Capability-Based Routes for Autonomous Vehicles

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

Dissertation

vorgelegt von

Moritz Lippert M. Sc.

aus Wertheim

Berichterstatter:	Prof. Dr. rer. nat. Hermann Winner
Mitberichterstatter:	Prof. Dr.-Ing. Krzysztof Czarnecki

Tag der Einreichung:	29.11.2022
Tag der mündlichen Prüfung:	17.01.2023

Darmstadt 2023

D 17

Lippert, Moritz: Capability-Based Routes for Autonomous Vehicles
Darmstadt, Technische Universität Darmstadt
Tag der mündlichen Prüfung: 17.01.2023

Bitte verweisen Sie auf:
URN: urn:nbn:de:tuda-tuprints-237775
URI: https://tuprints.ulb.tu-darmstadt.de/id/eprint/23777

Preface

Die vorliegende Arbeit entstand während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Fachgebiet Fahrzeugtechnik (FZD) der TU Darmstadt im Rahmen des Projektes UNICAR*agil*. Dieses wurde durch das Bundesministerium für Bildung und Forschung (BMBF) gefördert.

Mein besonderer Dank gilt meinem Doktorvater Prof. Dr. rer. nat. Hermann Winner, der mich seit 2018 über seine aktive Amtszeit als Professor hinaus betreut hat. Seine Ideen und Begeisterung für das Thema haben maßgeblich zum Erfolg dieser Arbeit beigetragen. Neben der fachlichen Betreuung hat er es immer verstanden, meine Motivation auch nach Rückschlägen hoch zu halten. Ohne diese Unterstützung und die Freiheiten, die er mir in der Gestaltung meines Arbeitsalltags ließ, wäre die vorliegende Arbeit nicht in dieser Form entstanden.

Weiterhin bedanke ich mich bei Prof. Dr.-Ing. Krzysztof Czarnecki von der University of Waterloo für die Übernahme des Korreferats und das Interesse an meiner Forschung.

Insbesondere möchte ich mich auch bei meinen Kolleginnen und Kollegen am Fachgebiet Fahrzeugtechnik (FZD) für die konstruktive Zusammenarbeit und Unterstützung sowohl durch fachliche als auch persönliche Gespräche bedanken. Besonders hervorzuheben ist die Zusammenarbeit mit Felix Glatzki zur gemeinsamen Entwicklung der Verhaltenssemantischen Szeneriebeschreibung, die für das Gelingen dieser Arbeit essentiell war. Zudem bedanke ich mich bei allen für die einzigartige Gemeinschaft bei FZD, die mir über den Arbeitsalltag hinaus viele schöne Erinnerungen beschert hat.

Ein weiterer Dank gebührt meinem Team des asc Darmstadt. Der gemeinsame sportliche Ausgleich und unser familiäres Verhältnis hat mir wichtige emotionale Unterstützung während meiner Promotionszeit geboten.

Zuletzt danke ich meinen Eltern für die bereichernden und intensiven, gemeinsamen Jahre und die Ermöglichung meines Bildungsweges, der mich letztendlich zu meiner Promotion geführt hat.

Darmstadt, November 2021.

Table of Contents

List of Symbols and Indices

Latin formula symbols:

Symbol	Unit	Description
a	$\mathrm{m/s^2}$	Acceleration
A	$\mathrm{m^2}$	Area
B	–	Set of type of boundary
c	–	Cost function
C	–	Sequence of behavior spaces
D	–	Behavioral demand of an element within a concatenation
d	m	Distance
DC	–	Set of driving capabilities
DR	–	Set of driving requirements
E	–	Element of concatenation
i	–	Running index
j	–	Running index
k	–	Running index
l	m	Length
m	–	Running index
M	–	Set of elements
n	–	Quantity
P	–	Set of type of traffic participants
r	m	Radius
TC	–	Set of test certificates
t	s	Time
T	–	Transition within a concatenation
v	$\mathrm{m/s}$	Speed
w	m	Width

Greek formula symbols:

Symbol	Unit	Description
α	rad	Angle
κ	$1/\mathrm{m}$	Curvature

Indices:

Symbol	Description
act	Actual
app	Approaching
AV	Autonomous vehicle
bound	Boundary
BS	Behavior space
C	Concatenation
conv	Conventional
DC	Driving capability
eff	Effective
fs	Free space
l	Left
lim	Limit
match	Matching
max	Maximum
min	Minimum
offLat	Lateral offset
offLon	Longitudinal offset
orig	Origin
pre	Preceding
proof	Proof
r	Right
rel	Relative
res	Resulting
reserv	Reservation
sm	Safety margin
tot	Total
TP	Traffic participant

List of Abbreviations

ADAS	Advanced Driver Assistance System
ADS	Automated Driving System
ASAM	Association for Standardization of Automation and Measuring Systems
AV	Autonomous Vehicle
BC	Boundary Capability
BR	Boundary Requirement
BSI	British Standards Institution
BSSD	Behavior-Semantic Scenery Description
CoG	Center of Gravity
DC	Driving Capability
DDT	Dynamic Driving Task
DIN	German Institute for Standardization (german: Deutsches Institut für Normung)
DR	Driving Requirement
GQ	Guiding Question
HARA	Hazard Analysis and Risk Assessment
ID	Identification Number
ISO	International Organization for Standardization
NHTSA	National Highway Traffic Safety Administration
ODD	Operational Design Domain
OR	Overtake Requirement
OSM	OpenStreetMap
OWM	Operational World Model
RASt	Guidelines for the Design of Urban Roads (german: Richtlinien für die Anlage von Stadtstraßen)
RC	Reservation Capability
ROD	Restricted Operational Domain
ROI	Region of Interest
Rq	Requirement
RQ	Research Question
RR	Reservation Requirement
RSS	Responsibility-Sensitive Safety

SOTIF	Safety of the Intended Functionality
SR	Speed Requirement
STPA	System-Theoretic Process Analysis
StVO	German Road Traffic Regulation (german: Straßenverkehrs-Ordnung)
XML	Extensible Markup Language

List of Figures

List of Tables

Kurzzusammenfassung

Das Streben nach der Automatisierung von Kraftfahrzeugen ist ein anhaltender Trend in der Automobilindustrie. Besonders herausfordernd ist dabei das Ziel, fahrerlos betriebene, autonome Fahrzeuge (AF) in den Straßenverkehr einzubringen. Zur Realisierung dieser Vision ist eine zielgerichtete Entwicklung der autonomen Fahrfunktionen unabdingbar. Ein gezielter Entwicklungsprozess ist allerdings nur möglich, wenn die Fahrfunktionen möglichst vollständig und passend auf das Einsatzgebiet (engl. ODD) zugeschnitten sind. Unabhängig vom Anwendungsfall haben alle AF eine Gemeinsamkeit: Fahren mindestens einer Route von A nach B - egal ob einfach oder komplex. Für den Betrieb muss deshalb sichergestellt werden, dass die Fahranforderungen (FA) der potentiellen Routen die Fahrfähigkeiten (FF) der AF nicht überfordern. Bisher gibt es keinen Ansatz, der eine Identifikation dieser Überforderung leistet.

Die vorliegende Arbeit stellt eine Methode zur routenbasierten Spezifikation von FA und FF für AF vor. Dabei wird der Kernforschungsfrage nachgegangen, wie Routen identifiziert werden können, deren FA die FF der AF nicht überfordern. Eine initiale Analyse zeigt die Abhängigkeiten zwischen Route und FA auf. Dabei stellt sich die in der ODD definierte Szenerie als fundamentale Grundlage für die Spezifikation von Verhaltensanforderungen als Teil der FA heraus. In Kombination mit den geltenden Verkehrsregeln definieren die Szenerieelemente die Verhaltensgrenzen für AF. Diese Grenzen werden mithilfe einer Analyse dieser Kombinationen gezielt als Verhaltensforderungen aus der Szenerie extrahiert und klassifiziert. Um die routenbasierte Spezifikation von FA zu ermöglichen, werden die Verhaltensforderungen in Form von Verhaltensräumen in eine generische Kartenrepräsentation überführt - die Verhaltenssemantische Szeneriebeschreibung (engl. BSSD).

Basierend auf der BSSD wird eine Methode entwickelt, die Verhaltensanforderungen anhand der routenbedingten Verkettung von Verhaltensräumen generiert. Als Ergebnis liegen neben der Methode selbst die zugehörigen Verhaltensanforderungen als Basis für die routenbasierte Spezifikation von FA und FF vor. Zur Spezifikation wird ein Konzept für den Abgleich von FA und FF vorgestellt. Es zeigt sich, dass die FA stark von Geometrie und Eigenschaft der Szenerieelemente abhängig sind, sodass gleiche Verhaltensanforderungen nicht zwangsweise gleiche FA bedingen. Diese Abhängigkeiten werden für die Spezifikation verwendet, die zugleich eine Definition von Abgleichskriterien für eine Auswahl von DRs und zugehörigen DCs ermöglicht. Um den Abgleich zu realisieren, wird eine fähigkeitsbasierte Routensuche entwickelt und umgesetzt. In die Routensuche fließen alle erarbeiteten Ergebnisse der Arbeit ein, sodass der gesamte Ansatz anhand der Anwendung auf ein reales Straßennetz evaluiert werden kann. Die Evaluation zeigt, dass die Identifikation von bewältigbaren Routen für AF anhand der Szenerie möglich ist und welche Hürden basierend auf identifizierten Defiziten noch überwunden werden müssen.

Abstract

The pursuit of vehicle automation is an ongoing trend in the automotive industry. Particularly challenging is the goal of introducing driverless autonomous vehicles (AVs) into road traffic. To realize this vision, a targeted development of autonomous driving functions is essential. However, a targeted development process is only possible if the driving functions are tailored as appropriately and completely as possible to the operational design domain (ODD). Regardless of use case, all AVs have one thing in common: driving at least one route from A to B - whether simple or complex. For operational purposes, it is therefore necessary to ensure that the driving requirements (DRs) of the potential routes within the ODD do not exceed the driving capabilities (DCs) of the AVs. Currently, there is no approach that accomplishes the identification of exceeded capabilities.

This work presents a method for route-based specification of DRs and DCs for AVs. It addresses the core research question of how to identify routes with DRs that do not exceed the DCs of AVs. An initial analysis reveals the dependencies between route and DRs. Thereby, the scenery defined in the ODD is found to be a fundamental basis for the specification of behavioral requirements as part of the DRs. In combination with the applicable traffic rules, the scenery elements define the behavioral limits for AVs. These limits are specifically extracted and classified as behavioral demands from the scenery using an analysis of these combinations. To enable a route-based specification of DRs, the behavioral demands are modeled as behavior spaces and transformed into a generic map representation - the Behavior-Semantic Scenery Description (BSSD).

Based on the BSSD, a method is developed that generates behavioral requirements based on the route-constrained concatenation of behavior spaces. As a result, in addition to the method itself, the associated behavioral requirements are available as a basis for the route-based specification of DRs and DCs. Constraints for the specification are defined by the developed concept for the matching of DRs and DCs. It is shown that the DRs are strongly dependent on the geometry and property of the scenery elements, so that equal behavioral requirements do not necessarily imply equal DRs. These dependencies are used for the specification enabling the definition of matching criteria for a selection of DRs and corresponding DCs. To realize the matching, a capability-based route search is developed and implemented. The route search incorporates all elaborated results of the work enabling the whole approach to be evaluated by applying it to a real road network. The evaluation shows that the identification of feasible routes for AVs based on the scenery is possible and which hurdles based on identified deficits still have to be overcome.

