_{y,\mathrm{reqObj}} = -\left(v_{y,\mathrm{obj}} \cdot \tau_{\mathrm{R,RSS}} - \frac{a_{y,\max} \cdot \tau_{\mathrm{R,RSS}}^2}{2} - \frac{\left(v_{y,\mathrm{obj}} - \tau_{\mathrm{R,RSS}} \cdot a_{y,\max}\right)^2}{2 \cdot D_{y,0}}\right) \tag{2–6}$$

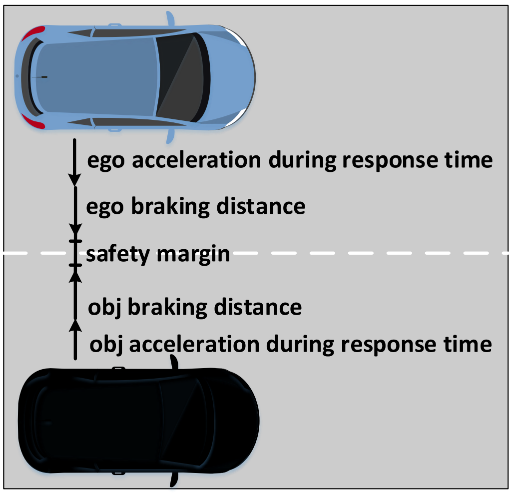


Figure 2–8: A safe lateral distance is specified according to Shalev-Shwartz et al.[52] as the sum of the ego-vehicle's and object's travelled distances when accelerating laterally during response time and thereafter immediately braking.

Safe distances in longitudinal and lateral direction have to be violated for occurrence of a collision. A dangerous situation occurs for two vehicles if both the longitudinal and lateral distances between them are non-safe. Hereby, the authors claim that the RSS model will never cause an accident if safety distances are maintained. A traffic participant is not necessarily responsible for the collision if he did not obey the right of way. The responsibility for an accident is assigned to the traffic participant who did not comply with a so called proper response even though he is prioritized. The proper response characterizes the set of actions required to be applied to avoid a potential collision. A proper response is to brake laterally, if beforehand there was a safe lateral distance or to brake longitudinally if beforehand there was a safe longitudinal distance. An evasive maneuver is legal only if the accident can be avoided without causing another one. Hence, an evasive maneuver has to comply with the longitudinal and lateral safety distances after the execution. Furthermore, RSS targets the occlusion of pedestrians. The automated vehicle is not blamed for a collision with an occluded pedestrian if it did not accelerate during response time, performed a longitudinal brake and if the average vehicle velocity is below the average pedestrian velocity in the time duration from first seen to full stop.

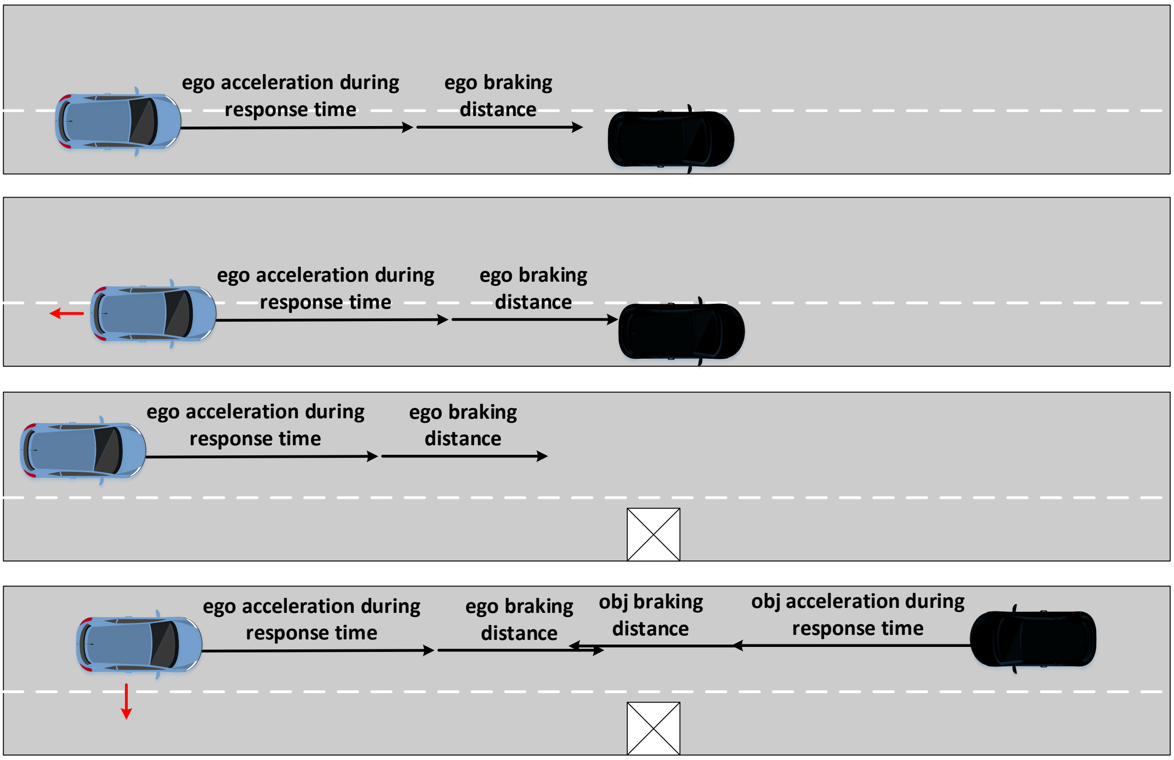


Figure 2–9: The upper two figures illustrate the proper response of longitudinally braking. When approaching a vehicle in front, only a non-safe lateral distance was present. Once the longitudinal distance becomes unsafe, the ego-vehicle has to brake longitudinally since beforehand the longitudinal distance was safe. The bottom two figure show the proper response of laterally braking. When changing the lane, a safe lateral distance was present. Once the longitudinal distance becomes unsafe, the ego-vehicle has to brake laterally since beforehand the lateral distance was safe.

However, RSS is a distance-based safety approach for automated vehicles: A deceleration is triggered if longitudinal and lateral safety distances are violated. RSS does not relate to safety by design. This thesis proposes an area-based definition of minimum perception requirements. The necessary perception- and safety-relevant space around the ego-vehicle is defined for the specific use case AVP. Compared to RSS lateral safety distances are considered by tractrix curves which take the bending of stopping envelopes into account. An integration of manually driven vehicles into the RSS concept is not specified concretely since it cannot be assumed that a human driver will follow the RSS policy and that corresponding response times are similar. RSS follows a vehicle-based concept. Infrastructure support is not taken into account. This thesis considers not only collision avoidance, but the overall safety design process for AVP.

Wachenfeld and Winner[53] estimated billions of test kilometers required to be driven for the verification of a highway chauffeur. Hereby, no state-of-the-art methods are present to overcome this dilemma. New methods are required for time-efficient testing, verification and validation of automated driving (AD) functions. Instead of testing random cases, the research project PEGASUS[54] (**P**roject for the **E**stablishment of **G**enerally **A**ccepted quality criteria, tools and methods as well as **S**cenarios and **S**ituations for approval of highly automated driving functions) addresses a scenario-based approach for testing, verification and validation of automated driving functions. Results of different workpackages were combined in an overall PEGASUS method for the assessment of highly automated driving functions. The overall process flow of the PEGASUS method consists of five basic blocks: *definition of requirements*, *data processing*, *information storage* and *processing in a database*, *assessment of the highly AD function* and *argumentation*. In the first step, logical scenarios, which describe the parameter space in the state space, are identified systematically for the AD function and recorded scenarios are converted into a common format (*data processing*). In parallel, requirements are defined as evaluation criteria for test cases (*definition of requirements*). In the third step, scenario descriptions are transferred into a database to define parameter spaces for logical test cases with pass and fail criteria. In the forth step, logical scenarios are executed in simulation and on proving grounds. Results are compared with the defined pass and fail criteria for evaluation of the AD function. In the last step, the predefined five-layer safety argumentation is compared with the evaluation. The PEGASUS method was applied exemplary on a SAE level 3+ highway chauffeur. The PEGASUS report concludes that additional use cases in other operational design domains have to be evaluated in future projects. Occurring scenarios for a highway chauffeur and AVP differ in the occurrence of handover and pickup zones, in the driver interaction during automated driving, in the execution of allowed maneuvers (e.g. reverse driving, intersection crossing, turning) as well as in the constraints for the operational design domain (e.g. weather conditions, expected velocities). This thesis investigates functional scenarios and maneuvers for a closed parking garage instead of the highway. This work formalizes necessary conditions for AVP.

---

[53] Wachenfeld, W.; Winner, H.: Die Freigabe des autonomen Fahrens (2015).

[54] Deutsches Zentrum für Luft- und Raumfahrt e. V.: The PEGASUS Method (2019).

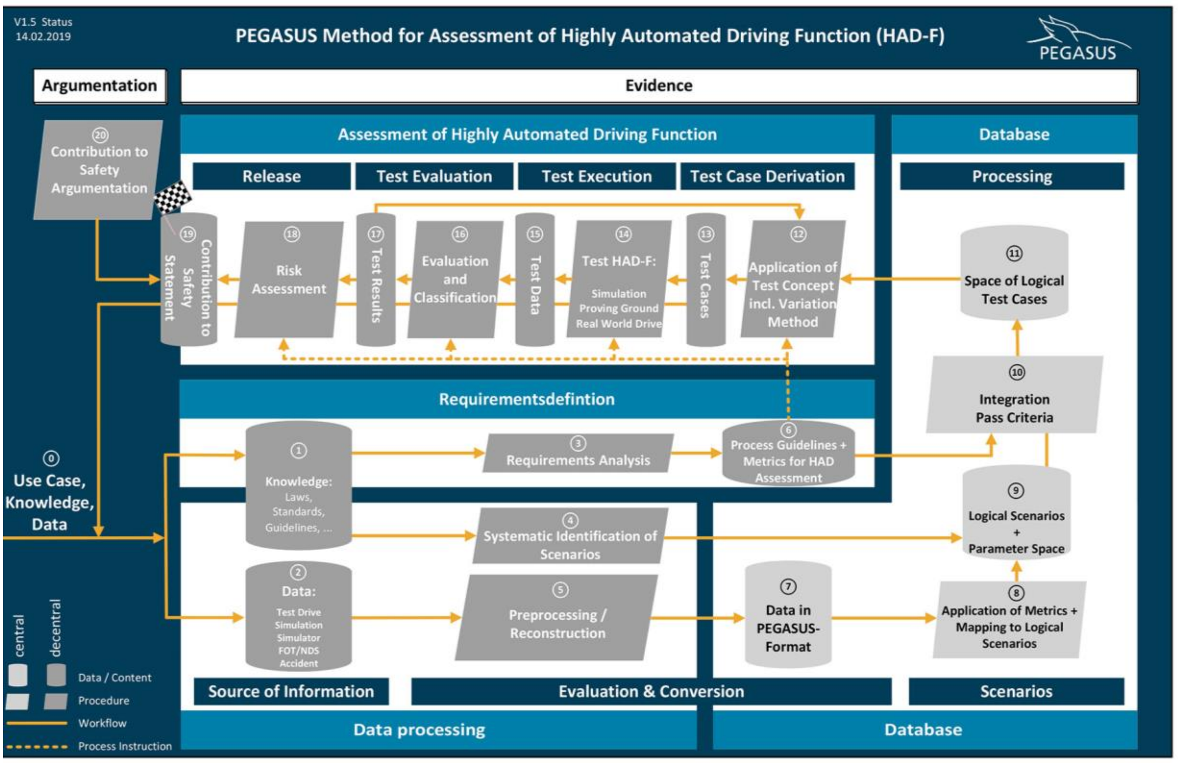


Figure 2–10: PEGASUS[54] targets a scenario-based approach for testing, verification and validation of automated driving functions. The PEGASUS method consists of five basic blocks: definition of requirements, data processing, information storage and processing in a database, assessment of the highly AD function and argumentation.

The research project ENABLE-S3[55] (European Initiative to Enable the Validation of highly Automated Safe and Secure Systems) investigated tools for a cost-efficient way to verify and validate automated functions from different domains, namely automotive, aerospace, rail, maritime, health and farming. 68 industrial and academic partners from 16 European countries provided a basis for future certification and homologation processes. Hereby, modular structures and standardized interfaces shall avoid vendor lock-in and the switching between tools and platforms. This has been shown in the automotive domains by pushing the standardization of Open Simulation Interface (OSI) and contributing to OpenDrive[56] and OpenScenario. Significant time and costs are saved due to the interchangeability of individual components and standardized descriptions for dynamic contents in driving simulations or for road networks. Some of the standardizations are addressed in chapter 7.

[55] Leitner, A. et al.: ENABLE-S3: Summary of Results (2019).

[56] Dupuis, M. et al.: OpenDRIVE Format Specification Rev. 1.5 (2019).

2.4 Summary

The state-of-the-art reveals diverse implementations of AVP systems ranging from fully vehicle-based to infrastructure-based AVP. Banzhaf et al.[57] investigates core components and platforms of automated valet parking systems in his survey on the future of parking. According to the author AVP promises the increase in parking capacity and decrease the land use of on-street parking spaces. This can be either established by parking vehicles denser or by allowing shunting operations. AVP has the potential to become one of the first considered driving systems for release due to the simplifications that can be made such as low velocities in a closed and controlled environment and the possibility of infrastructure-support. Banzhaf states that recent approaches aim to reduce the amount of required sensors and use close-to-market sensors to fulfill the valet parking function. Thereby, LIDAR- and camera-based localization approaches are preferred for AVP. Either online or offline maps are used. Offline maps may contain static obstacles and parking spot occupancies whereas online maps contain the dynamic data. Banzhaf et al. divides in his survey the motion planning in a route planner called global planner, a trajectory planner defined as local planner and a parking planner for the maneuvering. Thereby, the A*-algorithm is mostly implemented for the route planning in the state-of-the-art. Banzhaf concludes that none of the existing literature describes how to integrate the AVP into existing parking structures and which technological requirements have to be fulfilled. Banzhaf realizes that requirements for measurement accuracies are not addressed yet and have to be defined.

Einsiedler et al.[58] notices in his survey that modern vehicles primarily use global navigation satellite systems (GNSS) to determine their position. However, due to the lack of a line-of-sight the parking garage is a GPS-denied environment. Therefore, alternative positioning systems are demanded. Compared to GNSS-based outdoor positioning systems, no predominant indoor positioning technology has been established until today. The spectrum of indoor positioning technologies is broad and often used in combination. According to the authors all indoor positioning systems can be classified into the categories internal and external. Internal positioning systems determine their position with the help of the surroundings whereas for external systems the infrastructure is responsible for the localization of the vehicle. Additionally, the positioning systems can be distinguished between absolute and relative localization. Einsiedler observes that the following positioning systems are used in the state-of-the-art which are summarized in Table 2–2:

A. *Internal Systems*
   - *Visual systems*: Visual landmarks are installed in the parking garage. The landmarks have to be georeferenced manually integrated in a static map that is transmitted at

[57] Banzhaf, H. et al.: The future of parking: A survey on AVP with an outlook on high density parking (2017).

[58] Einsiedler, J. et al.: Vehicle indoor positioning: A survey (2017).

the entrance. The vehicle detects the landmark with its camera and calculates its position.

- *Vehicle odometry*: Based on the last known position, dead reckoning and digital maps, the vehicle can localize itself within the parking garage. However, vehicle odometry only reaches the precision requirements in combination with other indoor positioning systems.
- *LIDAR SLAM*: Simultaneous localization and mapping (SLAM) requires the construction of a map in an unknown environment while simultaneously localizing within. This allows the vehicle equipped with lidar sensor to maneuver inside the parking garage.

B. *External Systems*

- *LIDAR:* Infrastructural lidar sensors locate and track objects in a parking garage. The determined position is transferred to the vehicles
- *Visual systems:* A top-mounted camera-based system monitors the environment and detects the position of the objects.

Table 2–2: Indoor positioning accuracy according to Einsiedler et al.[58]

	Type	**Basic Technology**	**Position Accuracy**
Masuda et al.	Intern	Visual Landmark	n.a.
Jeevan et al.	Intern	Visual Landmark	< 0.60 m (median: 0.2 m)
Qu et al.	Intern	Visual odometry	< 5 m (median: 2 m)
Heissmeyer et al.	Intern	Optical beacons	0.29 m
Wagner et al.	Intern	Odometry and gyro	< 2.5 m (± 1 parking spot)
Bojja et al.	Intern	Odometry and gyro	< 2.5 m (confidence level 95%)
Kümmerle et al.	Intern	3D SLAM (LIDAR)	n.a.
Klemm et al.	Intern	2D SLAM (LIDAR)	n.a.
Ibisch et al.	Extern	LIDAR	<0.09 ± 0.06 m
Ibisch et al.	Extern	Multi-camera	< 1.2 m (median: 0.24 m ± 0.19 m)
Einsiedler et al.	Extern	Monocular camera	1.5 m (confidence level 95%)

Table 2–2 indicates that today's indoor positioning systems are able to locate objects within centimeter range. However, the survey of Einsiedler raises the question which longitudinal and lateral errors are acceptable for safe AVP systems. The issue which kind of indoor positioning system is required to meet the constraints of automated valet parking is still unresolved. To the best of the author's knowledge none of the upper publications concerns a definition of a minimum criterion for the measurement accuracy.

The described research results focus on the development of automated valet parking platforms and the improvement of today's algorithms. However, a definition of a bottom limit expected from AVP systems is not provided. Moreover, it is still unresolved if future AVP systems require modifications or if these are already sufficient. For example, the authors do not clarify if their sensor setup is sufficient for valet parking purposes in different parking facilities and if the vehicle perceives the safety-relevant spaces for all relevant critical scenarios. A specification of areas around the ego-vehicle which are mandatory to be investigated is not given. The issue of a minimum perception area around the vehicle remains yet undefined. The definition of a geometric and technology-independent perception zone would provide a commitment for AVP providers to fulfill these perception constraints.

The DARPA Urban Challenge influenced fully vehicle-based AVP concepts. These approaches are by far not the only way. The state-of-the-art shows that cooperative valet parking is of major interest. Future technical realizations focus on the provision of a digital map at the entrance in combination with the detection of free parking spaces to assign a free spot. Fully infrastructure-based AVP services benefit from the possibility of an early introduction into the market since the AVP service can be used by standard vehicles. However, implementations of infrastructure-based AVP systems are yet rarely to find. The choice for an AVP configuration lacks quantifiable statements which show under which constraints a specific configuration should be preferred. Furthermore, the state-of-the-art reveals three major types of configurations. However, other configurations can be investigated which provide major benefits. Considering the state-of-the-art, two main research questions can be derived as introduced in chapter 1:

- *RQ1*: What is the essential subset of minimum criteria all AVP configurations require to fulfill for safe operation?
- *RQ2*: Which degrees of infrastructure support are needed and what are their benefits?

Figure 2–11 indicates missing technical ways between fully vehicle- and fully infrastructure-based AVP defined in section 2.2 and links corresponding research questions. This thesis contributes to the specification of minimum criteria to ensure the necessary safety design by considering minimum safety requirements, the minimum required perception zone or the minimum required functional requirements (*RQ1*). Additionally, the detailed analysis for the distribution of functions between automated vehicle and infrastructure is provided to investigate further possible AVP configurations and corresponding benefits for parking garage operators and manufacturers.

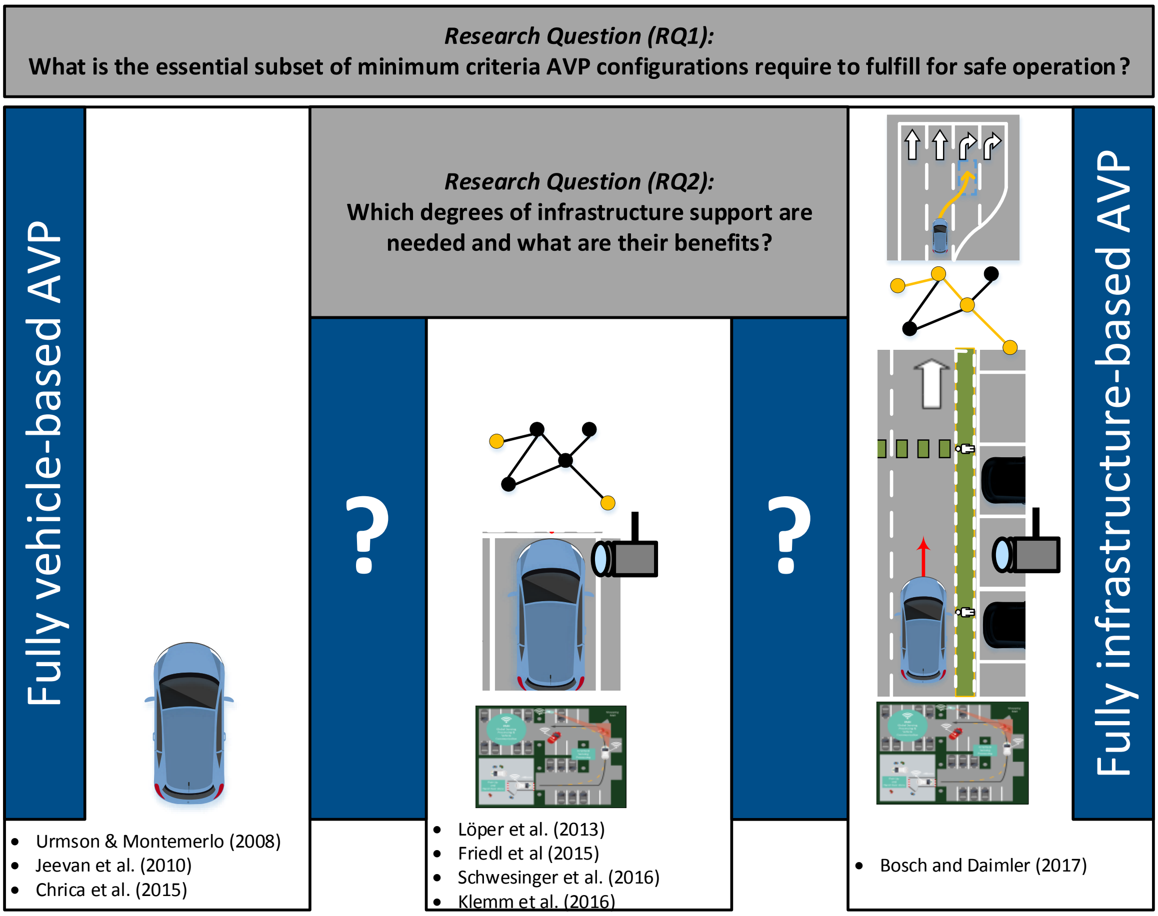


Figure 2–11: AVP configurations in the state-of-the-art with an increasing degree of infrastructure influence: fully vehicle-based AVP (left), provision of a static map, free parking space detection and inclusion of the mission planner (middle), fully infrastructure-based AVP (right).

The methodology described in chapter 1 is applied in order to contribute to the research questions starting with a scenario decomposition of the valet parking procedure. In the following chapter, a system description is given in the item definition which is in compliance with the ISO 26262 and SOTIF.

3 Item Definition

The development of fully automated vehicles in the upcoming future requires new methodologies to target safety challenge.[59] However, a broad range of parameters exists for automated driving systems concerning the system's behavior and the environment. Considering the overall system is fairly complex and too extensive.[60] A functional decomposition of the systems behavior is required to deal with the rising complexity. The international standard ISO 26262 suggests an item definition before the application of a hazard analysis and risk assessment (HARA). The item definition describes the functionality, interfaces and environmental conditions of the item. According to Ulbrich et al.[61], scenarios can be used to give a functional description of the system. Ulbrich describes a scene as a snapshot of the environment and the interaction of entities while time is progressing. A scenario presents actions and events of the traffic participants within a certain time frame (sequence of scenes). In this thesis, the system's functional behavior is decomposed into functional scenarios[62] in order to reduce the system's complexity and provide a functional description of the system. The following pre-conditions are hereby assumed for AVP:

- Infrastructure and automated vehicle may manage the perception and planning of the driving task cooperatively. The infrastructure may support the automated vehicle during the AVP service.
- The procedure of handing the automated vehicle over to and requesting it back from the infrastructure is instructed via a terminal (human-machine interface, HMI).
- Manually and automatically operated vehicles are allowed to enter the parking garage. A mixed traffic in the car park is assumed.
- Pedestrians, animals (e.g. dogs), stationary objects, etc. are potentially present in the parking facility. Special attention has to be paid to pedestrians due to a mixed traffic.
- Drivers and passengers have to leave the automated vehicle before AVP is activated. So, the driver is not further involved in the driving task and has no controllability during the AVP process.

These constraints serve as an input to break down the system's functional behavior into scenarios. As a first contribution towards the goal of safe AVP systems the following functional scenarios are proposed as introduced in Schönemann et al.[63].

---

[59] Wachenfeld, W.; Winner, H.: Die Freigabe des autonomen Fahrens (2015).

[60] Amersbach, C.; Winner, H.: Defining Required and Feasible Test Coverage for HAV (2019).

[61] Ulbrich, S. et al.: Defining and Substantiating the Terms Scene, Situation, and Scenario for AD (2015).

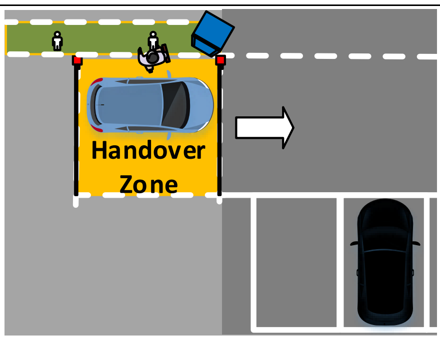
[62] cf. Form, T.: PEGASUS Method for Assessment of Highly Automated Driving Function (2018).

[63] Schönemann, V. et al.: Maneuver-based adaptive Safety Zone for infrastructure-supported AVP (2019).

3.1 Vehicle Handover to AVP System

Every automated valet parking procedure starts with the arrival of the vehicle at the handover zone in the parking garage. The AVP system requires an activation process for the AVP service in the handover zone. The driver and other passengers get off the vehicle. In such a handover scenario the system checks whether all requirements for automated valet parking are met e.g. whether the vehicle is located in the handover zone, is in standstill and, correctly oriented and, whether all doors are closed and all persons have left the handover zone. The driver or a passenger hands over the responsibility for the vehicle to the automated valet parking system by using a Human Machine Interface (HMI) to instruct a parking request. If the request is accepted, several options exist: the infrastructure sends a predefined trajectory to the vehicle, the vehicle calculates a trajectory by itself, or the trajectory is determined in a cooperative mode. The infrastructure may transfer a static map of the parking garage and a predefined trajectory to the corresponding parking spot. A parking spot can be assigned by the infrastructure system. After the parking request is instructed, the vehicle is handed over to the parking area management and the automation takes over the responsibility for the further steps of the driving task. The handover is successful if the specified constraints are met. Delays may result from activating the AVP process, from unloading items or from a shortage of handover spots during rush hour. Table 3–1 provides the scenario description for the vehicle handover.

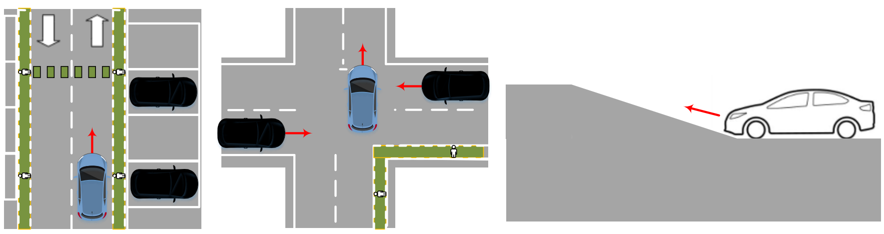
Table 3–1: Scenario description for vehicle handover to infrastructure system

Scenario Name	Vehicle handover to AVP system
Scenario ID	1
Procedure	1. Vehicle is parked by a human driver at the handover zone (in standstill, correctly oriented) 2. All passengers leave the handover zone and close vehicle doors. 3. User confirms the activation of the AVP process via an HMI.
Key Scenes	 Figure 3–1: Vehicle handover to the automation system for AVP
Successful end condition	Procedure constraints are met and system is ready for handover.

3.2 Automated Driving to a Point of Interest

After a successful handover, the vehicle is required to navigate driverless in the parking facility. Hereby it needs to navigate to different points of interest. The point of interest is defined as a desired location which mainly includes the assigned parking spot, the pickup zone or another point of interest such as a charging station. The system has to assign a safe mission. The destination's pose and its dimensions needs to be known in order to assign a mission. To this end, the automated vehicle requires to estimate its state such as its pose, its velocity and have knowledge about its dimensions and class to navigate in the parking garage (ego-vehicle state estimation). Additionally, other traffic participants have to be considered (object state estimation). The environment can be perceived via radar, lidar, camera and ultrasonic sensors. Once the required parameters are determined, a collision-free trajectory is calculated to the point of interest. Thereby, the system shall ensure that the vehicle stays in the statically defined drivable area. Perception and planning can be performed by the vehicle, the infrastructure or collaborative. Thereby, several degrees of infrastructure support are possible. The vehicle executes the desired control instructions. Several maneuvers have to be accomplished such as following a straight or curved lane, turning left/right, crossing of an intersection and driving on a ramp. The end state is reached if the vehicle arrives at the desired point of interest without colliding. This scenario does not include the maneuvering into the parking space. Table 3–2 shows the scenario specification for the automated driving to a point of interest.

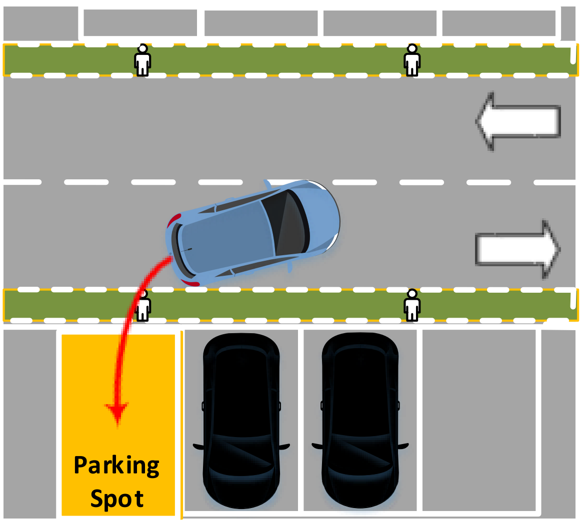
Table 3–2: Scenario description for automated driving to a point of interest

Scenario Name	Automated driving to a point of interest
Scenario ID	2
Procedure	1. Ego-vehicle and object state estimation 2. Mission and trajectory planning to point of interest 3. Execution of control commands 4. Data transmission between vehicle and infrastructure
Key Scenes	 Figure 3–2: Possible situations during navigating to a point of interest such as traversing parking spots (left), intersection crossing/ turning (middle) and driving on a ramp (right)
Successful end condition	Collision-free arrival at the desired point of interest.

3.3 Automated Maneuvering into the Parking Spot

When the automated vehicle arrives nearby the parking spot, the parking maneuver can be executed. Either the infrastructure has already checked the required free parking space and/or the vehicle takes over the analysis of the parking spot to decide whether the parking space is appropriate for parking. The system has to assign the free parking space for the automated vehicle. Thereafter, longitudinal or lateral actions have to be executed to place the vehicle properly. For such a parking maneuver, a precise positioning system is crucial. The vehicle may park forward or reverse. The parking spots are arranged from 0° to 90° with respect to the lane. The final state is successfully reached if the assigned parking spot is arrived collision-free, the vehicle size does not exceed the parking spot, the parking brake is set and the vehicle is on standby. A standby-mode ensures the automated vehicle's availability on call in case of a driver's handback request. Table 3–3 illustrates the maneuvering into the parking space.

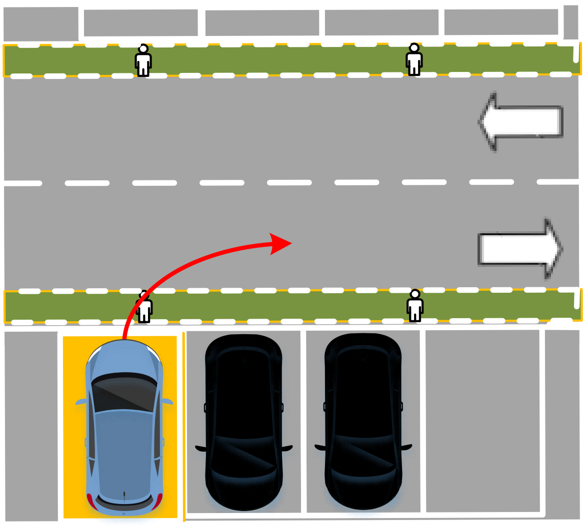
Table 3–3: Scenario description for automated maneuvering into the parking space

Scenario Name	Automated maneuvering into the parking space
Scenario ID	3
Procedure	1. Free Parking space detection 2. Trajectory planning into the parking space 3. Execution of parking control commands 4. Data transmission between vehicle and infrastructure
Key Scenes	 Figure 3–3: Maneuvering into an assigned parking spot
Successful end condition	Collision-free arrival, vehicle placed within parking markings, parking brake set and vehicle is on standby

3.4 Automated Leaving of the Parking Spot

Once the driver desires to continue his journey, (s)he has to send a handback request to the AVP system. If the driver initiates a handback request, the automated vehicle is triggered to leave the parking spot. The required trajectory to the pick-up zone is either planned by the ego-vehicle or received from the infrastructure. Maneuvering out of the parking spot is possible in forward and reverse direction. If no obstacles are located in the area required for maneuvering out of the parking spot, longitudinal and lateral driving actions can be performed. Leaving the parking spot is successful if it is collision-free and the automated vehicle is placed such that scenario *automated driving to a point of interest* can be executed. Table 3–4 provides the scenario description for the automated leaving of the parking space.

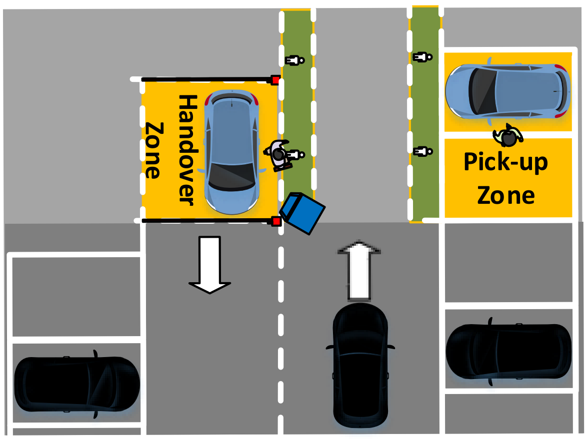
Table 3–4: Scenario description for automated leaving of the parking space

Scenario Name	Automated leaving of the parking space
Scenario ID	4
Procedure	1. Free space detection for maneuvering out 2. Trajectory planning for leaving the parking space 3. Execution of control commands 4. Data transmission between vehicle and infrastructure
Key Scenes	 Figure 3–4: Automated leaving of the parking spot after a handback request
Successful end condition	Collision-free leaving of the parking space and vehicle placed properly to execute scenario 2.

3.5 Vehicle Handover to Driver

After the driver requests his vehicle back, the ego-vehicle drives to the exit of the parking garage (scenario 2: automated driving to a point of interest). The automated vehicle has to be parked at the pickup-zone. The HMI confirms the successful arrival at the pick-up location. If the vehicle is located in the pick-up zone in standstill, the parking brake is set, the vehicle engine is turned off and automated valet parking is deactivated, the driver can enter the vehicle in order to continue his journey. If the constraints are met and no traffic participant is harmed, the scenario is considered to be successful. Delays may result from loading items into vehicles or from a shortage of pickup spots during rush hour. This may lead to additionally required pickup time for the driver and passengers. Table 3–5 presents the vehicle handover to the driver.

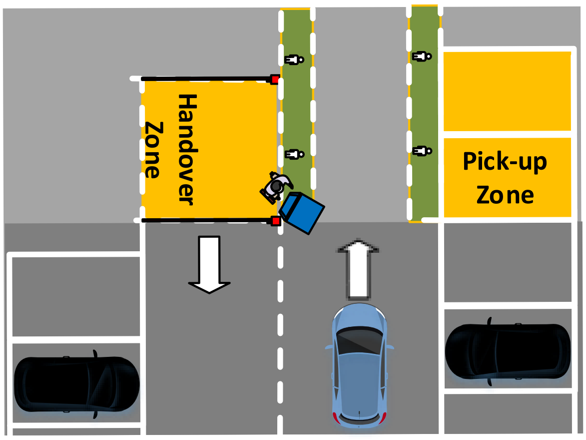
Table 3–5: Scenario description for vehicle handover to driver

Scenario Name	Vehicle handover to driver
Scenario ID	5
Procedure	1. Vehicle is parked at pickup zone (in standstill, correctly oriented) 2. System confirms the deactivation of the AVP process via an HMI. 3. Driver and passengers can enter the vehicle.
Key Scenes	 Figure 3–5: Handover of the vehicle to the driver at the pickup zone
Successful end condition	Upper constraints are met and system transitions to manually driving mode.

3.6 Aborting the Valet Parking Procedure

This scenario describes the abort of the valet parking service while driving inside the car park, which is equivalent to an early initiated handback request. The abort is instructed via the HMI in order to get back to the vehicle. The automated vehicle does not drive to the assigned parking spot but instead directly to the exit of the parking garage. The system shall determine a safe trajectory back to the pickup zone. Therefore, scenario 2 and 5 still have to be executed. Once the vehicle is located in the pick-up zone in standstill, the valet parking procedure can be deactivated and the driver is able to enter the vehicle. Table 3–6 shows the scenario characteristics for an abort of the valet parking service.

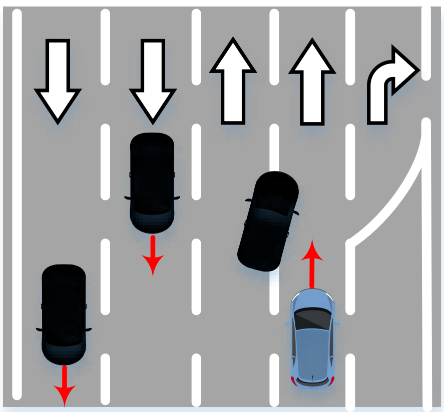
Table 3–6: Scenario description for the abort of the valet parking service

Scenario Name	Aborting the Valet Parking Procedure
Scenario ID	6
Procedure	1. Abort is instructed via a HMI 2. Automated vehicle performs scenario 2 and 5. 3. Driver and passengers can enter the vehicle.
Key Scenes	 Figure 3–6: Abort of the valet parking service and return of the automated vehicle to the pickup zone
Successful end condition	Upper constraints are met and system transitions to manually driving mode.

3.7 System Behavior outside the parking garage

Automated valet parking is designed to operate in a parking area with its characteristics. These characteristics such as velocity limitations, friction coefficient or occurring maneuvers are well known for a parking garage. Once the driver picks up his vehicle, the vehicle will leave the target operational design domain. However, automated valet parking will not be developed to operate in other operational design domains outside the parking garage such as on highways or urban scenarios. Unauthorized use of the valet parking function outside the operational design domain has to be prohibited since higher velocities and more complex driving scenarios have to be expected outside the parking area. Additionally, the infrastructure cannot support the vehicle and therefore cooperation is not possible anymore. Compared to the upper defined scenarios the driver may serve as a fallback and can take over. The case may be relevant for the controllability of a potential hazardous event. Table 3–7 illustrates the system behavior outside the parking garage.

Table 3–7: Scenario description for the system behavior outside the parking garage

Scenario Name	System Behavior outside the parking garage
Scenario ID	7
Procedure	1. Vehicle leaves operational design domain 2. Different scenarios and constraints are present outside the operational design domain. 3. Infrastructure support cannot be provided and driver may serve as a fallback.
Key Scenes	 Figure 3–7: More complex scenarios outside the operational design domain
Successful end condition	Unauthorized use of the valet parking function outside the operational design domain is prohibited.