1 Introduction

Autonomous and connected driving is a continuing trend in the international automotive industry. Starting with Advanced Driver Assistance Systems (ADASs) that merely support the driver in their most basic form, a strong development towards autonomous driving systems is currently emerging. These vehicles are characterized in particular by a high level of system complexity, as the human driving task is completely taken over by a driving automation system. In principle, such autonomous vehicles must move safely through road traffic during operation. In addition to collision avoidance, compliance with the applicable traffic regulations is a key factor in road safety. Even in the case of collision-free driving, secondary accidents involving other traffic participants potentially occur if the traffic rules are violated. Besides safety aspects, compliance with traffic regulations also contributes to road traffic efficiency. The functions to ensure such roadworthy operation of autonomous vehicles are typically defined in Operational Design Domains (ODDs). The ODD specifies operating conditions for which autonomous vehicles are developed and tested to function[1], ensuring safe operation. ODDs can be diverse and are usually based on the use case of autonomous vehicles. A vehicle with the use case of a highway chauffeur will move autonomously on highways accordingly, while an autonomous urban shuttle will be operated in urban areas. Obviously, the characteristics and complexity of use cases vary greatly, requiring different driving capabilities from autonomous vehicles. For safety validation of autonomous driving, it would therefore have to be proven that the autonomous vehicles have all the necessary capabilities to be operated safely in their ODD.

The question of how such safety validation can be achieved successfully and efficiently is currently still open. A well-known approach is the statistical proof of safety by driving very long distances in order to be able to make a statement about the failure rate of the system. This involves driving million or even billion of test kilometers, since the occurrence of challenging situations for the automation is statistically very rare[2]. Due to the almost impossible test effort of statistical proof, there is currently a trend towards safety-by-design approaches, which is also encouraged by the ISO/TR 4804[3]. The idea of this approach is that safety validation and assurance are explicitly considered and introduced already in an early stage of the development process, as also recommended by the ISO 21448[4], for example. It is expected that in this way the purely statistical safety validation can be partially replaced in order to reduce the overall testing effort.

For the development process of autonomous vehicles, the safety-by-design approach implies

---

[1] SAE: SAE J3016: Taxonomy and Definitions of Terms for Automation Systems (2021), p. 17.

[2] Wachenfeld, W.; Winner, H.: The Release of Autonomous Vehicles (2016), p. 425-449.

[3] ISO: ISO/TR 4804:2020: Road vehicles - Safety and cybersecurity for automated driving systems (2020).

[4] ISO: ISO 21448:2022: Road vehicles - Safety of the intended functionality (2022).

that the driving capabilities for the selected ODD are specified as clearly and completely as possible at the beginning. Regardless of the use case, the minimum mission of an autonomous vehicle for which capabilities must be available is always a trip from location A to location B. Every further mission again consists of routes that must be mastered by the autonomous vehicles. Different routes have different levels of difficulty that have to be overcome. It is absolutely relevant whether a road section is driven in one direction or the other, or whether a turn is made at an intersection or not. In order to fulfill the driving mission accordingly, it has to be ensured that the driving requirements of the route do not exceed the driving capabilities of the autonomous vehicle. Current approaches do not yet consider these route-based driving capabilities required in order to drive within the ODD.

1.1 Problem Analysis and Fundamental Terms

The relationship between the route of a driving mission and the driving capabilities required has not been sufficiently researched according to the current state of research and technology. While an ODD specification defines the operational domain of an autonomous vehicles, there is usually no information on the resulting driving requirements or driving capabilities when operating in the ODD[5]. Without this information, driving-related targeted development of autonomous vehicles is not efficient. It must always be assumed that the autonomous vehicles must master the ODD in its entirety with all possible combinations of the defined ODD elements. Therefore, the relationship between ODD, driving requirements and capabilities of autonomous vehicles with respect to the mission-based indispensable route is analyzed. In the course of this, fundamental terms for the present work are explained and defined.

A central element in this work is the autonomous vehicle. Therefore, the conceptual distinction from generally automated vehicles is considered first. Automated vehicles are divided into different levels of automation according to SAE J3016[6a]. The key criterion for differentiating automation systems is the dynamic driving task, which is defined as follows:

Dynamic Driving Task (DDT) contains ”all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic” [6b].

The DDT is again differentiated into two further sub-tasks to define the automation levels. First, it is necessary to ensure sustained control over the longitudinal and lateral movement of the vehicle. On the other hand, it is necessary to detect objects and events in the vehicle environment and to initiate reactions based on these. Both sub-tasks can basically be performed by a human driver or by an automation system. Depending on the division of tasks between the human driver and the

---

[5] Exceptions might be very limited ODDs, which are defined very specifically and thus hardly generalizable. Navya and EasyMile are manufacturers of AVs that develop on the basis of such narrowly chosen ODDs.

[6] SAE: SAE J3016: Taxonomy and Definitions of Terms for Automation Systems (2021). a: p. 17 ff.; b: p. 9.

automation system, the levels of driving automation are classified. Level 0, level 1 and level 2 are systems in which the human driver must permanently take over one of the two sub-tasks of the DDT. The human driver thus has permanent control over the system. Automation systems of level 3 take over the complete DDT temporarily, so that a handover of the DDT must take place between the vehicle and the human driver. Level 4 and level 5 automation systems permanently take over the complete DDT, no longer requiring the human driver to be in control of the vehicle. Since Level 4 and 5 systems perform the driving task completely and independently, these driving systems can also be referred to as autonomous[7]. The focus of this work is on these autonomous systems, which is why the term *autonomous vehicle* is used in the following:

Autonomous Vehicle (AV) in the context of this work, refers to a vehicle with a driving automation system that permanently takes over the DDT completely without the possibility of intervention by a human driver.

At the beginning of the development process, the function of an AV must basically be defined and sufficiently specified. Without a complete functional specification, it is possible that necessary functions will be implemented incompletely or not at all during the development process. In the worst case, this leads to AVs being released for public road traffic even though they do not function completely and safely in the intended area of application. For this reason, it is necessary to specify the ODD of an AV clearly and as completely as possible. For AVs, the ODD is defined according to SAE J3016 as follows:

Operational Design Domain describes ”operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographic, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics.”[8]

According to Czarnecki[9], the ODD mainly includes scenery constraints in addition to vehicle behavior and state constraints. Geyer et al.[10] define scenery as an environment for dynamic objects built from a structured collection of individual, static elements. Ulbrich et al.[11] use and extend this definition in the context of a work on a unified term definition for the automated driving community. As a subset of other terms, scenery is not explicitly formulated in a definition in this work. Therefore, based on the contribution of Ulbrich et al., the following definition of scenery is formulated for this work:

Scenery describes all geo-spatially stationary elements of a vehicle’s environment that provide a framework for its motion, based on metric, semantic, and topological information. Quasi-

---

[7] It is assumed that there is no possibility for a human driver to take over the DDT.

[8] SAE: SAE J3016: Taxonomy and Definitions of Terms for Automation Systems (2021), p. 17.

[9] Czarnecki, K.: Operational Design Domain for Automated Driving Systems (2018), p. 6.

[10] Geyer, S. et al.: Unified ontology for generating test and use–case catalogues for vehicle guidance (2014).

[11] Ulbrich, S. et al.: Terms Scene, Situation, and Scenario for Automated Driving (2015).

stationary weather and lighting conditions are understood to be part of the scenery, as are time-varying elements that represent attributes of spatially stationary elements.

Consequently, components of a scenery are the lane network, stationary elements such as traffic signs or curbs, vertical elevation, and environmental conditions. Without further elements and aspects, the scenery thus merely describes an empty road at given weather conditions and times of day.

As a first intermediate conclusion, an AV is ideally operated in the ODD intended for its operation. A central component of the ODD is the scenery. The ODD thus defines the scenery intended for the AV's trips. With respect to the DDT of an AV, the SAE J3016 defines the term *trip* as follows:

Trip describes ”the traversal of an entire travel pathway by a vehicle from the point of origin to a destination.”[12]

The trip of an AV is primarily determined by the route based on a driving mission of the AV. In common language understanding, a route is the defined way to get from one place to another place. It is initially irrelevant whether the route serves a specific purpose, is intended only for certain groups of people, or is intended for certain types of transportation. Thus, the route is simply ”a particular way or direction between places”[13]. Besides such general definition, there is no unified definition with respect to AVs. For this reason, this general definition is adapted in relation to autonomous driving. Based on the previous findings, a route should therefore be limited to ways within the scenery. As a part of the scenery, a route is defined as follows:

Route describes a particular way between two locations within a scenery.

It is obvious that a route mostly represents only a subset of the scenery[14]. In the extreme case, the route covers the entire scenery. However, this is very unlikely for larger sceneries, since the directionality of the route would require addressing both possible directions of travel. This intuitively contradicts the purpose of a route. From this it can be deduced that the route of an AV limits the scenery to be driven on. For the trip based on a route, only the parts of the scenery belonging to this route are relevant.

To ensure safe operation during a trip of the AV in compliance with traffic regulations, the applicable traffic regulations must be observed and complied with at all times. However, traffic rules alone are not sufficient to make a statement about specific rules of behavior within a scenery specified in the ODD. The traffic rules are closely linked to the elements of the scenery, so that only a combination of scenery and traffic rules can provide information about required behavior in road traffic. Given traffic rules in a country, the scenery consequently defines the rules of behavior in the public traffic area. Lippert et al.[15] define these scenery-based behavioral rules even more

---

[12] SAE: SAE J3016: Taxonomy and Definitions of Terms for Automation Systems (2021), p. 20.

[13] Cambridge University Press & Assessment: Meaning of route in English (2022).

[14] Exceptions are again very limited ODDs, which consist for example only of a single round trip.

[15] Lippert, M. et al.: Behavior-Semantic Scenery Description (BSSD) for Automated Driving (2022).

specifically as *behavioral demand*:

Behavioral demand describes the restriction of the legally allowed behavior of a traffic participant without specifying an explicit behavior.

Consequently, an AV is restricted in its legally possible behavior based on the scenery along a route. In this context, behavior means external behavior[16] or externally observable state changes of traffic participants[17]. In consensus of these two definitions, the following definition is used in this work:

Observable behavior describes the externally observable behavior of a road user, representing all externally observable actions and interactions with the environment.

As a result, an AV has an observable behavior while driving on a route within a scenery. Thereby, the observable behavior is limited by the behavioral demands that result from the route-related scenery. It can be logically concluded that the behavioral demands must be the basis for behavioral requirements of an AV. Behavioral requirements derived and specified based on the behavioral demands in turn define the observable behavior of the AV. In this way, the specification loop is closed so that it can be ensured that the vehicle behavior remains within the behavioral demands of the scenery of an ODD while driving on a route. Behavioral requirements are defined as follows:

Behavioral requirements describe requirements for the observable behavior of an AV with regard to function specification.

In addition to behavioral requirements, the ODD imposes other requirements on an AV. The classic *Sense-Plan-Act* scheme is considered, which was predominantly used in robotics long before AVs were an issue[18], but still is a prominent system architecture for AVs[19]. In order to fulfill the DDT accordingly, an AV must sense its environment, plan behavior based on this, and act according to the planned behavior. Thus, for a requirement specification based on the ODD to be as complete as possible, other requirements are needed in addition to the behavioral requirements. In the present work, these requirements will be considered in more detail. Initially, the following definition is sufficient:

Driving requirements describe requirements for the specification of the DDT that result from the ODD. Behavioral requirements are a part of these overall requirements.

Consequently, an AV must satisfy the route-based driving requirements of the ODD in order to operate in it. This means that an AV must have all the necessary driving capabilities required by the driving requirements. The driving requirements may differ due to their dependency on the

---

[16] Nolte, M. et al.: Skill- and ability-based development process for self-aware automated road vehicles (2017).

[17] Czarnecki, K.: Operational World Model Ontology for Automated Driving Systems - Part 2 (2018).

[18] Nilsson, N. J.: Principles of artificial intelligence (1982).

[19] Anderson, J. M. et al.: Autonomous Vehicle Technology: A Guide for Policymakers (2016), p. 58.

route-related scenery sections being driven through. Conversely, this means that different driving capabilities may be required to drive on different routes within the scenery. Driving capabilities are defined as follows:

Driving capabilities are capabilities which are necessary to drive within the scenery of an ODD. For this purpose, the driving capabilities must meet the driving requirements of the ODD.

Figure 1-1 shows the presented dependencies in an UML class diagram[20]. In the center, the route is highlighted as the central element. All entities that are limited on the basis of the route, i.e. are not fully exploited, are marked with a dashed frame line. The dependencies shown in the context of this problem analysis highlight the route as a crucial element in the specification of driving requirements and driving capabilities. Consequently, whether an AV is able to fulfill a driving mission depends significantly on the selected route. The route limits the scenery to the route-related parts, which propagates these limitations to the driving requirements. To the knowledge of the author of this work, current approaches and methods do not address this fundamental dependency between routes and required driving capabilities. Without taking this dependency into account, valuable information for development, test and operation of AVs is not used. Instead of always considering the ODD as a whole, the route-based consideration could contribute to a more targeted and efficient development and release process. Based on these finding, research objectives and research questions are derived in the following section.

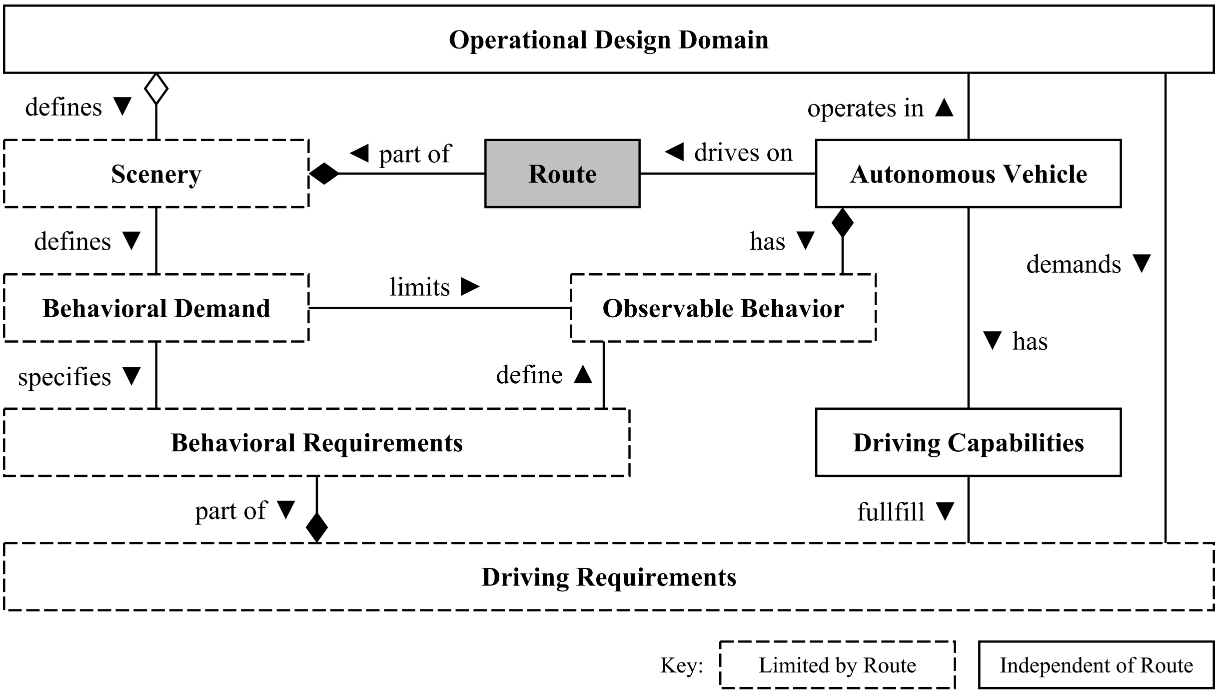


Figure 1-1: Relationship between ODD, driving requirements and capabilities.[21]
Legend: —— Association; —◇ Aggregation; —◆ Composition

---

[20] Object Management Group: Unified Modeling Language Specification Version 2.51 (2017).

[21] Adapted from Lippert, M.; Winner, H.: Behavioral Requirements for Automated Driving (2022).

1.2 Research Objectives and Research Questions

Driving on routes is an indispensable prerequisite for any use case of AVs. If at least one route, regardless of complexity or length, cannot be driven within the specified ODD of an AV, the AV fails to serve its purpose. For this reason, it must be ensured in the development process of AVs that the routes relevant for the respective use case are actually available in operation. The dependencies shown in the previous section are promising for establishing a traceable link between routes within an ODD and the resulting driving requirements and driving capabilities. Based on this relationship, a matching is possible in order to determine whether or not the driving requirements of a route exceed the actual driving capabilities of an AV. In order to achieve this matching and possible associated benefits, the following research objectives and sub-objectives are defined for this work:

- Development of a method for route-based specification and matching of driving requirements and driving capabilities for AVs.
    - The method uses the scenery of an ODD as a basis.
    - The method enables a route-based analysis of the scenery of an ODD.
    - The method ensures a matching between driving requirements of routes and driving capabilities of AVs.
- Analysis of the applicability of the method.
- Evaluation of the method with regard to the previously listed research objectives.

The superordinate Research Question (RQ) for achieving a match between driving requirements and driving capabilities is defined as follows:

RQ 0: *How to identify routes with driving requirements that do not exceed the driving capabilities of AVs?*

This superordinate RQ can only be answered and the targeted method achieved if the previously identified dependencies between route, ODD, driving requirements, and driving capabilities are correct. Therefore, the following research questions for this work are defined that specifically address these dependencies as additionally shown in Figure 1-2:

RQ 1: *What behavioral demands result from the scenery of an ODD?*

RQ 2: *How to design a representation of behavioral demands as a basis for deriving route-based driving requirements?*

RQ 3: *How are driving requirements derived based on the behavioral demands of a scenery?*

RQ 4: *How are driving capabilities to be designed so that routes within an ODD can be determined based on a matching of driving capabilities and driving requirements?*

In addition, the following research questions arise that address applicability analysis and evaluation of the overall method:

RQ 5: *Is the developed method applicable?*

RQ 6: *How is the developed method to be evaluated?*

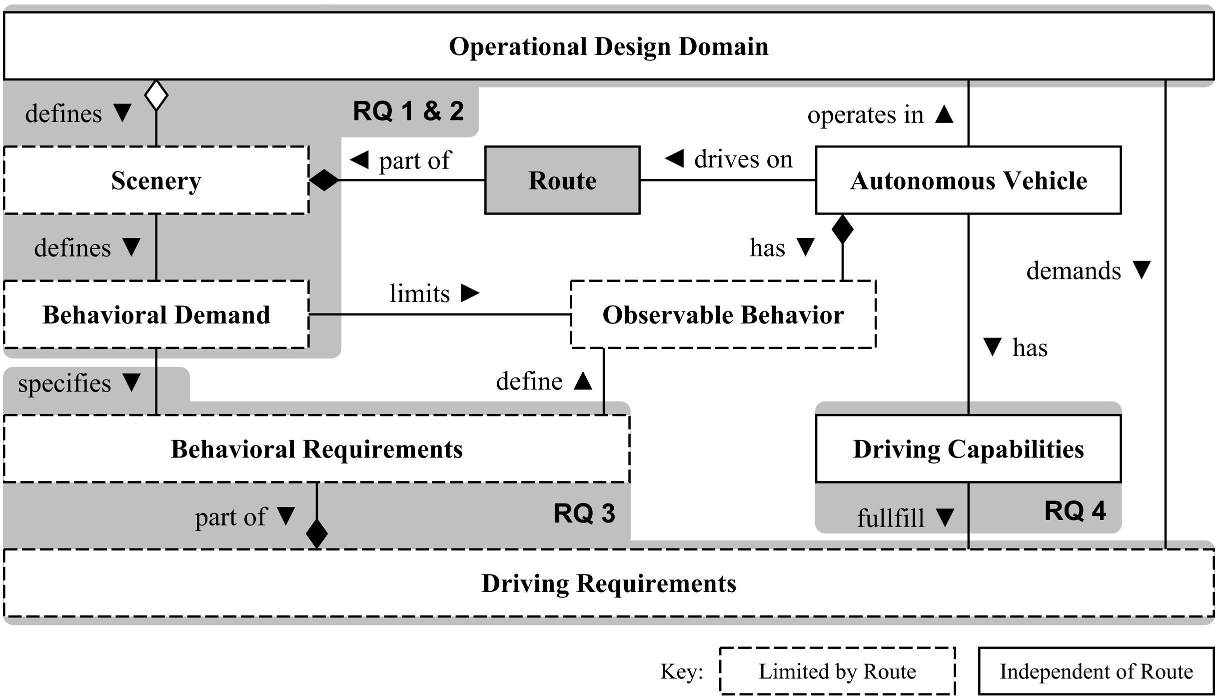


Figure 1-2: Research questions regarding the relationship between ODD, driving requirements and capabilities.[22]
Legend: —— Association; —◇ Aggregation; —◆ Composition

1.3 Research Methodology and Structure of Work

In order to achieve the research objectives and answer the research questions, the research methodology explained below is followed. The structure of the thesis is derived from the steps of this methodology.

In *Chapter 1*, the topic of the thesis is motivated and addressed. With the help of a problem analysis, relationships and deficits relevant to this work are identified. Based on this analysis, research objectives and research questions are derived and an appropriate research methodology for the work is developed.

Chapter 2 discusses the related work, which is intended to provide information on current research activities as well as approaches and solutions to the entities and their interdependencies addressed in Section 1.1[23]. Each entity and its possible connections to the other entities are systematically

---

[22] Adapted from Lippert, M.; Winner, H.: Behavioral Requirements for Automated Driving (2022).

[23] Cf. Figure 1-1.

investigated. The result of the research will be used as a basis for the further work steps by integrating already existing approaches or methods, if possible. At the same time, the identified deficits are explicitly addressed.

In *Chapter 3*, the scenery is analyzed with regard to the applicable traffic regulations. The identified behavioral demands that emerge from the scenery are then classified in the most information-efficient way possible. As a result of this chapter, classified behavioral demands are available, which are represented in a map representation in the next step.