4 Hazard Analysis and Risk Assessment

This chapter analysis hazards that may be present in AVP systems. The analysis is in compliance with the international Standard ISO 26262[64] which proposes a systematic approach to achieve functional safety for road vehicles. This chapter contributes to the specification of top level safety requirements called safety goals for AVP systems to avoid unreasonable risks. The vocabulary used in this thesis can be found in IS0 26262[65]. The identification of potential malfunctions to determine related safety goals is explored in a hazard analysis and risk assessment (HARA). This thesis proposes a systematical methodology in compliance with the international standard ISO 26262 to identify hazards according to the divide and rule policy. Thereby, the overall AVP service is broken down into functional scenarios[66] introduced in chapter 3. The previously defined functional scenarios in the item definition provide an abstraction of the system's behavior and serve as an input for a scenario-based hazard analysis and risk assessment (HARA). Since the overall system is split into a manageable small number of functional scenarios, the complexity is reduced and a situational analysis in the HARA can be performed for each scenario more specifically. As a result, a more complete set of safety goals can be potentially elaborated which in turn leads to a more extensive safety concept. The methodology is applied to the use case automated valet parking to derive minimum safety requirements from safety goals and to identify necessary and sufficient conditions. Figure 4–1 demonstrates the corresponding methodology. The chapter is taken from Schönemann et al.[67]

[64] ISO: ISO 26262: Road vehicles - Functional safety (2018).

[65] ISO: ISO 26262-1: Road vehicles - Functional safety - Part 1: Vocabulary (2018).

[66] Form, T.: PEGASUS Method for Assessment of Highly Automated Driving Function (2018).

[67] Schönemann, V. et al.: Scenario-based functional Safety for AD on the Example of AVP (2018).

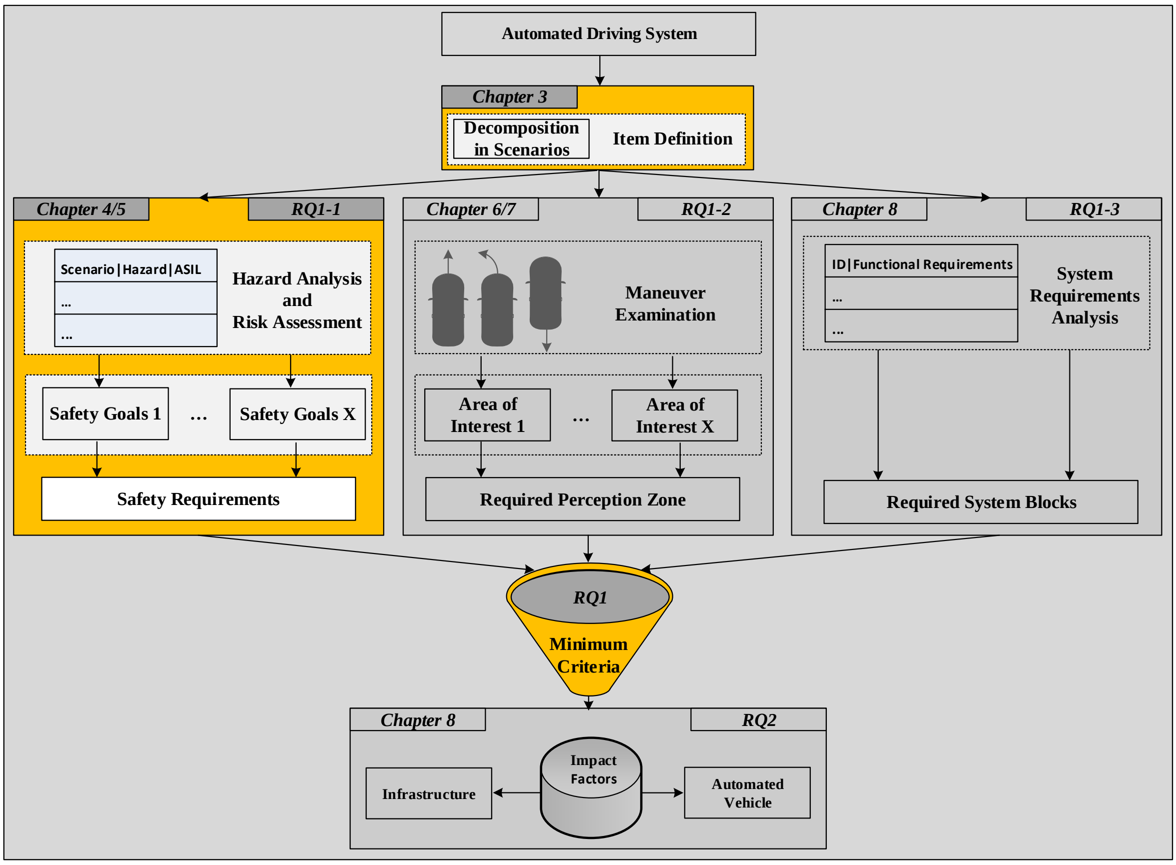


Figure 4–1: Scenario-based functional safety analysis for automated driving. The system's functional behavior is decomposed into functional scenarios and for each scenario a hazard analysis and risk assessment is performed to determine corresponding top level safety requirements called safety goals. Safety goals are further broken down into low level minimum safety requirements for AVP systems. Derived minimum safety requirements contribute to minimum criteria to ensure safety by design.

An extract of the developed hazard analysis and risk assessment is presented in Table 4–1. For clarity reasons, each safety goal is described by only one hazard.

Hazard 1 specifies a collision after an unintended activation of the AVP function inside the operational design domain. The user of the valet parking service tries to get into the vehicle just before it starts moving. The hazard occurs in the handover scenario in which the transition from manually to automated driving takes place. Thereby, the user might be located outside of the vehicle and wants to enter his vehicle which simultaneously initiates a valet parking procedure. The reasons for the user's intentions may vary between pulling out of personal belongings or unclear HMI communication.

Hazard 2 characterizes a collision due to incorrect data transmission between the infrastructure and the automated vehicle. The infrastructure may transmit an incorrect map or incorrect trajectories. The transmission of data starts at the handover scenario. As a result, the vehicle will collide with objects assuming transmitted data is not validated.

Hazard 3 to 5 differentiates between the collision of the automated vehicle with static objects, pedestrians and vehicles. The hazards take place during the scenario of automated driving to a point of interest and an error occurs in the sense-, plan-, act-phases of the processing. The differentiation is done due to the difference of relative velocities and passive safety capabilities. Static objects are in standstill whereas dynamic objects such as other vehicles are moving. Pedestrians do not have a deformable zone which protects from collisions and therefore are exposed to higher degrees of severity.

Hazard 6 presents a potentially safety-critical AVP system which continues the AVP service without emergency call after a collision. The automated vehicle continues the valet parking service without informing a supervisor of its insufficiency. The hazard occurs when driving to a point of interest or while maneuvering.

Hazard 7 categorizes a collision with pedestrians due to unintended leaving of the drivable area. The hazard may result from an error in the sense-, plan- or act-processing while driving such as an inaccurate localization or incorrect lane detection.

Hazard 8 describes a collision in which a passenger located inside the vehicle gets out of the vehicle while driving. Other users may initiate an abort of the valet parking procedure to prevent harmful consequences such as getting off the vehicle or being trapped inside. The hazard arises when a passenger is not detected inside the vehicle.

Hazard 9 illustrates a safety-critical traffic situation resulting from an unintended activation of the valet parking outside the operational design domain. Especially, the activation of a valet parking service when driving on a highway increases the severity for the traffic participants.

Table 4–1: Extract of the developed HARA for the use case valet parking, the extended HARA can be found in the appendix.

ID	Scenario	Failure Mode	Hazard	Specific Situation	Hazardous events & consequences	S	Rationale	E	Rationale	C	Rationale	ASIL	Safety Goal
1	1	Unintended activation of AVP inside the operational design domain	Safety-critical situation due to unclear handover status	Persons getting into the vehicle just before it starts moving	Collision with person	S1	Activation in low speed	E4	AVP activation process every handover	C3	Automated vehicle is uncontrollable	B	SG04
2	1	Incorrect data transmission by PAM	Collision due to incorrect data received by vehicle	Incorrect map/ path is loaded	Collision with person	S3	Incorrect speed profiles	E4	Communication between PAM and vehicle throughout every AVP	C3	Automated vehicle is uncontrollable	D	SG02
3	2	Missed detection	Collison with object	Automated vehicle crashes into object which in turn collides with persons	Medium structural damages or flying/ falling objects	S1	The vehicle’s medium speed causes lower kinetic energy	E3	Limited combination of dangerous objects for moving persons	C3	Automated vehicle is uncontrollable; Probably less than 90% persons are able to evade	A	SG09
4	2	Missed detection	Collison with other vehicle	Automated vehicle crashes into other vehicle	The system does not detect the vehicle	S1	Person protected in vehicle	E4	Encounters with moving vehicles every drive	C3	Limited space for evading maneuvers; Automated system cannot be controlled.	B	SG05
5	2	Missed detection	Collision with person	Person runs into moving vehicle	The AVP system does not detect the Person	S2	Collision at medium speed causes severe injuries	E4	Encounters with moving persons every drive	C3	Missed detection during fully automated driving	C	SG03
6	2	Missed emergency call	Disregarded emergency call after collision	Collision occurred	Unexpected continuation of AVP without emergency call	S2	Emergency call required if collision occurs; every second counts	E4	Encounters with moving persons every drive	C2	Other persons can still set up an emergency call	B	SG06
7	2	Unintended leaving of the drivable area	Vehicle falls off the brim and crashes into people	Automated driving close to the brim, people stand below the brim.	Collision with person	S3	Fatal injury	E4	Staying in drivable area has to be always ensured during AVP	C1	Other objects prevent vehicle from leaving drivable area	B	SG07
8	6	Missed passenger	Undetected passenger in vehicle getting out during AVP	Passenger tries to get off during AVP	Collision with person	S2	Collision at medium speed causes severe injuries	E4	Passengers almost every drive expected	C1	Passengers are able to stay in the vehicle	A	SG08
9	7	Unintended activation of AVP outside the operational design domain	Safety-critical traffic situation resulting from an unintended activation	Driving on highway	Unexpected vehicle behavior on highway	S3	Life-threatening injuries due to accidents at high speeds	E4	AVP is available during normal vehicle use	C3	Assumption: it is not possible to override	D	SG01

4.1 Safety Goals

After the hazards are identified, the corresponding risks need to be assessed and corresponding safety goals have to be formulated. Hereby, safety goals represent top-level safety requirements and are derived from the introduced hazard analysis and risk assessment (HARA). Elaborated safety goals represent necessary conditions for AVP systems. Elaborated safety goals inherit the hazard's Automotive Safety Integrity Level (ASIL) with ASIL D representing the highest and quality management (QM) the lowest safety risk. The ASIL serves as a recommendation, but is not a mandatory minimum threshold since the application of the ISO 26262[68] is not obligatory. Thereby, the ASIL determination is a function *f* of severity *S*, exposure *E* and controllability *C*, whereby

$$S = \{\mathrm{S1}, \mathrm{S2}, \mathrm{S3}\} \text{ with } S_i \in S \text{ and } i \leq 3 \land i \in \mathbb{N}\,, \tag{4–1}$$

$$E = \{\mathrm{E1}, \mathrm{E2}, \mathrm{E3}, \mathrm{E4}\} \text{ with } E_j \in E \text{ and } j \leq 4 \land j \in \mathbb{N}, \tag{4–2}$$

$$C = \{\mathrm{C1}, \mathrm{C2}, \mathrm{C3}\} \text{ with } C_k \in C \text{ and } k \leq 3 \land k \in \mathbb{N}. \tag{4–3}$$

The severity *S* estimates the extent of harm for the hazardous event. The exposure *E* contains the expected frequency of the hazard. The controllability *C* specifies the ability of hazard participants to avoid the occurring harm. The classification of the severity *S*, exposure *E* and controllability *C* results in five risk levels of the Automotive Safety Integrity Level given by

$$\mathrm{ASIL} = \{\mathrm{QM}, \mathrm{A}, \mathrm{B}, \mathrm{C}, \mathrm{D}\} \tag{4–4}$$

$$\Sigma_{SEC} = i + j + k = 10 \Longrightarrow \text{ASIL D} \tag{4–5}$$

$$\Sigma_{SEC} = 9 \Longrightarrow \text{ ASIL C} \tag{4–6}$$

$$\Sigma_{SEC} = 8 \Longrightarrow \text{ ASIL B} \tag{4–7}$$

$$\Sigma_{SEC} = 7 \Longrightarrow \text{ ASIL A} \tag{4–8}$$

$$\Sigma_{SEC} \leq 6 \Longrightarrow \text{ QM}. \tag{4–9}$$

The German Association of the Automotive Industry (VDA) released a situational catalogue for the classification of the exposure parameter.[69] A recommendation in both time and frequency domain is given for parking in a parking garage. For both cases, the exposure classification E4 is recommended. For a combinatorial analysis of the event parking and the given hazards (e.g. event parking in combination with unclear handover status) statistics are still missing. Therefore, the recommendation is accepted and most scenarios are classified

[68] ISO: ISO 26262: Road vehicles - Functional safety (2018).

[69] Verband der Automobilindustrie e.V.: VDA 702 E-Parameter according ISO 26262-3 (2015).

conservatively as E4. Since a fully automated vehicle without driver presence is not controllable, the classification C3 in terms of controllability is preferred. Considered parameters and corresponding assumptions are shown in Table 4–2.

Table 4–2: Assumptions for the categorization of ASILs for AVP systems

Parameter	Assumed Value
Maximum allowed velocity $v_{\max}$ inside the operational design domain	$v_{\max} \leq 30$ km
Maximum expected velocity $v_{\max}$ outside the operational design domain	$v_{\max} \gg 30$ km e.g. highway $v_{\max} \leq 120$ km
Exposure E for the event parking in time and frequency domain	E4
Controllability C for AVP systems without the driver's presence (in most cases)	C3

In this thesis, the definition and categorization of the following safety goals is introduced which were derived from the HARA as illustrated in Table 4–1.

Safety goal SG01 accounts for an unintended activation of the valet parking function outside of the parking garage area such as highways or urban environments. This safety goal receives the ASIL D since high velocities can be present (S3). Additionally, no safety mechanisms can be expected beforehand and therefore it is assumed that the AVP service is always available (E4).

Safety goal SG02 considers the case that incorrect data such as maps or trajectories are transmitted to the automated vehicle by the infrastructure. Incorrect speed profiles may cause fatal injuries (S3). Data transmission for the execution of the AVP-service is expected to be frequently (E4). Additionally, from the controllability prospective the automated vehicle is assumed to be uncontrollable (C3). This thesis therefore proposes ASIL D.

Safety goal SG03 and SG05 describe a collision with persons and vehicles. The major difference between a direct collision with a person and a person in a vehicle is the protective body. The latter situation is less severe. Hence, the severity class S2 and S1 are assigned, respectively. Encounters between vehicle and persons are expected during every AVP process (E4). In the context of uncontrollability for fully automated driving, risks are estimated to be ASIL C and ASIL B.

Safety goal SG04 prevents the vehicle from activating the valet parking function inside the parking garage unintendedly. The situation occurs every time within a valet parking procedure and as a result exposure is set to E4. In terms of severity the situation is assumed to be in low speed and collisions with a persons are less severe (S1) which finally results in ASIL B.

Safety goal SG06 notifies a human supervisor in case of a collision or fire. This considers an emergency call after a collision inside the parking garage. In case of a severe or life-threatening injury (S2) every second counts. Exposure is determined similarly to SG03 (E4). It is expected that pedestrians not involved in the collision are still able to set up an emergency call and controllability is classified as C2. The setting yields to ASIL B.

Safety goal SG07 ensures that the vehicle does not leave its specified operating area during AVP (E4) since the automated vehicle might crash into persons (S3). However, other objects such as barriers will prevent the automated vehicle from leaving its drivable area (C1) and ASIL B is expected.

Safety Goal SG08 disables the valet parking function if persons are still inside the automated vehicle. The mechanism prevents the possibility to get off the vehicle during AVP. Severity and exposure is assumed to be similar as in SG04 (S2, E4). Since no safety mechanisms are implemented beforehand, passengers are not able to override or push the emergency off switch. However, passengers are able to stay in the vehicle (C1). The risk is classified to ASIL A.

Safety Goal SG09 indicates a collision with an object which in return injures persons. The kinetic energy of such an object is expected to be low (S1) and the combination of dangerous objects and moving persons is unlikely (E3). Probably less than 90% of persons are able to evade (C3) which results in ASIL A.

After the safety goals are elaborated, their necessity and sufficiency is investigated. Necessity and sufficiency are terms to describe conditional statements[70]. These terms are introduced in the following to derive conditional statements between a safe AVP service and elaborated safety goals.

A condition G is necessary for an event H if H cannot be true unless G is true. In other words H implies G ($H \rightarrow G$). Therefore, it is never the case that H occurs and G does not occur. If there is a number of necessary conditions G_1, G_2 ..., and H is true, then all necessary conditions have to be fulfilled. This can be expressed by logical AND operations

$$H \rightarrow G_1 \wedge G_2 \wedge G_3 \wedge \dots \tag{4–10}$$

On the other hand, a condition G is sufficient for an event H if and only if it is never the case that G occurs and H does not occur. An event H has multiple sufficient conditions. The event H is fulfilled if only one sufficient condition is true. This is given by logical OR operations

$$G_1 \vee G_2 \vee G_3 \vee \dots \rightarrow H \tag{4–11}$$

[70] Facione, P. A.: A modal truth-tabular interpretation for necessary and sufficient conditions (1972).

Transferred to AVP and related safety goals, this results in the following conditional statement:

An AVP service is considered as safe if all necessary conditions for a safe AVP system are fulfilled. If safety goals are a subset of those necessary conditions, then a safe AVP system cannot occur if related safety goals are not fulfilled (logical AND operation). A safe AVP service implies the fulfillment of all related safety goals.

These safety goals (necessary conditions) are summarized in Table 4–3 and sorted according their ASIL.

Table 4–3: Safety goals/ necessary conditions for a safe automated valet parking. The ASIL serves as a recommendation, but is not a mandatory minimum threshold since the application of the ISO 26262[71] is not obligatory.

ID	Safety Goal	ASIL
SG01	Unintended activation of the valet parking function outside of the PAM-controlled parking area shall be prevented.	D
SG02	The integrity of the communication between the PAM and the vehicle shall be ensured if communication is present.	D
SG03	The system shall prevent a collision between automated vehicles and persons if persons are inside the parking garage.	C
SG04	Unintended activation of the valet parking function inside the PAM-controlled parking area shall be prevented.	B
SG05	The system shall prevent collisions with other vehicles.	B
SG06	The system shall notify a human supervisor in case of a collision or fire.	B
SG07	The system shall ensure that the vehicle stays within the (statically defined) drivable area during AVP.	B
SG08	The valet parking function shall be disabled if people are inside the vehicle.	A
SG09	The system shall prevent collision of automated vehicles with objects.	A

The HARA was performed to identify potential hazards. Top-level safety requirements called safety goals are elaborated and serve as necessary conditions for a safe AVP service. An unintended activation of the valet parking function outside of the PAM-controlled parking

[71] ISO: ISO 26262: Road vehicles - Functional safety (2018).

area and incorrect data transmission between PAM and vehicle are identified as most dangerous (ASIL D). ASILs serve as a recommendation, but are not obligatory. In the following chapter the defined safety goals will be further refined into low-level safety requirements by considering the processing flow. Necessary and sufficient conditions for the fulfillment of a safety goal will be marked in the following chapters.

5 Minimum Safety Requirements

The derivation of safety requirements for complex automated driving functions lacks a categorization in the literature to date to tackle the completeness issue. This chapter introduces a structure for a fault tree-based approach to derive safety requirements from safety goals systematically in compliance with the international standard of functional safety for road vehicles known as ISO 26262[72]. The approach utilizes a fault tree-based Sense-Plan-Act architecture to achieve a large coverage of possibly derivable safety requirements from safety goals. The methodology presented in this work provides means to systematically derive safety requirements from safety goals. A fault tree-based approach is proposed to ensure a larger coverage of safety requirements. The methodology presented in this chapter draws hereby inspiration from sequential robot control architectures known as Sense-Plan-Act or Sense-Model-Plan-Act architectures. Thereby, the signal processing steps of the sensor data acquisition, the environment modeling, the planning, and finally the actions are executed sequentially. Sequential architecture elements serve for achieving a long-term goal, e.g. the execution of a driving mission.[73] This thesis categorizes safety goal violations according to such sense-, plan-, act-failures architecture, as the sequential decision making process, following the sense plan act cycle, transfers well from mobile robots to AVP systems. Figure 5–1 indicates the safety analysis of a safety goal's violation. A violation of a safety goal occurs if at least one of the failure events in the sense-, plan-, and act-phase is present. The presented structure is applied on valet parking for use case specific derivation of minimum safety requirements. The safety requirements can be derived systematically by covering a larger set of safety requirements due to the application of a deductive fault tree-based approach. The methodology is suitable for safety goals which follow the specified sense-plan-act pattern. The approach is not suitable for all derived safety goals since for example C2X-communication does not follow the specified sense-plan-act pattern. In the following the terms Sense, Plan, Act and the corresponding breakdown into segments are introduced. The chapter is extracted from Schönemann et al.[74]

[72] ISO: ISO 26262: Road vehicles - Functional safety (2018).

[73] Hertzberg, J. et al.: Mobile Roboter (2012). p. 321.

[74] Schönemann, V. et al.: Fault Tree-based Derivation of Safety Requirements for AVP (2019).

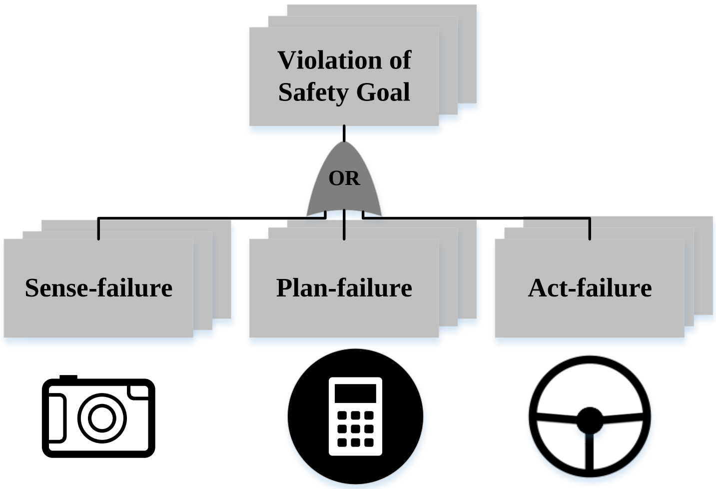


Figure 5–1: The sense-plan-act cycle is a common sequential system architecture for mobile robots. In this chapter it is transferred to derive low level safety requirements. A violation of a safety goal occurs hereby if at least one of the failure events in the sense-, plan-, and act-phase is present.

5.1 Minimum Requirements for Sensing

The sense phase contains the acquisition of sensor data and modelling of the environment. According to Dietmayer et al.[75] detecting static and dynamic objects and physically measuring them as precisely as possible, leads to three uncertainties which are visualized in Figure 5–2:

- State uncertainty: Represents the measuring errors of physical measured variables, especially the object's dimensions (length, width, height), the object's pose and the object's velocity.
- Existence uncertainty: Outlines the uncertainty whether an object captured by the sensors and mapped into the representation actually exists. This concerns mainly false positives and false negatives. For example, emergency braking should only be executed in case of a high existence probability.
- Class uncertainty: Describes uncertainty of the capability to classify the object's membership in order to predict the object's behavior. Type of object might be for example pedestrians, bicyclists, trucks, or cars. The degree of granularity is dependent on the use case.

[75] Dietmayer, K.: Predicting of machine perception for automated driving (2016).

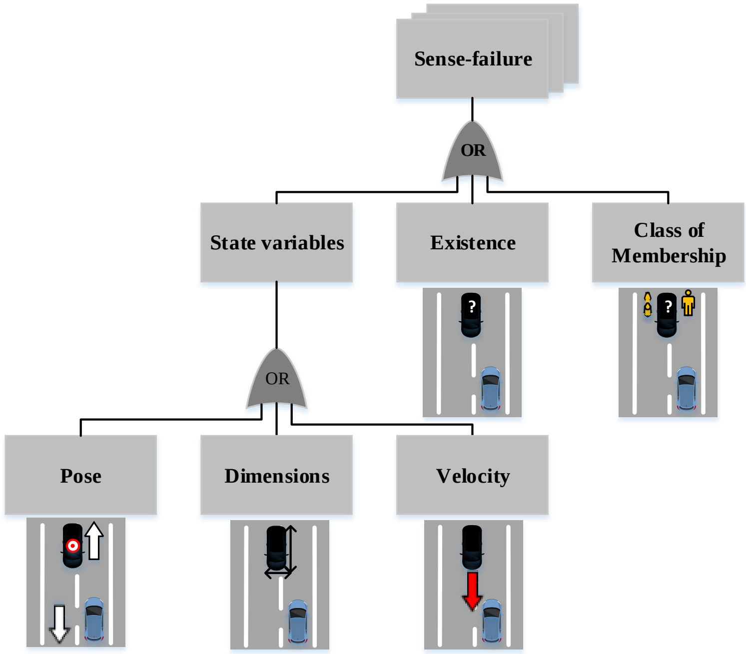


Figure 5–2: A sense failure occurs if uncertainties are present in the object's state variables, the object's existence or its class of membership. State variables are defined as the object's pose, the object's dimensions, and the object's velocity. The categorization according to Dietmayer et al.[75] was adapted for the derivation of low level safety requirements in the sense phase.

In order to avoid a collision between the ego-vehicle and other traffic participants both vehicles have to be able to execute a full stop without colliding. This thesis introduces a minimum required stopping distance d_{req} as visualized in Figure 5–3. This minimum required stopping distance consists of the ego-vehicle's stopping distance $d_{\mathrm{req,ego}}$, the object-vehicle's stopping distance $d_{\mathrm{req,obj}}$ and a safety margin d_{tol}

$$d_{\mathrm{req}} \geq d_{\mathrm{req,ego}} + d_{\mathrm{req,obj}} + d_{\mathrm{tol}} \tag{5–1}$$

The ego-vehicle's stopping distance $d_{\mathrm{req,ego}}$ is represented by

$$d_{\mathrm{req,ego}} \geq v_{\mathrm{ego}} \cdot \left(\tau_{\mathrm{B,lag}} + \tau_{\mathrm{R,ad}}\right) + \frac{v_{\mathrm{ego}}^2}{2 \cdot D_{0,\mathrm{ego}}} \tag{5–2}$$

with the ego-vehicle's velocity v_{ego}, the brake delay time $\tau_{\mathrm{B,lag}}$, the automated system's response time $\tau_{\mathrm{R,ad}}$, the always given deceleration capability $D_{0,\mathrm{ego}}$. The object-vehicle's stopping distance $d_{\mathrm{req,obj}}$ is calculated by

$$d_{\mathrm{req,obj}} \geq v_{\mathrm{obj}} \cdot \left(\tau_{\mathrm{B,lag}} + \tau_{\mathrm{R,obj}}\right) + v_{\mathrm{obj}} \cdot \tau_x + \frac{v_{\mathrm{obj}}^2}{2 \cdot D_{0,\mathrm{obj}}} \tag{5–3}$$

which is given by the object's velocity v_{obj}, the reaction time $\tau_{\mathrm{R,obj}}$, an additional duration τ_x due to different reaction times between automated and manually driven vehicles, an always given deceleration capability $D_{0,\mathrm{obj}}$. Ego-vehicle velocity v_{ego} is positive in the ego-vehicle's driving direction, object-vehicle velocity v_{obj} is positive in the object-vehicle's driving direction and the ego- and object deceleration capabilities $D_{0,\text{ego}}$ and $D_{0,\text{obj}}$ are positive in opposite driving direction of the respective vehicle. In the following, the ego-vehicle's and object-vehicle's deceleration capabilities are assumed to be equal.

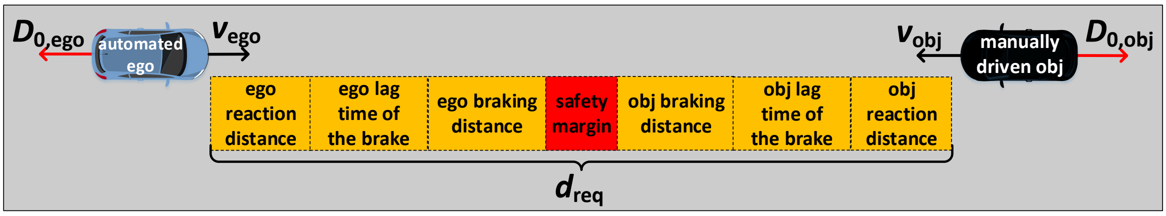


Figure 5–3: Minimum required stopping distances $d_{\text{req,ego}}$ and $d_{\text{req,obj}}$ consists of partial distances given by unequal reaction times, brake delay time, the braking process and a safety margin. Ego-vehicle velocity v_{ego} is positive in the ego-vehicle's driving direction, object-vehicle velocity v_{obj} is positive in the object-vehicle's driving direction and the ego- and object deceleration capabilities $D_{0,\text{ego}}$ and $D_{0,\text{obj}}$ are positive in opposite driving direction of the respective vehicle.

The minimum required stopping distance d_{req} is compared with the actually measured distance to the object which requires the knowledge of the object's position and its dimensions. The object's orientation and velocity are required to predict the moving behavior. The object's state variables only have to be known in a minimum required perception zone. The minimum required perception zone determines the required field of view and the corresponding range. In this area of interest objects have to be detected under all possible environment conditions in the PAM area even if these are occluded. The system has to reduce the automated vehicle's velocity till these requirements are met. Thereby, broken/ covered or misplaced sensors have to be diagnosed to ensure the environmental perception. The definition of the minimum required perception zone is given in chapter 6.

Beside the knowledge of the object's state variables, a definition of the acceptable measurement error valid for all AVP systems is necessary. Pose, size dimensions and velocity are in reality inaccurate. In the following the maximum allowed lateral and longitudinal measurement error will be presented.

Longitudinal Measurement Error: Minimum stopping distances have to be maintained in order to avoid a collision when an automated and manually driven vehicle are driving towards each other. The overall longitudinal error is given by the superposition of absolute longitudinal errors for the stopping distances $\Delta x_{\text{stop,ego}}$ and $\Delta x_{\text{stop,obj}}$ and the absolute longitudinal errors for the determination of the object's and ego-vehicle's state variables Δx_{obj} and Δx_{ego} as indicated in Figure 5–4

$$\Delta x_{\text{max}} = \Delta x_{\text{ego}} + \Delta x_{\text{stop,ego}} + \Delta x_{\text{stop,obj}} + \Delta x_{\text{obj}} < d_{\text{tol}} \tag{5–4}$$

Thereby, the lag time of the brake $\tau_{\text{B,lag}}$, response time τ_{R}, the additional duration τ_x and always given deceleration capability D_0 are fixed parameters when considering worst-case constraints for stopping distances. Only the measurement of the velocity v remains in the equation. The inaccurate measurement of the ego-vehicle's velocity v_{ego} and the object's velocity v_{obj} causes the absolute longitudinal error for the worst case stopping distances.

Therefore, the maximum allowed absolute longitudinal errors Δx_{max} shall not exceed the safety margin d_{tol} when determining the object's and the ego-vehicles pose, size and velocity in longitudinal direction. The safety margin prevents the vehicle from colliding with an object. The safety margin has to be set such that measurement inaccuracies in longitudinal direction are compensated by the safety margin d_{tol}.

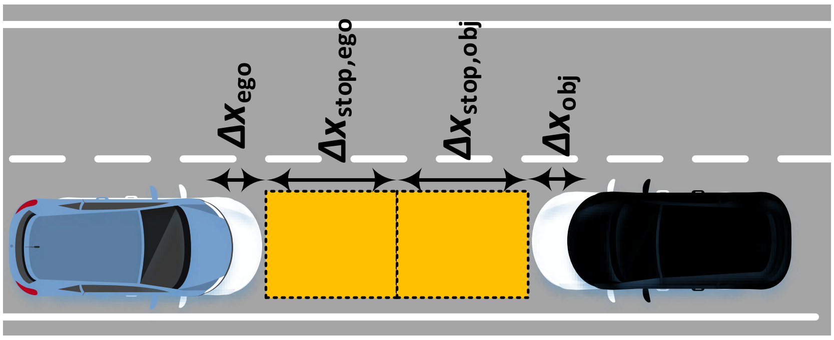


Figure 5–4: Maximum accepted longitudinal errors Δx_{max} for the determination of the ego's and the object's state variables and their corresponding stopping distances is restricted by the safety margin

Lateral Measurement Error: The system has to detect the object's state variables to avoid a collision. The maximum allowed absolute lateral error of measurement Δy_{max} is given by the narrowest part of the operational design domain $w_{\text{ODD,min}}$ and the vehicle width w_{V}. Considering the lateral error from lane center, results in

$$\Delta y_{\text{max}} \leq \frac{w_{\text{ODD,min}}}{2} - \frac{w_{\text{V}}}{2} \tag{5–5}$$

The maximum absolute lateral measurement error Δy_{max} is given by the present absolute measurement inaccuracies of the ego-vehicle Δy_{ego} and the object Δy_{obj}. The ego-vehicle has to estimate its own state variables (self-perception) and the state variables of the object (object state estimation)

$$\Delta y_{\text{max}} \leq \Delta y_{\text{ego}} + \Delta y_{\text{obj}} \tag{5–6}$$

In case of an infrastructure-based measurement the ego-vehicle's and the object-vehicle's state variables are measured equally inaccurate ($\Delta y_{\text{obj}} = \Delta y_{\text{ego}}$)

$$\Delta y_{\text{max}} \leq\ 2 \cdot \Delta y_{\text{ego}} \text{ for } \Delta y_{\text{obj}} = \Delta y_{\text{ego}} \tag{5–7}$$

Inserting (5–6) in equation (5–5) yields

$$\Delta y_{\text{ego}} \leq \frac{w_{\text{ODD,min}}}{2} - \frac{w_{\text{V}}}{2} - \Delta y_{\text{obj}} \text{ in general} \tag{5–8}$$

$$\Delta y_{\text{obj}} = \Delta y_{\text{ego}} \leq \frac{w_{\text{ODD,min}} - w_{\text{V}}}{4} \text{ for infrastructure-based AVP} \tag{5–9}$$

Where Δy_{obj} and Δy_{ego} denotes the maximum absolute lateral error each participant is allowed to perform. Figure 5–5 indicates an ego-vehicle driving straight and approaching an object-vehicle. The ego-vehicle estimates its state variables with an absolute lateral error

Δy_{ego}. Thereafter, the ego-vehicle measures the object with an absolute lateral error Δy_{obj} are present. If not considering absolute measurement errors, the ego-vehicle would assess a collision-free area, but in reality the ego-vehicle would collide with a traffic participant.

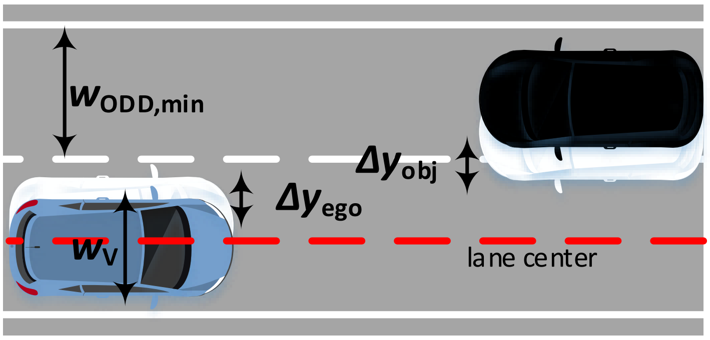


Figure 5–5: Maximum accepted lateral error for the determination of the object's state variables is given by the narrowest part in the operational domain $w_{\mathrm{ODD,min}}$, the vehicle width w_{V} and measurement inaccuracies Δy for state variables

Example: Considering Germany's traffic regulation[76], a maximum vehicle width of $w_{\mathrm{V,max}} = 2.50$ m can be found. However, for AVP systems a parking lot width of $w_{\mathrm{P,min}} > 2.50$ m is not profitable for the operator and a minimum parking lot width of Germany's parking garage regulation[77] $w_{\mathrm{P,min}} = 2.30$ m could be considered by not allowing to enter oversized vehicles. In that case, a look on the European's average passenger car size[78] of 2016 could be done. Adding a safety margin of 10 cm for withdrawn car mirrors on each side, we end up with an average vehicle width of around $w_{\mathrm{V,avg}} = 2$ m and therefore an overall error of size determination and object localization of less than $\Delta y_{\mathrm{ego}} \leq (w_{\mathrm{P,min}} - w_{\mathrm{V,avg}})/4 = 7.5$ cm. Looking at the survey of indoor positioning from Einsiedler et al.[79], today's valet parking systems are capable to localize in centimeter precision. However, none of the indoor navigation systems presented in the survey is capable to achieve the desired precision standalone.

Table 5–1 summarizes the safety requirements for the sense-phase to avoid collisions by detecting objects in the ego-vehicle's minimum required perception zone. The minimum required perception zone determines the required field of view and the corresponding range. The minimum required perception zone depends on the allowed maneuvers inside the parking garage. In the context of necessary conditions, the perception zone is therefore not considered as a statically defined area required to be valid for all parking garages, but rather as a maneuver-dependent definition valid for the individual parking garage. Its necessity is cou-

[76] Bundesministerium der Justiz und für Verbraucherschutz: StVZO (2012).

[77] Hessisches Ministerium der Justiz: Garagenverordnung - GaV (2014).

[78] International Council on Clean Transportation: European Vehicle Market Statistics Pocketbook (2017).

[79] Einsiedler, J. et al.: Vehicle indoor positioning: A survey (2017).

pled on executable maneuvers and constraints within the specific parking garage. The detailed specification is given in chapter 6. The derived safety requirements are necessary conditions for collision avoidance targeted in safety goals SG03, SG05 and SG09.

Table 5–1: Derivation of FSR3.1: “The system shall detect objects in its minimum required perception area.” Functional safety requirements are necessary conditions for a safe AVP. In terms of necessity the minimum required perception zone is seen as a parking garage-specific area.

ID	Functional Safety Requirement
FSR3.1.1	The system shall detect its own and the object’s state variables sufficiently accurate.
FSR3.1.1.1	The system shall detect its own and the object’s pose in its minimum required perception zone. The absolute lateral and longitudinal error for the object’s state variables shall be less than Δy_{ego} and Δx_{max} , respectively.
FSR3.1.1.1.1	The system shall detect objects in a front and rear horizontal field of view defined by the minimum required perception zone and a sufficiently high vertical field of view.
FSR3.1.1.2	The system shall determine its own and the object’s dimensions length ℓ_{obj}, width w_{obj}, height h_{obj} in its minimum required perception zone. The absolute lateral and longitudinal error for the object’s state variables shall be less than Δy_{ego} and Δx_{max}, respectively.
FSR3.1.1.3	The system shall determine its own and the object’s velocity v_{obj} in its minimum required perception zone. The absolute lateral and longitudinal error for the object’s state variables shall be less than Δy_{ego} and Δx_{max} , respectively.
FSR3.1.1.4	The system shall detect objects under all possible environment conditions in the PAM area.
FSR3.1.1.5	The system shall diagnose broken/ occluded or misplaced sensors.
FSR3.1.1.6	The system shall detect objects that are occluded from the vehicle’s view in its minimum required perception area.
FSR3.1.3	The system’s object classification shall not lead to harmful situational interpretation.

5.2 Minimum Requirements for Planning

After the AVP system received the required sensing information about its surrounding, a trajectory has to be planned accordingly. Hereby, the planning segment includes the situation comprehension and action planning. The transportation mission can be split into five tasks according to Lotz et al. [80] The starting point is the driving mission which is determined within the given road network and is required as the input for route planning. A behavior planer determines the sequence of maneuvers to reach the destination. For each maneuver, a specific trajectory is computed. These five steps are given in Figure 5–6:

- *Mission Planning*: In the first step, a mission has to be planned from the current location to the destination such as the next free parking space upon a service request or the exit in case of handback request.
- *Route Planning*: A route has to be determined in order to get to the destination. A Route planner determines a route based on the topological representation of the road network.
- *Behavior Planning*: Provides a sequence of maneuvers to reach the destination by considering other traffic participants, traffic rules and restrictions.
- *Maneuver Planning*: An element of the sequence provided by the behavior planner is selected which has to be executed.
- *Trajectory Planning*: A trajectory for the specified maneuver has to be calculated to perform instructions in the act-phase.