The map representation of the behavioral demands is developed in *Chapter 4*. First, a basic concept for the representation is created, which is then transformed into a generic map representation. Application examples with real scenery sections illustrate the developed representations.

Based on the map representation of behavioral requirements, a method for deriving behavioral requirements is developed in *Chapter 5*. The elaborated map representation is used as a basis for a route-based analysis of the scenery. As a result of this chapter, a procedure for deriving the behavioral requirements is available, which will be built upon in the following chapter.

The main goal of this work is to match driving requirements with driving capabilities. *Chapter 6* lays the foundation for this by specifying driving requirements and driving capabilities based on behavioral requirements. Furthermore, matching criteria are derived that form the basis for identifying capability-based routes.

Based on the matching criteria, a method for identifying capability-based routes is developed in *Chapter 7*. Using modified conventional route planning, routes with driving requirements that do not exceed the driving capabilities of AVs are identified.

In *Chapter 8*, the developed route planning method is applied to a real road network. The obtained results are discussed and evaluated.

The thesis is concluded with a conclusion and outlook in *Chapter 9*.

Figure 1-3 shows the described research methodology and structure of the work. The chapters and mainly addressed research questions are assigned to the individual work steps.

The research within *Chapter 3* and *Chapter 4* to address the research questions *RQ 1* and *RQ 2* has been conducted together with Felix Glatzki resulting in two joint publications. While Felix Glatzki focused on the work to identify and abstract the behavioral demands[24], the author of this dissertation focused on the development of the representation format to record and use these behavioral demands[25].

---

[24] Glatzki, F. et al.: Behavioral Attributes for a Behavior-Semantic Scenery Description (2021).

[25] Lippert, M. et al.: Behavior-Semantic Scenery Description (BSSD) for Automated Driving (2022).

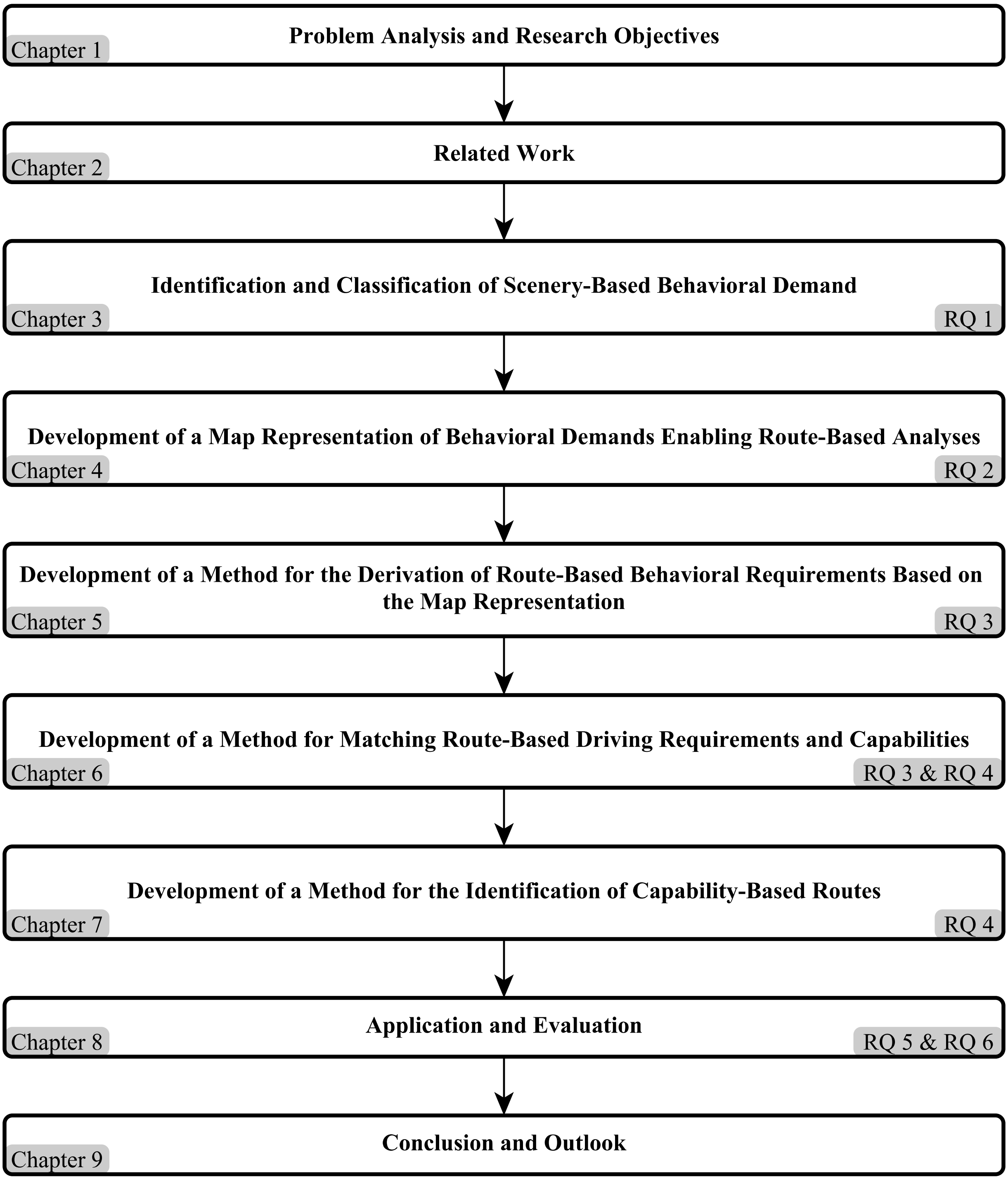


Figure 1-3: Research methodology and structure of work.

2 Related Work

Based on the derived research objectives and research questions, the analysis of related works is structured as follows. First, relevant fundamentals of AVs are covered. This serves both to understand the present work and to analyze and confirm the relationships identified in Section 1.1. Subsequently, work is presented that describes the scenery with behavioral reference. This section serves to identify possible approaches that already link scenery and behavior in some way. In addition, pure scenery descriptions are also considered, but they are suitable or used for behavior specification. Next, work that functionally specifies behavior, requirements, or capabilities is considered. This serves to identify any potential explicit dependencies between scenery or ODD and the resulting specifications. Lastly, work on route planners is considered. On the one hand, this develops a basic understanding of route planners and, on the other hand, identifies potentially existing approaches to route planners that have a similar goal as the present work. Finally, a conclusion of the related work is drawn with respect to the derived relationships and research objectives from Chapter 1.

2.1 Fundamentals of Autonomous Vehicles

In this section, legal framework and safety validation with related standards or regulations are briefly presented. Furthermore, the meaning of DDT and ODD and their relationship are discussed in more detail in this context.

2.1.1 Legal Framework and Safety Validation

Operating AVs on public roads is not only a challenge of technical feasibility but also of safety. Potentially, these vehicles entail risks to which the public is inevitably exposed when they are introduced into road traffic. For this reason, there are legal frameworks in place to ensure a certain level of safety. As a consequence, a safety validation has to be provided for AVs. This safety validation confirms that the vehicles are guaranteed to operate safely. The necessity and framework conditions of the safety validation are defined in international standards. Essentially, the following standards are authoritative for the development and operation of AVs:

- **ISO 26262: Road Vehicles - Functional Safety**[26]
  This standard defines functional safety as the absence of unreasonable risk in the case of hazards caused by faulty behavior of electric and/ or electronic systems. It assumes that the

---

[26] ISO: ISO 26262:2011: Road vehicles - Functional safety (2011).

specified vehicle behavior is fault-free. Thus, ISO 26262 has the following objective with respect to AVs: *AV functions are implemented safely.*

- **ISO 21448: Road Vehicles - Safety of the Intended Functionality (SOTIF)**[27]
  This standard defines SOTIF as the absence of unreasonable risk in the case of hazards posed by insufficiently specified behavior. This addresses exactly the behavioral specification assumed to be free of faults in ISO 26262. In particular, specification, verification and validation, as well as operation of the vehicles are mentioned to reduce the risk. Thus, ISO 21448 has the following goal with respect to AVs: *AV functions are specified safely.*
- **ISO/SAE 21434: Road vehicles - Cybersecurity Engineering**[28]
  This standard specifies requirements to minimize the risk posed by electric and/ or electronic systems in vehicles from a cybersecurity perspective. Thus, the goal of ISO/SAE 21434 with respect to AVs is: *AV functions are securely specified and implemented from a cybersecurity perspective.*

For a successful release of AVs for public road traffic, these standards must be met. To this end, various tests can be performed in the context of safety validation, both in the real world and in simulation, which provide proof of safety[29]. As described at the beginning of Chapter 1, statistical distance-based testing for safety validation is not yet possible with current methods due to rarely occurring relevant scenarios[30] in public traffic. The most prominent approach to solve this problem is the scenario-based testing approach[31]. In this approach, relevant scenarios that occur only randomly in the real world are to be specifically identified and tested in simulation or reality. In this way, the testing effort is potentially reduced. The standards mentioned as well as the safety validation will not be discussed further in the following, since there are already numerous related works in this area. Crucial for the present work is the knowledge about the need for safety validation and related testing - independent of the chosen approach.

In addition to aforementioned challenges for the development and operation of safe AVs, another important aspect must be considered that plays almost no role in non-automated vehicles. AVs must comply with country-specific traffic regulations. In concrete terms, this means that regardless of vehicle safety, compliance with these regulations must also be ensured. Even if a vehicle behaves perfectly safely, but violates traffic regulations for no justifiable reason, this is unacceptable. Moreover, compliance with traffic regulations contributes to safe traffic operation anyway. For example, if priority is correctly handled by all traffic participants, collisions are ideally not to be expected in priority situations. To some extent, compliance with traffic rules is part of the SOTIF, although this aspect is only indirectly addressed there. However, as shown in Section 1.1,

---

[27] ISO: ISO 21448:2022: Road vehicles - Safety of the intended functionality (2022).

[28] ISO/SAE: ISO/SAE 21434:2021: Road vehicles - Cybersecurity engineering (2021).

[29] Junietz, P. et al.: Evaluation of Different Approaches to Address Safety Validation of Automated Driving (2018).

[30] A detailed definition of the term *scenario* is provided in Subsection 2.2.1.

[31] Schuldt, F. et al.: Effiziente systematische Testgenerierung in virtuellen Umgebungen (2013).

traffic rules are highly relevant for behavioral specification, since behavioral limits are specified in combination with the scenery. This will be shown in the further course of the work.

2.1.2 Dynamic Driving Task

The definition of DDT has already been presented in Section 1.1. In this definition, DDT includes all operational and tactical tasks that are required for vehicle operation in road traffic. According to SAE J3016[32], strategic tasks such as the planning of trips or routes are explicitly excluded. Furthermore, the following subtasks of DDT are explicitly defined:

“1. Lateral vehicle motion control via steering (operational).
2. Longitudinal vehicle motion control via acceleration and deceleration (operational).
3. Monitoring the driving environment via object and event detection, recognition, classification, and response preparation (operational and tactical).
4. Object and event response execution (operational and tactical).
5. Maneuver planning (tactical).
6. Enhancing conspicuity via lighting, sounding the horn, signaling, gesturing, etc. (tactical).”

It can be seen that these tasks fit into the established sense-plan-act paradigm [33]. Since a sub-goal of the present work is to establish a relationship between scenery and driving requirements of AVs, the consideration of the sense-plan-act paradigm with the above-mentioned refined subtasks enables an analysis of the relationships in the further course of the work. At this point, a more in-depth explanation of the individual components of DDT is not necessary. Relevant tasks will be explained or discussed in the respective chapter, if necessary.

2.1.3 Operational Design Domain

As already defined in Section 1.1, the ODD describes the operational domain for which an AV is specified and developed[34]. The British standard PAS 1881[35] on assuring the safe operation of automated vehicles states that the ODD is an important part of the safety validation for AVs. Gyllenhammar et al.[36] even see the ODD as a supporting tool for safety validation, as its scope can be clearly delineated using the ODD. However, SAE J3016[32] itself only provides the definition of the term without going into specific components of the ODD. To specify the ODD, the International

---

[32] SAE: SAE J3016: Taxonomy and Definitions of Terms for Automation Systems (2021).

[33] Cf. Section 1.1.

[34] Except for AVs of automation level 5, as these vehicles technically no longer have any restrictions at all.

[35] BSI: PAS 1881:2022: Assuring the operational safety of automated vehicles – Specification (2022).

[36] Gyllenhammar, M. et al.: Towards an Operational Design Domain for Safety Argumentation of ADS (2020).

Organization for Standardization (ISO) is currently working on the ISO/DIS 34503[37], which is intended to serve as a supplement to the ISO 34502[38] for the scenario-based safety assessment of automated vehicles. In contrast to ISO, the British Standards Institution (BSI) has already published the BSI PAS 1883[39], which provides a taxonomy for the specification of the ODD. This standard again clearly states that the ODD is a key enabler for the specification of AV capabilities and limitations. To complement the standardization activities of ISO and BSI, the Association for Standardization of Automation and Measuring Systems (ASAM) is developing the standardized OpenODD format[40], which enables the machine-interpretable representation of defined ODDs. In addition to the ongoing standardization activities, the research community is also increasingly concerned with the topic of ODD specification and its role in the development and testing process of AVs, for example in a general context[41] or specifically for artificial intelligence applications[42].

Since the PAS 1883 is the only final published standard on ODD specification so far, this ODD taxonomy is presented below. At the highest layer, the taxonomy defines three attributes, which are complemented by further sub-attributes:

- *Scenery*: Contains non-movable elements of the ODD. These elements are divided into the attribute classes zones, drivable area, junctions, special structures, fixed road structures, and temporary road structures.
- *Environmental conditions*: Contains weather and atmospheric conditions. This includes the concrete attribute classes weather, particulates, illumination and connectivity.
- *Dynamic elements*: Contains moving elements. Associated attribute classes are traffic and subject vehicle.

The ODD taxonomy classifies the above attributes into further sub-attributes. In this way, the ODD specification becomes more concrete with each defined attribute. Except for a few and mostly incomplete examples, there is no publication that details the process of ODD specification itself and demonstrates it on a concrete ODD. However, there is a best practice guide[43] from the Automated Vehicle Safety Consortium (AVSC) that provides both a conceptual framework and a lexicon for describing ODDs. The AVSC suggests the following bottom-up approach for developing an ODD description:

1. Identification of the route network for the deployment of the AV
2. Characterization of the identified and fixed route network including infrastructure

---

[37] ISO: ISO/DIS 34503: Road Vehicles - Taxonomy for operational design domain (2022).

[38] ISO: ISO 34502:2022: Road vehicles - Scenario based safety evaluation framework (2022).

[39] BSI: PAS 1883:2020: ODD taxonomy for an automated driving system - Specification (2020).

[40] ASAM: OpenODD (2021).

[41] Erz, J. et al.: Ontology That Reconciles the ODD, Scenario-based Testing, and AV Architectures (2022).

[42] Ollier, G. et al.: Using Operational Design Domain in Hazard Identification for Automated Systems (2022).

[43] SAE ITC: AVSC Best Practice for Describing an Operational Design Domain (2020).

3. Identification of operational constraints within the route network
4. Formulation of a descriptive narrative

Consequently, it can be seen that the route network and the scenery represent a significant part of the ODD. According to Czarnecki[44] an ODD defines additional constraints on the behavior and state of the AV. As examples he mentions speed or loading (e.g. trailer) limitations. However, these limitations can also arise directly from the scenery itself in connection with traffic rules. For limitations that might occur only during the operation of AVs, for example due to degraded driving functions, Colwell et al.[45] define the so-called Restricted Operational Domain (ROD). Depending on the degradation present, the ROD represents only parts of the ODD specified for the full functional range of the AVs.

2.2 Behavior-Related Scenery Representation

In the following, scenery representations are described that are related to driving behavior, i.e. observable behavior. Thereby, the approaches do not necessarily have to show an explicit link between scenery and behavior. The scenery presentation can also serve as a basis for further steps towards behavior specification. Before presenting different types of approaches to scenery representations, fundamental terms in this context will be addressed.

2.2.1 Scene, Situation and Scenario

In addition to the fundamental terms in Section 1.1, there are also crucial terms for a uniform understanding of the development and safety validation related environment description of AVs within the automotive community. These also contribute to the understanding of the overall context in the present work. In Section 1.1, the *scenery* is defined as a fundamental component of this work. Since the scenery is also the key element of the mentioned environment related terms in the automotive domain, these closely related terms will be explained in the following. On the one hand, this confirms the significant part of the scenery in the functional specification derived in Section 1.1, and on the other hand, confusion of the terms in the following subsections is prevented. The definitions and explanations of the terms *scene*, *situation* and *scenario* are taken from Ulbrich et al.[46], since these terms are fundamentally established in the automotive community.

In addition to the scenery, the scene represents traffic participants and other dynamic elements:

---

[44] Czarnecki, K.: Operational Design Domain for Automated Driving Systems (2018).

[45] Colwell, I. et al.: An AV Safety Concept Based on Runtime Restriction of the ODD (2018).

[46] Ulbrich, S. et al.: Terms Scene, Situation, and Scenario for Automated Driving (2015).

Scene ”describes a snapshot of the environment including the scenery and dynamic elements, as well as all actors’ and observers’ self-representations, and the relationships among those entities. Only a scene representation in a simulated world can be all-encompassing (objective scene, ground truth). In the real world it is incomplete, incorrect, uncertain, and from one or several observers’ points of view (subjective scene).”

Consequently, in the context of a scene description, the scenery is complemented by dynamic elements and the self-representation of actors and observers. Dynamic elements have states and attributes, and non-classifiable dynamic information can also occur. These elements do not necessarily have to be in motion, but in principle have the capability to move by kinetic energy. Therefore, a vehicle waiting at a traffic signal or a vehicle stopped on a parking lane is just as much a dynamic element as a vehicle actively driving on the road. A self-representation includes skills and abilities, such as visual range or occlusion, as well as states and attributes of the actors and observers.

A situation includes the relevant entities of a scene due to its goal and value orientation. Thus, for example, the relevant part of the complete scene for a driving task is considered. In addition, the relevant goals and values as well as relevant function-specific situation aspects are considered:

Situation ”is the entirety of circumstances, which are to be considered for the selection of an appropriate behavior pattern at a particular point of time. It entails all relevant conditions, options and determinants for behavior. A situation is derived from the scene by an information selection and augmentation process based on transient (e.g. mission-specific) as well as permanent goals and values. Hence, a situation is always subjective by representing an element’s point of view.”

The following example illustrates the difference between a scene and a situation based on the goals. If the mission of an automated vehicle at an intersection requires crossing the intersection, a bicyclist who is also driving straight ahead in a bicycle lane next to the vehicle and crossing the intersection would be part of the scene due to his or her presence, but would not be part of the situation in terms of a relevance to the driving task. If, on the other hand, the AV’s goal is to turn right, the cyclist would be highly relevant to the driving task and thus also part of the situation.

A scenario is composed of scenes, actions and events as well as goals and values. The term is often used in the context of simulations, tests or functional descriptions for AVs. In contrast to a situation or scene, a scenario extends over a period of time:

Scenario ”describes the temporal development between several scenes in a sequence of scenes. Every scenario starts with an initial scene. Actions & events as well as goals & values may be specified to characterize this temporal development in a scenario. Other than a scene, a scenario spans a certain amount of time.”

As a result, scenarios describe the temporal sequence of actions or events and scenes. Typically, there is a starting scene that spreads out in a tree-like fashion through various actions and events to further scenes, whereby many different scenarios may result from an initial scene.

2.2.2 Structured Description

A first approach to representing the scenery is a simple description of the scenery elements. A written description does not require elaborate models or special tools, which is why it is a popular approach. Already for the design and construction of the transport infrastructure a detailed written description of the individual elements is needed and used. In Germany, there are various guidelines for this purpose, which describe, among other things, the required layout of urban roads[47], rural roads[48] or even autobahns[49,50]. For this purpose, the individual elements of the roads and the associated infrastructure are defined and described in detail and their geometric design is explained. In different design classes, lane width, number of lanes or even lanes for pedestrians and bicycle traffic are defined in this way. This is a pure description of the scenery without behavior references. Nevertheless, it can serve as a basis for specification as further work below shows.

In the context of traffic-psychological accident research, the representation of the environment from the driver's point of view is relevant. For this purpose, v. Benda et al.[51] developed a tabular classification system for traffic situations already in the early 1980s. The classification consists of five groups with different categories, which in turn have several characteristics. With the help of a codification of categories and characteristics, a systematic combination of all elements becomes possible, which is supposed to serve for the representation of every possible traffic situation. In addition to scenery elements such as road type, road layout and road course to describe the traffic ways, visibility conditions, traffic flow or behavior are also represented. However, driving behavior in this context refers to human driving mistakes and driving direction. To ensure a more practical applicability Fastenmeier[52,53] reduces this classification system. As a result, a classification is available which only contains the elements of scenery and selected driving direction at intersections.

For the specification of the ODD of Automated Driving Systems (ADSs) Czarnecki[54,55] defines

---

[47] FGSV: Richtlinien für die Anlage von Stadtstraßen (RASt) (2006).

[48] FGSV: Richtlinien für die Anlage von Landstraßen (RAL) (2012).

[49] FGSV: Richtlinien für die Anlage von Autobahnen (RAA) (2008).

[50] The German autobahn is different from typical highways, which is why the term *autobahn* is used.

[51] Benda, H. von et al.: Klassifikation und Gefährlichkeit von Straßenverkehrssituationen (1983).

[52] Fastenmeier, W. et al.: Autofahrer und Verkehrssituation (1995).

[53] Fastenmeier, W.: Die Verkehrssituation als Analyseeinheit im Verkehrssystem (1995).

[54] Czarnecki, K.: Operational World Model Ontology for Automated Driving Systems - Part 1 (2018).

[55] Czarnecki, K.: Operational World Model Ontology for Automated Driving Systems - Part 2 (2018).

an ontology[56] for an Operational World Model (OWM). Accordingly, OWMs form the basis for behavior specification as well as verification and validation of ADS. At the top level, the ontology is divided into five layers: road structure, road users, animals, other obstacles and environmental conditions. Each of these layers contains elements for describing the road environment for which attributes, relationships or even behaviors are defined. The road structure layer has been developed based on guidelines for road design such as mentioned in the beginning of this section.