Timing constraints for the start and end of each maneuver and the calculation of the maneuver trajectory have to be specified.

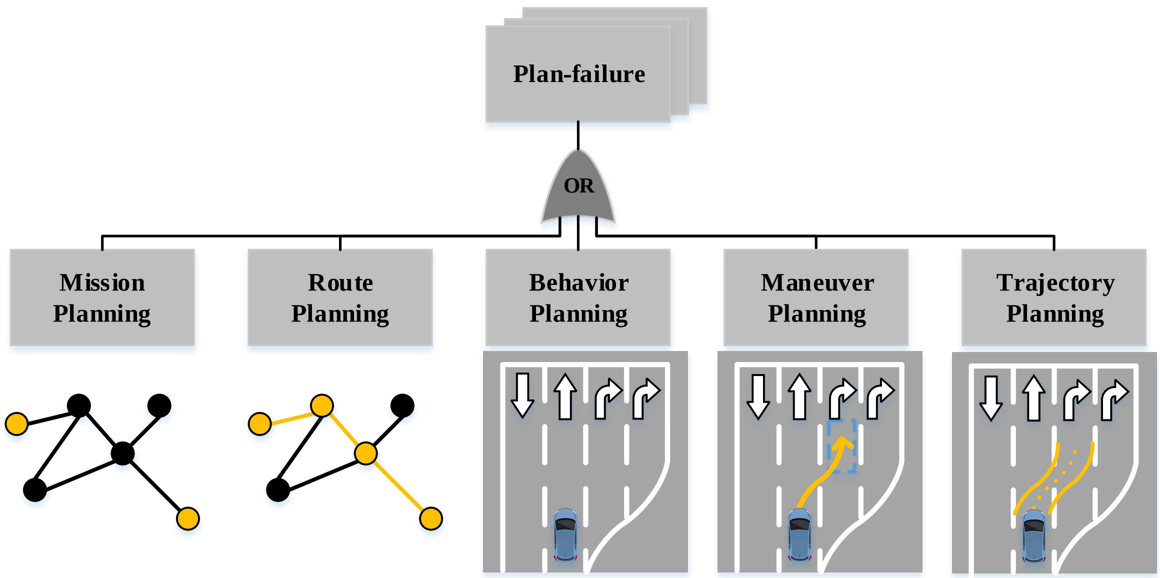


Figure 5–6: A plan failure is given by a failure in one of the planning submodules. The driving mission can be split into mission planning, route planning, behavior planning, maneuver planning, and trajectory planning. For maneuver and trajectory planning, timing constraints for calculation and

[80] Lotz, F. G.: Eine Referenzarchitektur für die assistierte und automatisierte Fahrzeugführung (2017). pp. 85 – 90.

execution are crucial. The split according to Lotz[80] was taken for automated driving without driver interaction to derive low level safety requirements.

The system has to localize its pose and requires the knowledge of the destination in order to plan a safe mission. The defined maximum lateral and longitudinal errors for the determination of the object's state variables have to be met at any point of time. Routes are computed based on graphs of road networks which have to be up-to-date, accessible and connected. The sequence of maneuvers has to be in compliance with the traffic regulations[81] for public road traffic or in compliance with the parking garage operator's regulations for non-public traffic. The collision free-trajectory has to be provided within the defined system's response time $\tau_{\mathrm{R,ad}}$. The system's response time specifies the worst-case expected time delay from the plausibility check until initiating the brakes. Therefore, the provision of the trajectory has to be fed into the brake actuators within the fixed worst case time constraint. Table 5–2 gives an overview of the safety requirements within the plan-phase to avoid collisions. The safety requirements represent necessary conditions for a safe AVP service.

Table 5–2: Derivation of FSR3.2: "The system shall not plan a harmful trajectory." Functional safety requirements are necessary conditions for a safe AVP.

ID	Functional Safety Requirement
FSR3.2.1	The system shall plan a safe mission.
FSR3.2.2	The system shall plan routes on up-to-date, drivable, connected road segments in compliance with corresponding regulations.
FSR3.2.3	The system shall assign maneuvers on up-to-date, drivable area in compliance with corresponding regulations.
FSR3.2.4	The system shall compute a feasible, collision-free maneuver within hard real-time constraints (= missing deadline leads to a collision).
FSR3.2.5	The system shall plan a collision-free trajectory within the defined system's response time $\tau_{\mathrm{R,ad}}$.

5.3 Minimum Requirements for Acting

The Act block represents the execution of the planned trajectory. The following vehicle control inputs are required for performing longitudinal and lateral vehicle dynamics: Steering,

[81] Bundesministerium der Justiz und für Verbraucherschutz: StVZO (2012).

shifting, accelerating, and braking. A complete electrification of actuators is a necessary condition.[82] Thereby, either the targeted steering, shifting, acceleration, and braking parameters are not plausible for the executed maneuver in terms of range and time or corresponding vehicle components are corrupted. The breakdown of possible Act-failures is illustrated in Figure 5–7.

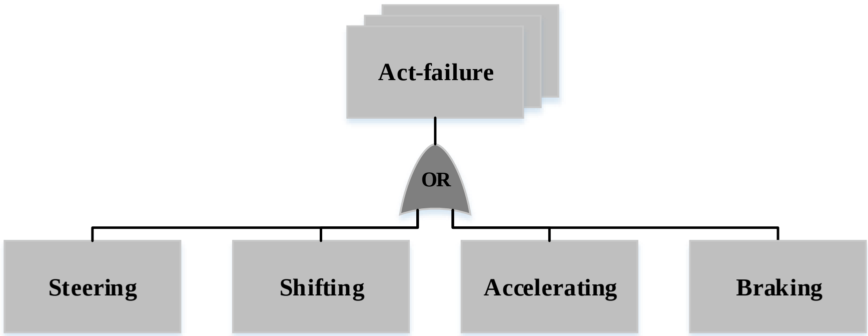


Figure 5–7: An act-failure is introduced by one of the primitives that are required for vehicle control mechanisms: Steering, shifting, accelerating, and braking.

Act-failures are not further broken down since an investigation is already done by e.g. Stolte et al.[83] and state-of-the-art. However, Stolte et al. do not provide a derivation of safety requirements for the sense and plan phase as introduced in this thesis. For the sake of completeness, necessary conditions for the acting are illustrated exemplary in Table 5–3. Thereby, mainly unintended control actions and the corruption or breakdown of necessary vehicle components have to be prevented. Unintended control actions are either incorrect in range or in time.

Table 5–3: Derivation of FSR3.3: "The vehicle shall prevent unintended control actions." Functional safety requirements are necessary conditions for a safe AVP.

ID	Functional Safety Requirement
FSR3.3.1	The system shall detect corrupted or uncalibrated actuators and breakdown of necessary vehicle components.
FSR3.3.2	The system shall prevent unintended steering.
FSR3.3.3	The system shall prevent unintended shifting.
FSR3.3.4	The system shall prevent unintended accelerating.
FSR3.3.5	The system shall prevent unintended braking.

[82] Cacilo, A. et al.: Hochautomatisiertes Fahren auf Autobahnen–Industriepolitische Schlussfolgerungen (2015).

[83] Stolte, T. et al.: Safety goals and functional safety requirements for actuation systems of AV (2016).

5.4 Remaining Safety Requirements

The presented sense-plan-act approach is not applicable for all safety goals. The remaining safety goals are discussed in the following. The derived safety requirements can be seen as necessary conditions for the fulfilment of related safety goal in a logical AND relationship.

Safety goal SG01 concerns an unintended activation of the valet parking function outside of the PAM-controlled area. This is prevented by detecting if the automated vehicle is located within the handover zone. The safety mechanism avoids the activation outside the operational design domain where higher velocities lead to increased severity. Whereas SG01 targeted the outside activation, the safety goal SG04 prevents an unintended activation inside the PAM-controlled area. This is achieved by the fulfillment of all following necessary conditions

- Detecting if the vehicle is in standstill.
- Checking if persons are located in the handover zone.
- Checking if doors are closed.
- Not activating the valet parking function without user or PAM permission.

Safety goal SG02 provides the integrity of the communication between the infrastructure and the vehicle. The integrity of communication between infrastructure and vehicle is ensured by controlling transmitted safety-relevant information for authentication, identification, error correcting, and manipulation. The transmitted data has to be encrypted to provide the required degree of security.

Safety goal SG06 performs a full stop and a notification of a human supervisor in case of collision or fire. The AVP system requires to detect fire and collisions. Safety goal SG07 ensures that the vehicle stays within the (statically defined) drivable area during AVP by detecting the (statically defined) drivable area and placing computed trajectories within the drivable area. Thereby, the defined lateral error Δy_{ego} for the lateral control of the automated vehicle shall not be exceeded.

Finally, safety goal SG08 disables the AVP service if persons are inside the vehicle to prevent passengers getting out while driving or being trapped inside the vehicle.

The overall safety requirements are summarized in Table 5–4. This chapter in this thesis contributes to minimum criteria for AVP systems by deriving low level safety requirements (necessary conditions) for all AVP configuration. This chapter targeted the determination of minimum safety requirements to avoid unreasonable risks in compliance with ISO 26262. Potential harmful hazards are analyzed and assessed to address the functional safety and the safety of the intended functionality defined in the SOTIF[84] with the aim to minimize risks of harm AVP systems.

[84] International Organization for Standardization: ISO/PAS 21448: Road vehicles - SOTIF (2019).

Table 5–4: Derivation of functional safety requirements for derived safety goals. Functional safety requirements are necessary conditions for related safety goals.

ID	Safety Goal (SG)/ Functional Safety Requirement (FSR)	SG
SG01	Unintended activation of the valet parking function outside of the PAM-controlled parking area shall be prevented.	
FSR1.1	The system shall detect if the automated vehicle's position is located within the handover zone.	SG01
SG02	The integrity of the communication between the PAM and the vehicle shall be ensured if communication is present..	
FSR2.1	The system shall control transmitted safety relevant information for authentication, identification, error correcting, and manipulation. Transmitted data shall be encrypted.	SG02
FSR2.1	The system shall receive safety-relevant information in time.	
SG04	Unintended activation of the valet parking function inside the PAM-controlled parking area shall be prevented.	
FSR4.1.1	The system shall detect if the automated vehicle is in standstill.	
FSR4.1.2	The system shall detect persons in the handover zones.	SG04
FSR4.1.3	The system shall detect if doors are closed.	
FSR4.1.4	The system shall have the ability to activate and deactivate the valet parking function.	
FSR4.1.5	The system shall not activate the valet parking function without user or PAM permission.	
SG06	The system shall notify a human supervisor in case of a collision or fire.	
FSR6.1	The system shall detect collisions.	
FSR6.2	The system shall detect fire in the parking garage.	
FSR6.3	The system shall stop the valet parking service by applying an emergency brake of automated vehicles in case of a fire.	SG06
FSR6.4	The system shall notify a human supervisor.	
SG07	The system shall ensure that the vehicle stays within the (statically defined) drivable area during AVP.	
FSR7.1	The system shall detect the (statically defined) drivable area.	
FSR7.2	The system shall place the automated vehicle's trajectories within the drivable area.	SG07
FSR7.3	The maximum lateral error of the automated vehicle's lateral control with respect to the lane center shall not exceed Δy_{ego}.	
SG08	The valet parking function shall be disabled if people are inside the vehicle.	
FSR8.1	The system shall detect whether people are inside the vehicle.	SG08

6 Minimum Required Perception Zone

This chapter introduces a maneuver-dependent *minimum required perception zone (MRP zone)* in which the monitoring of static and dynamic objects is mandatory to achieve the safety goal of collision avoidance. A *minimum required safety zone (MRS zone)* is a subset of the MRP zone and defines the boundary for which the deceleration has to be triggered by an AVP system to avoid collisions. The MRP zone and the MRS zone are based on a mathematical description of minimum stopping distances and therefore are crucial for collision avoidance. To the best of the author's knowledge, neither a minimum required perception zone nor a minimum required safety zone has been defined for AVP systems in literature so far. Additionally, a specification for the infrastructure support for cooperative AVP is given in this context. The magnitude of the MRP zone is maneuver-specific and therefore an investigation of occurring maneuvers in a parking garage is required. In particular, the minimum required perception zone specifies areas of interest around the ego-vehicle in which the traffic participant's parameters have to be determined for collision avoidance. Hence, the MRP zone provides a description of the relevant space in the environment perception task that is executed by the parking area management system and the automated vehicle. The results of this work can be used for the integration of the necessary safety design for the maneuver-specific parking garage. Additionally, the defined MRP zone is considered as a minimum criterion a valet parking system has to provide to minimize the risks of harm. A violation of the MRS and MRP zone indicates potentially safety-critical AVP systems since required safety-relevant areas are not covered. For the specification of the perception zone the following methodology is applied:

As illustrated in Figure 6–1 the overall valet parking system was split into functional scenarios that occur during the execution of the valet parking procedure as introduced in chapter 3. According to Ulbrich et al.[85] a scenario describes snapshots of the environment and the interaction of entities while time is progressing. Following the proposed split in chapter 3 subsequent major scenarios were considered for the derivation of the MRP zone: vehicle handover to parking area management system, automated driving to a point of interest, automated maneuvering into the parking space, automated leaving of the parking space, vehicle handover to driver and aborting the valet parking procedure. Each scenario is hereby examined according to specific maneuvers that are instructed by the automation system. Maneuvers also are extracted from layouts of car parks.[86] The determination of the safety distances depends on the object's class which ideally is known. If the class type equals a vehicle, it can be distinguished whether the potential collision partner is manually driven or driverless. This kind of information could be provided by the parking area management system or C2C. If the vehicle is operated driverless, it was registered by the PAM during the handover and

[85] Ulbrich, S. et al.: Defining and Substantiating the Terms Scene, Situation, and Scenario for AD (2015).

[86] Pech, A. et al.: Parkhäuser - Garagen (2009). pp. 375 – 408.

tracked. If no object information is provided, it should be assumed that the potential collision partner is a manually driven vehicle. The assumption is valid since, compared to an automated vehicle, more conservative parameters will be assigned to the collision partner. Even if the assumption is false, a sufficient safety distance is still provided. Furthermore, the moving behavior of the potential collision partner can be examined in order to check whether the object is moving towards the ego-vehicle, moving away or neither moving away nor moving towards. Worst case constraints such as timing, maximum allowed velocity and minimum required deceleration are defined for the operational domain and serve as an input for each maneuver to specify a minimum required safety distance for collision avoidance. The superposition of these safety distances leads to a new term: the *minimum required safety zone MRS zone*. The safety zone adapts its size according to the performed maneuver as well as the dynamic driving parameters of the engaged traffic participants such as velocities, timing constraints and deceleration capabilities. This thesis contributes to the definition of a MRP and MRS zone as minimum criteria. The MRP and MRS zone is introduced in Schönemann et al.[87]

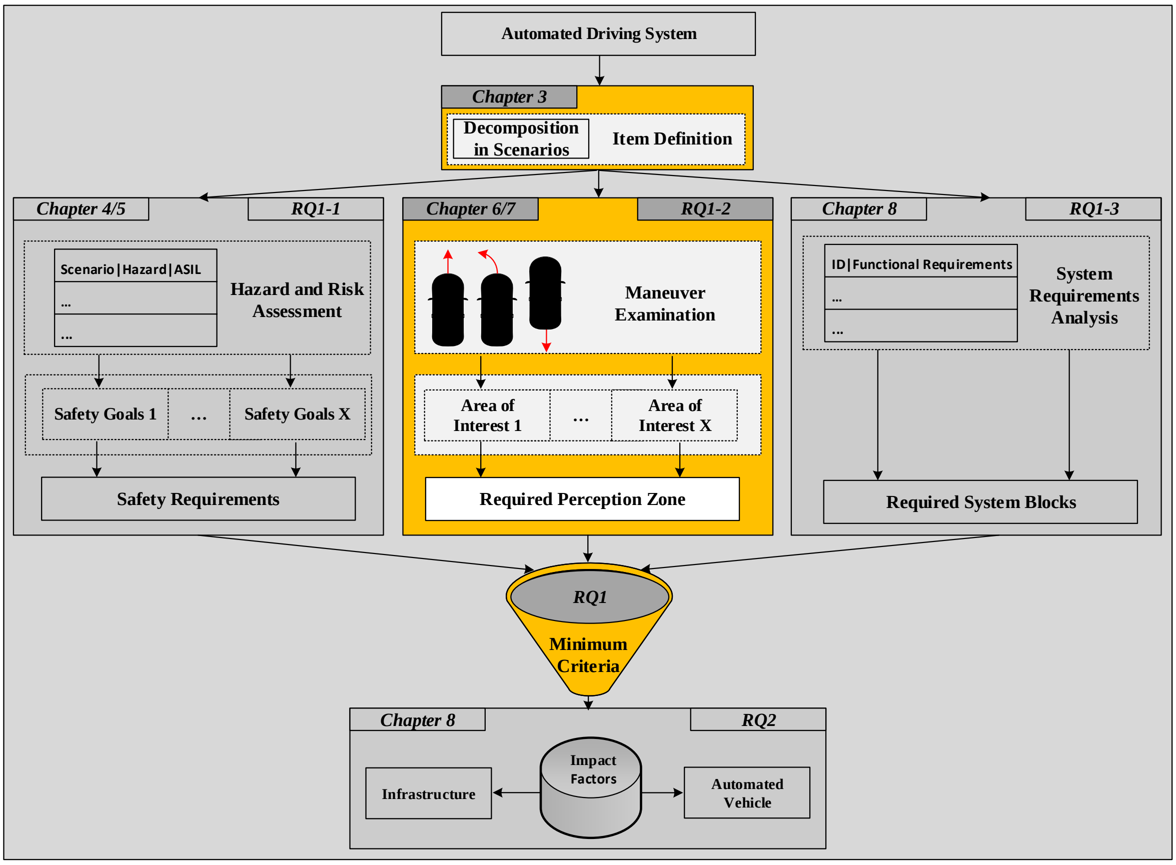


Figure 6–1: The *MRP zone* specifies the minimum area around the ego-vehicle which is required to be monitored. The MRP zone is maneuver-specific and therefore an investigation of occurring maneuvers in a parking garage is required. Functional scenarios are investigated for possible maneuvers. Worst-case constraints are injected for calculation of worst-case safety distances.

[87] Schönemann, V. et al.: Maneuver-based adaptive Safety Zone for infrastructure-supported AVP (2019).

6.1 Maneuver Examination and Worst Case Constraints

In this thesis functional scenarios and car park layouts from Pech[88] are considered to derive maneuvers for AVP. A stopping distance is required for each maneuver in order to avoid a collision with traffic participants. The stopping distance refers to the travelled distance from the point when the object is firstly measured until the vehicle is in standstill. The stopping distance includes the reaction distance and braking distance. The superposition of these maneuver-specific stopping distances leads to the introduction of a *minimum required perception (MRP)* and a *safety (MRS) zone*. The MRS zone adapts its distances according to the performed maneuver as well as dynamic driving parameters of the engaged traffic participants such as velocities, timing constraints and deceleration capabilities. The following maneuvers were found:

M1. Following a straight or curved lane: This maneuver includes the primitives accelerate and decelerate for longitudinal control as well as lane keeping for lateral control. The ego-vehicle's position is thereby kept at the lane center.

M2. Driving backwards: This maneuver is executed during the maneuvering into or leaving of the parking spot.

M3. Crossing an intersection: If the vehicle arrives at an intersection, turning left, turning right or crossing the intersection is possible. The maneuver addresses the crossing of the intersection.

M4. Turning left/right: A turn is required at intersection crossings and when leaving the parking space to the left or to the right for parking spaces oriented in lateral direction.

Additionally, occlusion may occur for the defined maneuvers. Occlusion of objects by other traffic participants or by parking construction may cause undetected objects inside the ego-vehicle's MRP zone without the vehicle's knowledge.

Before the safety distances are determined systematically, the defined worst case constraints used here should be mentioned. These assumptions serve as constraints to calculate the stopping distances. Once worst-case safety distances are determined, they are also valid for less critical situations and should avoid collisions. Thereby, the parameters are defined as vehicle velocity v, system response time $\tau_{\mathrm{R,ad}}$ from the plausibility check until the initiation of the brakes, driver reaction time $\tau_{\mathrm{R,md}}$, response time of the brakes $\tau_{\mathrm{R,b}}$, time delay of the brake until buildup of deceleration $\tau_{\mathrm{B,b}}$, a minimum guaranteed deceleration $D_{\min} = \mu_{\min} \cdot g$ given by the expected friction coefficient $\mu_{\min}$ and gravity constant g. In a parking garage, the authors assume a maximum allowed forward velocity of $v_{\mathrm{max,f}}$, a velocity in reverse $v_{\mathrm{max,r}}$ and a maximum allowed velocity at intersections $v_{\mathrm{max,i}}$. Additionally, a safety margin d_{tol} is required to prevent a collision. These rather conservative considerations are used in

[88] Pech, A. et al.: Parkhäuser - Garagen (2009). pp. 375 – 408.

the operational design domain and are summarized in Table 6–1. However, parking garage operators or manufacturers can adjust the worst case constraints according their individual system capabilities.

Table 6–1: Pre-defined worst case constraints for automated valet parking

ID	Description	Assumed Worst Case Constraints
C01	Maximum allowed velocities: in forward $v_{\text{max,f}}$, in reverse $v_{\text{max,r}}$, at intersections $v_{\text{max,i}}$	[89] $v_{\text{max,f}} = 30\ \text{km/h}$ $v_{\text{max,r}} = 10\,\text{km/h}$ $v_{\text{max,i}} = 10\,\text{km/h}$
C02	Worst-case expected time delays: system response time from the plausibility check until initiating the brakes $\tau_{\text{R,ad}}$, driver reaction time $\tau_{\text{R,md}}$, lag time of the brake $\tau_{\text{B,lag}}$ given by the response time of the brake $\tau_{\text{R,b}}$ and the time until buildup of deceleration $\tau_{\text{B,b}}$	$\tau_{\text{R,ad}} = 0.3\ \text{s}$ $\tau_{\text{R,md}} = 1.5\ \text{s}$ $\tau_{\text{B,lag}} \approx \tau_{\text{R,b}} + \frac{\tau_{\text{B,b}}}{2}$ [90] $\tau_{\text{B,lag}} = 0.2\ \text{s}$
C03	Always given deceleration $D_0 = \mu_{\text{min}} \cdot g$ for object- and ego-vehicle	$D_0 = 8\ \frac{\text{m}^2}{\text{s}}$
C04	Safety margin d_{tol}	$d_{\text{tol}} = 0.5\ \text{m}$

6.2 Derivation of a Minimum Required Perception Zone

In this subsection a minimum required perception and safety zone is derived based on the defined maneuvers in section 6.1 and worst case constraints in Table 6–1. The ego- and object vehicle shall have sufficient space to potentially accomplish a full stop. Hereby, the stopping distances of the ego- and object-vehicle are required to be considered. These stopping distances for all maneuvers can be expressed by a main equation which contains the minimum required stopping distance d_{req} given by the ego-vehicle's stopping distance $d_{\text{req,ego}}$, the object-vehicle's stopping distance $d_{\text{req,obj}}$ and a safety margin d_{tol} as indicated in Figure 6–2. The ego-vehicle's and object-vehicle's deceleration capabilities are assumed to be equal.

[89] Reschka, A.: Safety Concept for Autonomous Vehicles (2016). p. 473.

[90] Breuer, B.; Bill, K. H.: Brake Technology Handbook (2008).

Main Equation	
$d_{\mathrm{req}} \geq d_{\mathrm{req,ego}} + d_{\mathrm{req,obj}} + d_{\mathrm{tol}}$	
$d_{\mathrm{req}} \geq (v_{\mathrm{ego}} + v_{\mathrm{obj}}) \cdot (\tau_{\mathrm{B,lag}} + \tau_{\mathrm{R}}) + v_{\mathrm{obj}} \cdot \tau_x + \dfrac{v_{\mathrm{ego}}^2 + v_{\mathrm{obj}}^2}{2 \cdot D_0} + d_{\mathrm{tol}}$	(6–1)

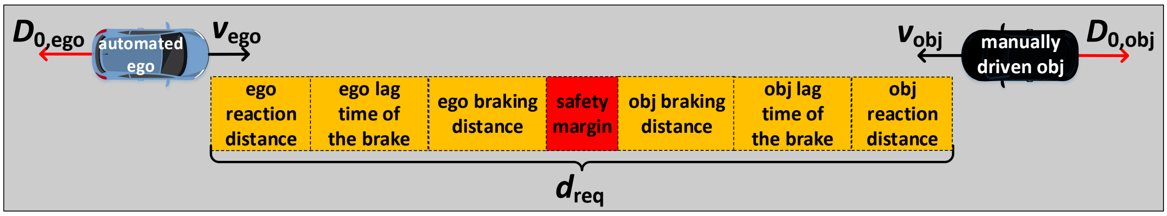


Figure 6–2: When approaching an object in standstill, the ego and object vehicle's stopping distance consists of the reaction distance, the distance travelled due to the lag time of the brake, the braking distance and a safety margin. The reaction times between a manually driven and an automated vehicle differ.

Thereby, the moving behavior (moving towards, moving away or in standstill) of the object needs to be considered to identify the required cases for the MRP and MRS zone. The distinction of the moving behavior for each maneuver will be explored in the following. Dependent on the executed maneuver and considered case the response time τ_{R} and duration τ_x may vary.

M1. Following a straight or curved lane

When the ego-vehicle follows the lane there are three cases regarding the stopping distances:

- Case (M1,a): In case of bi-directional traffic a detected object may move towards the ego-vehicle. In this case, it is useful to distinguish between two possibilities: A collision of two vehicles and either both vehicles are braking (M1,a1) or only the automated vehicle is braking (M1,a2).
- Case (M1,b): The object is moving away and $v_{\mathrm{ego}} > v_{\mathrm{obj}}$. This is the case when the ego-vehicle drives behind an object vehicle with lower velocity.
- Case (M1,c): The object is neither moving towards the ego-vehicle nor moving away. This may be a static object such as a wall.

For each of these cases different stopping distances have to be considered. In case (M1,a1), it is assumed that both vehicles react at the same time. The object vehicle can either be manually driven or driverless. Thus, the worst case object's reaction time $\tau_{\mathrm{R,obj}}$ has to be taken into account. The overall required stopping distance is given by the overlap of the single stopping distances. The time constraints are $\tau_{\mathrm{R}} = \tau_{\mathrm{R,ad}}$ and $\tau_x = \tau_{\mathrm{R,obj}} - \tau_{\mathrm{R,ad}}$.

Equation (6–1) produce the maximum spanned safety zone for the worst-case $v_{\mathrm{ego}} = v_{\mathrm{obj}} = v_{\mathrm{max,f}}$. This can be seen as the minimum required perception range $d_{\mathrm{req,f}}$ to the front for AVP. Once the object is measured in this area, the safety zone adapts its size according to the object's velocity and reaction capability as presented in Figure 6–3. Thereby, the object vehicle may appear in 180° around the collision crossing point. For the manually driven vehicle the driver's reaction time has to be injected into the formula by $\tau_{R,obj} = \tau_{R,md}$, whereas for an automated vehicle as a collision partner the equation (6–1) simplifies by setting $\tau_{R,obj} = \tau_{R,ad}$.

The case (M1,a2) occurs if the automated vehicle has to be in standstill for collision avoidance and only the control of the automated vehicle is possible ($v_{obj}^2/(2 \cdot D_0) = 0$). The required distance d_{req} is then given by the stopping distance of the ego-vehicle and the driven distance of the manually operated or automated vehicle when the ego-vehicle's velocity is zero ($\tau_x = v_{ego}/D_0$)

Case (M1,b) can be approximated by assuming an object that is not moving since stopping in front of a standing object is always more safety critical compared to objects that are moving away. When considering this approximation, the object has no impact on the stopping distance and therefore the stopping distance is only influenced by the ego-vehicle's parameters. This is achieved by setting $v_{obj} = 0$ in equation (6–1). The same considerations can be applied to case (M1,c), since case (M1,b) is reduced to case (M1,c).

Figure 6–3 demonstrates all three cases and Table 6–2 summarizes corresponding constraints which need to be injected into the main equation to determine the required distances.

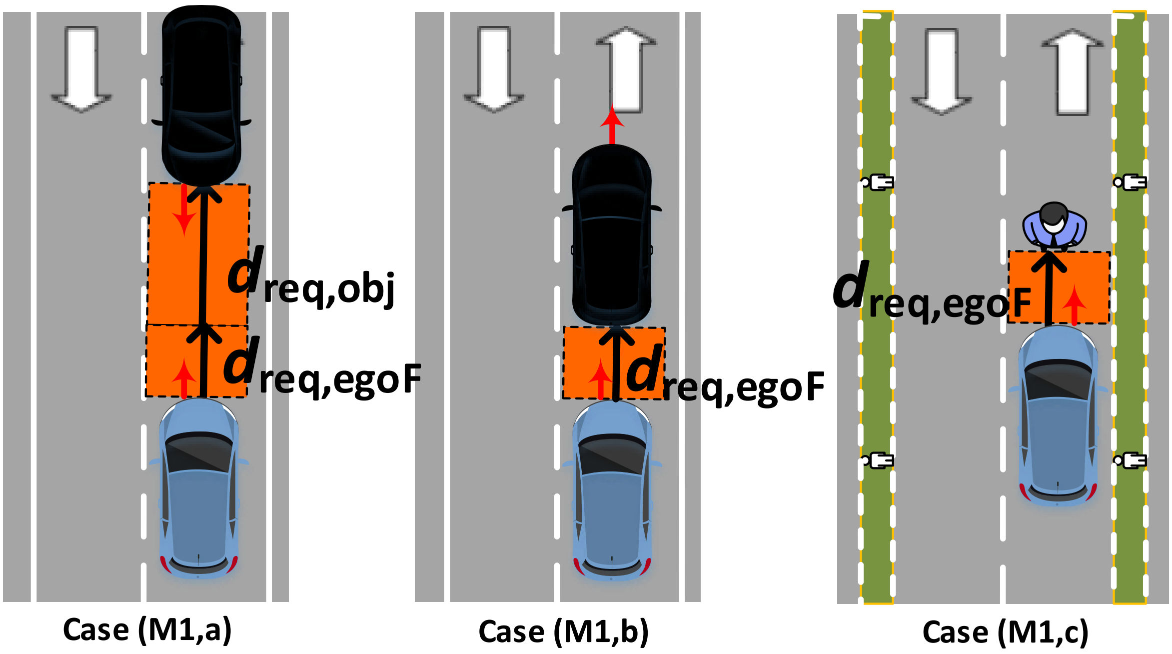


Figure 6–3: Minimum required stopping distances for following a straight or curved lane: (Case M1,a) object is moving towards the ego-vehicle, (Case M1,b) object is moving away and $v_{ego} > v_{obj}$, (Case M1,c) object is neither moving away nor moving towards

M2. Driving backwards

This maneuver has similar characteristics to the maneuvers *following a straight lane or turning left/right.* Similarly, three cases occur while driving in reverse:

- Case (M2,a): The detected object is moving towards the ego-vehicle
- Case (M2,b): The object is moving away and $v_{\text{ego}} > v_{\text{obj}}$
- Case (M2,c): The object is neither moving towards the ego-vehicle nor moving away.

The stopping distances are calculated as described in the maneuver *following a straight or curved lane* and *turning left/right*, but considering that the ego-vehicle is driving in reverse and an object is detected to the rear. The minimum required perception range to the rear for AVP is given for $v_{\text{ego}} = v_{\text{max,r}}$, $v_{\text{obj}} = v_{\text{max,f}}$ and $\tau_{\text{R,obj}} = \tau_{\text{R,md}}$. Once an object is measured in this area, the safety zone adapts its size according to the object's parameters.

M3. Crossing an intersection

When the ego-vehicle enters an intersection or when leaving the parking spot as shown in Figure 6–4, traffic participants coming from the side need to have at least a minimum distance $d_{\text{req,obj}}$ to the ego-vehicle in order to be able to successfully brake in case of an emergency. The required distance is dependent on whether the object-vehicle is manually driven or driverless. By setting $\tau_x = 0$, $v_{\text{ego}} = 0$ and $\tau_{\text{R}} = \tau_{\text{R,obj}}$ in equation (6–1) we get

$$d_{\text{req}} \geq d_{\text{req,obj}} + d_{\text{tol}} = v_{\text{obj}} \cdot \left(\tau_{\text{B,lag}} + \tau_{\text{R,obj}}\right) + \frac{v_{\text{obj}}^2}{2 \cdot D_0} + d_{\text{tol}} \tag{6–2}$$

For an automated collision partner approaching from the side with a velocity v_{obj}, the required safety distance is given by setting the reaction time $\tau_{\text{R,obj}} = \tau_{\text{R,ad}}$. If no information is provided about the type of object, the system assumes that the object is a manually driven vehicle. The assumption is valid since rather conservative parameters are allocated to the traffic participant ($\tau_{\text{R,md}} > \tau_{\text{R,ad}}$). A sufficient safety distance is assigned by $\tau_{\text{R,obj}} = \tau_{\text{R,md}}$. Table 6–2 includes the constraints that need to be injected in the main equation.

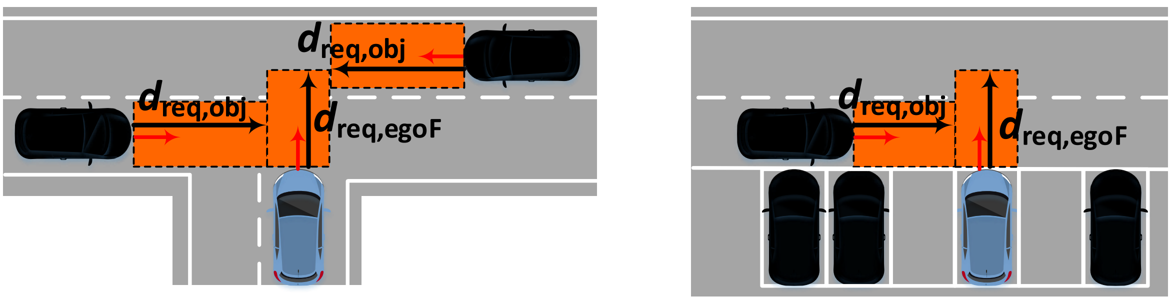


Figure 6–4: Minimum required stopping distances for crossing an intersection (left) which reveals similar characteristics to leaving the parking spot (right). Traffic participants coming from the side require in worst case a minimum distance $d_{\text{req,obj}}$ to the ego-vehicle to brake successfully.

M4. Turning left/ right

This maneuver includes the same safety distances as described in the maneuver *crossing an intersection* except that turns are performed by the ego-vehicle. Same dependencies occur: either the vehicle-type has to be known or a manually driven vehicle as a worst case is assumed to provide a sufficient safety distance. When steering is applied the vehicle requires more area than its vehicle width. In case of turning left/ right the vehicle covers a tractrix curve. The examination of tractrix curves are also used for construction purposes of road networks[91] and have a large impact on the construction regulations of today's car parks. If the vehicle drives a circular path with a constant wheel angle, all points move around the center of a circle. The extension of the rear axle is perpendicular to the longitudinal vehicle axle and goes through the center of rotation (CR). The allowed steering angles depend on the vehicle type and its geometry. Considering the two track vehicle model and the Ackermann condition, then the track width has to be taken into account which leads to a difference between the inner and outer steering angle. Thereby, the inner wheel has a larger steering angle than the outer wheel which results in an inner radius and a larger outer radius. The covered area can be determined easily with the help of the Pythagorean theorem. The inner rear wheel point and the outer front vehicle body point determine the corresponding tractrix curves. The tractrix curves create the inner and outer limits of the travelled envelope. The relevant vehicle points forming the travelled envelopes are different for left and right turning. The calculation of the envelope is based on a rectangular bounding box which is sufficient for worst case inspection. However, trailers are not taken into account. Figure 6–5 demonstrates the determination of the tractrix curves and the bending of the ego-vehicle's stopping envelope. Beside the ego-vehicle's stopping envelope, neighboring stopping envelopes are bent and therefore partially shifted towards the rear axle.

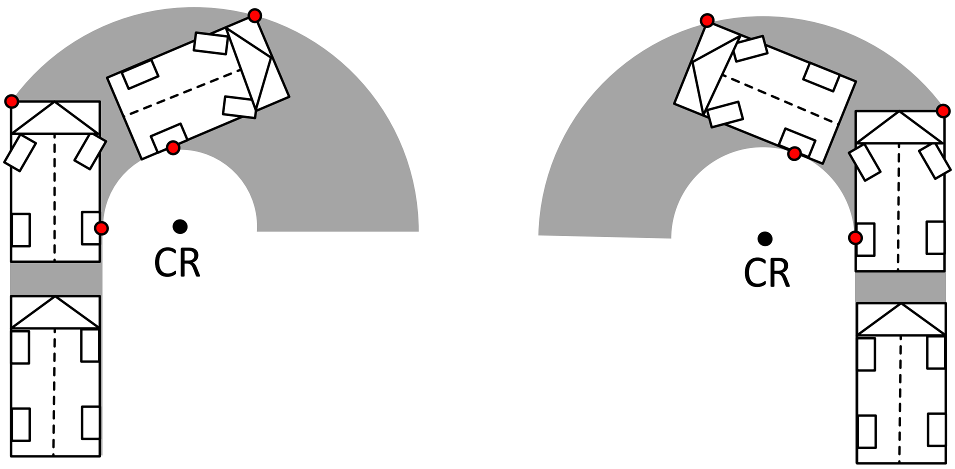


Figure 6–5: Determination of tractrix curves which create the vehicle's travelled envelope for a right and left turn (left, right). The inner rear wheel points and the outer front vehicle body points form the inner and outer limits of the envelope.

---

[91] Forschungsgesellschaft für Straßen- und Verkehrswesen e. V.: Richtlinien für die Anlage von Straßen, Abschnitt Knotenpunkte (RAS-K-1) (1988).

The ego-vehicle might be overtaken by an object-vehicle in the parking garage. If the ego-vehicle indicates a turning left or right during the overtaking process, it needs to detect the object-vehicle to the rear to prevent the potential collision. Thereby, the minimum required stopping distance of the object-vehicle $d_{\mathrm{req,obj}}$ is considered as worst-case. When the ego-vehicle is steering, $d_{\mathrm{req,obj}}$ is shifted towards the rear axle. The bending is shown in Figure 6–7.

Overall perception zone

The superposition of the derived maneuver-based stopping distances shows that the overall MRP zone is created by the ego-vehicle's and the object's travelled envelopes given by their widths w_{V} and stopping distances $d_{\mathrm{req,ego}}$, $d_{\mathrm{req,obj}}$. A radius with the object's stopping distance $d_{\mathrm{req,obj}}$ can be spanned around the collision crossing point to the front and to the rear. Furthermore, the ego-vehicle's stopping envelope $w_{\mathrm{V,ego}} \cdot d_{\mathrm{req,ego}}$ has to be added when following a straight lane or driving backwards. Once the object is oriented in a 90° angle to the ego-vehicle such as at intersections, only the object's stopping envelope $w_{\mathrm{V,obj}} \cdot d_{\mathrm{req,obj}}$ has to be considered. As a result, the MRP zone is given by the ego-vehicle and the object's travelled envelope as shown in Figure 6–6. The main equation and overall maneuver specific constraints are listed in Table 6–2.