Another structured description in the context of AVs is described by Schuldt et al.[57]. A generic 4-layer model is used to describe scenarios in the context of methodological testing of AVs. The layers base road network, situation-specific adaptations to the base road network, description and regulation of actors, and environmental conditions define in combination the desired scenarios. In the context of an ontology-based scene generation for autobahns[58], Bagschik et al.[59] extend this model by another layer. In the further developed model, the basic road network is essentially considered in two separate layers road-level and traffic infrastructure. In order to create a database for the validation of AV, Bock et al.[60] further develop this model into a 6-layer model. Scholtes et al.[61] provide guidelines for this purpose, which serve the structured description and classification of the urban traffic environment. In addition to slight modifications of the previous layers, the 6-level model includes a new sixth layer, digital information, which describes, for example, cellular network coverage. The current state of the layer model represents scenery in four of the six layers. Only the layers for dynamic objects and digital information are not part of the scenery.

2.2.3 Ontology-Based Representation

The representation of the traffic environment using an ontology is a popular approach. Gruber[62] provides the most prominent definition of ontology as a basis for artificial intelligence approaches as well as knowledge representation. According to this definition the ontology is ”an explicit specification of a conceptualization”. The conceptualization is understood as ”an abstract, simplified view of the world that we wish to represent for some purpose”. In the context of environment representation for AVs, the ontology thus serves an explicit specification of the abstracted operational world of vehicles.

Using Bagschik et al.[59] as an example, the concrete implementation of an ontology for scene generation for German autobahns is described in the following. Road traffic rules, functional

---

[56] The ontology has the form of a written description and is not modeled or implemented using a corresponding language in the sense of informatics. Therefore, this ontology approach is assigned to structured description. Nevertheless, a modeling of this approach is conceivable.

[57] Schuldt, F. et al.: Effiziente systematische Testgenerierung in virtuellen Umgebungen (2013).

[58] Cf. Subsection 2.2.3.

[59] Bagschik, G. et al.: Ontology based Scene Creation for the Development of Automated Vehicles (2018).

[60] Bock, J. et al.: Data basis for scenario-based validation of HAD on highways (2018).

[61] Scholtes, M. et al.: Structured Description and Categorization of Urban Traffic and Environment (2021).

[62] Gruber, T. R.: A translation approach to portable ontology specifications (1993).

descriptions, guidelines, traffic sign catalogs, scenario catalogs, and expert knowledge serve as the basis for the ontology. These different knowledge elements are represented using the ontology. Based on the ontology, knowledge-based combination is then performed using the ontology rules to generate the scenes. The organization of all the information of the knowledge elements used is enabled based on the 5-level model[63] developed for this purpose. A scene is built layer by layer. First, a street layout is chosen from the street design guidelines. Then, lane markings or even guardrails are added to the road layer defined in this way in the second layer. If there are temporary adjustments to the first two layers, these can be added in the third layer. Objects such as various vehicles are added in layer 4. Environmental conditions such as weather or lighting are specified in the fifth layer. With the help of the rules and relationships defined in the ontology, the scenes are composed in this way. Thereby, relations like *consists_of*, *has_left_neighbor* or *located_on* are used in the ontology to model the relationships. This ontology is further developed in other works for the automatic generation of scenarios for German autobahns[64,65]. Arman et al.[66] use a similar ontology for a general context awareness model, where the organization of the knowledge elements differs and the model is more intended for urban road sections.

The aforementioned ontologies only deal with road segments, so intersections and junctions cannot be represented. Hülsen et al.[67] present an ontology that allows modeling specifically of intersection situations. The goal is a well-founded and efficient decision making of the planning level of AVs. Thereby, the statements for describing the relationships of the individual elements are similar to those presented before. Of particular note is the representation of traffic rules. For example, priority is assigned based on the relationships between traffic participants and road elements. The traffic participants with right of way represented in the situation have the statement *hasRightOfWay* with respect to the other traffic participants. Geometric information is also partially stored, such as the angles of the intersection arms. Buechel et al.[68] present a similar ontology, but for scene representation of road segments and intersections. In addition, they define a traffic rule ontology that represents various traffic rules as a complement to the rest of the framework. Zhao et al.[69,70] present an ontology that explicitly addresses the decision making efficiency of AVs, but specifically for uncontrolled intersections and narrow roads. The ontology consists of three sub-ontologies, one of which explicitly represents the map with the road network[71]. To model the relationships between the individual elements, the previously known statements are used.

---

[63] Cf. Subsection 2.2.2.

[64] Bagschik, G. et al.: Wissensbasierte Szenariengenerierung für Betriebsszenarien auf Autobahnen (2018).

[65] Bagschik, G.: Systematischer Einsatz von Szenarien für die Absicherung automatisierter Fahrzeuge (2022).

[66] Armand, A. et al.: Ontology-based context awareness for driving assistance systems (2014).

[67] Hülsen, M. et al.: Traffic intersection situation description ontology for advanced driver assistance (2011).

[68] Buechel, M. et al.: Ontology-based scene modeling, situational awareness and decision-making for AVs (2017).

[69] Zhao, L. et al.: Ontology-based decision making on uncontrolled intersections and narrow roads (2015).

[70] Zhao, L. et al.: Fast decision making using ontology-based knowledge base (2016).

[71] Zhao, L. et al.: Ontology-Based Driving Decision Making: Feasibility at Uncontrolled Intersections (2017).

Ulbrich et al.[72] and Regele[73] use graph-based ontologies to represent a world model. Here, the traffic participants' paths are modeled as edges so that a graph network can be modeled. Hamilton et al.[74] also uses a graph network and extends the ontology for a route determination. Based on the route, simple behavior rules can be queried. However, the concept is designed for very simple rural roads. A final example of another use case is the knowledge-based road modeling of Fricke et al.[75]. Using an ontology, explicit a-priori knowledge based on map information is used to identify possible errors or deviations in the map used for driving. Of particular note in this approach is the abstraction of traffic rules into three layers. In contrast to other approaches, at the rule level, for example, no distinction is made between a city entrance sign and a 50 km/h limit sign. On this layer, both signs are equivalent, since both require a 50 km/h limit.

2.2.4 Map-Based Representation

Due to their geolocalized information, digital maps offer the possibility to anticipate environmental conditions relevant to the driving task, such as approaching a complex intersection or sudden changes in traffic rules[76]. Unlike the previously described approaches, maps represent a complete road network that is usually already explicit and does not require additional modeling of the scenery. Each map has a map format that is used to specify, manipulate, and represent the map. Different use cases require different map formats. In the following, some map formats are presented.

A widely used and general mapping project is OpenStreetMap (OSM)[77,78]. OSM provides the public with the possibility to access as well as create geographic data of the world open source. To this end, the map format is intuitive and simple. Based on the Extensible Markup Language (XML) syntax, the map is built using the bottom-up principle. The map is modeled using only five elements. Nodes are points and represent locations. If several nodes are connected, a way is created to represent streets, paths or even rivers. Ways can not only be open, but also closed like a loop. These closed ways can be further modeled as areas, so that for example buildings can be represented. Relations are the last and most flexible element. With the help of relations it is possible to define relations among all other elements and thus represent new information. For example, a bus route can be defined that connects any number of ways. Tags are used to add further information to the elements mentioned. For example, a way can be tagged as a priority road with a certain number of lanes and a speed limit. Besides the flexibility mentioned above,

---

[72] Ulbrich, S. et al.: Context representation, environment modeling and information aggregation for AD (2014).

[73] Regele, R.: Using Ontology-Based Traffic Models for More Efficient Decision Making of AVs (2008).

[74] Hamilton, A. et al.: Semantic-based approach for route determination and ontologyupdating (2013).

[75] Fricke, J. et al.: Towards Knowledge-based Road Modeling for Automated Vehicles (2021).

[76] Armand, A. et al.: Digital Maps for Driving Assistance Systems and Autonomous Driving (2017).

[77] Haklay, M.; Weber, P.: OpenStreetMap: User-Generated Street Maps (2008).

[78] OpenStreetMap Contributors: OpenStreetMap (2022).

OSM itself does not offer the possibility to generate lane-accurate maps. All roads are defined as linestrings.

In addition to this and other general maps, there are map formats specifically designed for the purpose of autonomous driving. A detailed digital map was already used for autonomous driving of the historic Bertha Benz route in 2013[79]. Based on the OSM formalism, the format *liblanelet*[80] describes lane-accurate maps using *lanelets*. A lanelet represents an atomic lane segment characterized by a right and a left boundary. Traffic rules such as speed limits or right of way are modeled using *regulatory elements* and assigned to the lanelets. The format allows routing through the lanelet network, making it a suitable basis for AVs. However, the maps are modeled based on predefined routes, which is problematic if other routes are to be followed. To compensate for this and other weaknesses of the format, Poggenhans et al.[81] present *Lanelet2*, a map format extended and generalized based on liblanelet. Lanelets in this format are more fine-grained and form atomic lane segments within which topology and traffic rules do not change. The edges of the lanelets are labeled based on their type, such as curb or dashed line, so that crossing is allowed or not depending on traffic rules. This allows an AV to potentially decide for itself which lane-accurate route it will take. Regulatory elements were also taken from liblanelet and further developed. Lanelet2 also uses the OSM formalism and is built bottom-up like OSM and liblanelet. This allows an efficient and explicit representation of the static traffic environment, which can be enriched with additional traffic regulatory information.

Digital maps in particular are essential for the simulation of AVs, which is why ASAM provides the standardized map format OpenDRIVE[82]. The format also uses XML syntax to represent roads with lanes, markings, traffic signs and other features with high accuracy. Roads are modeled along *reference lines*, which are used to precisely position and align all other features. The modeling of traffic rules is only supported to a very limited extent. OpenDRIVE maps are used, among other things, to simulate complex driving maneuvers within scenarios. For the definition of these scenarios, ASAM provides the OpenSCENARIO[83] format. Similar frameworks for scenario-based simulation of AVs in virtual environments are for example CommonRoad[84] or GeoScenario[85]. Both formats use the OSM formalisms and liblanelet to model the road network.

---

[79] Ziegler, J. et al.: Making Bertha Drive - An Autonomous Journey on a Historic Route (2014).

[80] Bender, P. et al.: Lanelets: Efficient map representation for autonomous driving (2014).

[81] Poggenhans, F. et al.: Lanelet2: A high-definition map framework for the future of automated driving (2018).

[82] ASAM: OpenDRIVE (2021).

[83] ASAM: OpenSCENARIO (2022).

[84] Althoff, M. et al.: CommonRoad: Composable benchmarks for motion planning on roads (2017).

[85] Queiroz, R. et al.: GeoScenario: An Open DSL for Autonomous Driving Scenario Representation (2019).

2.2.5 Abstracted Representation

Previous approaches attempt to reflect the real world as it is. However, there are approaches that intentionally model abstractions to get closer to a higher-level goal. Lopez et al.[86] describe the complex process of scenario interpretation using urban intersections as an example. To simplify the process for an AV, they introduce so-called *primary situations*. Primary situations are abstracted snapshots of the scenarios that are crucial for AV decision making. They are defined based on possible conflicts of the considered AV with other traffic participants or infrastructure elements. Each primary situation has at least one *target point*, associated *Region of Interests (ROIs)*, and *relevant objects* within these ROIs. The target points are used to represent the position and speed of the AV along the selected path within a scenario. For turning at intersections, nine target ponints are defined. For example, when turning left, there is one target point that indicates the conflict with oncoming traffic. Accordingly, it is defined as a possible stopping point with an ROI in the oncoming traffic lane. Based on these abstracted elements, decision making is modeled using flowcharts, within which the target points are passed through in sequence according to different conditions.

An even more abstract approach is presented by Butz et al.[87]. The so-called *SOCA* represents a method for domain analysis of AVs. This method abstracts traffic situations using *zone graphs*. Thus, an abstracted representation of the scenery is achieved, which is used for a behavioral analysis of an AV under consideration. The zone graphs are defined based on specific types of scenery, taking into account the goals of the AV under consideration. There are different types of zones, which in turn are associated with different types of edges. For example, zones are defined as *driving zones* (e.g. for AV), *position zones* (e.g. for other traffic participants with priority), or *information zones* (e.g. for traffic signs). The zones are connected with *intention*, *threat* or *information* edges. For a 4-way intersection, for example, three different zone graphs are constructed for turning right or left and driving straight ahead. Each graph contains a different sequence of zones and edges. The concrete layout including the geometries of the scenery is completely abstracted, so that only the information necessary for a behavior analysis remains.

2.3 Functional Specification of Autonomous Vehicles

This section presents work on the functional specification of AVs. The focus is on work that particularly specifies observable behavior, requirements and capabilities.

---

[86] Perdomo Lopez, D. et al.: Scenario Interpretation based on Primary Situations at Urban Intersections (2017).

[87] Butz, M. et al.: SOCA: Domain Analysis for Highly Automated Driving Systems (2020).

2.3.1 Behavior Specification

A general approach to the behavioral specification of AVs is presented by Censi et al.[88]. They specifically address the externally observable behavior of AVs, which is simply defined as observable behavior in this thesis[89]. The authors postulate that this behavior is subject to constraints that are not only based on traffic rules and geometric constraints of the road, but also arise from liability, ethics and culture. To specify this variety of possible behavioral rules for autonomous agents, they introduce *rulebooks*. Essentially, a rulebook consists of a pre-ordered set of rules. Rules form the atomic elements of the behavior specification and are defined as scoring functions within a violation metric. Due to the prioritization of different rules, the violation of safety constraints is penalized higher than the violation of traffic rules.

There are approaches that focus exclusively on the specification of traffic rule-related vehicle behavior. A whole research community is concerned with the formalization of traffic rules for, among others, highways[90], interstates[91], uncontrolled intersections[92] or intersections in general[93]. Basically, the country-specific traffic rules are analyzed and converted into a machine-readable format. The behavior rules formalized in this way are used, among other applications, for the verification of driving behavior, as shown by Pek et al.[94] using the example of an online verification. However, in addition to verification, the formalized behavior rules can also be used to specify driving behavior.

Beyond the formalization of country-specific traffic rules, Shalev-Shwartz et al.[95] take a very unique approach. Within their developed Responsibility-Sensitive Safety (RSS) model they define five own common sense rules for a multi-agent environment. These rules state for example ”Do not hit someone from behind” or ”Right-of-way is given, not taken”. The authors claim that if these rules are strictly followed, no collisions will occur. However, this assumes that each individual agent adheres to the rules. To make this theoretical construct work, they formalize these rules in a mathematical model. Since this approach is not based on real traffic rules, it is rather theoretical and currently not practical.

The behavioral specification of AVs is not always directly based on existing or self-defined traffic rules. In a more general approach, NHTSA[96] or even the AV technology company Waymo[97] define

---

[88] Censi, A. et al.: Liability, Ethics, and Culture-Aware Behavior Specification using Rulebooks (2019).

[89] Cf. Section 1.1.

[90] Esterle, K. et al.: Formalizing Traffic Rules for Machine Interpretability (2020).

[91] Maierhofer, S. et al.: Formalization of Interstate Traffic Rules in Temporal Logic (2020).

[92] Karimi, A.; Duggirala, P. S.: Formalizing traffic rules for uncontrolled intersections (2020).

[93] Maierhofer, S. et al.: Formalization of Intersection Traffic Rules in Temporal Logic (2022).

[94] Pek, C. et al.: Using online verification to prevent autonomous vehicles from causing accidents (2020).

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

[96] Thorn, E. et al.: A Framework for Automated Driving System Testable Cases and Scenarios (2018).

[97] Waymo: Waymo Safety Report (2021).

so-called *behavioral competencies* that are tested for the specified ODD of AVs. General rules and traffic rules are of course included, but compared to the previous approaches, the behavioral competencies go beyond that. For example, with respect to traffic rules, one competency is ”Detect and Respond to Speed Limit Changes and Speed Advisories.” In contrast, another behavioral competence is ”Detect and Respond to Vehicle Control Loss” and thus addresses the motion control level of AVs. A methodology for deriving this behavioral specification is not explained, which is why no statement can be made about the degree of completeness.

2.3.2 Requirement and Capability Specification

Requirements and capabilities are often not clearly separated in the literature, so they are considered together in this chapter.

Czarnecki[98] defines high-level safety requirements for driving behavior and performance of ADS. To ensure safety, these requirements must not be violated. The requirements are derived from accident data with respect to physics, traffic rules, and expected behavior of traffic participants. In total, five categories of requirements are defined: *Vehicle stability*, *assured clear distance ahead*, *minimum separation*, *traffic regulations* and *driving best practices*. The first three categories explicitly address the collision avoidance of AVs. Traffic regulations and best practices explicitly refer to compliance with rules. However, Czarnecki emphasizes that most of the rules are safety-related. The requirements of the different categories are described and explained in the publication, but not formulated as explicit sentences, as is the case, for example, in a requirement specification.

In his dissertation, Reschka[99] specifies requirements for an AV with a specific use case. The requirements are derived systematically on the basis of framework conditions, state of the art, operational environment, pathological scenarios, general target behavior, safe states and driving speed. The systematic approach is based on the analysis and discussion of the individual subject areas. The requirements are written down concretely in sentences.

Other studies[100,101,102] specify requirements on the basis of a Hazard Analysis and Risk Assessment (HARA) as also required, for example, by already mentioned ISO 26262 or ISO 21448. Based on an item definition, a hazard identification is first performed. The identified hazards are classified with regard to various risk levels and then evaluated. To minimize the risks, safety goals are developed on this basis to counteract the hazards. The safety goals correspond to high-level safety requirements. With the aid of further methods, such as a System-Theoretic Process Analysis

---

[98] Czarnecki, K.: ADS High-Level Quality Requirements Analysis - Driving Behavior Safety (2018).

[99] Reschka, A.: Fertigkeiten- und Fähigkeitengraphen für automatisierte Fahrzeugen (2017).

[100] Stolte, T. et al.: Hazard analysis and risk assessment for an automated unmanned protective vehicle (2017).

[101] Bagschik, G. et al.: A System’s Perspective Towards an Architecture Framework for Safe AVs (2018).

[102] Schönemann, V. et al.: Scenario-Based Functional Safety for Automated Valet Parking (2019).

(STPA)[103] or a Fault Tree Analysis[104], these top-level requirements can be broken down, for example, to functional safety requirements[105,106] or to arbitrary sub-system levels[107].

In addition to the publications on requirements specification, there are only a few publications in the literature for explicit capability specification. A prominent approach is provided by Reschka et al.[108], presenting so-called *ability and skill graphs*. Abilities are defined as the set of required conditions to fulfill a part of the DDT. Skills are abstract representations of the parts of the DDT and are modeled in graphs for the purpose of online monitoring of the current system performance. Together, abilities and skills cover all aspects of the DDT. Ability graphs are derived directly from the system-level requirements. The graph thus represents an abstract representation of the DDT. In a follow-up work on the automated generation of skill graphs, Jatzkowski et al.[109] slightly adapt the terms and continue to work exclusively with skills. Overall, the DDT is divided into seven skill categories: *system skills*, *behavioral skills*, *planning skills*, *perception skills*, *data acquisition skills*, *action skills* and *actuation skills*. A behavioral skill is for example *lane keeping* as part of the DDT. The publications present methods for modeling the relationships and dependencies among the skills, but no concrete method for specifying the skills. For the selection of skills, well-known methods of requirements specification are used.

2.4 Route Planning

Road networks can usually be navigated in many different ways. Therefore, there are often several possible routes for driving from a starting point to a destination. Nowadays, routes are almost exclusively determined using route search algorithms. Typically, the route is chosen to be either time-optimal or distance-optimal. This means that the route search algorithm has to find either the fastest or the shortest route. The shortest path problem has been solved for a long time by Dijkstra[110] and finding the fastest route has also long been state of the art. A detailed survey of current approaches to route planning in transportation networks can be found in Bast et al.[111]. For the present work, the new development of a route planner is not relevant, but rather the possibilities to influence the route search of established approaches. According to Bast et al., a road network for routing is modeled as a directed graph consisting of edges and nodes. Each edge

---

[103] Leveson, N. G.: STPA: A New Hazard Analysis Technique (2012).

[104] IEC: IEC 61025:2006 - Fault Tree Analysis (FTA) (2006).

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

[106] Schönemann, V. et al.: Fault tree-based Derivation of Safety Requirements for Automated Valet Parking (2019).

[107] Klamann, B. et al.: Defining Pass-/Fail-Criteria for Particular Tests of Automated Driving Functions (2019).

[108] Reschka, A. et al.: Ability and skill graphs for vehicle guidance systems (2015).

[109] Jatzkowski, I. et al.: Automatic Construction of Skill Graphs for Online Monitoring (2021).

[110] Dijkstra, E. W.: A note on two problems in connexion with graphs (1959).

[111] Bast, H. et al.: Route Planning in Transportation Networks (2016).

has a non-negative length. Depending on the optimization criterion such as shortest or fastest route, the edges are weighted. For example, to determine the shortest route, the edges are simply weighted by their own lengths. Based on this, the route search algorithm searches for the path along the edges of the graph that has the lowest weight. Other optimization criteria require other weighting metrics, which are usually included in cost functions for weighting the edges. In this way, route search can be adapted for arbitrary optimization criteria.

The topic of route search for AVs has not yet been prominently addressed in the literature. This is probably due to the fact that more attention has been paid to other problems yet to be solved. Nevertheless, there are works that assess current planning approaches as insufficient due to new requirements of AVs. Taha and Abu Ali[112] see four categories of planning metrics needed for AVs. Among others, they identify energy efficiency and safety as necessary optimization metrics that need to be developed specifically for an operation of AVs. Neidhardt and Suske[113] also believe that the shortest or fastest route is no longer necessarily the best option for AVs. Due to the varying complexity of road traffic and the varying levels of automation of AVs, they see the need for new optimization criteria. To this end, they present road-based criteria that could influence the route search for AVs. For example, the presence of road markings, the conflict potential when turning, or the complexity of intersections are mentioned. The different criteria are divided into classes, which serve as a basis for weighting the edges of the route graph. The authors consider the presented approach only theoretically without presenting an application. Furthermore, the origin of the mentioned criteria is unclear. A connection between criteria and corresponding, modified requirements for AVs is not apparent. Nevertheless, the approach pursues a very similar goal as intended in the present work.