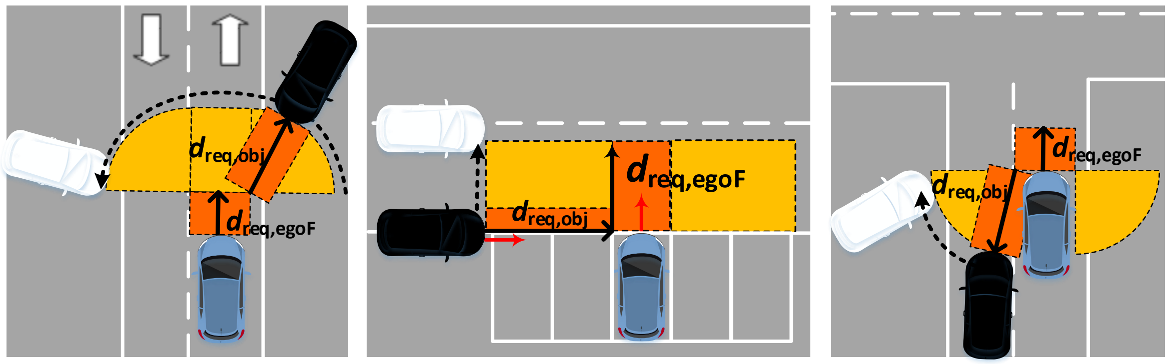


Figure 6–6: Minimum required perception (MRP) zone to the front given by the superposition of the ego-vehicle's and object's travelled worst case stopping envelopes. The object's stopping envelope is moved around the ego-vehicle's stropping envelope boundary when driving on a straight lane (left) or when crossing an intersection (middle). A potential overtaking has to be detected just before the ego-vehicle indicates a left or right turn to avoid a collision (right). The minimum required safety (MRS) zone (red) considers the critical objects in the vicinity of the ego-vehicle and adapts the required stopping envelopes according the present velocities.

Table 6–2: Main equation for the required stopping distance and maneuver-specific constraints for determining the minimum required safety zone

Main Equation	
$d_{\mathrm{req}} \geq (v_{\mathrm{ego}} + v_{\mathrm{obj}}) \cdot (\tau_{\mathrm{B,lag}} + \tau_{\mathrm{R}}) + v_{\mathrm{obj}} \cdot \tau_x + \frac{v_{\mathrm{ego}}^2 + v_{\mathrm{obj}}^2}{2 \cdot D_0} + d_{\mathrm{tol}}$	
Maneuvers	**Safety Zone**
Following a straight or curved lane & Driving backwards	$\tau_{\mathrm{R}} = \tau_{\mathrm{R,ad}}$ **Obj moving towards ego, both braking:** $\tau_x = \tau_{\mathrm{R,obj}} - \tau_{\mathrm{R,ad}}$ **Obj moving towards ego, only ego braking:** $\frac{v_{\mathrm{obj}}^2}{2 \cdot D_0} = 0, \tau_x = \frac{v_{\mathrm{ego}}}{D_0}$ **Obj neither moving away nor moving towards ego:** $v_{\mathrm{obj}} = 0$
Crossing an intersection	$\tau_x = 0$ $v_{\mathrm{ego}} = 0$ $\tau_{\mathrm{R}} = \tau_{\mathrm{R,obj}}$

The area of the overall MRP zone A_{MRP} consists of the MRP zone in forward direction $A_{\mathrm{MRP,F}}$ and in reverse direction $A_{\mathrm{MRP,R}}$. This is formulized by

$$A_{\mathrm{MRP}} := \{A_{\mathrm{MRP,F}}, A_{\mathrm{MRP,R}}\} \tag{6–3}$$

The area of the forward MRP zone $A_{\mathrm{MRP,F}}$ consists of perception areas covered in the maneuvers *following a straight or curved lane* (A_{M1}), *crossing an intersection* (A_{M3}) and *turning left/ right* (A_{M4})

$$A_{\mathrm{MRP,F}} := \{A_{\mathrm{M1}}, A_{\mathrm{M3}}, A_{\mathrm{M4}}\} \tag{6–4}$$

A mathematical description of the covered areas $A_{\mathrm{M1}}, A_{\mathrm{M3}}, A_{\mathrm{M4}}$ for each maneuver is given by placing the origin of the coordinate system in the center of the ego-vehicle's bounding box. Figure 6–7 shows the formed MRP zone when driving straight and the corresponding bending in case of turning. Table 6–3 provides the mathematical description of the forward MRP zone $A_{\mathrm{MRP,F}}$ without bending.

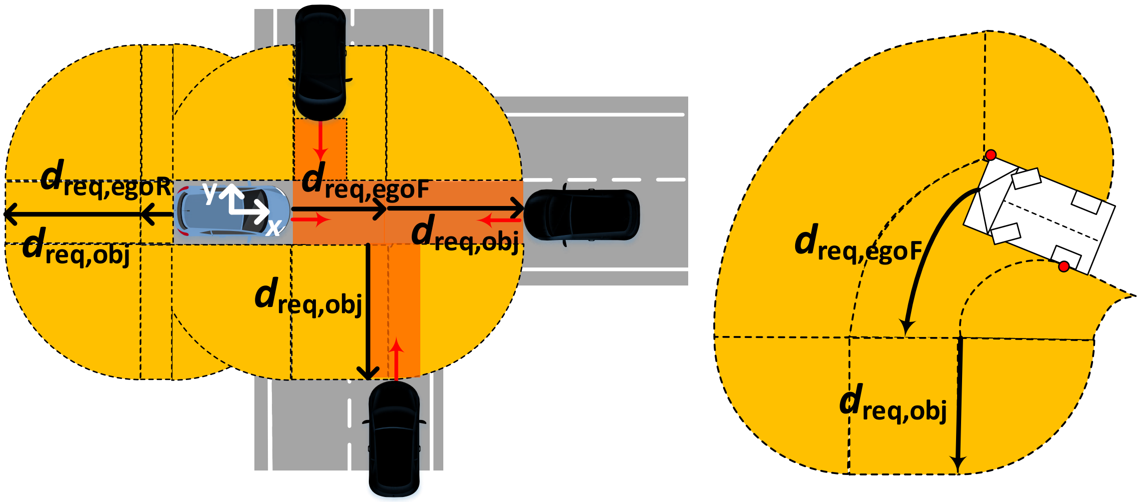
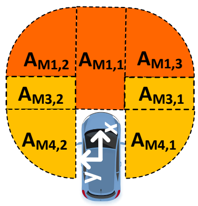
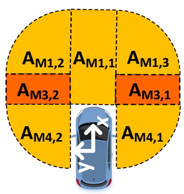
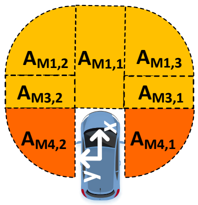


Figure 6–7: Overall minimum required perception (MRP) zone (yellow) to the front and to the rear given by the superposition of the ego-vehicle's and object's travelled worst case stopping envelopes (left). The MRP zone is bent dependent on the steering angle of the inner and outer wheel (right). The minimum required safety (MRS) zone (red) considers the critical objects around the ego-vehicle and adapts the required stopping envelopes according the present velocities. The origin of the coordinate system is placed in the center of the bounding box to give a mathematical description of the forward MRP zone $A_{\text{MRP,F}}$.

Table 6–3: Mathematical description of the forward MRP zone $A_{\text{MRP,F}}$ without bending consisting of perception areas covered in the maneuvers *following a straight or curved lane* (A_{M1}), *crossing an intersection* (A_{M3}) and *turning left/ right* (A_{M4}).

Covered Area	Maneuver
$A_{\text{M1}} := \{A_{\text{M1,1}}, A_{\text{M1,2}}, A_{\text{M1,3}}\}$ $A_{\text{M1,1}} := \left\{(x,y) \in \mathbb{R}^2 : \begin{array}{c} \frac{\ell_{\text{V}}}{2} \leq x \leq \frac{\ell_{\text{V}}}{2} + d_{\text{req,ego}} + d_{\text{req,obj}} + d_{\text{tol}}, \\ -\frac{w_V}{2} \leq y \leq \frac{w_V}{2} \end{array}\right\}$ $A_{\text{M1,2}} := \left\{(x,y) \in \mathbb{R}^2 : \begin{array}{c} \frac{\ell_{\text{V}}}{2} + d_{\text{req,ego}} \leq x \leq \frac{\ell_{\text{V}}}{2} + d_{\text{req,ego}} + d_{\text{req,obj}} + d_{\text{tol}}, \\ \frac{w_V}{2} < y \leq \frac{w_V}{2} + \sqrt{\left(d_{\text{req,obj}} + d_{\text{tol}}\right)^2 - \left(x - \frac{\ell_{\text{V}}}{2} - d_{\text{req,ego}}\right)^2} \end{array}\right\}$ $A_{\text{M1,3}} := \left\{(x,y) \in \mathbb{R}^2 : \begin{array}{c} \frac{\ell_{\text{V}}}{2} + d_{\text{req,ego}} \leq x \leq \frac{\ell_{\text{V}}}{2} + d_{\text{req,ego}} + d_{\text{req,obj}} + d_{\text{tol}}, \\ -\frac{w_V}{2} - \sqrt{\left(d_{\text{req,obj}} + d_{\text{tol}}\right)^2 - \left(x - \frac{\ell_{\text{V}}}{2} - d_{\text{req,ego}}\right)^2} \leq y < -\frac{w_V}{2} \end{array}\right\}$	*M1: Following a straight or curved lane* 
$A_{\text{M3}} := \{A_{\text{M3,1}}, A_{\text{M3,2}}\}$ $A_{\text{M3,1}} := \left\{(x,y) \in \mathbb{R}^2 : \begin{array}{c} \frac{\ell_{\text{V}}}{2} \leq x \leq \frac{\ell_{\text{V}}}{2} + d_{\text{req,ego}}, \\ -\frac{w_V}{2} - d_{\text{req,obj}} - d_{\text{tol}} \leq y < -\frac{w_V}{2} \end{array}\right\}$ $A_{\text{M3,2}} := \left\{(x,y) \in \mathbb{R}^2 : \begin{array}{c} \frac{\ell_{\text{V}}}{2} \leq x \leq \frac{\ell_{\text{V}}}{2} + d_{\text{req,ego}}, \\ \frac{w_V}{2} < y \leq \frac{w_V}{2} + d_{\text{req,obj}} + d_{\text{tol}} \end{array}\right\}$	*M3. Crossing an intersection* 

Covered Area	Maneuver
$A_{\mathrm{M4}} := \{A_{\mathrm{M4,1}}, A_{\mathrm{M4,2}}\}$ $A_{\mathrm{M4,1}} := \left\{ (x,y) \in \mathbb{R}^2 \colon \begin{array}{c} \frac{\ell_{\mathrm{V}}}{2} - d_{\mathrm{req,obj}} - d_{\mathrm{tol}} \leq x \leq \frac{\ell_{\mathrm{V}}}{2}, \\ -\frac{w_V}{2} - \sqrt{\left(d_{\mathrm{req,obj}} + d_{\mathrm{tol}}\right)^2 - \left(x - \frac{\ell_{\mathrm{V}}}{2}\right)^2} \leq y < -\frac{w_V}{2} \end{array} \right\}$ $A_{\mathrm{M4,2}} := \left\{ (x,y) \in \mathbb{R}^2 \colon \begin{array}{c} \frac{\ell_{\mathrm{V}}}{2} - d_{\mathrm{req,obj}} - d_{\mathrm{tol}} \leq x \leq \frac{\ell_{\mathrm{V}}}{2}, \\ \frac{w_V}{2} < y \leq \frac{w_V}{2} + \sqrt{\left(d_{\mathrm{req,obj}} + d_{\mathrm{tol}}\right)^2 - \left(x - \frac{\ell_{\mathrm{V}}}{2}\right)^2} \end{array} \right\}$	*M4. Turning left/ right* 

Occlusion

Occlusion of the ego-vehicle's sensor view may be present in one of the upper defined maneuvers. This may occur when the vehicle traverses walls, ramps or parked vehicles and cannot perceive safety-relevant areas due to occlusion. The system has to manage potential collisions for each of the upper described maneuvers even if the collision partner is occluded for the ego-vehicle. The issue can only be solved by one of the two options: reducing the allowed velocities in the parking garage or receiving support from the infrastructure. Velocity reduction results in decreased stopping distances and a shrinkage of the MRP zone. However, such a reduction in velocity decreases time-efficiency of the AVP function. Infrastructure may support the automated vehicle with infrastructure sensors (e.g. top/sideways-mounted) which will not be occluded by traffic participants or by parking construction. Hereby, the required information from safety areas have to be transmitted to the ego-vehicle. The occluded area for the ego-vehicle has to be perceived by the infrastructure sensors and has to replace the ego-vehicle's sensor view.

The case of driving on a ramp requires the system to distinguish whether a detected object is a ramp. Here, similar safety distances as described for *following a straight or curved lane* have to be considered just that the deceleration depends on the slope α of the ramp

$$D_{\mathrm{res}} = D_0 \mp g \cdot \sin\alpha \tag{6–5}$$

These safety distances can be provided by the infrastructure system as shown in Figure 6–8. The case of driving towards a ramp demonstrates that occlusion of the ego-vehicle's view is unavoidable and that the vertical dimension is similarly safety-relevant. The MRP and MRS zone requires to cover a three-dimensional space/ volume for collision avoidance.

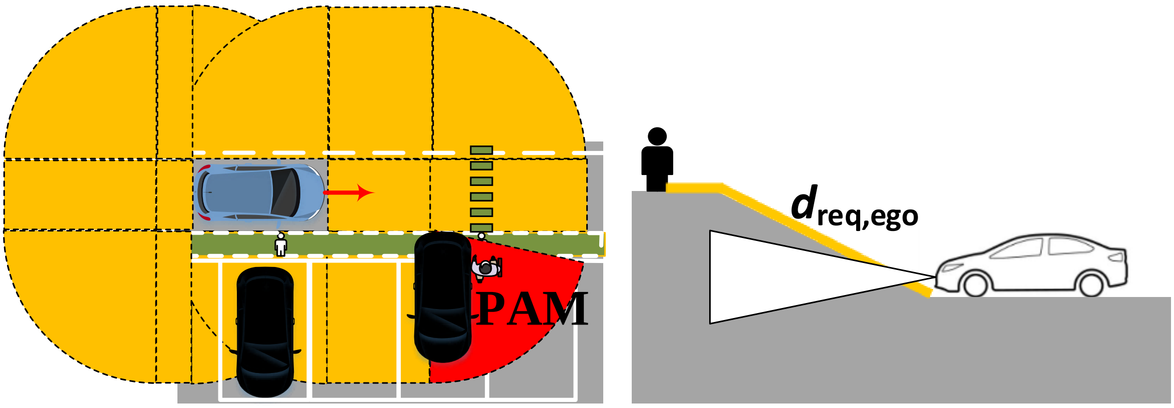


Figure 6–8: Covered perception area at an intersection (left). Relevant object which is not in the ego-vehicle's sensor view when driving towards a ramp (right)

6.3 Reduction of Perception Requirements

A maximum spanned MRP zone valid for all maneuvers inside all parking garages is a sufficient condition, but not a necessary condition for a specific parking garage. As stated, the MRP zone is seen maneuver-dependent and therefore its necessity depends on the allowed maneuvers and type of objects inside the individual parking garage. If specific maneuvers or specific traffic participants are not allowed in the parking garage, then a maximum spanned MRP zone can be reduced and required perception requirements can be adjusted. The reduction of perception requirements can be used in the safety design phase of the AVP system to save unnecessary costs and time effort. The reduction of the MRP zone is possible for automated traffic only or for mixed traffic.

6.3.1 Automated Traffic Only

A parking garage could be divided into two separate blocks or simply ban manually driven vehicles. In the case of two separate blocks, the first block is assigned to automated vehicles only. Manually driven vehicles or pedestrians from the second block are forbidden to enter the automated block. Hence, in the first block automated vehicles can be considered as the worst case. Expected worst-case reaction times are decreased due to the allowance of automated traffic only. The stopping distance reduction due to automated traffic only is shown in Figure 6–9 as well as in Figure 6–10 and is given by the ratio between the stopping distance of manually driven and automated vehicles

$$1-\frac{d_{\mathrm{req,ad}}(v_{\mathrm{obj,ad}}=v)}{d_{\mathrm{req,md}}(v_{\mathrm{obj,md}}=v)}=1-\frac{\left(\tau_{\mathrm{B,lag}}+\tau_{\mathrm{R,ad}}\right)+\frac{v}{2\cdot D_0}}{\left(\tau_{\mathrm{B,lag}}+\tau_{\mathrm{R,md}}\right)+\frac{v}{2\cdot D_0}} \tag{6–6}$$

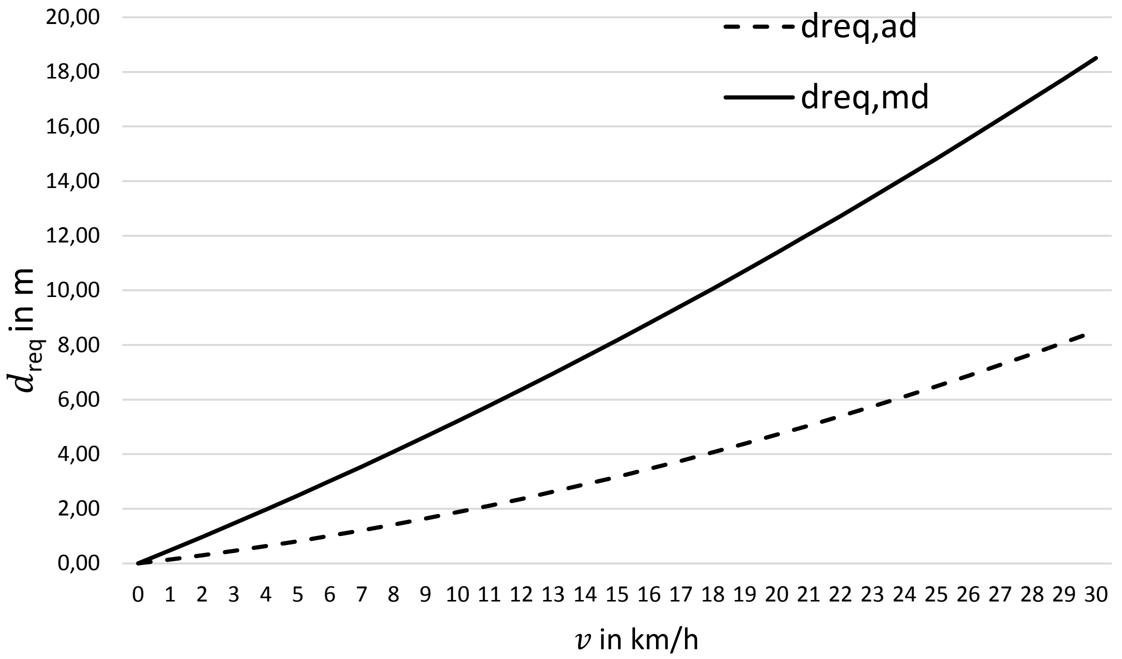


Figure 6–9: Plotted stopping distance for a manually driven and automated vehicle against increasing velocity. A reduction in stopping distance is achieved due to a lower response time. Worst-case constraints such as $\tau_{\mathrm{B,lag}} = 0.2$ s, $\tau_{\mathrm{R,ad}} = 0.3$ s, $\tau_{\mathrm{R,md}} = 1.5$ s as defined in Table 6–1 are considered. The reduction in percentage is shown in Figure 6–10.

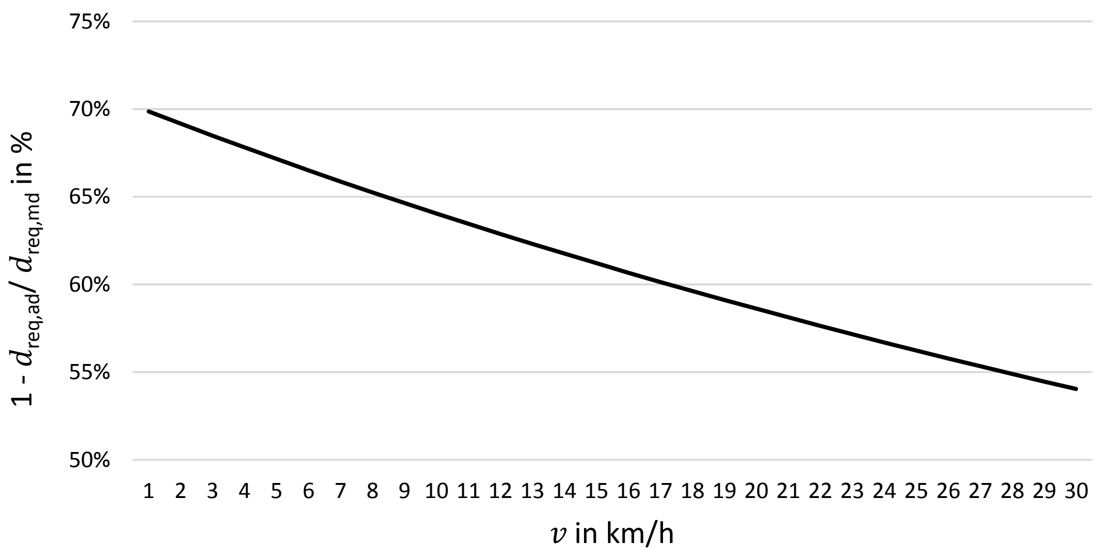


Figure 6–10: Plotted reduction in stopping distance due to automated traffic in comparison to mixed traffic against increasing velocity $v = v_{\mathrm{obj,ad}} = v_{\mathrm{obj,md}}$ in the parking garage. The decrease in stopping distance is accomplished by having shorter response times. The reduction is given by the ratio between the stopping distance of a manually driven and automated vehicle as indicated in equation (6–9). Worst-case constraints $\tau_{\mathrm{B,lag}} = 0.2$ s, $\tau_{\mathrm{R,ad}} = 0.3$ s and $\tau_{\mathrm{R,md}} = 1.5$ s as defined in Table 6–1 are considered. The plot shows that a reduction potential of over 50% can be achieved in the operational velocity range of AVP by introducing automated traffic only.

Additionally, there are possibilities to adjust perception requirements by restricting the types of executable maneuvers for automated vehicles which will be investigated in the following:

- *One-way traffic:* Two-way traffic may be prevented inside the parking garage and only one-way traffic can be established. As a result, the required perception range to the front can be reduced since automated vehicles are only expected to move towards the ego-vehicle when maneuvering into or out of the parking spot (maneuvering speed $v_{\mathrm{man}} = 10\ \mathrm{km/h}$).
- *Lack of intersections:* If the parking garage does not contain any intersections, then side areas of the MRP zone can be reduced since no speeding vehicles are expected. Hence, vehicles at maneuvering velocities $v_{\mathrm{man}} = 10\ \mathrm{km/h}$) can be assumed. The need of side areas to the front when leaving the parking spot can be reduced by parking in forward direction. The leaving of the parking spot has to be executed in reverse direction. This is beneficial since the perception to the front can be reduced.
- *Ban of overtaking/ One-lane traffic:* One-lane traffic or a ban of overtaking may prohibit the overtaking of the ego-vehicle. As a result, rear areas can be decreased for a worst case of a maneuvering vehicle.

The reduction in stopping distance due to restriction of maneuvers leads to a decrease of expected velocities. The impact is shown in Figure 6–11 and is given by the ratio between the stopping distance of manually driven and automated vehicles

$$1 - \frac{d_{\mathrm{req,manAD}}(v_{\mathrm{obj,ad}} = v_{\mathrm{man}} = 10\ \mathrm{km/h})}{d_{\mathrm{req,md}}(v_{\mathrm{obj,md}} = v)} = 1 - \frac{v_{\mathrm{man}}\left(\tau_{\mathrm{B,lag}} + \tau_{\mathrm{R,ad}}\right) + \frac{v_{\mathrm{man}}^2}{2 \cdot D_0}}{v \cdot \left(\tau_{\mathrm{B,lag}} + \tau_{\mathrm{R,md}}\right) + \frac{v^2}{2 \cdot D_0}} \tag{6–7}$$

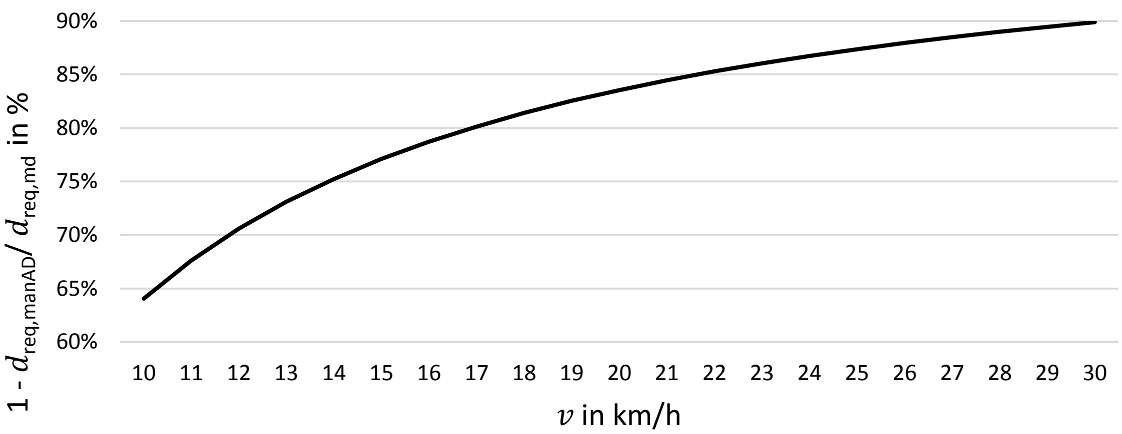


Figure 6–11: Plotted reduction in stopping distance in comparison to mixed traffic and no restrictions against increasing allowed velocity v in the parking garage. The reduction of the stopping distance is achieved by considering automated traffic and restricting maneuvers in the parking garage. The decrease in stopping distance is achieved by lower expected velocities. The reduction is given by the ratio between the stopping distance of a manually driven vehicle with increasing velocity and the stopping distance of an automated vehicle at fixed maneuvering velocity as indicated in equation (6–7). Worst-case constraints $\tau_{\mathrm{B,lag}} = 0.2$ s, $\tau_{\mathrm{R,ad}} = 0.3$ s and $\tau_{\mathrm{R,md}} = 1.5$ s as defined in Table 6–1 are considered. The plot demonstrates that a reduction in stopping distance of over 60% can be achieved by restricting allowed maneuvers inside the parking garage.

The reduction in stopping distance decreases the areas of the MRP zone. Figure 6–12 visualizes the reduction of the MRP zone for automated driving traffic (decrease of response time) and the restriction of executable maneuvers (decrease of expected velocities) in comparison to mixed traffic and no restrictions. The reduction in stopping distances allows to decrease perception requirements for the individual parking garage. The necessary safety design can be configured for the specific parking garage by saving costs and efforts. Furthermore, parking garage operators can restrict constraints in the parking garage such to influence the required safety design and corresponding costs.

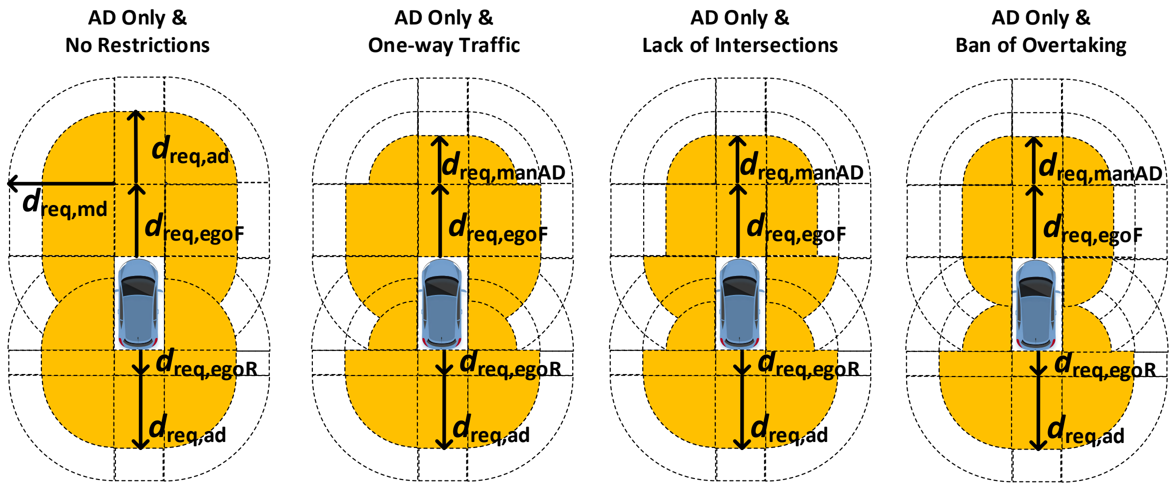


Figure 6–12: Reduction of the stopping distance due to the allowance of automated vehicles only (left), further decrease of the front perception area by considering one-way traffic (middle left), reduction of front side areas due to the lack of intersections in the parking garage (middle right) and further decrease of stopping distance due to a ban of overtaking (right).

However, there are possibilities to adjust perception requirements without losing mixed traffic in the parking garage, e.g. by only restricting executable maneuvers. In the following, these restrictions will be discussed in detail.

6.3.2 Mixed Traffic

The restriction of executable maneuvers can be adapted for a mixed traffic. However, the worst-case reaction time has to be taken into account.

- *One-way traffic:* In case of one-way traffic, oncoming manually driven vehicles do not have to be considered. As a result, the required perception range to the front can be reduced by considering a worst case of a running child[92] or a manually driven vehicle during maneuvering ($v_{\text{run,child}} \approx v_{\text{man}} = 10\,\text{km/h}$) as a worst case. Adults and teenagers are assumed to be aware of the parking garage circumstances.
- *Lack of intersections:* If the parking garage does not contain any intersections, then side areas of the MRP zone can be reduced since no speeding vehicles are expected.

[92] Ahlgrimm, J. et al.: A10 Fußgängerunfälle (2017). p. 421.

As a result, only the occurrence of running children or manually driven vehicles which are leaving the parking spot needs to be taken into account. It is assumed that the vehicle velocity for leaving the parking space is around the worst-case velocity of a running child ($v_{\mathrm{run,child}} \approx 3\ \mathrm{m/s}$).

- *Ban of overtaking/ One-lane traffic:* One-lane traffic or a ban of overtaking may prohibit the overtaking of the ego-vehicle. Corresponding perception areas can be decreased by considering the worst case of a maneuvering vehicle.

The stopping distance is given by the ratio between the stopping distance of manually driven and a running child

$$1 - \frac{d_{\mathrm{req,manMD}}(v_{\mathrm{obj,md}} = v_{\mathrm{man}} = 10\ \mathrm{km/h})}{d_{\mathrm{req,md}}(v_{\mathrm{obj,md}} = v)} = 1 - \frac{v_{\mathrm{man}}\left(\tau_{\mathrm{B,lag}} + \tau_{\mathrm{R,md}}\right) + \frac{v_{\mathrm{man}}^2}{2 \cdot D_0}}{v \cdot \left(\tau_{\mathrm{B,lag}} + \tau_{\mathrm{R,md}}\right) + \frac{v^2}{2 \cdot D_0}} \tag{6–8}$$

Figure 6–13 shows the reduction in stopping distance according equation (6–8) for assumed constraints. A reduction is mainly present for higher allowed velocities in the parking garage.

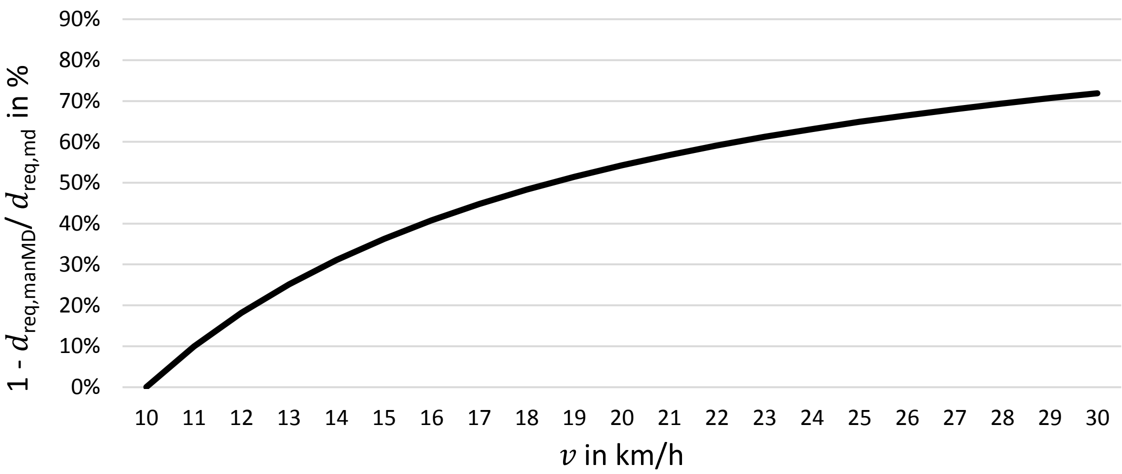


Figure 6–13: Plotted reduction in stopping distance against increasing velocity v in the parking garage. The decrease in stopping distance is achieved by considering mixed traffic and restriction of maneuvers (lower expected velocities). The reduction is given by the ratio between the stopping distance of a manually driven vehicle with increasing velocity and the stopping distance of a manually driven vehicle with fixed maneuvering velocity as indicated in equation(6–8). Worst-case constraints $\tau_{\mathrm{B,lag}} = 0.2$ s, $\tau_{\mathrm{R,ad}} = 0.3$ s and $\tau_{\mathrm{R,md}} = 1.5$ s as defined in Table 6–1 are considered. The plot indicates that reduction in stopping distance of below 70% can be achieved for allowed velocities up to 30 km/h in the parking garage.

The reduction in stopping distance decreases the areas of the MRP zone. Figure 6–14 demonstrates the reduction of the MRP zone for a mixed traffic and the restriction of executable maneuvers (decrease of expected velocities) in comparison to mixed traffic and no restrictions.

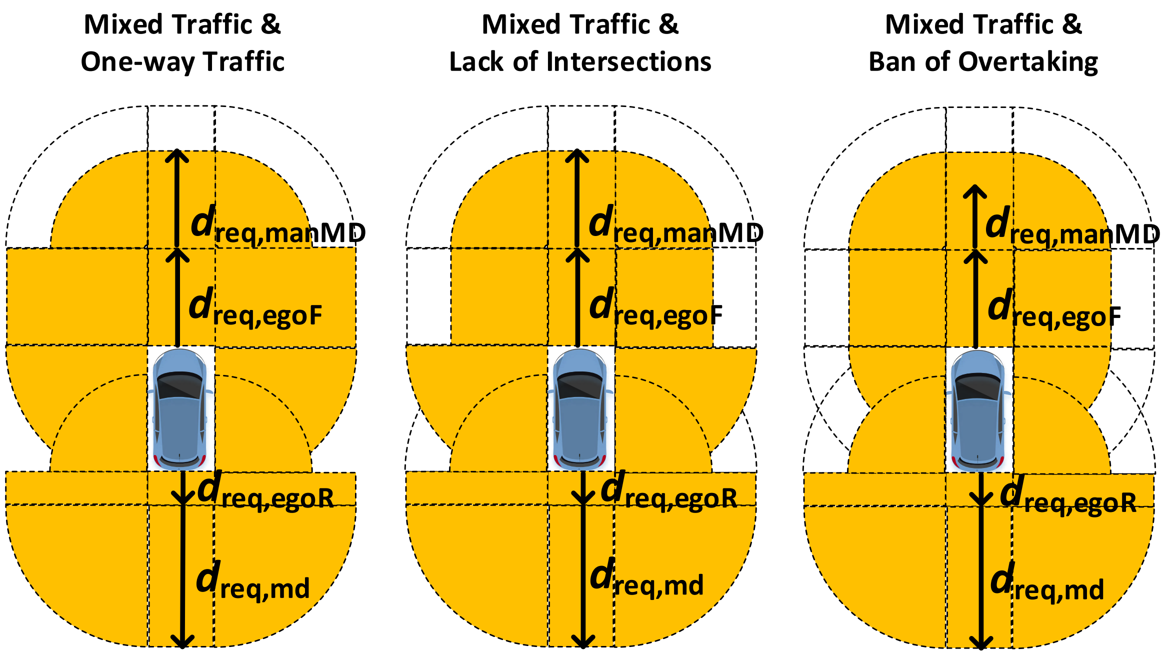


Figure 6–14: Reduction of the stopping distance due to the decrease of the front perception area by considering one-way traffic (left), reduction of front side areas due to the lack of intersections in the parking garage (middle) and further decrease of stopping distance due to a ban of overtaking (right).

6.4 Minimum Required Safety Zone

The overall MRP zone is built by the superposition of minimum required stopping envelopes of the ego and of the object vehicle. Minimum required stopping envelopes were defined for investigated maneuvers in the parking garage. The minimum required stopping distances were calculated by injecting worst case constraints into a main equation. An overlap of the minimum required stopping envelopes will lead to an unavoidable critical situation, e.g. the object vehicle does not receive the minimum required stopping distance. The point prior to an overlap of the ego vehicle's and of the object's minimum required stopping envelopes defines the last possible border for which a valet parking system has to brake. Therefore, the following minimum criterion serves for collision avoidance:

A potential collision occurs if minimum required stopping distances are not provided between the collision point and ego (distance $\overline{EC}$) or object (distance $\overline{OC}$). The collision point is categorized as the first overlapping point between the stopping envelopes. The local constraint to avoid a collision can be formulated as

$$\overline{EC} \leq d_{\text{req,ego}} \tag{6–9}$$

$$\overline{OC} \leq d_{\text{req,obj}} \tag{6–10}$$

The equations (6–5) and (6–7) serve as the trigger condition for the deceleration of the ego-vehicle. The constraints characterize the last possible threshold for which the deceleration has to be triggered for a valet parking system. The created area for the given time frame leads to the term: *minimum required safety (MRS) zone*. The MRS zone is a subset of the MRP zone and defines the border for deceleration. Figure 6–15 illustrates the trigger criteria and the relationship between MRP and MRS zone. The MRS zone cannot be defined as a necessary condition for collision avoidance due to its limitations as discussed in the following.

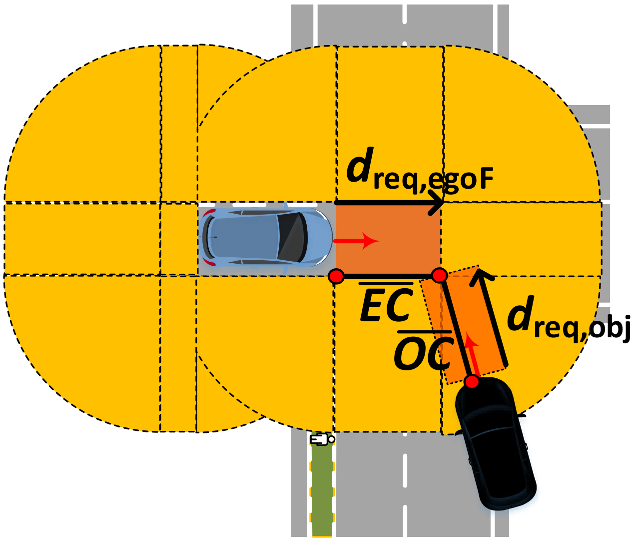


Figure 6–15: Trigger criteria for deceleration to avoid a collision. Perception zone (yellow) and safety zone (red) due to the fulfilling of the trigger criteria. The safety zone is a subset of the perception zone.

6.5 Limitations

The MRP zone provides a technology-independent and geometric representation of areas. A major benefit is therefore its validity for all AVP configurations. The description of the safety-relevant space is independent of the function distribution. Vehicle-based or infrastructure-supported valet parking systems require to perceive the space. Even if used technologies will change over time, the definition will be still valid. The developer has to decide which sensors he prefers to perceive all safety-relevant areas or which approach he applies.

However, the definition of the required perception zone has its limitations. This can be illustrated with the aid of the main equation. First of all, worst case constraints have to be known. This concerns the lag time of the brake $\tau_{B,lag}$, the corresponding reaction or response time τ_R and the minimum expected deceleration capability D_{min}. The minimum guaranteed deceleration $D_{min} = \mu_{min} \cdot g$ is given by the friction coefficient μ and gravity constant g. Thereby, the minimum available friction coefficient has to be known. This is commonly known for a closed environment such as a parking garage. However, the friction coefficient in a non-closed environment is heavily dependent on the weather conditions such as rain and snow as well as the used materials and surfaces. The decrease of the friction coefficient in other operational domains, increases the required perception and safety zones. An enlargement of the safety zone causes the automated driving system to trigger an early deceleration which might result in an increase of the false positive rate. A high false positive rate may hinder the application in other use cases. A solution for this issue could be to restrict the usage of the automated system for specific weather conditions or for specific surface materials.

Furthermore, the safety zone assumes a steady movement of objects. At each time step, it is assumed that the object is moving uniformly. Additional predictions are not targeted and require knowledge. More precisely, it is unknown what the object's intention is. The lack of knowledge about the object's upcoming maneuvers might trigger unnecessary deceleration as depicted in Figure 6–16. Unnecessary braking in the use case valet parking is less critical due to low speeds. Drivers have to provide a safe distance in case of an emergency braking. However, especially for drivers in manually driven vehicles unnecessary braking can be annoying. The application of the safety zone in other use cases such as a highway pilot causes more critical scenarios. A solution for the described issue is the provision of the object's planned moving behavior e.g. by transmitting the information via C2C. Relevant data could be the planned maneuver in case of an automated vehicle or the current steering angle and/or indicator state in case of a manually driven vehicle. At this point, it should be mentioned that the prediction of the object's moving intention is part of today's state-of-the-art.[93] However, motion prediction cannot guarantee collision-free maneuvers.

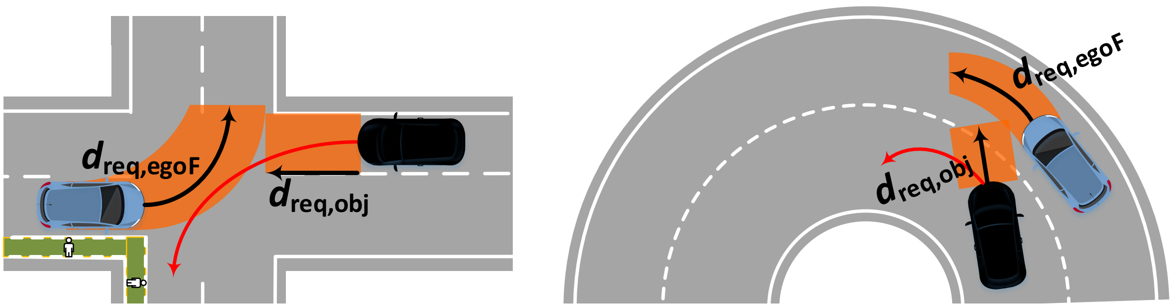


Figure 6–16: The object's predicted moving behavior and its actual intention might differ which causes unnecessary deceleration. Left: The ego and object vehicle's intention is to turn left, but the predicted moving behavior is driving straight. An overlap of the stopping envelopes causes the ego-vehicle to decelerate. Right: Driving on a curved straight line and expected straight formed stopping envelope of the object vehicle. The ego vehicle is triggered to brake due to the lack of knowledge about the object's actual intention.

In this chapter, two main contributions towards a definition of minimum criteria and safe AVP systems were proposed, namely the definition of a maneuver-based and technology-independent *minimum required perception (MRP)* and *minimum required safety (MRS)* zone. The MRP zone can be used for the design of the necessary sensor coverage for a maneuver-specific parking garage. Parking garages and automated vehicles can be equipped with the necessary sensor coverage by saving costs through necessity. As one part of the minimum

[93] Lefèvre, S. et al.: A survey on motion prediction and risk assessment for intelligent vehicles (2014).

criteria, the MRP zone can be integrated in the early safety design phase to minimize potential harm. Parking garage operators may restrict constraints such as executable maneuvers, types of vehicles or velocities to integrate the necessary safety design. Furthermore, the MRP zone defines the currently acceptable velocities for collision avoidance and can be used to identify safety critical and time-inefficient spots such as ramps or occlusions in the parking garage. The safety critical spots can be equipped with infrastructure sensors to increase safety and time-efficiency. The MRS zone can be used for collision avoidance by considering the boundary of the deceleration triggering. While this chapter introduced MRP and MRS zones based on a mathematical and geometrical concept, the following chapter presents a proof of concept implementation in a simulated parking facility.

7 Implementation

Virtual driving simulations provide means for rapid prototyping and evaluation of software for AVP prior and in parallel to physical deployment. The implementation of the elaborated minimum required safety (MRS) zone serves hereby a proof of concept for the mathematical and geometric models introduced in chapter 6. This chapter describes the implementation and test setup and presents the simulation framework, standardized interfaces and synchronization tools in detail to demonstrate the interconnection of the components. The MRS zone was implemented in a driving simulation tool chain called Virtual Test Drive[94] (VTD). The MRS zone module was implemented in C++ and outputs a deceleration signal which serves as an input for Virtual Test Drive to avoid collisions in a virtual environment. The automated vehicle follows a predefined trajectory in a simulated parking garage and reacts to its surrounding by keeping required stopping distances and by decelerating the vehicle in case of an upcoming collision. Standardized interfaces are used to enable plug-in characteristics. Standardized interfaces such as the Open Simulation Interface or the Functional Mock-up interfaces ease the functional development when using different simulation platforms and distributed components. In the following, the test setup and its subsystems are explained in detail.

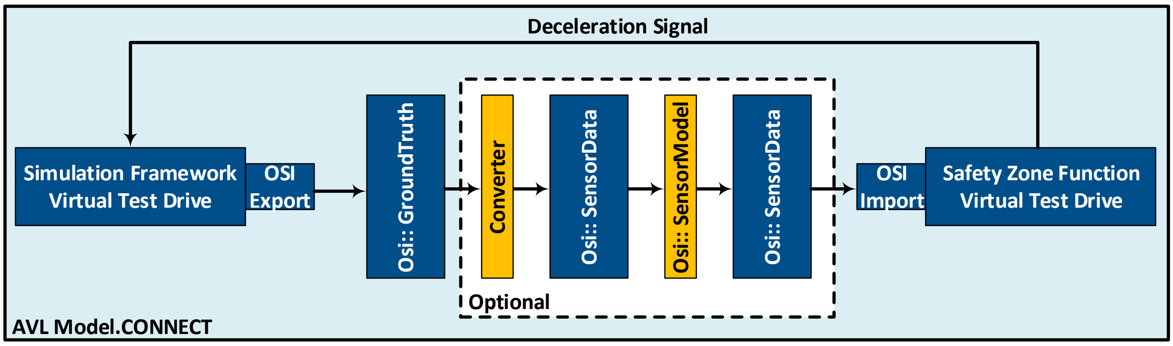


Figure 7–1: The simulation framework Virtual Test Drive (VTD) supports the generic interface for sensor-based environment perception called Open Simulation Interface (OSI). Ground truth data such as the object's pose, dimensions and velocities are forwarded into the safety zone function. In case of a triggering event a deceleration signal is fed into the simulation framework for collision avoidance. Optionally, a sensor model can be plugged in between to simulate a more realistic behavior.

7.1 Virtual Test Drive

Virtual Test Drive (VTD) is a simulation framework which provides a complete tool chain for road generation, scenario definition and image generation. VTD is a modular framework which provides a virtual environment for the automotive industry. The system is divided in

[94] Dupuis, M.: Virtual Test Drive User Manual (2017).

three categories: core components for the standard setups, optional add-ons and additional tools. The driving simulator is a linux-based system with the following core components:

- *SimServer*: A simulation server and a parameter server manage the corresponding VTD processes and configuration parameters. The simulation server reads an Extensible Markup Language (XML)-based process which contains all relevant entries and the instructions for the individual components. The user can specify additional processes that should run on the host.
- *Vtgui*: The graphical user interface (GUI) enables the creation, loading and saving of projects, the start/ stop functions and projects the status of the VTD tasks.
- *Image Generator*: The image generator displays the 3D scenery and the corresponding video data. The real-time processing of the image generator depends on several factors such as the CPU performance, the graphics card and the complexity of the designed scenario. Different weather conditions such as rain, sunlight or fog can be visualized according the selected conditions in the GUI.
- *ModuleManager*: The module manager runs sensor, dynamics and custom plug-ins. Sensor plugins are filtering the simulated environment. Filtered data can be used to apply algorithms for active safety systems. Each sensor can be configured separately. A perfect sensor model provides the ground truth data of the environment within the defined sensor range. The dynamic plugins are simulating the vehicle's dynamics behavior. The vehicle dynamics are based on a single track module, but a two track model can be selected as well.
- *TaskControl*: The task control Unit manages the main instruction and data flow. The module communicates via various protocols to provide interfaces for components. The control unit manages the timing correctness of input and output data. Two interfaces are thereby used: A Simulation Control Protocol (SCP) for the exchange of instructions between simulation and the outside world as well as a Runtime Data Bus (RDB) which distributes run-time data of simulation objects to any data receiver. SCP allows the transmission of actions and events to other objects whereas RDB provides relevant information for other components.
- *Scenario Editor*: The scenario editor allows to configure traffic and test scenarios. Vehicles and pedestrians and their moving behavior can be set as desired. Additionally, it is possible to select between several vehicle models and pedestrian types. For both object types a specific path can be arranged which will be followed with a defined velocity. The content is saved in a XML-based scenario description which contains the settings for vehicles, drivers, pedestrians and the visual database.
- *Road Designer*: The integrated road designer is an interactive editor for creating road networks with an extensive library of 3D objects. Visual and logical road networks can be created based on a large database. The database allows to select between various tiles and to create a parking garage according the user's preference. The logical

description of road networks is based on an open file format called OpenDrive. OpenDrive[95] is vendor-independent, internationally well-known standard since 2006 and contains all key feature of the real road networks. Geometries and features are described in a XML-based file format. The format is organized in nodes and enables the compatibility with different applications.

Figure 7–2 illustrates the overview of the VTD components with the central task and data control unit which manages the data flow via interfaces to enable the driving simulator's key capabilities.

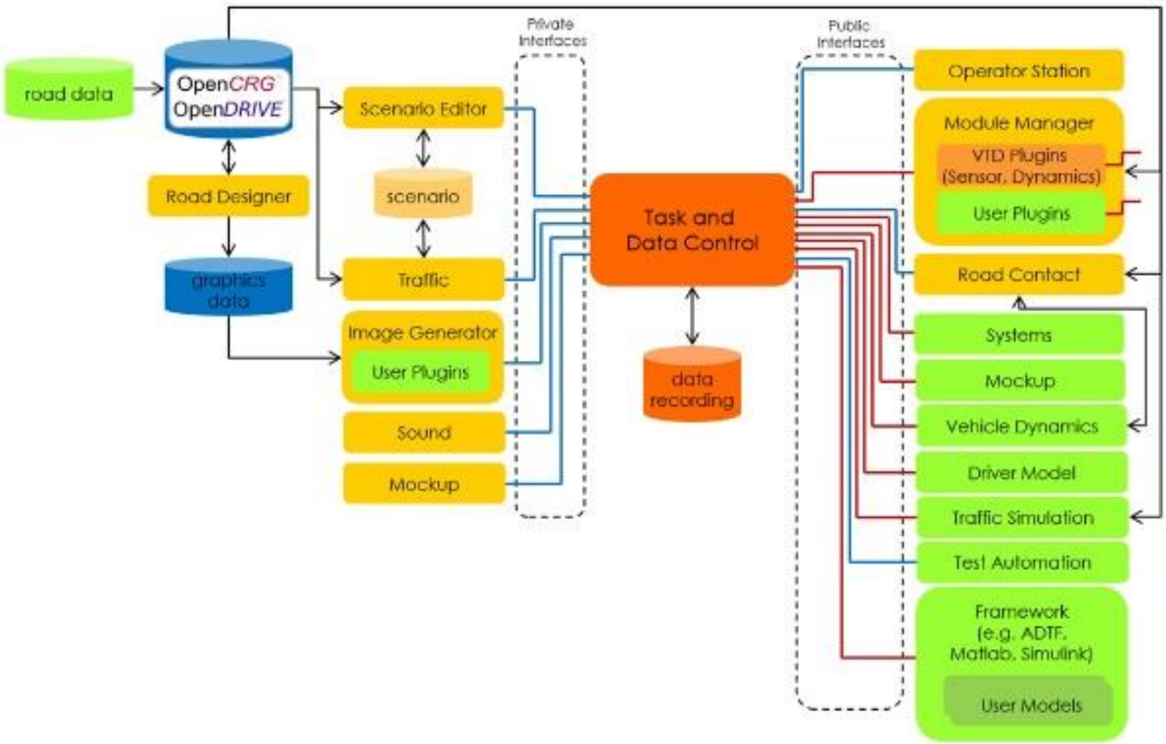


Figure 7–2: Virtual Test Drive developed by VIRES[96] provides a simulation environment of automated driving scenarios which allows rapid prototyping and in depth testing of software components. Virtual Test Drive components are managed by a task and data control unit which ensures interfaces for other modules such as an image generator or a module manager

7.2 Open Simulation Interface

A generic interface ease the connection between the function development framework and the simulation environment. The Open Simulation Interface (OSI) enables the compatibility between automated driving functions and different driving simulation frameworks. It simplifies the integration of virtual testing and the interchangeability of individual components

[95] Dupuis, M. et al.: OpenDRIVE Format Specification Rev. 1.5 (2019).

[96] Dupuis, M.: Virtual Test Drive User Manual (2017). p. 29

such as sensor models. The OSI is a data structure which describes the object-based environment perception. It contains two major data structures: *GroundTruth* and *SensorData* interface. The *GroundTruth* interface provides the ideal and non-faulty description of objects in a global coordinate system. It is the object output of the simulation framework. The *GroundTruth* structure provides information such as environment conditions, traffic signs, road markings or the object's state variables (pose, dimension, velocity). The *SensorData* interface can either be used to forward ideal sensor data or non-ideal and limited simulated data in a sensor coordinate system as a representation for real world sensor behavior. It includes the sensor output with its uncertainties. Since OSI 3.0.0, two additional interfaces have been integrated: *FeatureData* and *SensorViewConfiguration*. *FeatureData* lists a set of simple features in a sensor coordinate system to simulate object detection or feature fusion. *SensorViewConfiguration* allows the user to configure the sensor view that should be provided by the environment simulation. It specifies the input configuration that is desired by the sensor model.

7.3 Model.CONNECT

An integration platform is required to tackle the issue of simulation models which are composed of multiple component models. Model.CONNECT[97] is a tool for interlinking simulation models into one virtual prototype. Thereby, the models use a standardized interface called Functional Mockup Interface (FMI). The virtual prototype is assembled from multiple models. The FMI standard allows to develop systems which consist of a combination of models from internal or external partners and which are designed by using different modelling tools. The intention is to enable the coupling of simulation tools via an interface standard. A master controls the data exchange and synchronization between subsystems (slaves). It is a tool-independent standard that supports model exchange and co-simulation. The tool supports more than 20 different simulation tools such as Virtual Test Drive, IPG, MATLAB, Simulink and others. It eases the connection of models from different domains and applications and provides the synchronization for distributed systems. In the context of the implementation Model.CONNECT is used to synchronize the components and monitor their input and output signals.

7.4 Minimum Required Safety Zone

The MRS zone function receives ground truth data from the simulation framework in the open simulation interface format. The function extracts all relevant state parameters of its

[97] AVL List GmbH: Model.CONNECT Overview (2019).

surrounding such as the ego's and the object's pose, its velocity and its dimensions. The ego vehicle's state variable's and worst case timing constraints are injected into the formula

$$d_{\mathrm{req,ego}} \geq v_{\mathrm{ego}} \cdot \left(\mathrm{t}_{\mathrm{B,lag}} + t_{\mathrm{R,ad}}\right) + \frac{v_{\mathrm{ego}}^2}{2 \cdot D_{\mathrm{min}}} + d_{\mathrm{tol}} \tag{7–1}$$

to calculate the ego vehicle's required stopping distance. Thereafter, a bounding box around the vehicle is created by using the C++ boost library for planar boxes and polygon geometry data. The bounding box can be extended by the length of the ego-vehicle's stopping envelope. Similarly, the object-vehicle's stopping distance $d_{\mathrm{req,obj}}$ is calculated by considering the worst case for the object stopping distance of both vehicles moving towards each other and both are braking given by

$$d_{\mathrm{req,obj}} \geq v_{\mathrm{obj}} \cdot \left(\mathrm{t}_{\mathrm{B,lag}} + t_{\mathrm{R,obj}}\right) + \frac{v_{\mathrm{obj}}^2}{2 \cdot D_{\mathrm{min}}} + d_{\mathrm{tol}} \tag{7–2}$$

A bounding box around the object is spanned and extended by its stopping envelope. The boost library provides functions to identify an intersection of created geometries. As a result, an overlap of stopping envelopes between ego- and object-vehicle can be detected. The deceleration of the ego-vehicle is triggered once an overlap takes place. Figure 7–3 demonstrates the bounding boxes and their extensions.

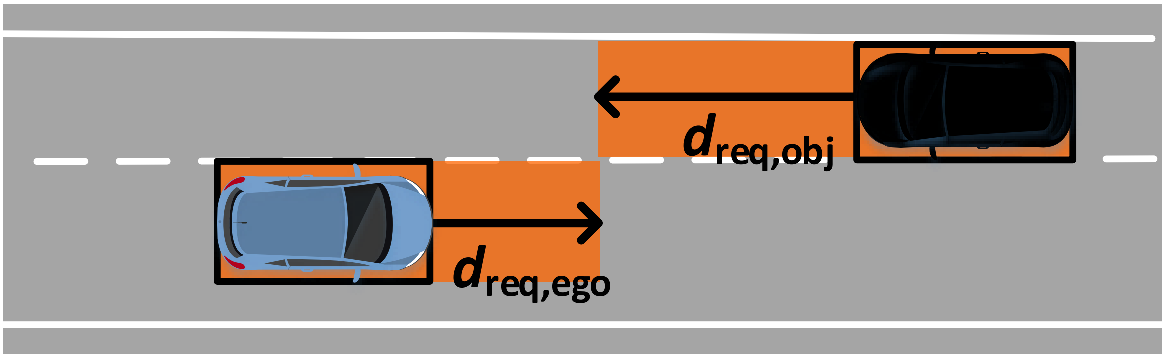


Figure 7–3: A bounding box around the ego- and the object-vehicle is spanned and extended by its stopping envelope. An overlap of stopping envelopes is detected to trigger a deceleration of the ego-vehicle and avoid collisions.

7.5 Test Scenarios

The implementation was tested for the maneuvers *following a straight lane, intersection crossing* and *turning left/right* which will be described in the following. Ego- and object-vehicle are represented by their bounding boxes and stopping envelopes. Figure 7–4 shows two object vehicles approaching the ego-vehicle. The left figure displays the 3D scenery and the corresponding video data of the image generator. The middle figures demonstrate the top view in the scenario editor with the traffic participants in a parking garage scenario. The right figures provide the visualization of bounding boxes and corresponding stopping envelopes in a top view. The upper figures indicate the triggering event whereas the lower figures present the situation chronological after the triggering event. Thereby, the ego-vehicle is following a straight lane while the object's intention in front is to execute a left turn. The traffic participants require to have at least a minimum distance $d_{\mathrm{req,obj}}$ to the ego-vehicle's stopping envelope in order to successfully brake in case of an emergency. The required distance is dependent on whether the object-vehicle is manually driven or driverless. In the given test scenarios, a worst case is taken in which all object vehicles are assumed to be manually driven. While turning left, the object appears in the ego-vehicles stopping envelope. The intersection of the stopping envelopes causes the ego-vehicle to decelerate. The deceleration reduces the ego-vehicle's stopping envelope such that the overlap has vanished. The appearing lack of an overlap means that the straight lane can be followed again.

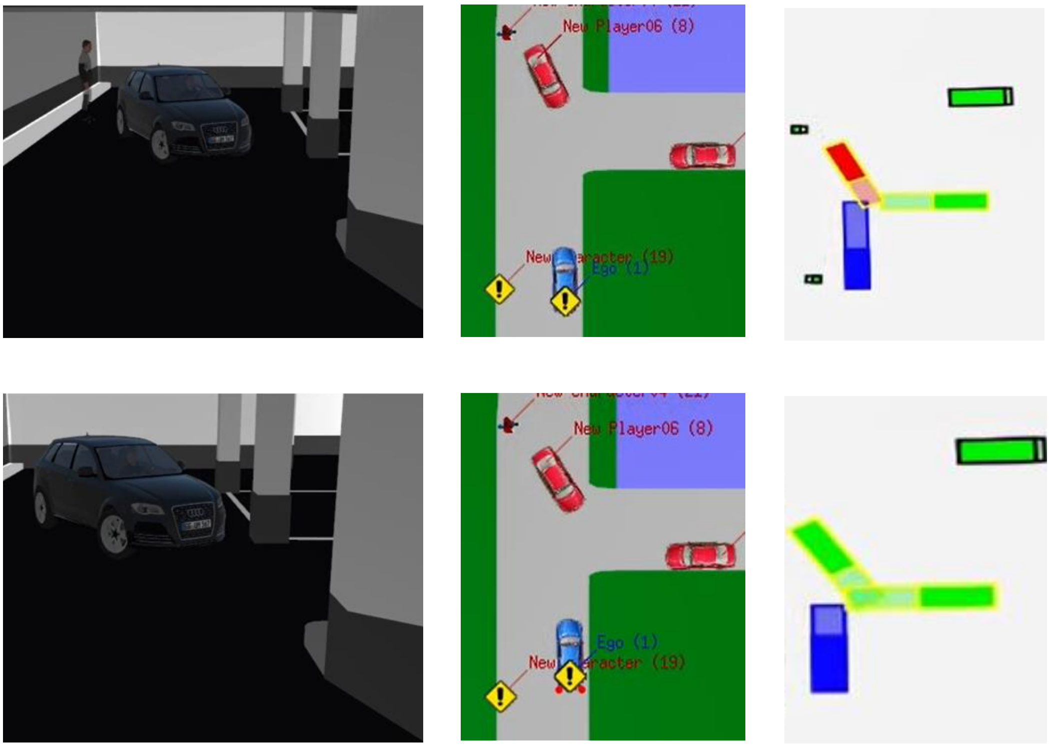


Figure 7–4: 3D scenery in the image generator (left) for the maneuver *following a straight lane*. Top view of the scenario editor in VTD (middle) and visualization of the stopping envelopes including the bounding boxes in a widget (right). The ego-vehicle is triggered to decelerate due to the intersection of stopping envelopes. Upper subfigures present the overlap of stopping envelopes whereas the lower subfigures show the reduction of stopping distances after deceleration.

In the next phase, the automated vehicle approaches an *intersection crossing*. An object vehicle is coming from the right and is hidden behind a wall. The object vehicle is actually occluded and the vehicle sensors do not have any line of sight. Therefore, the examination of the required areas by infrastructure sensors (e.g. top-mounted) is necessary. The provision of the safety zone is simulated by using ideal ground truth data. The object can still be detected although it is occluded by the wall. This approach is used to test the safety zone and not to test a sensor model. The implementation is tested for the deceleration in time to avoid collisions. It is not used to model a realistic perception behavior, but this can be investigated by integrating a more realistic sensor model in the open simulation interface instead of using ground truth data. However, ground truth data is used to test the safety function for the triggering condition. The object vehicle is oriented in a 90° angle to the automated vehicle and only the object stopping envelope contributes to the safety zone. Figure 7–5 presents the 3D scenery in virtual test drive, the corresponding top-view of the scenario editor and the created stopping envelopes of the traffic participants. The overlap of stopping envelopes causes the ego-vehicle to brake. The braking signal is indicated by the rear lights in the scenario editor. The object vehicle receives priority until required safety distances can be met. If sufficient distances are provided, the ego-vehicle will reinitiate the acceleration to cross the intersection.

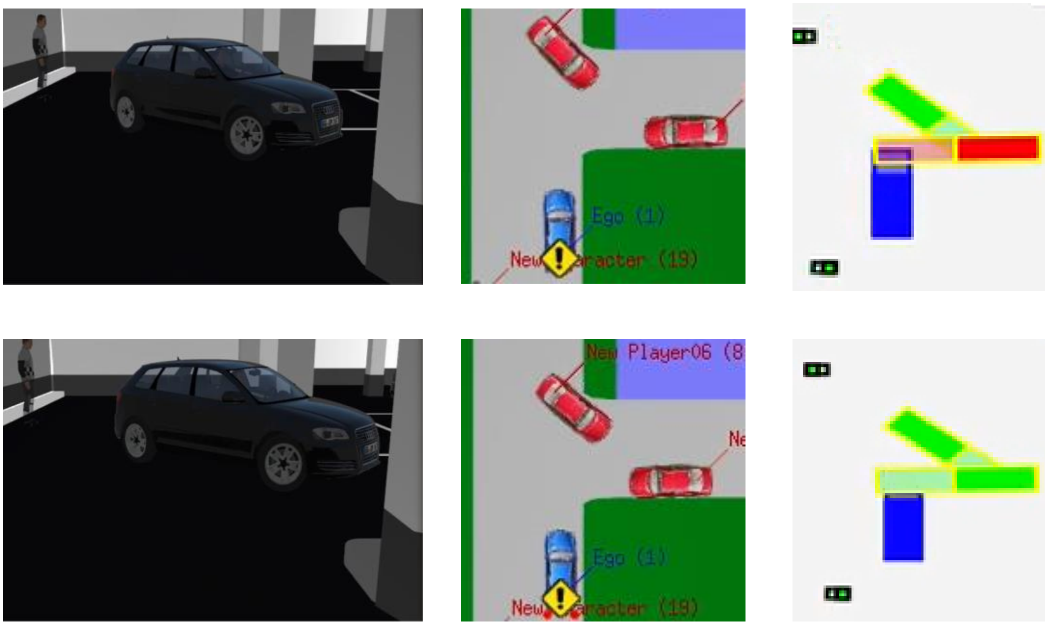


Figure 7–5: 3D scenery in the image generator (left) for the maneuver *intersection crossing*. Top view of the scenario editor in VTD (middle) and visualization of the stopping envelopes including the bounding boxes in a widget (right). The ego-vehicle is triggered to decelerate due to the overlap of stopping envelopes. Upper subfigures present the overlap of stopping envelopes whereas the lower subfigures show the reduction of stopping distances after deceleration.

In the next step, the automated vehicle's intention is to perform a left turn. However, on the opposite lane an object vehicle is moving towards the ego-vehicle and creates its straight stopping envelope. A left turn at this point in time would not provide sufficient space for the object vehicle to brake. The intersection between the tractrix curve and the object's stopping envelope triggers the ego-vehicle's deceleration to avoid the potential collision. Compared to a crossing of an intersection steering has to be considered. When steering is applied the vehicle requires more space than its vehicle width takes up. In case of turning left/ right the vehicle forms a tractrix curve. The vehicle's travelled envelope can be easily determined by applying tractrix curves. The inner wheel performs a larger steering angle in comparison to the outer wheel. As a result, an inner radius and a larger outer radius is established. The inner and outer radius determine the boundaries of the travelled envelope. The covered area can be determined easily with the help of the two track model and the Ackermann condition. The inner rear wheel point and the outer front vehicle body point form the corresponding tractrix curves. The relevant vehicle points forming the travelled envelopes are changing cross-wise for left and right turning. The calculation of the tractrix curve is based on a rectangular bounding box for worst case inspection. Figure 7–6 demonstrates the corresponding maneuver and the triggering event to avoid the collision.

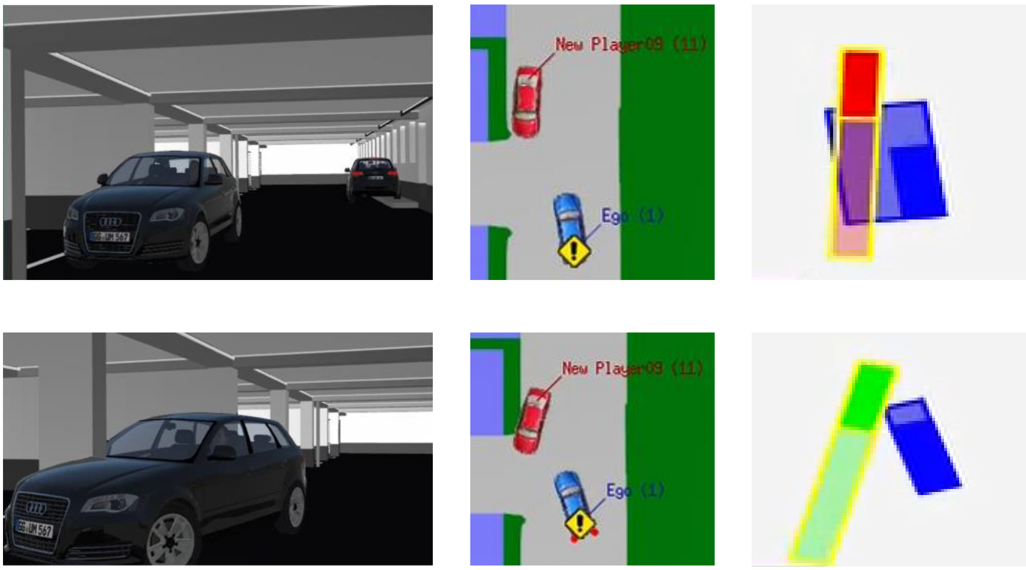


Figure 7–6: 3D scenery in the image generator (left) for the maneuver *turning left*. Top view of the scenario editor in VTD (middle) and visualization of the stopping envelopes including the bounding boxes in a widget (right). The ego-vehicle is triggered to decelerate due to the overlap of stopping envelopes. Upper subfigures present the overlap of stopping envelopes whereas the lower subfigures show the reduction of stopping distances after deceleration. The tractrix is simplified by a rectangle.

7.6 Summary

The presented implementation and test scenarios serve as a proof of concept rather than an attempt to validate the safety function. A prototype of the safety zone is integrated in a simulation environment using standardized interfaces to enable future development. The demonstration shall present the feasibility and applicability for collision avoidance in the context of automated valet parking The proof of concept implementation provides hereby a basis for further in depth testing of the proposed concept. To this end, it could for example be extended by a testing framework. Such a testing framework should provide the following capabilities:

- *Parking garage types:* Each parking garage has its constructional characteristics such as different types of intersection crossings, parking spots, ramps and occlusions.
- *Object type*: A mixed traffic leads to numerous object classes which have different moving behaviors. Even every vehicle type provides diversified boundaries for the tractrix curves by their inner and outer turning radius and the corresponding formed stopping envelope. Steering capabilities depend on the vehicle geometry and its design.
- *Velocities:* The variation of velocity provides different sizes of stopping envelopes.

- *Friction coefficient*: The stopping distance is determined by the deceleration given by the friction coefficient and the gravity. Different surfaces and tire materials result in a varying friction coefficient.
- *Measurement inaccuracies*: The determination of the ego's and the object's state variables leads to measurement inaccuracies. These become more relevant once sensor models instead of ground truth data are used.

A testing framework could be implemented based on a software-in-the-loop (SIL) or hardware-in-the-loop (HIL) platform. The ego-vehicle can be dropped on a HIL testbed and different dummy targets can be moved towards the ego-vehicle by varying their velocities. The ego-vehicle can be placed on a chassis dynamometer which uses a roller assembly to simulate the moving behavior. Dummy targets can be rotated around the ego to investigate whether the minimum required perception is fulfilled and the safety measures are triggered. Thereafter, the ego-vehicle's actuators can be examined for the required deceleration signal. The testbed serves for frontal and reverse collision avoidance. Additionally, steering will bend the ego-vehicles stopping envelope which can be tested using the described testbed.

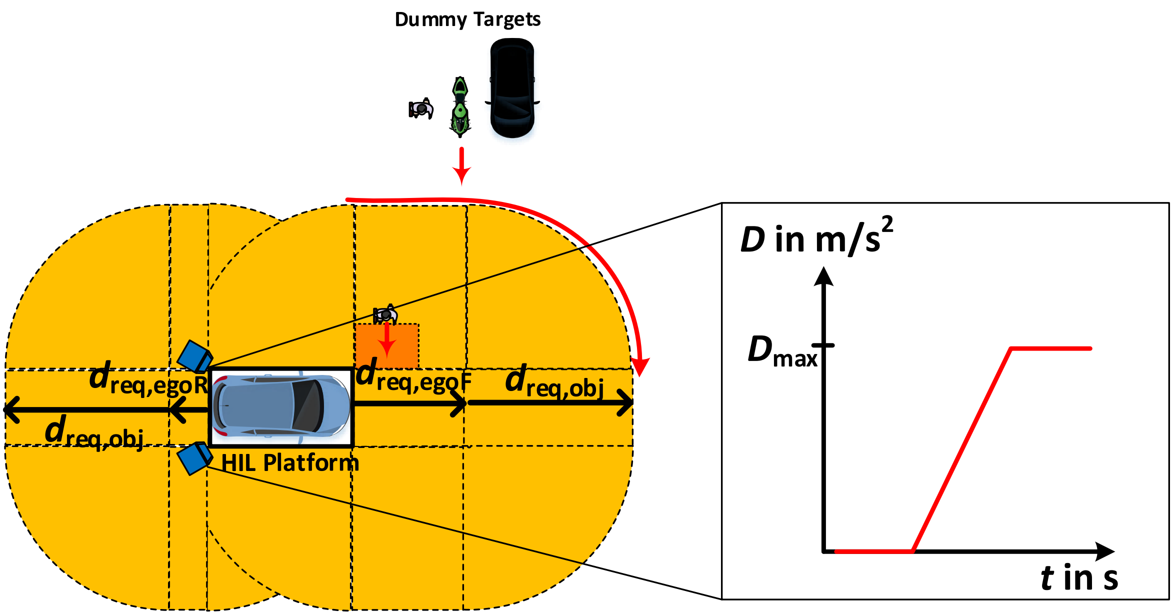


Figure 7–7: HIL platform with ego-vehicle placed on a chassis dynamometer and dummy targets moving towards the ego-vehicle. The actuators are investigated for a deceleration *D* signal in time.

The safety requirements valid for the minimum perception zone will be used to derive possible AVP configurations. Especially, the minimum perception zone shows its impact on time-efficiency and safety of the valet parking system. The elaborated safety zone and corresponding trigger conditions can be taken as a minimum criterion to avoid collisions. The investigated results will be used in the following to justify the module allocation between automated vehicle and infrastructure.

8 Derivation of AVP Configurations

This chapter introduces the derivation of different AVP configurations, which allow car manufactures or parking garage operators to choose between different distributions and implementations of AVP systems. Hereby, the impacts costs, efficiency, safety and availability are taken into account for the distribution of function modules. Figure 8–1 indicates the applied methodology to derive possible system configurations for automated valet parking. In the item definition the overall valet parking procedure was analyzed and split into scenarios that occur during the execution. The following scenarios were investigated: vehicle handover to the PAM system, automated driving to a point of interest, automated maneuvering into the parking space, automated leaving of the parking space, and aborting of the AVP process. Each scenario is examined according to functional requirements (functions) that the system has to provide to manage the dynamic driving task. Functional system requirements are grouped to form function modules. The function modules can either be assigned to the parking area management (PAM) and/ or to the automated vehicle. Impact factors such as costs, efficiency, safety and availability are investigated for the distribution process. The evaluation provides the input for possible system configurations. The configurations vary between the degree of costs, efficiency, safety and availability. The selection of a specific system configuration depends on the parking garage operator’s and car manufacturer’s constraints and/or preference.

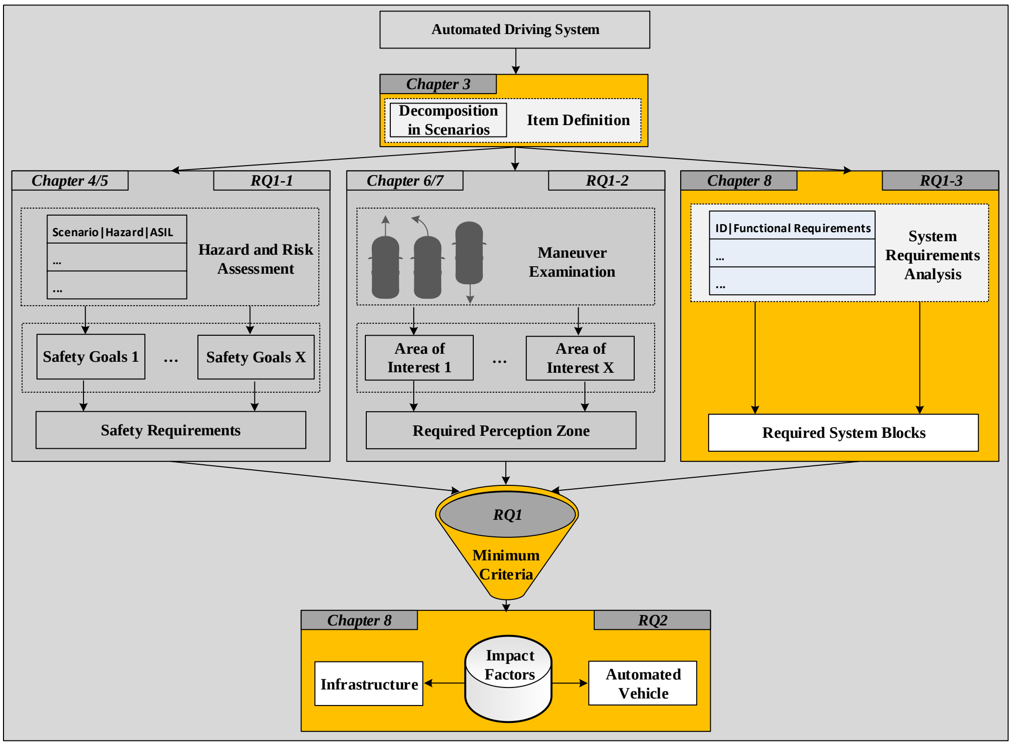


Figure 8–1: Decomposition of the automated driving system in functional scenarios that occur during infrastructure-supported valet parking. Functional system requirements are derived from functional scenarios and are assigned to function modules. The function modules are distributed between the infrastructure and the automated vehicle according to impacts.

Hereby, three options exist: the function is executed by the PAM, the automated vehicle or in a cooperative mode. Considering the possibility of all three options and a number of function modules n_{func}, the number of possible AVP configuration n_{AVP} is given by

$$n_{\text{AVP}} = 3^{n_{\text{func}}} \tag{8–1}$$

For ten function modules $n_{\text{func}} = 10$ this results in $n_{\text{AVP}} = 3^{10} = 59049$ combinations are derivable and even more are possible if various cooperation modes are taken into account. The example illustrates that it is not feasible to evaluate all AVP configurations. Therefore, this thesis discusses the benefits of the allocation on module level and not on configuration level. Functional system requirements are derived from functional scenarios to build function modules, which can be distributed between the infrastructure and the automated vehicle. This work assumes the fulfillment of minimum requirements for AVP such as the need for a sufficient amount of handover and pickup zones, the capability of vehicles to drive automated and switch to standby as well as activation of electric park brakes. The derived functional requirements include the perception to estimate the ego-vehicle's and the object's state such as their pose, velocity, dimensions, existence and class. The system has to be able to activate the AVP function to transition from manually driving to automated mode and to plan a safe trajectory to the desired point of interest. The trajectory execution requires the control of the automated vehicle's steering, shifting, accelerating and braking. Data transmission between infrastructure, automated vehicle and terminal has to be done via a C2X module. The AVP user requires a HMI to pay service and to get feedback about the current status. Table 8–1 summarizes the functional system requirements and required system modules.

Table 8–1: Derived functional system requirements from functional scenarios are assigned to function modules

Function Module	Functional System Requirements
Self-Perception: Ego-Vehicle State Estimation	• The system shall determine the ego-vehicle's pose, its velocity and have knowledge about its dimensions and class. • The system shall detect whether all doors are closed.
Env. Perception: Object Pose, Velocity, Dimension and Class Estimation	• The system shall determine the object's pose, velocity, dimensions, existence and class located in areas of interest under all possible environmental conditions.
Static Map Provision	• The system shall provide a static map of the parking garage.
Parking Space Occupation Status	• The system shall detect free and occupied parking spaces.

Function Module	Functional System Requirements
Mission Planner	• The system shall have the ability to activate and deactivate the valet parking function. • The system shall assign a safe mission. • The system shall know the destination position and dimensions of the handover and pickup zones as well as of parking spaces. • The system shall assign free parking spaces for automated vehicles.
Route Planner	• The system shall determine a collision-free route to the destination.
Behavior & Maneuver & Trajectory Planner	• The system shall plan maneuvers based on the current traffic situation with its traffic participants in compliance with traffic regulations. • The system shall plan a collision-free trajectory on up-to-date, accessible and connected drivable areas to the destination.
Trajectory Controller	• The system shall control the automated vehicle's steering, shifting, accelerating and braking.
C2X	• The system shall be able to transmit data between PAM, automated vehicles and a terminal.
HMI	• The system shall inform the driver about the current status. The system shall provide the ability to cancel the valet parking process and to pay service.

The AVP system architecture is based on the reference architecture of Lotz[98] for assisted and automated vehicle guidance. A reference architecture contains the most important function modules. Thereby, the architecture is split into a three-level hierarchy of the driving task according to Donges[99,100]. At navigation level, a suitable route is chosen from an available road network by considering accidents, traffic congestion or roadworks. The actual dynamic driving task is performed at guidance and stabilization level. At guidance level, the desired track and speed are derived from the traffic scenery for open-loop control. Finally, at stabilization level the driver has to compensate the deviations which occurred at guidance level

[98] Lotz, F. G.: Eine Referenzarchitektur für die assistierte und automatisierte Fahrzeugführung (2017). p. 130.

[99] Donges, E.: Aspekte der aktiven Sicherheit bei der Führung von Personenkraftwagen (1982).

[100] Donges, E.: Driver behavior models (2014).

via corrective actions (closed-loop control). Applied to the reference architecture of automated valet parking, the following three-level categorization is done:

At navigation level, the mission planner assigns the destinations such as the next free parking space upon a service request or the exit in case of handback request. After the definition of a mission, the route planner determines a route based on the topological representation of the road network. A best possible route can only be planned if a topological road network is known a priori. The determination is done by using a graph which represents the road network. The AVP system may take into account the current status of free/ occupied parking spaces in the parking garage.

At guidance level, the behavior planner shall select a sequence of behaviors that enables the vehicle to reach the assigned destination by taking into account other traffic participants or objects and the traffic regulations. An element of the behavior sequence is selected in the maneuver planner. The selection is based on the traffic scenery which contains the relevant information in the scenario perceived by the environment sensors. The environment perception module includes the object state estimation such as the determination of the object's pose, its velocity, its dimensions, its existence probability and its class. The local scenery is mapped into an appropriate representation such as a digital map. The possibility of a maneuver is restricted by the traffic scenery and the behavior of its traffic participants. Therefore, for the decision process not only a snapshot of the traffic scenery is required, but also the predicted moving behavior of the identified objects. The information has to be passed to the trajectory planner to determine a collision-free trajectory based on the maneuver specification of the behavior planner. The world model is required to provide the predicted moving behavior at trajectory level. The execution status of the trajectory planner has to be fed back to the maneuver planner to react according the dynamic environment.

At stabilization level, the low-level stabilization of the requested trajectory takes place. Deviations between target and actual trajectory are evaluated and minimized via control commands. The trajectory controller requires the input of the ego-vehicle's state estimation which is captured by the vehicle's internal sensors. The trajectory controller outputs target control commands that are executed by the vehicle's actuators for acceleration, braking and steering purposes. The control loop of the overall system starts again by perceiving the environment with its sensors and by reinitiating the navigation, guidance and stabilization. Figure 8–2 visualizes the overall control loop in a reference architecture for automated valet parking.

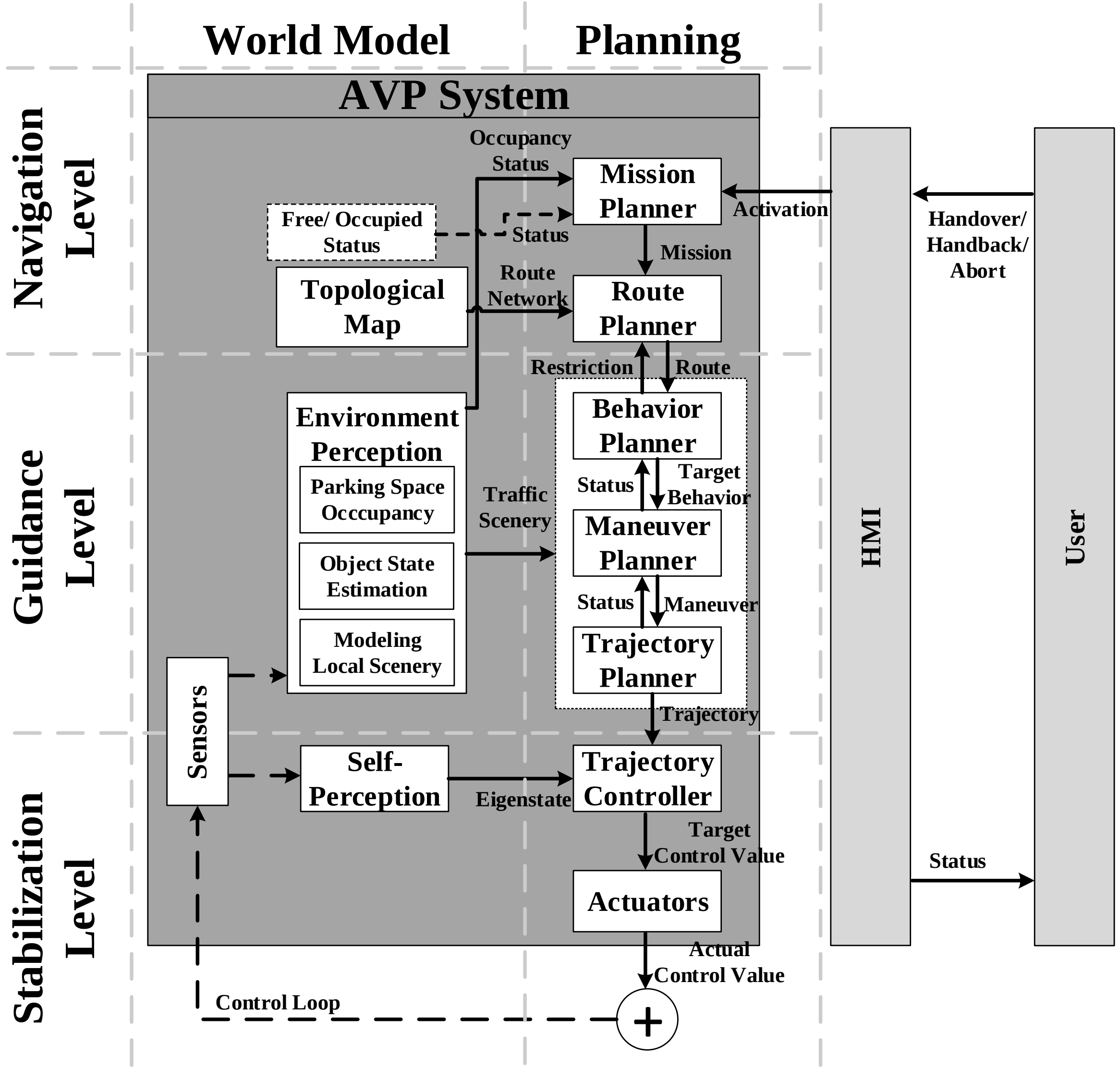


Figure 8–2: Reference architecture for automated valet parking divided into a three-level hierarchy according to Donges. At navigation level, a suitable route is determined from a road network. At guidance level, a desired trajectory is selected which deviations have to be compensated via corrective actions at stabilization level.

8.1 Distribution of Functions

After identifying all the modules needed for AVP, it is required to analyze for each function module whether an integration into the infrastructure or the vehicle is more reasonable. For this purpose, valid impact factors have to be determined for each module in order to quantify the comparison. This thesis applies the following impact factors:

- *Costs*: Characterizes additional efforts and expenses that have to be made to realize the described functionality apart from today’s state-of-the-art parking garages or vehicles.
- *Time efficiency*: Describes a quick handover, parking and pickup process to increase the vehicle throughput in a parking garage and decrease congestion.

- *Safety*: Refers to a collision-free AVP process and the avoidance of critical scenarios.
- *Availability*: Specifies the impact if the functionality cannot be performed anymore. The degree may vary from a single AVP vehicle in standstill to a complete breakdown of the AVP service.

Thereby, the impact factor availability has the same influence on all modules listed in Table 8–1: Derived functional system requirements from functional scenarios are assigned to function modules. In the following, each module will be evaluated according to the impacts on cost, time-efficiency, safety and availability to analyze whether an integration into the parking area management system or the automated vehicle is more recommended. Figure 8–3 demonstrates the distribution process.

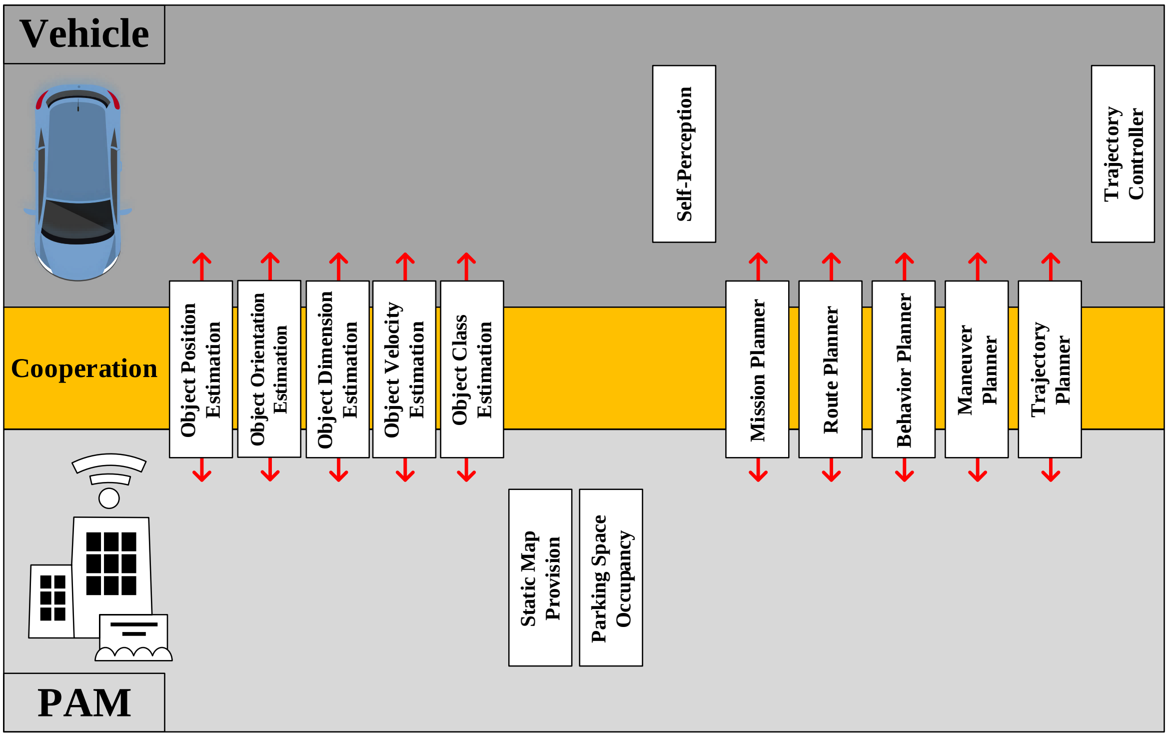


Figure 8–3: Distribution of function modules between PAM and the automated vehicle. Each module is evaluated according the impact factors cost, time-efficiency, safety and availability. A function can be allocated to the PAM, to the vehicle or executed in cooperation. The number of possible AVP combinations is given by the number of non-excluded distributable function modules n_{func} and can be determined by $n_{\text{AVP}} = 3^{n_{\text{func}}}$. This thesis therefore proposes a comparison on function module level rather than on system level. The function modules static map provision and parking space occupancy are assigned to the infrastructure whereas the self-perception and the trajectory controller remain in the vehicle.

A. *Self-Perception: Ego-Vehicle State Estimation*

Sensors for measuring driving dynamics are now part of the standard equipment of today's vehicles. Some of the most important sensors are:

- Wheel speed sensors: Provide information about the movement of the wheel in terms of velocity, acceleration and direction. They are already used in today's driver assistance systems such as Anti-lock Braking System (ABS), Traction Control System (ASR), and Electronic Stability Control (ESC).

- Steering angle sensors: Determine the steering wheel position through the measured steering angle. Its most important function is to support the ESC.
- Angular rate and acceleration sensors: Provide information about the rotational movements in all three spatial axes as well as the accelerations in X, Y, Z.

Sensors for measuring the vehicle's driving dynamics already provide sufficient information and have been proven in vehicle use. Therefore, there is no need to outsource these functionalities into the infrastructure, except for the ego-vehicle's localization, which is part of the environment perception. The module remains inside the vehicle.

B. Static Map Provision

A static map contains relevant information about the road network, the location of ramps, pickup zones and parking spaces for time-efficient navigation. The static map is stored and transferred at the entrance to the automated vehicle.

Costs: A static map containing all relevant information has to be stored on a storage device and C2I sender module is required for map transfer. As the receiver, the automated vehicle requires a C2I receiver module.

Time efficiency: A best possible route can only be planned if a topological road network is known a priori. The static map provides the road network and relevant points of interest to eliminate the search process.

Safety: Additionally, landmarks can be placed inside the static map for the reduction of localization inaccuracies. Drivable areas in which trajectories are placed are known. Static objects can be avoided.

Availability: A crash of the provision results either in a blocked AVP service at the entrance for arriving customers or decreases the time efficiency of the search process. Automated vehicles which have received the static map are still able to continue the AVP process.

The infrastructure is the only entity that may contain the a priori knowledge. Therefore, the infrastructure includes the function module of map provision.

C. Parking Space Occupancy Status

The occupancy status is needed by the mission planner to assign a free parking space. Most of today's parking garages are equipped with barrier or light barrier systems to count the number of entering and exiting vehicles.[101] However, an a priori knowledge of a free parking spot requires additional infrastructure sensors to assign a free parking spot at the entrance.

Costs: An a priori knowledge of a free parking spot requires additional infrastructure sensors to assign a free parking spot at the entrance. Some parking facilities are already supporting parking guidance to a free parking spot.[102] The solutions are based on ultrasonic sensors, camera or induction loops. The occupancy status is visualized with optical signals for drivers. In comparison, today's vehicles are already equipped with camera and ultrasonic sensors to detect a free parking spot and to support the driver in the maneuvering process.[103] The major benefit lies therefore not in the detection of a free parking spot, but rather in the elimination of the time-consuming search process.

Time efficiency: The occupancy status reduces the time-consuming search for a free parking space. More details can be found in the evaluation of the mission planner.

Availability: A crash of the provision results either in a blocked AVP service at the entrance for new customers or decreases the time efficiency of the search process. Automated vehicles which received an assignment are still able to continue the AVP process.

D. Environment Perception: Object Pose, Velocity, Dimension and Class Estimation

The environment perception consists of the function modules *object pose estimation*, *object velocity estimation*, *object dimension estimation* and *object class estimation*. The environment perception shall determine the object's state parameters in the MRP zone. Additional sensors may have to be installed in today's parking facilities or in vehicles.

Costs: Generally speaking, the integration of the environment perception module into the infrastructure pays off if the costs for all AVP vehicles for environment perception exceed the costs of an infrastructure-based realization. A major issue is that automated vehicles are not just used in a parking garage and therefore require environmental sensors in other areas such as in urban areas, on the highway or on rural roads. If the environment perception outside of the parking garage is not realized infrastructure-based, an integration of the modules into vehicles will be mandatory. Costs depend on characteristics of a parking facility and on used sensor technologies which will change in the future. Additionally, different entities such as manufacturers, operators and finally the users will bear the costs for AVP. It is therefore nearly not possible to quantify costs for environment perception and establish comparability for the deployment of function modules into the vehicle or the infrastructure. As a result, this thesis describes rather additional efforts that have to be implemented in today's standard parking garages and vehicles.

---

[101] Pech, A. et al.: Parkhäuser - Garagen (2009). pp. 223 – 231.

[102] Q-Free ASA: Parking Guidance Solutions (2019).

[103] Gotzig, H.: Parking Assistance (2016).

Today's road vehicles are partially equipped with radar, camera and ultrasonic sensors e.g. for adaptive cruise control (ACC), automated emergency braking (AEB) or for parking assistance. These sensors may perform the tasks of object's pose, velocity, dimension and class estimation. However, vehicle sensors may not cover the full MRP zone and are prone to occlusion. Indoor localization in a GNSS-denied environment is neither a standard equipment in today's parking garages nor in modern vehicle's and is still a research topic.[104] The infrastructure may support the localization process by providing a static map and corresponding landmarks or even track vehicles with its sensors. The vehicle may combine odometry with another indoor positioning system such as SLAM[104] to accomplish required measurement accuracies for self-localization.

Safety: In terms of safety, the infrastructure-based perception benefits from top-mounted sensors as objects that are occluded for the vehicle can be detected. Therefore, as indicated in Figure 3, areas of interest can be perceived that are actually covered from the ego-vehicle's view. The areas of interest are given by the superposition of stopping distances (envelopes) between collision partners. The size of these envelopes depends on the performed maneuver as well as the dynamic driving parameters of the engaged traffic participants such as velocities, timing constraints and deceleration capabilities. The perception of occluded areas can only be solved through cooperation with the infrastructure.

Time efficiency: As illustrated in Figure 8–4 an infrastructure-based environment perception ensures the detection of occluded areas and allows to operate the valet parking service at higher velocities since detection in covered areas is provided and slowing down is only required if a potential collision partner is present. Required safety distances can be maintained and the throughput of vehicles can be increased. The size of stopping envelopes can be decreased for a vehicle-based perception by reducing allowed velocities in a parking garage. If the vehicle velocity is slowed down significantly, required stopping distance will reduce such that the system is safe. A too large restriction in velocity decreases the throughput of the parking garage and will annoy manual drivers in mixed traffic.

Availability: In terms of availability, the infrastructure has a major disadvantage if no redundancy or vehicle-fallback is established. A collapse of a single module located in the infrastructure will lead to a total breakdown of the AVP service and may even block manually driven vehicles to continue their parking procedure (single point of failure). An error of an in-vehicle module causes the breakdown of a single vehicle only which can be carted away manually.

The implementation of a perception module into the infrastructure has the potential to increase safety and time-efficiency of AVP, but has the drawback of additional expenses for infrastructure sensors.

[104] Einsiedler, J. et al.: Vehicle indoor positioning: A survey (2017).

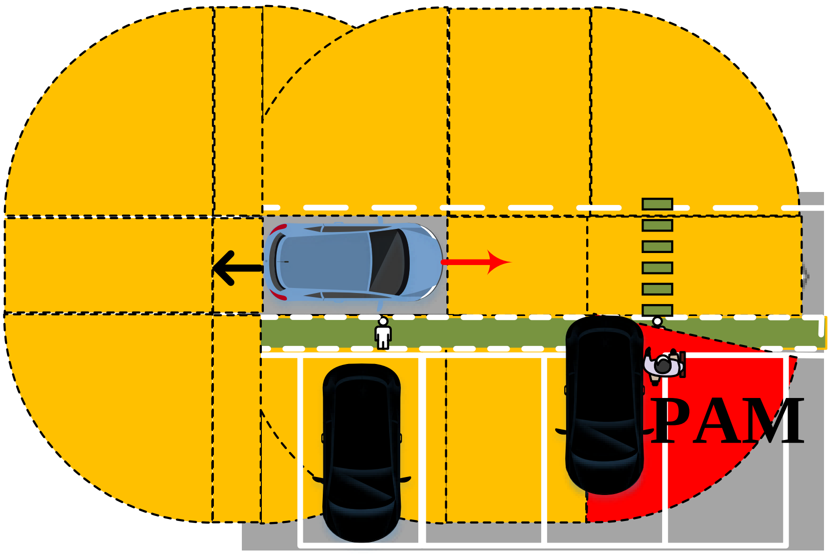


Figure 8–4: Area of interest occluded from the vehicle's view and required PAM-support for collision avoidance.

E. Mission Planner

The mission planner is responsible for assigning a safe mission such as a free parking space. The integration of the mission planner into the infrastructure can lead to considerable time savings for AVP.

Costs: The parking space occupancy status has to be observed by the infrastructure in order to be able to instruct a mission such as a free parking space at the entrance. Therefore, additional environment sensors have to be implemented in the car park and a measure to avoid the occupation e.g. by reserving the parking spot or by reassigning a new mission. In contrast, the vehicle will be already equipped with environment sensors to fulfill the driving tasks of other use cases.

Safety: A direct trajectory without detours causes a shorter driven distance in the parking garage. A shorter driven distance will on average lead to less interaction with traffic participants. More occurring critical scenarios can be avoided by just decreasing the driven distance within the parking garage per automated vehicle.

Time efficiency: Simultaneous monitoring of all parking spaces allows it to instruct a free parking space at the start of the AVP. A time-consuming search for a parking space is eliminated and the vehicles can drive directly to a free parking space. A mechanism is required to either keep the assigned parking space reserved or to reassign a new parking spot. A shortened search process could be particularly advantageous in a parking garage with a high occupancy rate or intensive parking space demands. The throughput can be significantly increased if congestion can be decreased by directing the vehicle to the free parking space or to the exit. For that, the time difference for a search process is investigated if the module would be integrated into the infrastructure compared to an implementation in a vehicle. The parking module will very likely access the same environment modules for the free space detection as required for the environment perception. The distance that a vehicle has to drive in an average parking garage shall be compared between an infrastructure- and a vehicle-based concept in order to quantify the time savings.

Figure 8–5 shows a parking garage configuration with its dimensions in length L_{Garage} and width W_{Garage}. Parking spaces are arranged in a matrix with i columns and j rows. Automated vehicles start at the handover zone and have to be placed at the pickup zone if a handback is instructed. We assume that in best case the automated vehicle uses its sensors to detect the exit's location nearby the entry and that the vehicle's search algorithm tries to find a parking space nearby the exit for a rapid handback. If a free parking space is located in the 1st row and in the 1st column, there is no benefit concerning the overall driven distance regardless of whether the free parking space is detected by the vehicle or assigned by the PAM. The overall driven distance from the entry to the parking space and from the parking space to the exit is the same. This is a best case for the automated vehicle. However, in the worst case the 1st quadrant is occupied, the automated vehicle will have to drive around the 1st quadrant to detect if there is any free parking located and then continue searching in the 2nd row or the 2nd column. The additional distance d that is driven by the vehicle is the superposition of circumferences around occupied row and column parking spaces. These can be calculated by introducing the number of occupied entries n_{occ} according to

$$d \approx \left(2 \cdot \frac{L_{\text{Garage}}}{i} + 2 \cdot \frac{W_{\text{Garage}}}{j}\right) \cdot n_{\text{occ}} \tag{8–2}$$

Considering a typical parking garage of around 20.000 m^2 with a total capacity of 600 vehicles, but only 60% occupation, $L_{\text{Garage}} = 100$ m, width $W_{\text{Garage}} = 40$ m, 5 levels, 2 rows ($j = 2$), 3 columns ($i = 3$) per level and $n_{\text{occ}} = 18$ (first 3 levels are occupied), results in $d \approx$1900 m and additional required time of $t \approx 680\,\text{s}$ for an average velocity of $v = 10\,\text{km/h}$. The example illustrates that uncertainty of the destination will lead to a higher congestion and decrease the efficiency of the throughput.

Availability: Total breakdown of the AVP service if no redundancy or vehicle-fallback is established. An error of an in-vehicle module causes the breakdown of a single vehicle only.

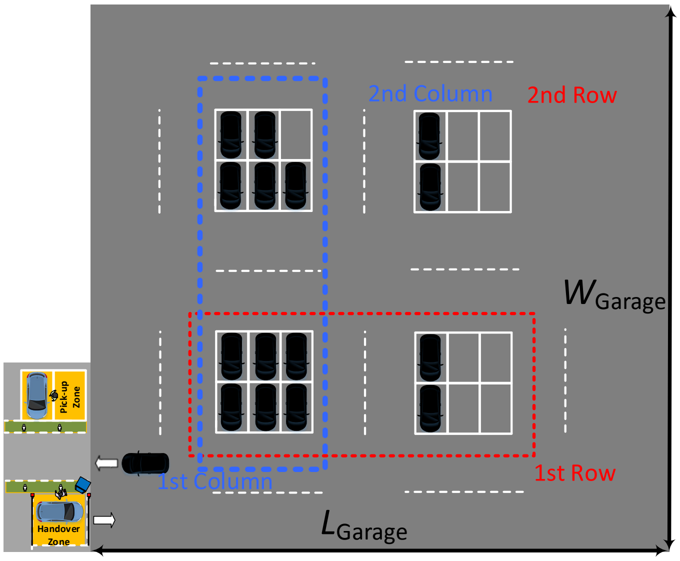


Figure 8–5: Parking garage with length L_{Garage} and width W_{Garage}, parking spaces are arranged in a matrix with i columns and j rows. An in-vehicle mission planner forces the vehicle to drive around each matrix entry to find a free parking space.

F. Route Planner

The route planner determines a global route to the destination and requires the ego-vehicle's position, the mission and at least the route network of a static map as inputs. The automated vehicle has no knowledge about the route network beforehand. Thus, an automated vehicle cannot plan a route unless it receives a route network from the PAM.

Costs: A route network map can be stored by the PAM without owning the environment module. Additional hardware, software and C2X is required to ensure the transmission of data between PAM and vehicle.

Time efficiency: A route that is blocked or congested can be avoided and an alternative route can be used. Therefore, vehicles can still arrive at their destination earlier although traveling a longer distance. The advantage of an overview leads to shorter handback and parking duration, especially in rush hour.

Safety: The avoidance of additional driven distance leads to less interaction between traffic participants and therefore results in less frequent critical situations on average.

Availability: Total breakdown of the AVP service if no redundancy or vehicle-fallback is established. An error of an in-vehicle module causes the breakdown of a single vehicle only.

G. Behavior & Maneuver & Trajectory Planner

The behavior & maneuver planner shall provide maneuvers based on the current traffic situation in compliance with traffic regulations whereas based on the suggested maneuvers the trajectory planner calculates a collision-free trajectory on up-to-date, accessible and connected drivable areas to the destination. A separation of the planners in different entities will result in additional C2I data transmission. The trajectory planner requires the input data of the traffic scenery. To avoid a huge amount of data transmission, it might be useful to place environment perception as well as behavior and trajectory planner into the same entity.

Cost: In the upcoming future, planners will be included in automated vehicles to perform tasks in other use cases such as in a highway pilot. A vehicle will be already equipped with the corresponding hardware and software but may require the adaption to a parking garage. An integration into the PAM will require additional hardware and software to process data for many vehicles and coordinate them.

Time efficiency: The PAM-based knowledge of the other traffic participants' moving behavior provides the capability of coordination and decrease of congestion. More efficient management of several participants is possible.

Safety: The PAM as the coordinator can assign collision-free trajectories based on prior knowledge, whereas an automated vehicle has no prior knowledge about the other automated vehicle's intentions and has to predict future maneuvers. The prediction of other automated vehicles' behavior is not required for the PAM. Only a prediction of manually driven vehicles and persons is necessary.

Availability: Total breakdown of the AVP service if no redundancy or vehicle-fallback is established. An error of an in-vehicle module causes the breakdown of a single vehicle only.

H. Trajectory Controller

The task of the trajectory controller is to keep deviations of required and actual control signals of the automated vehicle's steering, accelerating and braking at a minimum. There is no benefit by outsourcing the trajectory controller into the infrastructure. In either way, the vehicle actuators require the control signals from the trajectory controller. An in-vehicle implementation reduces additional delay and unnecessary C2X data transmission. Therefore, it is suggested to place the module inside the vehicle.

I. C2X Communication

The module enables the communication between the PAM and the vehicle. The transmission of data is required if one of the upper modules is integrated into the PAM. If the PAM does not support the vehicle, only the instructions for a handover or handback have to be sent to the vehicle.

Costs: A vehicle-centric AVP service does not require any C2X communication and costs can be saved. There are several degrees in terms of costs for the communication module. The integration of a mission and route planner requires additional C2X modules mainly at the entrance, whereas perception and other planner modules demand the availability in a complete parking garage.

The results of the analysis are summarized in Table 8–2. Only modules which are not yet assigned or optional are considered.

Table 8–2: Evaluation of perception, planning and controlling modules based on the impacts factors costs, safety, efficiency and availability to distribute AVP modules between the infrastructure (parking area management, PAM) and the automated vehicle

<table>
<tr><th>Impacts</th><th colspan="2">Self-Perception</th><th>Static Map Provision</th><th>Parking Space Occupancy Status</th><th colspan="3">Environment Perception</th></tr>
<tr><td></td><td>Vehicle</td><td>PAM</td><td>PAM</td><td>PAM</td><td colspan="2">Vehicle</td><td>PAM</td></tr>
<tr><td>Costs</td><td>++</td><td>-</td><td>-</td><td>-</td><td colspan="2">/</td><td>/</td></tr>
<tr><td>Safety</td><td>++</td><td>-</td><td>+</td><td>/</td><td>lower v:
+</td><td>higher v:
--</td><td>higher v:
++</td></tr>
<tr><td>Time Efficiency</td><td>++</td><td>-</td><td>++</td><td>++</td><td colspan="2">-</td><td>++</td></tr>
<tr><td>Availability</td><td>+</td><td>--</td><td>-</td><td>-</td><td colspan="2">+</td><td>--</td></tr>
</table>

Impacts	Mission Planner		Route Planner		Behavior & Maneuver & Trajectory Planner		Trajectory Controller	
	Vehicle	PAM	Vehicle	PAM	Vehicle	PAM	Vehicle	PAM
Costs	+	-	+	-	+	-	+	-
Safety	-	++	-	+	-	+	+	-
Time Efficiency	-	++	-	+	-	+	+	-
Availability	+	--	+	--	+	--	+	--

8.2 Possible AVP Configurations

The analysis of the defined impact factors for distribution of functions between the automated vehicle and the infrastructure, as presented in Table 8–2, reveals conflicts between the different objectives. As can be seen from the discussion, there is a tradeoff between costs and the system's efficiency. The gap can be narrowed by investing for example in a static map provision or parking occupancy detection to establish mission and route planning. An increase in velocity increases the minimum required perception zone for collision avoidance. Integration of some functions into the PAM without any fallback options paralyzes the whole AVP service including manually driven vehicles if not prevented by construction. A collapse of an in-vehicle function results in a single breakdown Since the number of possible AVP configurations is $n_{\mathrm{AVP}} \geq 3^{n_{\mathrm{func}}}$, it is not feasible to evaluate all AVP configurations. In the following, each upper defined functional module is assigned gradually to the infrastructure to demonstrate the resulting impacts exemplary. Starting from a fully vehicle-based AVP configuration each functional module from perception to planning is flipped over to the infrastructure. Hence, the beneficial influence of an increasing infrastructure support will be described. This thesis does neither demand the identification of an optimal AVP configuration nor the completeness of possible AVP configurations. However, the benefits of infrastructure support should be illustrated in the following. The AVP configurations are visualized in Figure 8–6 and corresponding system architectures for each configuration will be introduced.

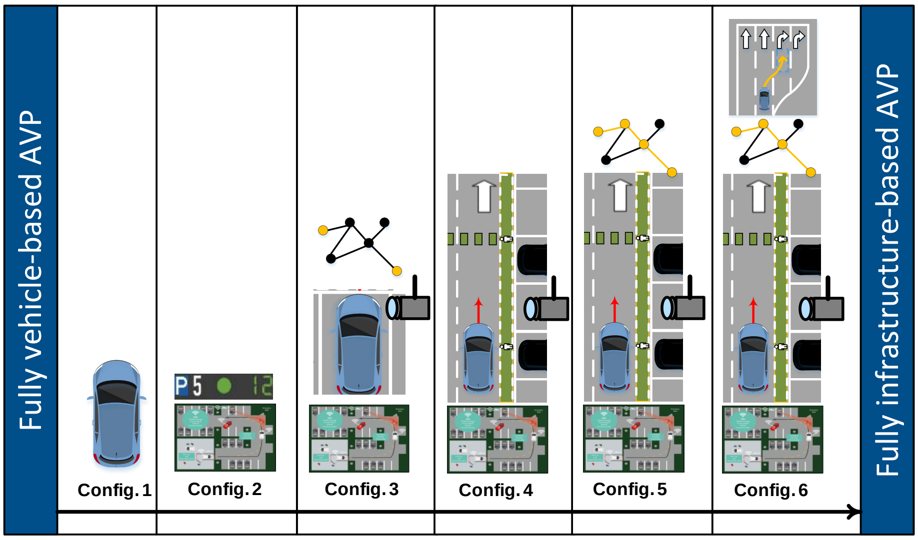


Figure 8–6: AVP configurations with an increasing takeover of functions by the infrastructure: fully vehicle-based AVP (Config.1), provision of a static map and the amount of free parking spaces (Config.2), inclusion of the mission planner and parking space observation (Config.3), integration of the object state estimation (Config.4), embedding of the route planner (Config.5) and all remaining planning modules (Config.6) into the infrastructure.

Configuration 1: Figure 8–7 shows a fully vehicle-based concept which results in the least integration effort for the infrastructure. The major advantage of the vehicle is that its functionalities are required in other use cases and thus efforts lie mainly in the software development of an AVP service. However, the inexpensiveness has its disadvantages, especially in time efficiency. If no infrastructure-based perception is present, a free parking space and the corresponding route cannot be assigned a priori. Furthermore, areas of interest that are occluded from the vehicle's view cannot be perceived for collision avoidance. The efficiency is not just decreased by longer distances. It is also decreased due to the reduction in velocity to investigate the minimum required perception zone.

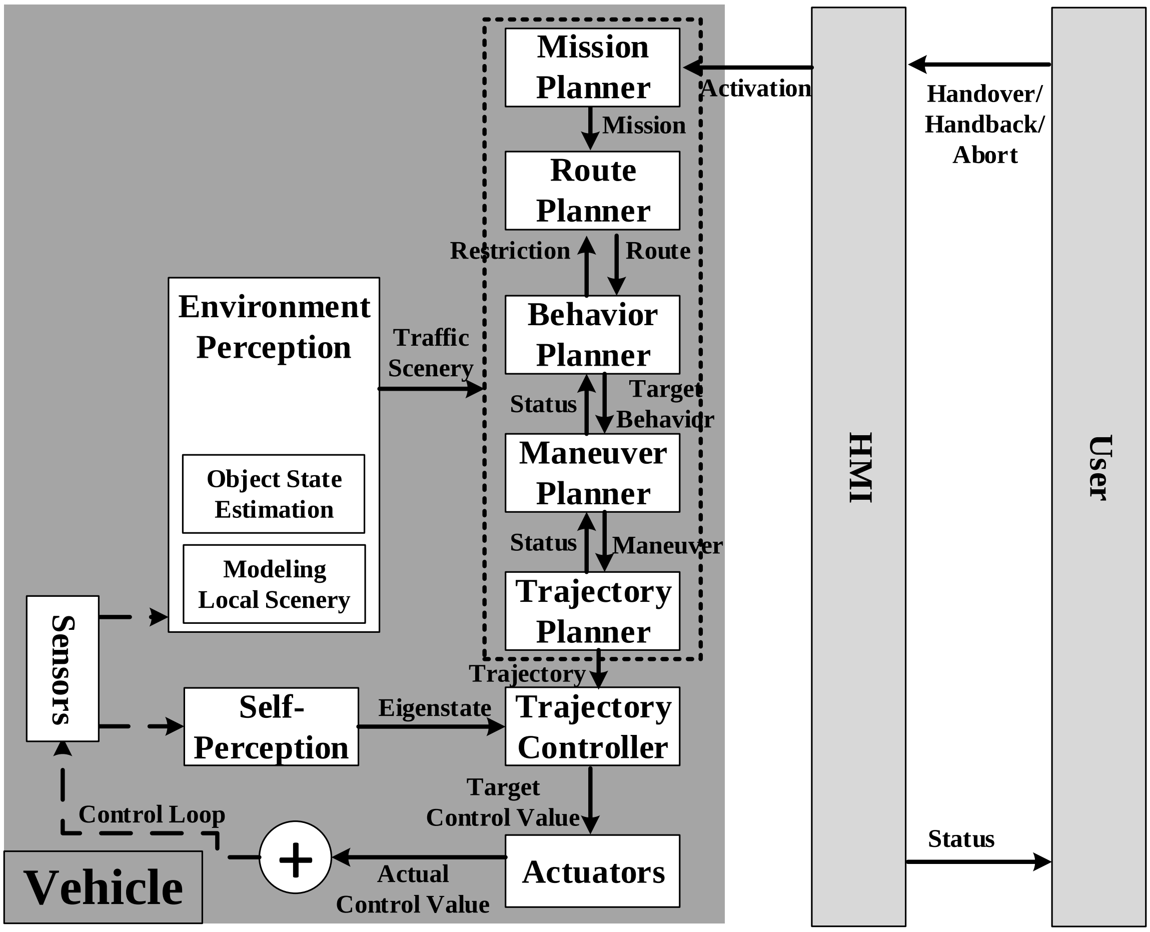


Figure 8–7: AVP configuration 1 is a fully vehicle-based AVP system architecture in which the AVP service is executed by the automated vehicle standalone. No additional active support is required by the infrastructure. Perception, planning and execution of control commands is managed by the vehicle. The vehicle does not know the location of a free parking spot a priori. The environment perception provides the traffic scenery for the search of a free parking spot.

Configuration 2: Figure 8–8 shows the parking area management (PAM) system's provision of a static (topological) map containing the floor plan of the parking garage. The static map is stored initially and is transferred at the entrance to the automated vehicle. The amount of occupied and free parking spaces can be detected indirectly by counting the number of vehicle entries and exits through a light barrier system in the parking garage. By transmitting this knowledge, the vehicle gains information of desired locations such as exits, ramps and parking spaces and can estimate the occupancy status to target the correct parking garage level. Thereafter, the vehicle can determine a route to the desired parking level. Additional distances to drive are reduced without implementing environment sensors in the parking garage. However, velocities have to be limited in case of occlusion. All planning modules from mission to trajectory planner still remain in the vehicle.

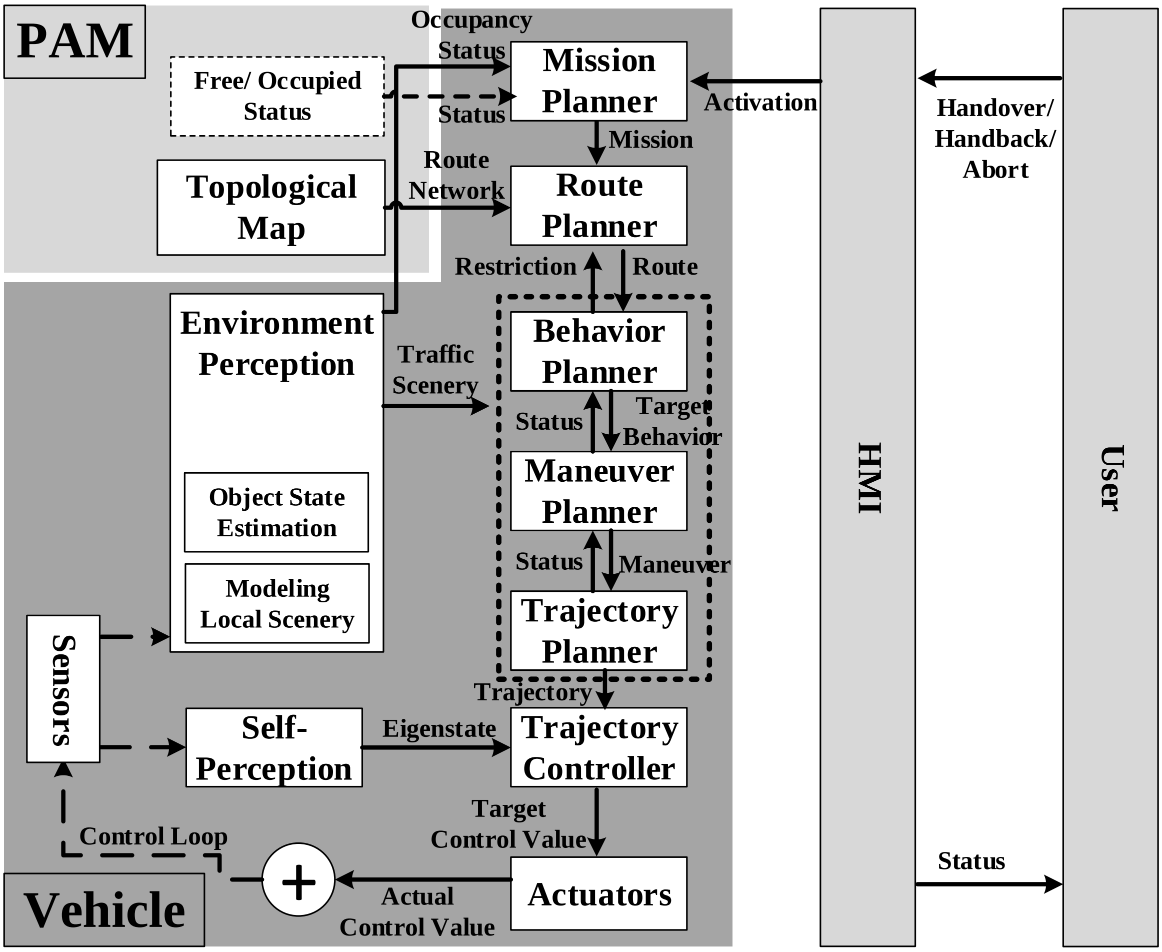


Figure 8–8: AVP configuration 2 demonstrates a parking area management (PAM) system which transfers a topological map and the status of free/ occupied parking spots gathered by a light barrier system found in today's parking facilities. This information provides knowledge about relevant point of interests such as exits, ramps and parking locations to increase time-efficiency. The vehicle determines which level of the parking facility should be targeted to find a free parking space. Perception and planning modules remain inside the vehicle by receiving limited support by the infrastructure via a topological map and the parking status. The implementation of environment sensors inside the infrastructure is not required. Today's parking facilities require minimal modifications such as a communication module for C2I and data storage for map provision

Configuration 3: Figure 8–9 illustrates the inclusion of the mission planner and the parking space observation in combination with a topological map. From now on, sensors for parking space occupancy have to be implemented in the parking garage in order to instruct the vehicle to a specific free parking space. Mission planning is taken over by the PAM to assign a free parking space at the entrance. Driven distances are heavily reduced due to the exact knowledge of the destination. However, only parking spaces are investigated for occupancy. The remaining area in the parking garage has to be perceived by the vehicle which will be exposed to occlusion. Hence, limitations in velocity are given by the minimum required perception zone.

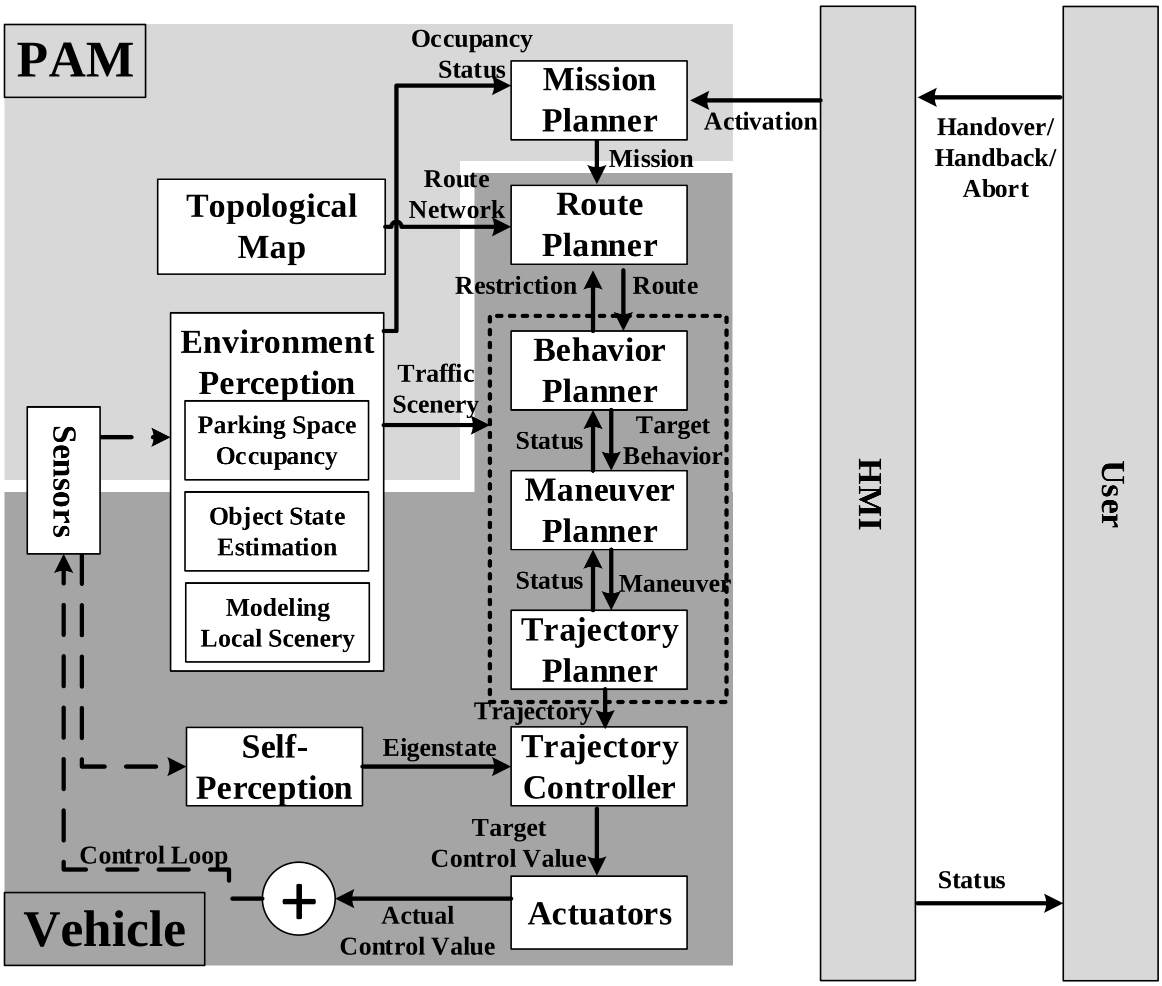


Figure 8–9: AVP configuration 3 illustrates a parking area management system (PAM) which transfers a topological map and assigns a free parking spot to the automated vehicle at the entrance of the parking garage. The determination of the occupancy status requires additional modifications such as infrastructure sensors. The automated vehicle can directly navigate towards the parking spot without searching procedures. The infrastructure observes only parking space area, but no lanes. Other perception and planning modules remain in the vehicle.

Configuration 4: Figure 8–10 demonstrates the incorporation of the object state estimation into the PAM. Beside the perception of the parking space occupancy, areas of interest in the parking garage can be provided. Areas of interest that are occluded from the vehicle's view are detected via a top view. The vehicle does not have to be slowed down unnecessarily in case of occlusion. A time efficient route in this configuration is still calculated by the vehicle. The PAM provides the traffic scenery for the behavior, maneuver and trajectory planner.

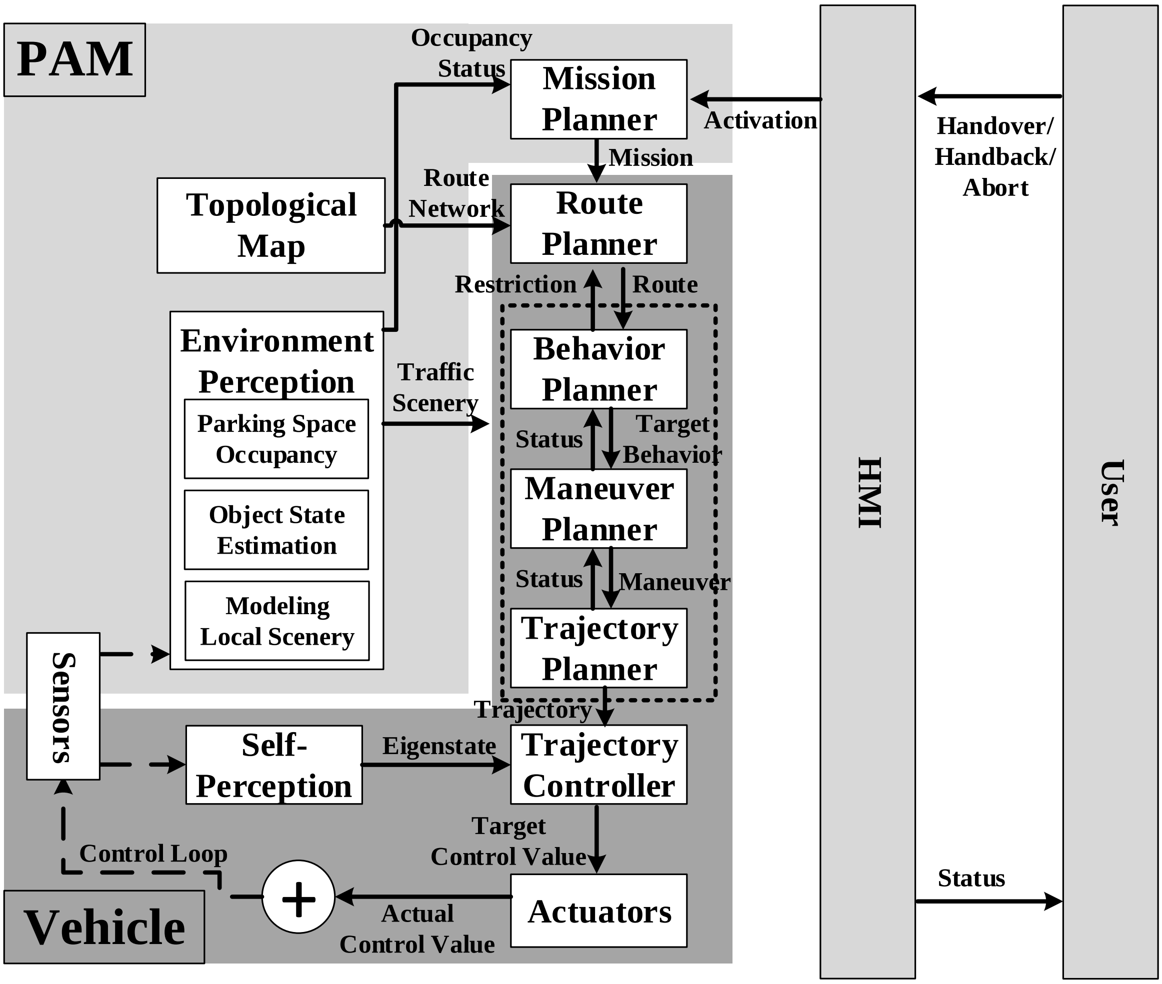


Figure 8–10: AVP configuration 4 assigns a topological map and parking space occupancy to the parking area management (PAM) system. The PAM perceives the overall parking facility and transfers the traffic scenery to the vehicle. Infrastructure sensors are less sensitive to occlusion and ensure the observation of safety-relevant areas which are occluded for the vehicle's sensor view. Time-efficiency is increased due to the increase in vehicle velocities.

Configuration 5: Beside the provision of a static map and the perception, the infrastructure embeds the route planner. Figure 8–11 illustrates the PAM-takeover of the route planner for vehicle coordination and congestion avoidance. If a route is heavily congested, the perception module is able to detect the circumstances and propose another route to decrease further congestion. Time efficiency can be further increased by avoiding crowded paths.

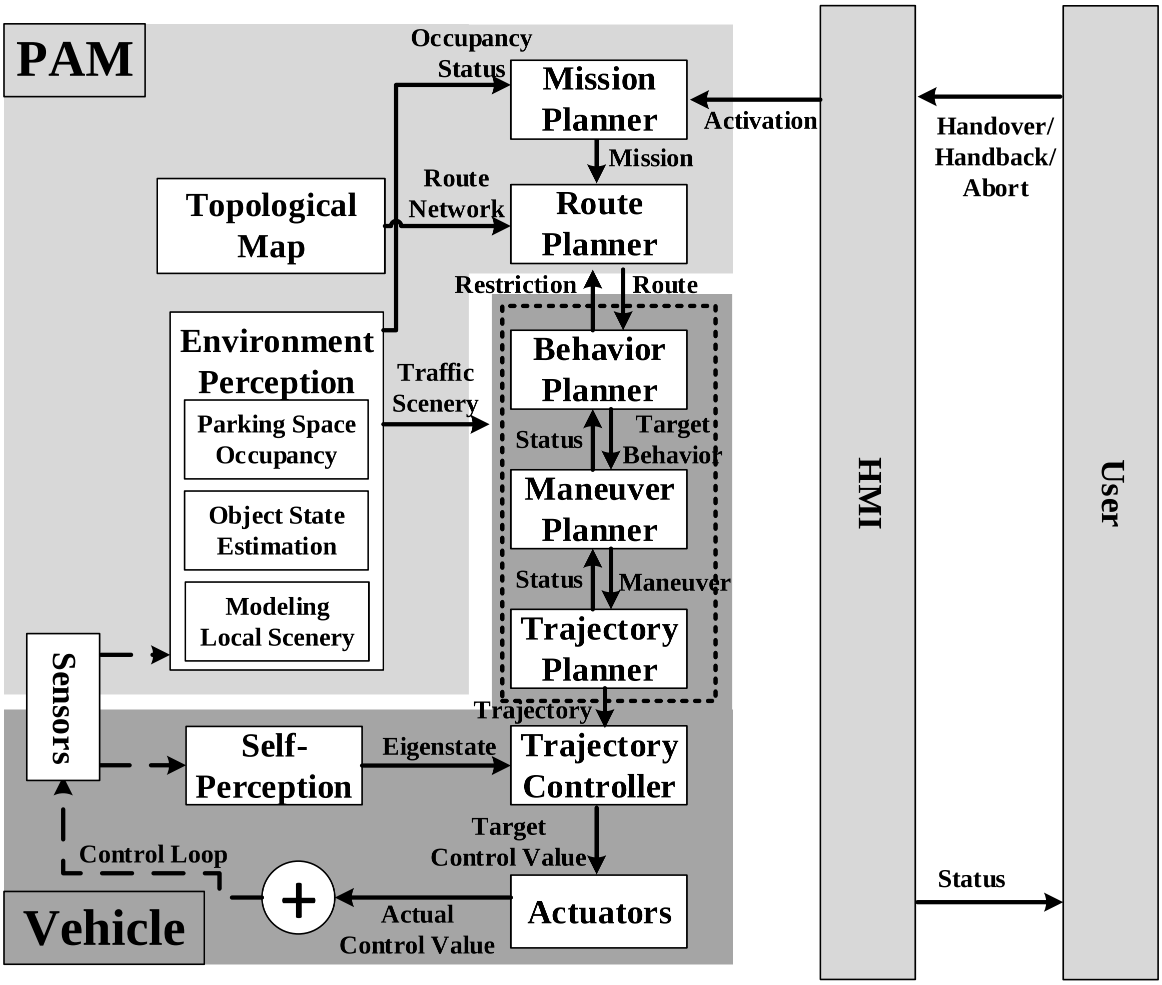


Figure 8–11: AVP configuration 5 assigns a route planner to the parking area management (PAM) system. A route planner determines the route to a point of interest based on the road network of the topological map. A centralized route planner allows to detect congested routes for traffic rerouting. Congested routes may appear due to a vehicle breakdown or occurred accidents.

Configuration 6: Figure 8–12 exhibits a fully infrastructure-based AVP system. The PAM takes over the environment perception and all planning modules. Behavior, maneuver and trajectory planner to know the traffic participant's trajectories a priori and improve safety and time efficiency are integrated into the PAM. In the vehicle remains the trajectory controller and the self-perception module. The automated vehicle executes the control commands provided by the infrastructure.

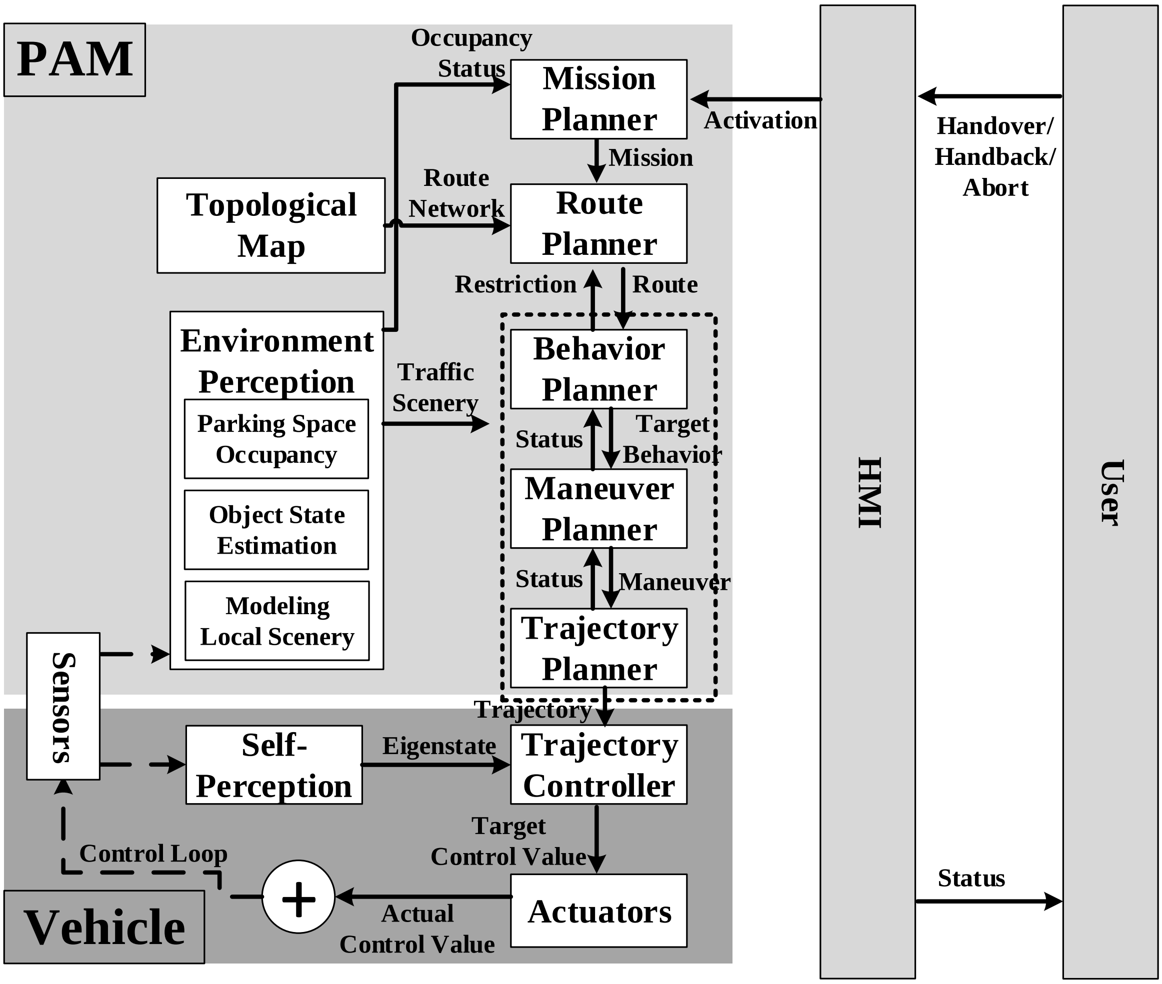


Figure 8–12: AVP configuration 6 illustrates the infrastructure takeover of perception and planning modules such that the vehicle only executes control commands. A static map and a free parking space is transmitted by the parking area management (PAM) to the vehicle at the handover zone. Hereby, mission planner and corresponding detection of parking space occupancy are allocated to the PAM. The environment perception module is assigned to the infrastructure. Route, behavior, maneuver and trajectory planner are integrated into the PAM. As a result, trajectories of automated vehicles are known a priori and can be taken into account for collision-free intention prediction and planning.

The described AVP configurations with gradually shifting of distributable functions towards the infrastructure show the major benefits of an infrastructure support: Least costs with PAM support are given by transferring a static map and the free/ occupied status gathered by a light barrier system present in today's parking garages. The parking space occupancy status requires additional infrastructure sensors, but allows a priori assignment of a free parking spot. An infrastructure-based object state estimation ensures higher velocities. The takeover of route to trajectory planning avoids congestion and provides knowledge of trajectories.

8.3 Migration Concepts

The derivation of various AVP configurations raises the question whether today's existing parking garages can be used for an AVP service or if the construction of new parking facilities is required. A smooth transition from the current state to a widely used AVP system is desired. However, still some issues need to be solved before the introduction of AVP systems in today's parking garages is possible. Existing parking garages differ in the already integrated technology. Some of the equipped technology shall briefly described to derive possible migration concepts:

- *Barrier Systems*: Barrier systems can be often found at entrances and exits of today's parking garages. The systems control the output and receipt of parking ticket and require an average check-in time of around 7 to 10 seconds. Light barrier systems are capable to count the number of free/ occupied parking spaces by counting the number of entering and exiting vehicles. Radio Frequency Identification (RFID) ensures contactless entrance and exit at short distances. [105]
- *Parking Space Occupancy:* A sensor detects a vehicle's presence or absence and updates the information. Some parking facilities are already detecting free or occupied parking spaces with infrastructure sensors to visualize drivers possible parking space availabilities. Observation of parking space occupancy is based on infrastructure sensors such as ultrasonic sensors, camera or induction loops.[106] Different types of parking detection sensors are discussed by Lin et al.[107]
- *Guidance Systems:* Guidance systems shall ensure driving path to several potential parking spaces to avoid search time. Parking space sensors sense the status and transmit the information to guidance systems.[108]
- *Surveillance Cameras:* Some parking garages are already equipped with surveillance cameras to protect against theft or vandalism.
- *Ticket machine:* Ticket machines serve as payment stations in parking garages. Existing parking garages provide mainly payment of service by cash or bank card.

In the following, a migration concept shall be discussed in the sequence of occurring functional scenarios. It is described which steps need to be solved for a smooth introduction of AVP systems in today's existing parking garages:

Vehicle handover to AVP system & vehicle handover to driver: An AVP service starts with the handover of the automated vehicle at the handover zone. The activation process consists of the conditions: vehicle standstill, no person located in the handover zone, all doors closed

[105] Pech, A. et al.: Parkhäuser - Garagen (2009). pp. 225 - 233.

[106] Q-Free ASA: Parking Guidance Solutions (2019).

[107] Lin, T. et al.: A Survey of Smart Parking Solutions (2017).

[108] Qiu, R.: A System framework of active parking guidance and information system (2010).

and required user or PAM permission. The handover as well as the corresponding pickup process may last additional time. In comparison to the barrier system's check-in times of around 7 to 10 seconds, this may mean that several handover and pickup zones will be needed to accomplish appropriate handover and pickup times especially at rush hour. Timpner et al.[109] shows that pick-up times of about 1 min are possible. Thereby, the availability of the AVP service has to be given. The separation of entrances for manually driven and automated vehicles could be considered to avoid annoyed customers. Even in case of separation, AVP systems have to provide value in terms of comfort and time savings to receive the acceptance of customers. This also may result in appropriate ways for service payment which avoid waiting queues, e.g. by paying via app rather than using a conventional ticket machine. The functionalities of a typical terminal found in today's parking garages need to be extended. An intuitive HMI concept is required for the communication between users and AVP systems to instruct handover/ handback requests, to retrieve the current vehicle status or to pay service.

Automated driving to a point of interest: When driving to a point of interest, the infrastructure may support optionally. A static map of the corresponding parking facility can be stored and transferred optionally at the entrance. An integration of device storage and C2I modules into the infrastructure will be necessary for the transmission of the digital map. Additional infrastructure sensors are required for the parking space occupancy status if these are not already integrated. The occupancy status in today's parking garages is visualized with optical signals for drivers, but needs to be transferred to automated vehicles. If perception modules are outsourced into the infrastructure, the parking garage has to be equipped with environment sensors for object state estimation, especially at locations in which occlusion is unavoidable such as ramps. As a result, planning and perception modules will require additional processing units for signal processing and C2I modules for data transmission. Occurred blocking which may be solved easily by human drivers e.g. by performing evasive maneuvers or tight maneuvering, become more challenging for automated vehicles e.g. if evasion is prohibited by safety design. Deadlocks formed by automated behavior have to be prevented to ensure the availability of the overall parking service. A human supervisor may support in terms of troubleshooting such as blocked automated vehicles, collisions, breakdown of function modules or activation issues. Limitations in indoor positioning[110] or in measurement accuracy may restrict vehicle types simply due to narrow parking construction. The results of the MRP and MRS zone show that restrictions of executable maneuvers or restrictions in velocity may have to be introduced for cost-efficient AVP systems.

Automated maneuvering into the parking space/ Automated leaving of the parking space: When parking the automated vehicle, an optimal utilization of the parking area is desired for

[109] Timpner, J. et al.: k-Stacks: High-density valet parking for automated vehicles (2015).

[110] Einsiedler, J. et al.: Vehicle indoor positioning: A survey (2017).

capacity and throughput purposes, especially for peak demands. High density parking[111,112] is a promising solution for the increasing demand of parking spaces in urban areas by packing vehicles denser since humans do not need to access automated vehicles in the parking area. Ferreira et al.[113] presents parking layouts which reduces 50% of the necessary parking space compared to conventional parking. However, high density parking becomes challenging in a mixed traffic since vehicle doors should be openable. This may result in a separation of existing parking garages in two parking space blocks to enable high density parking in a mixed traffic and to ensure optimal utilization of parking area.

Further issues:

The advances towards electromobility[114,115] still have two major disadvantages: reduced driving ranges and increased charging duration. AVP may ease the traveler's transfer by charging electric vehicles while these are parking. Consequently, charging stations to provide additional service have to be integrated in today's parking facilities either for each parking space or by sharing charging stations. Electric vehicles are switched once the charging process has finished. The switching process has the advantage of less required charging stations. A docking process of automated charging to serve different vehicle types has to be established. Finally, a legal basis is required in case of caused harm to participants in the parking garage. A legal basis is required to clarify the responsibilities between manufacturers which design AVP systems, parking garage operators which provide AVP systems and customers which use the systems. The issue becomes especially crucial if a cooperation between infrastructure providers and manufacturers of automated vehicles takes place.

The discussion shows that a major issue for today's parking garages will be a quick handover and pick-up process at rush hour to ensure time savings. Additional efforts lie in the preservation of service availability, the infrastructure support of automated vehicles, the implementation of high density parking, the integration of e-mobility for AVP systems as well as the provision of a legal basis. The derived AVP configurations and minimum criteria ease the migration of AVP systems in today's existing and newly constructed parking garages by integrating the necessary safety design for a preferred AVP configuration. Parking garage operators and manufacturers can influence their required degree of infrastructure support by maneuver or vehicle type restriction. Both can choose between personally preferred version of AVP configurations based on the relevance of costs, time-efficiency, safety, availability and accessibility.

---

[111] Timpner, J. et al.: k-Stacks: High-density valet parking for automated vehicles (2015).

[112] Banzhaf, H. et al.: High density valet parking using k-deques in driveways (2017).

[113] Ferreira, M. et al.: Self-automated parking lots for autonomous vehicles based on vehicular ad hoc networking (2014).

[114] Schwesinger, U. et al.: Automated valet parking and charging for e-mobility (2016).

[115] Klemm, S. et al.: Autonomous multi-story navigation for valet parking (2016).

9 Conclusion and Outlook

Automated Valet Parking (AVP) systems are one of the first systems in automated driving that may be introduced soon by manufacturers[116]. The race of the development has already started.[117] However, a clear definition of minimum criteria for AVP systems is crucial to ensure safety by design in the early development process. The minimum criteria shall hereby consider diverse parking garage topologies and the required allocation of responsibilities between the infrastructure and the automated vehicle for a safe AVP service. The integration of minimum criteria in the early design process shall hereby minimize the risks of harm.

In particular, the state-of-the-art reveals a lack of minimum criteria for the use case AVP. Today's standards assume for AVP the minimum capability of longitudinal and the lateral control performance, the monitoring of the driving environment and a minimal risk state in case of a fallback situation. None of the existing literature describes how to integrate AVP into existing diverse parking structures and which necessary conditions are expected from cooperative AVP systems to prevent risks of harm. Today's technical realizations focus on the provision of a digital map at the entrance in combination with the detection of free parking spaces to assign a free spot. However, additional beneficial AVP configurations are possible which were not yet addressed in the state-of-the-art. Two major research questions (*RQ*) were derived in this thesis:

- *RQ1*: What is the essential subset of minimum criteria AVP configurations require to fulfill for safe operation?
- *RQ2*: Which degrees of infrastructure support are needed and what are their benefits?

The contributions of this thesis regarding the identified research questions can be mainly summarized as follows:

First, this thesis decomposes the AVP service into functional scenarios for system abstraction.[118] Functional scenarios are used to give a functional description of the system. Major scenarios are the vehicle handover to the parking area management system, automated driving to a point of interest, automated maneuvering into the parking space, automated leaving of the parking space, vehicle handover to driver and aborting the valet parking procedure. Identified functional scenarios serve as an input for the followed derivation of safety requirements from safety goals, the specification of a minimum required perception zone and the identification of function modules.

[116] Gasser, T. M. et al.: Rechtsfolgen zunehmender Fahrzeugautomatisierung (2012). pp. 7-8

[117] Banzhaf, H. et al.: The future of parking: A survey on AVP with an outlook on high density parking (2017).

[118] Schönemann, V. et al.: Scenario-based functional Safety for AD on the Example of AVP (2018).

Second, this thesis introduces the derivation of low level safety requirements from safety goals in compliance with the international standard ISO 26262 and SOTIF.[119] The hazard analysis and risk assessment has revealed that an unintended activation of the valet parking function outside of the infrastructure-controlled parking area and incorrect data transmission between parking area management are categorized as most dangerous. Moreover, a key factor is to avoid collisions between the ego-vehicle and other objects such as pedestrians or manually driven vehicles. Thereby, the object's state variables, its existence and class have to be determined to successfully avoid a collision. The state variables include the object's dimensions, the object's pose and the object's velocity. A threshold is defined for the maximum allowed longitudinal and lateral measurement error of automated vehicles.

Third, this thesis presents the mathematical and geometrical formulation of a minimum required perception (MRP) and safety (MRS) zone.[120] In particular, a definition of an area, in which the determination of the object's state variables, its existence and its class is mandatory for collision avoidance, is given. The magnitude of this area is maneuver-specific and therefore an investigation of occurring maneuvers for each individual parking garage is required. The maneuvers *following a straight lane*, *driving backwards*, *crossing an intersection*, *turning left/right* have been investigated. The worst case for the resulting stopping distance is formed when a manually driven vehicle moves with the maximum allowed velocity towards the ego-vehicle and both vehicles are breaking. In case of turning left/ right the vehicle covers a tractrix curve. The superposition of the ego- and object's stopping envelopes at maximum allowed velocities for the executable maneuvers in the operational design domain forms the MRP zone. A reduction of the MRP zone is possible by introducing automated driving only or by restricting executable maneuvers in the parking garage. The MRS zone, a subset of the MRP zone, determines the last possible border in which a deceleration requires to be triggered. However, the MRS zone has its limitations. The MRS zone assumes a linear moving behavior of the object due to the knowledge lack of its intention. A prototype of the MRS zone shall present the feasibility and applicability for collision avoidance (proof of concept) in the context of automated valet parking, but requires additional extensive testing.

Fourth, this thesis illustrates the functional modules to derive needed AVP configurations. Hereby, the derivation of needed AVP configurations required the identification of function modules of an AVP architecture. In the first step, system requirements are assigned to function modules. The function modules form an AVP system architecture. The architecture is split into a three-level hierarchy of the driving task according to Donges[121,122]. At navigation level, a suitable route is chosen from an available road network by considering the road

[119] Schönemann, V. et al.: Fault Tree-based Derivation of Safety Requirements for AVP (2019).

[120] Schönemann, V. et al.: Maneuver-based adaptive Safety Zone for infrastructure-supported AVP (2019).

[121] Donges, E.: Aspekte der aktiven Sicherheit bei der Führung von Personenkraftwagen (1982).

[122] Donges, E.: Driver behavior models (2014).

network. At guidance level, a behavior planner selects a sequence of behaviors that enables the vehicle to reach the assigned destination by taking into account other traffic participants or objects and the traffic regulations. A maneuver of the sequence is selected in the maneuver planner and is passed to the trajectory planner to determine a collision-free trajectory based on the maneuver specification. At stabilization level, the deviations between target and actual trajectory are evaluated and minimized via corrective control actions (closed-loop control).

Finally, this thesis demonstrates the distribution of function modules between the infrastructure and the automated vehicle. The analysis shows that there is no optimal system architecture for the given impacts. A tradeoff exists between overall costs, time efficiency, safety, and availability of AVP systems with today's vehicles. The analysis illustrates that the number of derivable AVP configurations is too large for comparison on configuration level. Therefore, this thesis presents the benefits of infrastructure support by gradually assigning function modules towards the PAM. A fully vehicle-based AVP has to perform the automated driving task without the help of an infrastructure (*Configuration 1*). Time-efficiency can be increased at minimum effort by transmitting a static map and the amount of free and occupied parking spaces (*Configuration 2*). Further efficiency can be established at the costs of environment sensors by detecting free and occupied parking spaces to assign free parking spaces directly at the entrance (*Configuration 3*). An increase in vehicle velocity triggers the need for an infrastructure-based environment perception. Infrastructure sensors provide required occluded areas (*Configuration 4*). If the PAM additionally takes over the route planner, several vehicles can be coordinated for most time-efficient placement and congestion avoidance (*Configuration 5)*. An infrastructure-based AVP takes over all perception and planning modules and sends the required control commands to the automated vehicle (*Configuration 6)*.

The contributions of this thesis add value to the design of future AVP systems:

AVP configurations and minimum criteria ease the migration of AVP systems in today's existing and in newly constructed parking garages. Minimum criteria lay the foundation for the development of a necessary safety design. *Manufacturers and suppliers* benefit from the identification of minimum criteria by integrating the derived minimum criteria in their early system development process to ensure *safety by design*. Safety by design will minimize the risks of harm caused by developed AVP systems. Hereby, the safety by design affects the infrastructure and the automated vehicle. The fulfillment of minimum criteria can be achieved cooperatively between the infrastructure and the automated vehicle. This thesis illustrates the needed infrastructure-support for AVP systems. However, manufacturers have the option to distribute the functions between both entities according their preferences to accomplish the defined minimum criteria. *Manufacturers and suppliers* benefit from the specification of necessary conditions for AVP systems. The developers only require to consider the necessity for an individual parking garage and therefore save efforts by avoiding unnecessary above needed safety performance. Safety requirements are reduced by considering the specific parking garage topology such as the executable maneuvers or reducing required stopping distances by parameter adjustment for the individual parking garage. For example, the defined MRP zone can be used for the necessary sensor coverage for a maneuver-specific parking garage and the integration of required infrastructure support at specific locations such as ramps or occlusions. These safety critical spots can be equipped with infrastructure sensors to increase safety and time-efficiency. AVP systems can be configured with the necessary sensor coverage by saving costs through necessity. AVP systems can be configured according the required safety performance for the individual parking garage. The MRP and MRS zone provide the option to control velocities dependent on the distance to occlusions and to traffic participants. The MRS zone can be integrated for collision avoidance. Parking garage operators are more willing to invest in AVP systems which provide less risks of harm to customers.

Parking garage operators benefit from AVP services with less risks of harm. As a result, less harm caused by AVP systems will ensure less collisions and therefore will positively influence the availability and throughput of the parking garage. Customers will accept a safe AVP service more likely. Parking garage operators save costs by only investing in the required safety configuration for their specific parking garage. There is no need to pay for a more extensive AVP system. Furthermore, parking garage operators can restrict executable maneuvers, vehicle velocities or vehicle types to reduce safety requirements and corresponding costs for their infrastructure modifications. Layouts for newly constructed parking garages can be designed to ensure time-efficient and safe AVP systems. A safe AVP service provides the opportunity to integrate high density parking for the increase of parking capacity. The progression of e-mobility in combination with AVP systems allows the parking garage operator to integrate charging stations in the parking garage and provide additional value for customers. Parking garage operators can select between AVP configurations according the constraints present in their parking facilities. They can prefer which distribution of functions is more beneficial for their individual circumstances. Some may favor a low cost application whereas others find time-efficient services more attractive.

Customers of the parking garage benefit from the reduced risk and a safer execution of the AVP service. They are more willing to use and pay for a safer AVP system which saves their valuable time and releases them from the burden of parking manually. A safer AVP system causes less harm to health and life of parking garage participants. Since the parking garage operator invested in a parking garage-specific safety configuration, lower costs of the operator's modifications are shifted towards customers. Safe AVP systems indirectly enable high density parking and charging stations. Customers may benefit from lower parking ticket prices due to high density parking. Parked electric vehicles of customers are charged during the parking process.

However, still many issues are unresolved in the AVP domain. Future work needs to be done to pave the way for automated parking pilots. This thesis proposes a three-fold strategy:

First, AVP systems have to provide value in terms of comfort and time savings to receive the acceptance of customers. This may mean to ensure a flowing traffic through the increase of handover/ pickup zones and provide solutions for a breakdown of the AVP system. Long waiting times need to be avoided. The AVP system needs to be migrated in today's existing parking garages.

Second, AVP systems need to be beneficial for parking garage operators and manufacturers. AVP systems have to be economically. The commercialization of AVP systems requires customers willing to pay for AVP systems. This may result in high density parking which increase the demands on future AVP systems in terms of time efficiency, localization and additional constructional changes.

Third, legislative authorities need to approve AVP systems. This raises the question of liability in case of accidents or fatalities. As a first step, the elaborated minimum criteria can be used as a checklist to ensure safety by design. Minimum criteria for AVP systems will also be required for liability reasons. A more complete set of minimum criteria is desired to additionally minimize risks of harm. The corporation of independent entities, operators and manufacturers is required to increase the set of minimum criteria and integrate them in the early system development phase. Minimum criteria need to be specified on low level instead of at overall system level. For example, maximum allowed lateral and longitudinal errors for state variables have to be broken down on parameter level to assign individual errors for the determination of position, orientation, dimension and velocity. Furthermore, a threshold for the existence probability to specify the accepted amount of false positive and false negative detections is desired. Further verification and validation of the minimum required safety zone and its applicability could be progressed. Hereby, the limitation in motion prediction for collision avoidance has to be addressed.

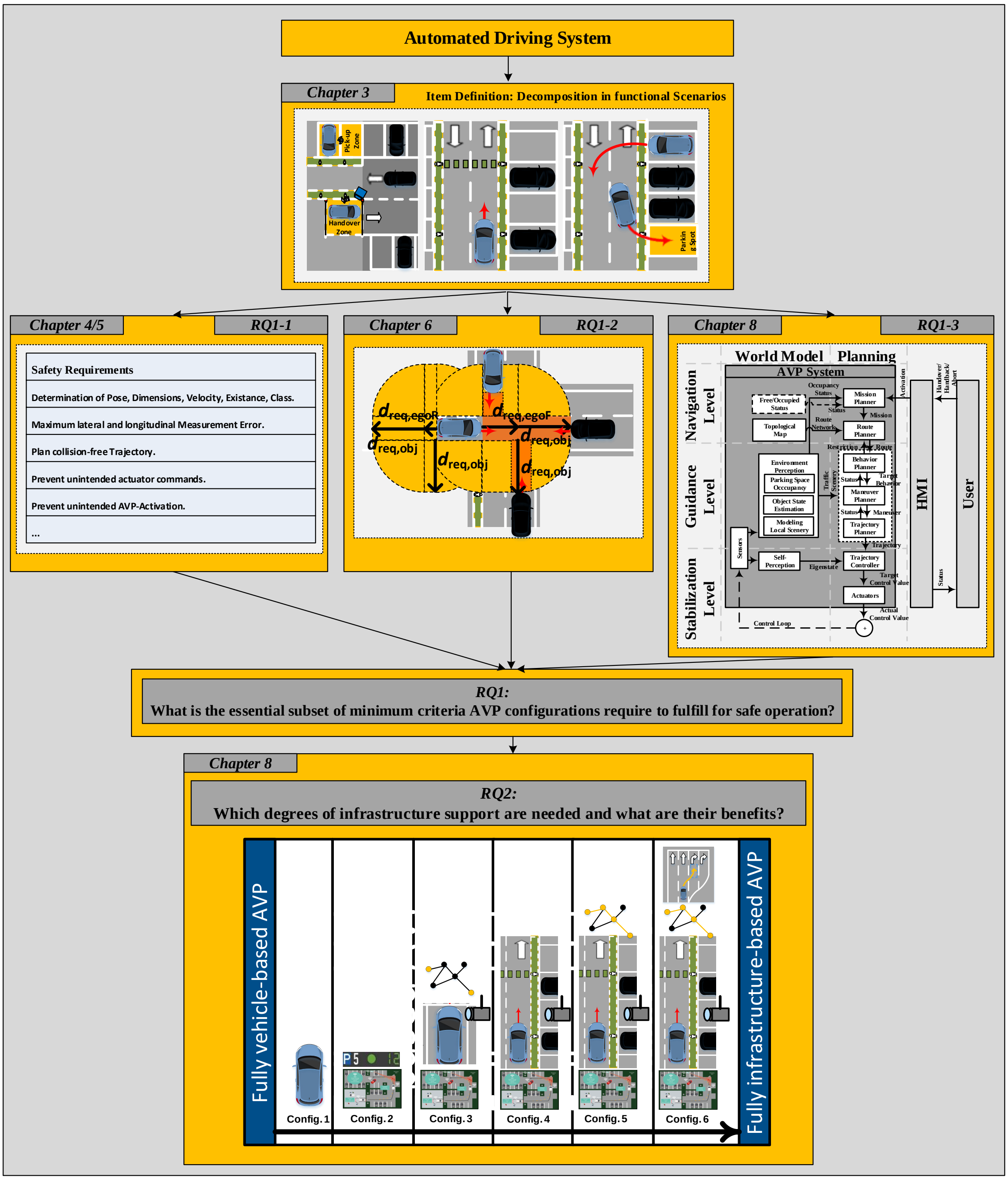


Figure 9–1: Decomposition of the automated driving system in functional scenarios which served as input for the specification of safety requirements from safety goals (left), a minimum required perception zone (middle), identification of required module functions (right) to derive minimum criteria for AVP and characterize possible degrees of infrastructure support

A Appendix

A.1 Preliminary Hazard Analysis and Risk Assessment

Table 9–1: Preliminary hazard analysis and risk assessment (HARA) which shows an initial high-level screening to identify hazards for automated valet parking. The Automotive Safety Integrity Level (ASIL) QM is not shown for clarity purposes. Repetitive hazards are listed once in the single scenario.

Scenario	Failure Mode	Hazard	Specific Situation	Hazardous events & consequences	S	Rationale	E	Rationale	C	Rationale	ASIL	Safety Goal
1	Unintended activation of AVP inside the operational design domain	Safety-critical situation due to unclear handover status	Persons getting into the vehicle just before it starts moving	Collision with person	S1	Activation in low speed	E4	AVP activation process every handover	C3	Automated vehicle is uncontrollable	B	SG04
1	Unintended activation of AVP inside the operational design domain	Collision due to unclear handover status	Persons are still located inside handover zone, but vehicle starts moving	Collision with person	S1	Activation in low speed	E4	AVP activation process every handover	C3	Automated vehicle is uncontrollable	B	SG04

Scenario	Failure Mode	Hazard	Specific Situation	Hazardous events & consequences	S	Rationale	E	Rationale	C	Rationale	ASIL	Safety Goal
1	Opened doors not detected	Collision with open doors	Driver forget to (completely) close door/trunk door	vehicle may start moving while doors are still open and may collide	S1	Activation in low speed	E4	AVP activation process every handover	C3	Automated vehicle is uncontrollable	B	SG04
1	Incorrect detected vehicle positioning	Safety-critical situation due to incorrect positioning	Vehicle is not positioned in handover zone	vehicle may start moving while position is incorrect	S1	Activation in low speed	E4	AVP activation process every handover	C3	Automated vehicle is uncontrollable	B	SG04
1	Incorrect detected vehicle orientation	Safety-critical situation due to incorrect orientation	Vehicle is not oriented correctly in handover zone	vehicle may start moving while orientation is incorrect	S1	Activation in low speed	E4	AVP activation process every handover	C3	Automated vehicle is uncontrollable	B	SG04
1	Incorrect detected vehicle velocity	Safety-critical situation due to vehicle velocity	Vehicle is not in standstill in handover zone	vehicle is moving while still in the initializing process	S1	Activation in low speed	E4	AVP activation process every handover	C3	Automated vehicle is uncontrollable	B	SG04
1/6	Missed passenger	Undetected passenger in vehicle getting out during AVP	Passenger tries to get off during AVP	Collision with person	S2	Collision at medium speed causes severe injuries	E4	Passengers almost every drive expected	C1	Passengers are able to stay in the vehicle	A	SG08
1/6	Missed passenger	Undetected passenger in vehicle	Passenger is trapped inside the vehicle.	Trapping inside closed vehicle	S2	Potential dehydration	E4	Passengers almost every drive expected	C1	Passengers are able to call help	A	SG08

Scenario	Failure Mode	Hazard	Specific Situation	Hazardous events & consequences	S	Rationale	E	Rationale	C	Rationale	ASIL	Safety Goal
1/2	Incorrect data transmission by PAM	Collision due to incorrect data received by vehicle	Incorrect map/ path is loaded	Collision with person	S3	Incorrect speed profiles	E4	Communication between PAM and vehicle throughout every AVP	C3	Automated vehicle is uncontrollable	D	SG02
2	Data transmission not in time by PAM	Collision due to correct, but not in time received data by vehicle	Safety-relevant data is not received in time.	Collision with person	S3	Brake signal not in time	E4	Communication between PAM and vehicle throughout every AVP	C3	Automated vehicle is uncontrollable	D	SG02
2	Loss of data communication	Collision due to loss of data communication	Safety-relevant data is not provided	Collision with person	S3	Collision at medium speed causes severe injuries	E4	Communication between PAM and vehicle throughout every AVP	C3	Automated vehicle is uncontrollable	D	SG02
2	Missed or incorrect detection in position, orientation, dimensions	Collison with object	Automated vehicle crashes into object which in turn collides with persons	Medium structural damages or flying/ falling objects	S1	The vehicle’s medium speed causes lower kinetic energy	E3	Limited combination of dangerous objects for moving persons	C3	Automated vehicle is uncontrollable; Probably less than 90% persons are able to evade	A	SG09

Scenario	Failure Mode	Hazard	Specific Situation	Hazardous events & consequences	S	Rationale	E	Rationale	C	Rationale	ASIL	Safety Goal
2	Incorrect detection of class	Collison with person	Automated vehicle predicts incorrect moving behavior of object	Incorrect interpretation of moving behavior leads to collision	S2	Collision at medium speed causes severe injuries	E4	Encounters with moving persons every drive	C3	Automated vehicle is uncontrollable	C	SG03
2	Vehicle not compliant with regulations	Collison with person	Automated vehicle operates not in compliance with traffic regulations	Persons and vehicles are not expecting the moving behavior.	S2	Collision at medium speed causes severe injuries	E4	Encounters with moving persons every drive	C3	Automated vehicle is uncontrollable	C	SG03
2	Missed fuel status	Safety-critical situation due to missed fuel status	vehicle is moving with low fuel and shuts down	Collision with person	S2	Collision at medium speed causes severe injuries	E4	AVP usage every drive	C1	Energy status controlled by drivers beforehand	A	SG03
2	Missed or incorrect detection in position, orientation, dimensions	Collison with other vehicle	Automated vehicle crashes into other vehicle	The system does not detect the vehicle	S1	Person protected in vehicle	E4	Encounters with moving vehicles every drive	C3	Limited space for evading maneuvers; Automated system cannot be controlled.	B	SG05
2	Safety-critical mission planned	Collison with person	Automated vehicle plans trajectory to safety-critical destination	Vehicle moves towards safety-critical destination	S2	Collision at medium speed causes severe injuries	E4	Mission planning every drive	C3	Automated vehicle is uncontrollable	C	SG03
2	Safety-critical route planned	Collison with person	Automated vehicle plans route to safety-critical destination	Vehicle moves towards safety-	S2	Collision at medium speed causes severe injuries	E4	Route planning every drive	C3	Automated vehicle is uncontrollable	C	SG03

Scenario	Failure Mode	Hazard	Specific Situation	Hazardous events & consequences	S	Rationale	E	Rationale	C	Rationale	ASIL	Safety Goal
				critical destination								
2	Safety-critical trajectory planned	Collison with person	Automated vehicle plans safety-critical trajectory	Vehicle moves towards safety-critical destination	S2	Collision at medium speed causes severe injuries	E4	Trajectory planning every drive	C3	Automated vehicle is uncontrollable	C	SG03
2	Incorrect interpretation of traffic scenery	Collison with person	Automated vehicle interprets scenery as not safety-critical	Vehicle misses safety-critical traffic scenery	S2	Collision at medium speed causes severe injuries	E4	Trajectory planning every drive	C3	Automated vehicle is uncontrollable	C	SG03
2	Missed deadline for computed trajectory	Collison with person	Automated vehicle misses deadline for trajectory provision.	Vehicle brakes after delay	S2	Collision at medium speed causes severe injuries	E4	Trajectory planning every drive	C3	Automated vehicle is uncontrollable	C	SG03
2	Missed or incorrect detection in position, orientation, dimensions	Collision with person	Person runs into moving vehicle	The AVP system does not detect the Person	S2	Collision at medium speed causes severe injuries	E4	Encounters with moving persons every drive	C3	Missed detection during fully automated driving	C	SG03
2	Incorrect determination of own position, orientation, dimensions or velocity	Collision with person	The AVP system does not determine safety-relevant parameters sufficiently accurate.	Safety-critical AVP system due to inaccuracy	S2	Collision at medium speed causes severe injuries	E4	Encounters with moving persons every drive	C3	Missed detection during fully automated driving	C	SG03

Scenario	Failure Mode	Hazard	Specific Situation	Hazardous events & consequences	S	Rationale	E	Rationale	C	Rationale	ASIL	Safety Goal
2	Missed emergency call	Disregarded emergency call after collision	Collision occurred	Unexpected continuation of AVP without emergency call	S2	Emergency call required if collision occurs; every second counts	E4	Encounters with moving persons every drive	C2	Other persons can still set up an emergency call	B	SG06
2	Unintended leaving of the drivable area	Vehicle falls off the brim and crashes into people	Automated driving close to the brim, people stand below the brim.	Collision with person	S3	Fatal injury	E4	Staying in drivable area has to be always ensured during AVP	C1	Other objects prevent vehicle from leaving drivable area	B	SG07
2	Vehicle component breakdown	Safety-critical driving behavior	Breakdown of safety-relevant vehicle component	Collision with person	S2	Collision at medium speed causes severe injuries	E2	Unlikely breakdown of vehicle component	C3	Automated vehicle is uncontrollable	A	SG03
2	No actuator signal	Safety-critical actuator signal	Vehicle actuator sends no actuator signal to controller.	Collision with person	S2	Collision at medium speed causes severe injuries	E4	Frequent computation of actuator signals.	C3	Automated vehicle is uncontrollable	C	SG03
2	Unintended accelerating signal	Safety-critical accelerating signal	Vehicle actuator sends unintended accelerating signal to controller.	Collision with person	S2	Collision at medium speed causes severe injuries	E4	Frequent computation of actuator signals.	C3	Automated vehicle is uncontrollable	C	SG03
2	Unintended braking signal	Safety-critical braking signal	Vehicle actuator sends unintended braking signal to controller.	Collision with other vehicle	S1	Person protected in vehicle	E4	Frequent computation of actuator signals.	C3	Automated vehicle is uncontrollable	B	SG03

Scenario	Failure Mode	Hazard	Specific Situation	Hazardous events & consequences	S	Rationale	E	Rationale	C	Rationale	ASIL	Safety Goal
2	Unintended steering signal	Safety-critical steering signal	Vehicle actuator sends unintended steering signal to controller.	Collision with person	S2	Collision at medium speed causes severe injuries	E4	Frequent computation of actuator signals.	C3	Automated vehicle is uncontrollable	C	SG03
2	Missed deadline for computed actuator signal	Safety-critical actuator signal	Vehicle actuator sends correct, but delayed signal to controller.	Collision with person	S2	Collision at medium speed causes severe injuries	E4	Frequent computation of actuator signals.	C3	Automated vehicle is uncontrollable	C	SG03
2	Missed detection of fire	Safety-critical encounters with pedestrians	Vehicle continues AVP service during fire	Collision with person	S3	Collision at medium speed in combination with fire	E2	Unlikely fire outbreak	C3	Automated vehicle is uncontrollable	B	SG03
2	Missed detection of collision	Breakdown of safety-relevant vehicle components	Vehicle continues AVP service after collision	Uncontrolled proceeding of the AVP service after collision	S3	Collision at medium speed in combination with fire	E4	Encounters with moving persons every drive	C3	Automated vehicle is uncontrollable	B	SG03
3	Parking brake not applied.	Safety-critical situation due to roll off in standby	Vehicle is not in standstill in parking spot	vehicle is moving while still in standby	S1	Activation in low speed	E4	AVP activation process every handover	C3	Automated vehicle is uncontrollable	B	SG04

Scenario	Failure Mode	Hazard	Specific Situation	Hazardous events & consequences	S	Rationale	E	Rationale	C	Rationale	ASIL	Safety Goal
4	Unintended activation of a hand-back request inside the operational design domain	Safety-critical situation due to unintended handback status	Persons getting into the vehicle just before it starts moving	Collision with person	S1	Activation in low speed	E4	AVP activation process every handover	C3	Automated vehicle is uncontrollable	B	SG04
7	Unintended activation of AVP outside the operational design domain	Safety-critical traffic situation resulting from an unintended activation	Driving on highway or in urban areas	Unexpected vehicle behavior on highway	S3	Life-threatening injuries due to accidents at high speeds	E4	AVP is available during normal vehicle use	C3	Assumption: it is not possible to override	D	SG01

List of References

Ahlgrimm, J. et al.: A10 Fußgängerunfälle (2017)
Ahlgrimm, Jörg; Burg, Heinz; Dettinger, Jürgen; Moser, Andreas: A10 Fußgängerunfälle, in: Handbuch Verkehrsunfallrekonstruktion, Springer, 2017

Amersbach, C.; Winner, H.: Functional decomposition: An approach to reduce the approval effort (2017)
Amersbach, Christian; Winner, Hermann: Functional Decomposition: An Approach to Reduce the Approval Effort for Highly Automated Driving, in: 8. Tagung Fahrerassistenz, 2017

Amersbach, C.; Winner, H.: Defining Required and Feasible Test Coverage for HAV (2019)
Amersbach, Christian; Winner, Hermann: Defining Required and Feasible Test Coverage for Scenario-Based Validation of Highly Automated Vehicles, in: 22nd IEEE Intelligent Transportation Systems Conference (ITSC), 2019

AVL List GmbH: Model.CONNECT Overview (2019)
AVL List GmbH: Model.CONNECT Overview; https://www.avl.com/documents/10138/2699442/Model.CONNECT%E2%84%A2+Overview, 2019, Access 05.06.19

Banzhaf, H. et al.: High density valet parking using k-deques in driveways (2017)
Banzhaf, Holger; Quedenfeld, Frank; Nienhuser, Dennis; Knoop, Steffen; Zollner, J. M.: High density valet parking using k-deques in driveways (2017), in: IEEE Intelligent Vehicles Symposium 2017

Banzhaf, H. et al.: The future of parking: A survey on AVP with an outlook on high density parking (2017)
Banzhaf, Holger; Nienhüser, Dennis; Knoop, Steffen; Zöllner, J. M.: The future of parking: A survey on automated valet parking with an outlook on high density parking (2017), in: IEEE Intelligent Vehicles Symposium 2017

Bartlett, J. S.: Best and Worst Cars and SUVs for Visibility (2019)
Bartlett, Jeff S.: Best and Worst Cars and SUVs for Visibility; https://www.consumerreports.org/car-safety/best-and-worst-cars-and-suvs-for-visibility/, 2019, Access 15.06.2019

Breuer, B.; Bill, K. H.: Brake Technology Handbook (2008)
Breuer, B.; Bill, K. H.: Brake Technology Handbook, Issues 689, SAE International, Warrendale, Pennsylvania (USA), 2008

Bundesministerium der Justiz und für Verbraucherschutz: StVZO (2012)
Bundesministerium der Justiz und für Verbraucherschutz: Straßenverkehrs-Zulassungs-Ordnung (StVZO), 2012

Cacilo, A. et al.: Hochautomatisiertes Fahren auf Autobahnen–Industriepolitische Schlussfolgerungen (2015)
Cacilo, Andrej; Schmidt, Sarah; Wittlinger, Philipp; Herrmann, Florian; Bauer, Wilhelm; Sawade, Oliver; Doderer, Hannes; Hartwig, Matthias; Scholz, Volker: Hochautomatisiertes Fahren auf Autobahnen–Industriepolitische Schlussfolgerungen, 2015

Chirca, M. et al.: Autonomous valet parking system architecture (2015)
Chirca, Mihai; Chapuis, Roland; Lenain, Roland: Autonomous valet parking system architecture, in: 2015 IEEE 18th International Conference on Intelligent Transportation Systems, 2015

Continental AG: Pull Up and Have Your Car Parked for You (2017)
Continental AG: Pull Up and Have Your Car Parked for You – Continental Implements Fully Automated Valet Parking, 2017

Daimler AG: Remote Parking Pilot: Remote parking with the smartphone app (2015)
Daimler AG: Remote Parking Pilot: Remote parking with the smartphone app; https://media.daimler.com/marsMediaSite/ko/en/9361355, 2015

Daimler AG: Daimler and Bosch jointly premiere automated valet parking in China (2018)
Daimler AG: Daimler and Bosch jointly premiere automated valet parking in China, 2018

Deutsches Zentrum für Luft- und Raumfahrt e. V.: The PEGASUS Method (2019)
Deutsches Zentrum für Luft- und Raumfahrt e. V.: The PEGASUS Method; https://www.pegasusprojekt.de/, 2019, Access 26.06.2019

Dietmayer, K.: Predicting of machine perception for automated driving (2016)
Dietmayer, Klaus: Predicting of machine perception for automated driving (2016), in: Maurer, M., Gerdes, J.C., Lenz, B., Winner, H. (Eds.) - Autonomous Driving

Donges, E.: Aspekte der aktiven Sicherheit bei der Führung von Personenkraftwagen (1982)
Donges, Edmund: Aspekte der aktiven Sicherheit bei der Führung von Personenkraftwagen, in: Automob-Ind (2), Issues 27, 1982

Donges, E.: Driver behavior models (2014)
Donges, Edmund: Driver behavior models, in: Handbook of driver assistance systems: Basic information, components and systems for active safety and comfort, pp. 1–12, 2014

Dupuis, M.: Virtual Test Drive User Manual (2017)
Dupuis, Marius: Virtual Test Drive User Manual; https://redmine.vires.com/attachments/download/7389/VTDUserManualRevO.pdf, 2017, Access 04.06.2019

Dupuis, M. et al.: OpenDRIVE Format Specification Rev. 1.5 (2019)
Dupuis, Marius; Hekele, Esther; Biehn, Andreas: OpenDRIVE Format Specification Rev. 1.5; http://www.opendrive.org/docs/OpenDRIVEFormatSpecRev1.5M.pdf, 2019

Ebberg, J.: Bosch and Daimler demonstrate driverless parking in real-life conditions (2017)
Ebberg, Jörn: Bosch and Daimler demonstrate driverless parking in real-life conditions, 2017

Einsiedler, J. et al.: Vehicle indoor positioning: A survey (2017)
Einsiedler, Jens; Radusch, Ilja; Wolter, Katinka: Vehicle indoor positioning: A survey, in: 2017 14th Workshop on Positioning, Navigation and Communications (WPNC), 2017

Facione, P. A.: A modal truth-tabular interpretation for necessary and sufficient conditions (1972)
Facione, Peter A.: A modal truth-tabular interpretation for necessary and sufficient conditions, in: Notre Dame Journal of Formal Logic (2), Issues 13, pp. 270–272, 1972

Ferreira, M. et al.: Self-automated parking lots for autonomous vehicles based on vehicular ad hoc networking (2014)
Ferreira, Michel; Damas, Luis; Conceicao, Hugo; d'Orey, Pedro M.; Fernandes, Ricardo; Steenkiste, Peter; Gomes, Pedro: Self-automated parking lots for autonomous vehicles based on vehicular ad hoc networking (2014), in: IEEE Intelligent Vehicles Symposium

Form, T.: PEGASUS Method for Assessment of Highly Automated Driving Function (2018)
Form, Thomas: PEGASUS Method for Assessment of Highly Automated Driving Function; http://en.sip-adus.go.jp/evt/workshop2018/file/PEGASUS_SIP-adus_Thomas_Form.pdf, 2018, Access 02.07.2019

Forschungsgesellschaft für Straßen- und Verkehrswesen e. V.: Richtlinien für die Anlage von Straßen, Abschnitt Knotenpunkte (RAS-K-1) (1988)
Forschungsgesellschaft für Straßen- und Verkehrswesen e. V.: Richtlinien für die Anlage von Straßen, Abschnitt Knotenpunkte (RAS-K-1), in: Plangleiche Knotenpunkte (RAS-K-1) Ausgabe, 1988

Friedl, M. et al.: Vollautomatisiertes Valet Parking: Funktions-und Planungsarchitektur (2015)
Friedl, Martin; Hupka, Adrian; Tanzmeister, Georg: Vollautomatisiertes Valet Parking: Funktions-und Planungsarchitektur, in: 10. Workshop Fahrerassistenz-systeme, 2015

Gasser, T. M. et al.: Rechtsfolgen zunehmender Fahrzeugautomatisierung (2012)
Gasser, Tom M.; Arzt, Clemens; Ayoubi, Mihiar; Bartels, Arne; Bürkle, Lutz; Eier, Jana; Flemisch, Frank; Häcker, Dirk; Hesse, Tobias; Huber, Werner; Lotz, Christine; Maurer, Markus; Ruth-Schumacher, Simone; Schwarz, Jürgen; Vogt, Wolfgang: Rechtsfolgen zunehmender Fahrzeugautomatisierung, Berichte der Bundesanstalt für Strassenwesen - Fahrzeugtechnik (F), Issues 83, Wirtschaftsverl. NW Verl. für neue Wissenschaft, Bremerhaven, 2012

Gasser, T. M.; Westhoff, D.: BASt-study: Definitions of automation and legal issues in Germany (2012)
Gasser, Tom M.; Westhoff, Daniel: BASt-study: Definitions of automation and legal issues in Germany, in: Proceedings of the 2012 road vehicle automation workshop, 2012

Gotzig, H.: Parking Assistance (2016)
Gotzig, Heinrich: Parking Assistance, in: Winner, Hermann et al. (Eds.): Handbook of Driver Assistance Systems, Springer International Publishing, Cham, 2016

Grubmüller, S. et al.: Automated Driving from the View of Technical Standards (2016)
Grubmüller, Stephanie; Plihal, Jiri; Nedoma, Pavel: Automated Driving from the View of Technical Standards, in: Horn, Martin; Watzenig, Daniel (Eds.): Automated Driving: Safer and More Efficient Future Driving, Springer International Publishing, 2016

Hertzberg, J. et al.: Mobile Roboter (2012)
Hertzberg, Joachim; Lingemann, Kai; Nüchter, Andreas: Mobile Roboter, SpringerLink Bücher, Springer Vieweg, Berlin, Heidelberg, 2012

Hessisches Ministerium der Justiz: Garagenverordnung - GaV (2014)
Hessisches Ministerium der Justiz: Verordnung über den Bau und Betrieb von Garagen und Stellplätzen (Garagenverordnung - GaV), in: Verordnung, 2014

Ibisch, A. et al.: Towards autonomous driving in a parking garage (2013)
Ibisch, André; Stümper, Stefan; Altinger, Harald; Neuhausen, Marcel; Tschentscher, Marc; Schlipsing, Marc; Salinen, Jan; Knoll, Alois: Towards autonomous driving in a parking garage: Vehicle localization and tracking using environment-embedded lidar sensors, in: 2013 IEEE Intelligent Vehicles Symposium (IV), 2013

IEC SC 65A: Functional safety of electrical/electronic/programmable electronic safety-related systems (2010)
IEC SC 65A: Functional safety of electrical/electronic/programmable electronic safety-related systems, 3, rue de Varembé, Case postale 131, CH-1211 Genève 20, Switzerland, 2010

International Council on Clean Transportation: European Vehicle Market Statistics Pocketbook (2017)
International Council on Clean Transportation: European Vehicle Market Statistics Pocketbook 2017/18; http://eupocketbook.org/wp-content/uploads/2017/11/ICCT_Pocketbook_2017.pdf, 2017, Access 30.04.2019

International Organization for Standardization: ISO/PAS 21448: Road vehicles - SOTIF (2019)
International Organization for Standardization: ISO/PAS 21448: Road vehicles - Safety of the intended functionality, 2019

ISO: ISO 26262: Road vehicles - Functional safety (2018)
International Organization for Standardization: ISO 26262: Road vehicles - Functional safety, 2018

ISO: ISO 26262-1: Road vehicles - Functional safety - Part 1: Vocabulary (2018)
International Organization for Standardization: ISO 26262-1: Road vehicles - Functional safety - Part 1: Vocabulary, 2018

ISO: ISO 26262-3: Road vehicles - Functional safety - Part 3: Concept phase (2018)
International Organization for Standardization: 2: ISO 26262-3: Road vehicles - Functional safety - Part 3: Concept phase, 2018

Jeevan, P. et al.: Realizing autonomous valet parking with automotive grade sensors (2010)
Jeevan, Prasanth; Harchut, Frank; Mueller-Bessler, Bernhard; Huhnke, Burkhard: Realizing autonomous valet parking with automotive grade sensors, in: 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2010

Klemm, S. et al.: Autonomous multi-story navigation for valet parking (2016)
Klemm, Sebastian; Essinger, Marc; Oberländer, Jan; Zofka, Marc R.; Kuhnt, Florian; Weber, Michael; Kohlhaas, Ralf; Kohs, Alexander; Roennau, Arne; Schamm, Thomas; others: Autonomous multi-story navigation for valet parking, in: 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), 2016

Lefèvre, S. et al.: A survey on motion prediction and risk assessment for intelligent vehicles (2014)
Lefèvre, Stéphanie; Vasquez, Dizan; Laugier, Christian: A survey on motion prediction and risk assessment for intelligent vehicles, in: ROBOMECH Journal (1), Issues1, p. 1, 2014

Leitner, A. et al.: ENABLE-S3: Summary of Results (2019)
Leitner, Andrea; …; Slavik, Zora: ENABLE-S3: Summary of Results; https://drive.google.com/file/d/15c1Oe69dpvW5dma8-uS8hev17x-6V3zU/view, 2019, Access 02.07.2019

Lin, T. et al.: A Survey of Smart Parking Solutions (2017)
Lin, Trista; Rivano, Herve; Le Mouel, Frederic: A Survey of Smart Parking Solutions, in: IEEE transactions on intelligent transportation systems (12), Issues 18, pp. 3229–3253, 2017

Löper, C. et al.: Automated valet parking as part of an integrated travel assistance (2013)
Löper, Christian; Brunken, Claas; Thomaidis, George; Lapoehn, Stephan; Fouopi, Paulin P.; Mosebach, Henning; Köster, Frank: Automated valet parking as part of an integrated travel assistance, in: 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013), 2013

Lotz, F. G.: Eine Referenzarchitektur für die assistierte und automatisierte Fahrzeugführung (2017)
Lotz, Felix G. O. *1.: Eine Referenzarchitektur für die assistierte und automatisierte Fahrzeugführung mit Fahrereinbindung, 2017

Min, K.; Choi, J.: A control system for autonomous vehicle valet parking
Min, Kyoungwook; Choi, Jeongdan: A control system for autonomous vehicle valet parking, in: IEEE 2013 – 13th International Conference

Min, K.-W.; Choi, J.-D.: Design and implementation of autonomous vehicle valet parking system (2013)
Min, Kyoung-Wook; Choi, Jeong-Dan: Design and implementation of autonomous vehicle valet parking system, in: 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013), 2013

Montemerlo, M. et al.: Junior: The stanford entry in the urban challenge (2008)
Montemerlo, Michael; Becker, Jan; Bhat, Suhrid; Dahlkamp, Hendrik; Dolgov, Dmitri; Ettinger, Scott; Haehnel, Dirk; Hilden, Tim; Hoffmann, Gabe; Huhnke, Burkhard; others: Junior: The stanford entry in the urban challenge, in: Journal of Field Robotics (9), Issues 25, pp. 569–597, 2008

NHTSA: Preliminary Statement of Policy Concerning Automated Vehicles (2013)
National Highway Traffic Safety Administration: Preliminary Statement of Policy Concerning Automated Vehicles, 2013

Pech, A. et al.: Parkhäuser - Garagen (2009)
Pech, Anton; Warmuth, Günter; Jens, Klaus; Zeininger, Johannes: Parkhäuser - Garagen, BaukonstruktionenSonderband, 2. Edition, Springer, Wien [u.a.], 2009

Pluta, W.: Lass das Parkhaus das Auto parken! (2017)
Pluta, Werner: Lass das Parkhaus das Auto parken!, 2017

Q-Free ASA: Parking Guidance Solutions (2019)
Q-Free ASA: Parking Guidance Solutions; https://www.q-free.com/solution/parking-guidance-systems/, 2019, Access 16.07.2019

Qiu, R.: A System framework of active parking guidance and information system (2010)
Qiu, Robin (Ed.) A System framework of active parking guidance and information system, IEEE, Piscataway, NJ, 2010

Rauskolb, F. et al.: Caroline: An Autonomously Driving Vehicle for Urban Environments (2008)
Rauskolb, F.; Berger, K.; Lipski C; Magnor M: Caroline: An Autonomously Driving Vehicle for Urban Environments, in: Jounral of Field Robotics (9), Issues 25, 2008

Reschka, A.: Safety Concept for Autonomous Vehicles (2016)
Reschka, Andreas: Safety Concept for Autonomous Vehicles, in: Maurer, Markus et al. (Eds.): Autonomous Driving, Springer Berlin Heidelberg, Berlin, Heidelberg, 2016

Robert Bosch GmbH: Die Infrastruktur kennt den Weg. (2018)
Robert Bosch GmbH: Die Infrastruktur kennt den Weg.; https://www.bosch-mobility-solutions.de/de/highlights/automatisierte-mobilit%C3%A4t/automated-valet-parking/, 2018, Access 11.06.2019

SAE International Standard J3016: Taxonomy for Automated Driving Systems (2014)
SAE International Standard J3016: Taxonomy and Definitions for Terms related to On-Road Motor Vehicle Automated Driving Systems, SAE International, 2014

Schönemann, V. et al.: Scenario-based functional Safety for AD on the Example of AVP (2018)
Schönemann, Valerij; Winner, Hermann; Glock, Thomas; Otten, Stefan; Sax, Eric; Boeddeker, Bert; Verhaeg, Geert; Tronci, Fabrizio; Padilla, Gustavo G.: Scenario-based functional Safety for automated Driving on the Example of Valet Parking, in: Future of Information and Communication Conference, 2018

Schönemann, V. et al.: Fault Tree-based Derivation of Safety Requirements for AVP (2019)
Schönemann, Valerij; Winner, Hermann; Glock, Thomas; Sax, Eric; Boeddeker, Bert; Vom Dorff, Sebastian; Verhaeg, Geert; Tronci, Fabrizio; Padilla, Gustavo G.: Fault Tree-based Derivation of Safety Requirements for Automated Driving on the Example of cooperative Valet Parking, in: 26th International Technical Conference on The Enhanced Safety of Vehicles (ESV), 2019

Schönemann, V. et al.: Maneuver-based adaptive Safety Zone for infrastructure-supported AVP (2019)
Schönemann, Valerij; Duschek, Mara; Winner, Hermann: Maneuver-based adaptive Safety Zone for infrastructure-supported Automated Valet Parking, in: , 2019

Schwesinger, U. et al.: Automated valet parking and charging for e-mobility (2016)
Schwesinger, Ulrich; Bürki, Mathias; Timpner, Julian; Rottmann, Stephan; Wolf, Lars; Paz, Lina M.; Grimmett, Hugo; Posner, Ingmar; Newman, Paul; Häne, Christian; others: Automated valet parking and charging for e-mobility, in: 2016 IEEE Intelligent Vehicles Symposium (IV), 2016

Shalev-Shwartz, S. et al.: On a Formal Model of Safe and Scalable Self-driving Cars (2017)
Shalev-Shwartz, Shai; Shammah, Shaked; Shashua, Amnon: On a Formal Model of Safe and Scalable Self-driving Cars, 2017

Singh, S.: Non-traffic surveillance: fatality and injury statistics in non-traffic crashes, 2012 to 2014 (2016)
Singh, Santokh: Non-traffic surveillance: fatality and injury statistics in non-traffic crashes, 2012 to 2014, 2016

Stolte, T. et al.: Safety goals and functional safety requirements for actuation systems of AV (2016)
Stolte, Torben; Bagschik, Gerrit; Maurer, Markus: Safety goals and functional safety requirements for actuation systems of automated vehicles, in: 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), 2016

Szymberski, R.: Construction Project Safety Planning (1997)
Szymberski, R.: Construction Project Safety Planning, in: TAPPI Journal Vol. 80(11), pp. 69–74, 1997

Timpner, J. et al.: k-Stacks: High-density valet parking for automated vehicles (2015)
Timpner, Julian; Friedrichs, Stephan; van Balen, Johannes; Wolf, Lars: k-Stacks: High-density valet parking for automated vehicles, in: IV2015, Seoul, South Korea, IEEE, [Piscataway, New Jersey], 2015

Ulbrich, S. et al.: Defining and Substantiating the Terms Scene, Situation, and Scenario for AD (2015)
Ulbrich, Simon; Menzel, Till; Reschka, Andreas, et al. (Eds.) Defining and Substantiating the Terms Scene, Situation, and Scenario for Automated Driving, IEEE, 2015

United Nations: Vienna Convention on Road Traffic (1968)
United Nations: Vienna Convention on Road Traffic, 1968

Urmson, C. et al.: Autonomous Driving in Urban Environments: Boss and the Urban Challenge (2008)
Urmson, C.; Anhalt, J.; Bagnell D; Baker, C.: Autonomous Driving in Urban Environments: Boss and the Urban Challenge, in: Journal of Field Robotics 25(8), 2008

van de Poel, I.; Robaey, Z.: Safe-by-Design: from Safety to Responsibility (2017)
van de Poel, Ibo; Robaey, Zoë: Safe-by-Design: from Safety to Responsibility, in: Nanoethics (3), Issues 11, pp. 297–306, 2017

VDA: Automation: From Driver Assistance Systems to Automated Driving (2015)
Verband der Automobilindustrie: Automation: From Driver Assistance Systems to Automated Driving, in: VDA Magazine-Automation, p. 2, 2015

Verband der Automobilindustrie e.V.: VDA 702 E-Parameter according ISO 26262-3 (2015)
German Association of the Automotive Industry: VDA 702 E-Parameter according ISO 26262-3; https://www.vda.de/en/services/Publications/Publication.~1289~.html, 2015

Wachenfeld, W.; Winner, H.: Die Freigabe des autonomen Fahrens (2015)
Wachenfeld, W.; Winner, H.: Die Freigabe des autonomen Fahrens, in: Maurer, M.; Gerdes, J. C.; Lenz, B., Winner, H. (Eds.): Autonomes Fahren, Springer Berlin Heidelberg, 2015

Wachenfeld, W. H.: How Stochastic can Help to Introduce Automated Driving (2017)
Wachenfeld, Walther H. K.: How Stochastic can Help to Introduce Automated Driving, 2017

Zixiong, J.: Report shows extreme shortage of parking spaces in China's megacities (2017)
Zixiong, Jin: Report shows extreme shortage of parking spaces in China's megacities; https://news.cgtn.com/news/3d67544e7a49444e/share_p.html, 2017, Access 20.05.2019

Own Publications

Schönemann, Valerij.; Winner, Hermann; Glock, Thomas; Otten, Stefan; Sax, Eric; Boeddeker, Bert; Verhaeg, Geert; Tronci, Fabrizio; Padilla, Gustavo G.: Scenario-based functional safety for automated driving on the example of valet parking. In: Arai K., Kapoor S., Bhatia R. (eds) Advances in Information and Communication Networks. Future of Information and Communication Conference, Advances in Intelligent Systems and Computing, vol. 886, pp. 53-64. Springer, Cham, 2018, Singapur.

Schönemann, Valerij; Duschek, Mara; Winner, Hermann: Maneuver-based adaptive Safety Zone for infrastructure-supported Automated Valet Parking. In: Proceedings of the 5th International Conference on Vehicle Technology and Intelligent Transport Systems - Volume 1: VEHITS, pp. 343-351, 2019, Heraklion, Crete, Greece.

Schönemann, Valerij; Glock, Thomas; Sax, Eric; Boeddeker, Bert; vom Dorff, Sebastian; Verhaeg, Geert; Tronci, Fabrizio; Padilla, Gustavo G.; Winner, Hermann: Fault tree-based Derivation of Safety Requirements for Automated Driving on the Example of cooperative Valet Parking. In: Proceedings of the 26th International Technical Conference on The Enhanced Safety of Vehicles (ESV), 2019, Eindhoven, Netherlands.

Junietz, Philipp; Wachenfeld, Walter; Schönemann, Valerij; Domhardt, K.; Tribelhorn, Wadim; Winner, Hermann: Gaining Knowledge on Automated Driving's Safety - The risk-free VAAFO tool. In: Control Strategies for Advanced Driver Assistance Systems and Autonomous Driving Functions, pp. 47-65, Springer, Cham, 2019.

Supervised Theses

Marius Fischer, Maschinenbau: Bewertung von Systemarchitekturen für das vollautomatisierte Valet-Parken. Bachelor-Thesis Nr. 1297/17, 2017

Maximilian Bock, Maschinenbau: Erarbeitung von Sicherheitsanforderungen für das vollautomatisierte Valet-Parken. Master-Thesis Nr. 648/17, 2017

Chenxu Guo, Verkehrswesen: Erarbeitung von Sicherheitsmechanismen bei Degradation eines vollautomatisierten Fahrzeugs im Parkhaus. Master-Thesis Nr. 655/17, 2017

Florian Krull, Wirtschaftsingenieurwesen: Erarbeitung eines Funktionstests für das vollautomatisierte Fahren im Parkhaus. Master-Thesis Nr. 670/17, 2017

Mara Duschek, Computational Engineering: Erarbeitung einer Sicherheitszone für das vollautomatisierte Valet-Parken. Master-Thesis Nr. 674/17, 2017

Bo Sun, Maschinenbau: Integration einer Sicherheitszone anhand eines bestehenden Sensormodells für das vollautomatisierte Valet-Parken. Bachelor-Thesis Nr. 1328/18, 2018

Lukas Jung, Maschinenbau: Ableitung von Testfällen für Sicherheitsanforderungen des vollautomatisierten Valet-Parkens. Master-Thesis Nr. 685/18, 2018

Sebastian Östreicher, Maschinenbau: Dekomposition von Sicherheitsanforderungen für das vollautomatisierte Valet-Parken. Master-Thesis Nr. 710/18, 2018

Philipp Chrysalidis, Maschinenbau: Erarbeitung eines Sicherheitskonzepts für vollautomatisiertes Fahren auf einem Versuchsgelände. Master-Thesis Nr. 711/18, 2018