2.5 Conclusion

In this section, the related work discussed is summarized in terms of the relationships identified in Section 1.1 and the research objectives derived in Section 1.2. Based on these findings, the individual steps of the methodology are then run through and elaborated.

Conclusion on Fundamentals of AVs

The legal framework for the development and operation of AVs requires, among other things, the safety validation of the SOTIF. Thus, already the specification of AVs has to be safe. In addition, there are country-specific traffic rules that must be followed. While compliance with traffic rules helps to ensure SOTIF, it is necessary from a legal perspective anyway - regardless of any contribution to safety. Since the relationship presented in Section 1.1 considers the specification

---

[112] Taha, A.-E.; Abu Ali, N.: Route Planning Considerations for Autonomous Vehicles (2018).

[113] Neidhardt, E.; Suske, D.: Route Planning Based on Street Criteria for Autonomous Driving Vehicles (2021).

of AVs based on observable behavior, functional safety and cybersecurity are not in the scope of this work. However, this does not mean that these conditions do not have to be met.

Based on the legal frameworks, it is thus necessary that the DDT of AVs is specified in a safe and traffic-regulation-compliant manner. Essentially, this means that an AV senses the relevant environment, plans driving behavior based on it, and executes the behavioral decision (Sense-Plan-Act). As a result, the AV exhibits the observable behavior defined in Section 1.1. However, AVs may only execute the DDT in the ODD specifically specified for driving. An ODD consists of three fundamental components: Scenery, environmental conditions, and dynamic elements. The AVSC describes a procedure for specifying these elements, explicitly requiring the specification of a route network including the associated transportation infrastructure. The operational conditions for AVs should therefore be derived and described directly based on this specified route network. This confirms the strong relationship derived in Section 1.1 between an AV with observable behavior, the ODD, the scenery, and the potential routes for operation. This reinforces the motivation for scenery-based derivation of behavioral demands on the observable behavior of AVs.

Conclusion on Behavior-Related Scenery Descriptions

The established conceptual definitions in the automotive community for describing and representing the traffic environment are all based on the notion of sceneries. Also, the considered works on the different representations of the environment all use the scenery in some way. It can be seen that the scenery is already used extensively for the specification of scenes, situations and scenarios for both the development and testing of automated driving functions. Indirectly, the scenery is thus used in various approaches to define behavioral demands. However, these behavioral demands are not explicitly named, but are an implicit side product. For example, developed test scenarios and their constraints reflect part of the behavioral demands, but these are neither explicitly named nor considered in isolation. In terms of a behavioral description, abstract description approaches come closest to the goal of an explicit representation of behavior. However, map-based approaches such as Lanelet2 already partially consider behavioral rules in the form of traffic rules. This further reinforces the motivation for deriving the behavioral demands in the present work. In this context, abstract approaches like SOCA show the possibility to derive and consider behavior detached from the scenery. Map formats such as Lanelet2 , on the other hand, show that map-based scenery representations can be directly linked to behavioral information. Thus, to achieve the goal of route-based matching between scenery driving requirements and AV driving capabilities, a method or format needs to be developed that combines both worlds: scenery and behavior.

Conclusion on Functional Specification of AVs

There is some work on the specification of behavior, requirements, and capabilities of AVs, but none of it is based on a systematic derivation with respect to scenery. Vehicle behavior is specified either in a very general way, based on custom rules, or strictly on traffic rules. These approaches all fail to derive the required driving behavior for a given route within the ODD. The situation is similar for approaches to specifying requirements and capabilities. Requirements are derived either systematically based on rule sets, underlying conditions, accident data, and other aspects, or in a classical manner based on hazard and risk identification methods. Even in the case where requirements are derived at the behavioral level, there is a lack of reference to scenery or route within the ODD. Capabilities are not specified in isolation in the literature, but rather defined based on requirements. Thus, to the knowledge of the author of this work, there is no approach that systematically derives driving requirements or driving capabilities based on specific sceneries or routes within the ODD. Therefore, in addition to creating a linkage between scenery and behavioral demands, the derivation of requirements and capabilities based on this linkage must also be sought in order to achieve the goal of this thesis.

Conclusion on Route Planning

The identification of the fastest or shortest route within a road network has long been state of the art. In terms of AVs, there is little work addressing new route planning requirements based on automated operation. Nevertheless, it can be seen that, for example, from a safety perspective, routes need to be planned based on new optimization criteria. For this purpose, a concept is presented in the literature that provides optimization criteria for route planning based on road criteria. The criteria are chosen in such a way that, depending on the degree of automation, AVs follow the optimal route according to the DDT. Thus, optimal is no longer synonymous with shortest or fastest route. This approach is only considered theoretically and not elaborated more concretely. A connection between the mentioned road criteria and the resulting driving requirements is not shown or evident. However, this approach reinforces the motivation for identifying routes with driving requirements that do not exceed the driving capabilities of AVs. Thus, in addition to linking scenery and behavior as well as deriving scenery-based driving requirements and capabilities, appropriate optimization criteria must also be developed for the desired identification of routes.

3 Scenery-Based Behavioral Demand

In order to holistically describe behavioral demands based on the scenery, it is first necessary to identify behavioral demands that result from the scenery. If the relevant behavioral demands are known it is possible to link them to the scenery. In this context, behavioral demands are referred to as *relevant* if they occur in sceneries relevant for automated driving. By relevant sceneries for automated vehicles, conventional sceneries in the context of road traffic are meant. Sceneries such as unpaved ways in fields, meadows, forests, deserts or even ice and snow landscapes do not belong to these conventional sceneries, which is why their possible behavioral demands are excluded in this work[114]. The focus of this work is on urban sceneries with as many different facets as possible[115].

The scenery alone does not allow any conclusions to be drawn about the behavioral demands that apply. Some kind of guidance is needed that gives clear instructions about what rules apply to certain combinations of the individual scenery elements. What is the meaning of the different traffic signs or the different road markings? What are the relationships between traffic signs and the rest of the scenery elements? The guidance for rule-based interpretation of this information available in the scenery is generally referred to as traffic regulations and may well differ from country to country. A simple example shows how significant the differences between traffic regulations may be. In North America, and for the most part in Europe, the right-hand driving rule applies, which states that all traffic participants should drive on the right-hand side of the road. On the other hand, in the British Isles or in Australia, the left-hand driving rule applies, so that traffic participants there must orient themselves on the left side of the road. The individual scenery elements hardly differ, if at all. Consequently, the same scenery can place different behavioral demands on traffic participants depending on the locally applicable traffic rules.

Regardless of the location of a scenery, the road traffic regulations in force there must always be consulted in order to obtain the correct behavioral demands. In the context of this work, the German Road Traffic Regulation (StVO)[116] is used to analyze the applicable behavioral demands. Nevertheless, there is the claim that the resulting behavioral demands are universally usable, so that the same behavioral demands can be used regardless of location. This requires a classification of behavioral demands that assigns a class to as many behavioral demands as possible. Different road traffic regulations would impose different behavioral demands for certain combinations of scenery elements, but it should be possible to clearly assign them to a class. For example, a

---

[114] For special use cases such as military AVs, these sceneries might still become relevant.

[115] Although the focus is on urban sceneries, an application beyond that, such as on country roads or highways, is not excluded. On the contrary, the goal is to achieve an approach that is as universal as possible. However, examples and application will be limited to urban areas.

[116] BMJ: Straßenverkehrs-Ordnung (StVO) (2013).

demand about stopping before entering an intersection should always be assigned to the same class, regardless of a specific mechanism of action that leads to that demand. In the following sections, the combination of scenery and road traffic regulation is first analyzed and the resulting behavioral demands are then classified[117].

3.1 Identification of Behavioral Demands[118]

The identification of behavioral demands is based on an analysis of the StVO. Due to the context of automated driving, only behavioral demands on motor vehicles are considered. This analysis would be possible analogously for other types of traffic participants based on the applicable traffic regulations. However, excluding considerations of the applicable traffic regulations for the other traffic participant types does not mean that they need not be considered at all. Interactions between different types of traffic participants regulated by the StVO require consideration of all relevant traffic participants. Relevant is any traffic participant type involved in at least one behavioral demand on motor vehicles. A grouping of traffic participant types into an equivalence class is potentially possible if the same combination of these types always occurs in all behavioral demands involving these traffic participant types.

Before different traffic participant types can be considered in an analysis in the following, the term traffic participant must first be clarified. The Explanations to the German Road Traffic Regulations define a traffic participant as follows:

Traffic participant is anyone who uses public ways within the scope of public use, whereby action or omission in breach of duty has a direct effect on a traffic process in the public traffic space.[119]

Based on this definition, it is clear that traffic participant types are diverse. A list of all traffic participant types is provided, for example, by the Federal Statistical Office in context of accident statistics[120]. This list contains 16 different superclasses for traffic participant types, some of which contain further characteristics. Generally known classes are, for example, motorcycle, passenger

---

[117] All subsequent analyses use the StVO[116], unless otherwise stated. Appendixes to the StVO are explicitly referenced.

[118] Parts of this section have already been published in Glatzki, F. et al.: Behavioral Attributes for a Behavior-Semantic Scenery Description (2021).

[119] Summarized and translated from German: ”Verkehrsteilnehmer ist, wer öffentliche Wege im Rahmen des Gemeingebrauchs benutzt. Die Verkehrsteilnahme setzt ein verkehrserhebliches Verhalten voraus. Dies erfordert ein Handeln oder pflichtwidriges Unterlassen, das unmittelbar auf einen Verkehrsvorgang einwirkt. Verkehrsbezogen ist dabei ein Verhalten, wenn es sich schon oder noch wenigstens teilweise im öffentlichen Verkehrsraum abspielt.”, BMJ: Erläuterungen zur Straßenverkehrs-Ordnung (2019), p. 5.

[120] Statistisches Bundesamt (Destatis): Verkehrsunfälle - Grundbegriffe der Verkehrsunfallstatistik (2022).

car, bus, truck, rail vehicle, bicycle and pedestrian[121].

Guiding questions are formulated to structure the analysis to identify behavioral demands. Traffic participants, by definition, use public ways to get around or even stay in public traffic spaces. Thus, it is first necessary to clarify what these potential public traffic spaces for residence and movement look like. Potential spaces in this context are spaces for which a motor vehicle has permission to reside and move. The next step is to check which conditions are attached to the residence of a motor vehicle in the potential spaces, i.e. under which conditions the vehicle is generally allowed to be there. Furthermore, it has to be identified whether there are further conditions or behavioral rules attached to driving in these spaces. These rules relate specifically to the movement of the motor vehicle. Finally, since a vehicle may have to observe additional behavioral rules when moving between spaces, these cases are also considered. This results in a total of four Guiding Questions (GQs):

- **GQ 1:** In which traffic spaces is a motor vehicle allowed to be?
- **GQ 2:** What conditions are attached to the residence in traffic spaces?
- **GQ 3:** What behavioral rules shall a motor vehicle observe when driving in traffic spaces?
- **GQ 4:** What behavioral rules shall a motor vehicle consider when moving between traffic spaces?

In the following sections, these guiding questions are discussed and answered. These considerations are intended to provide insight into where behavioral demands come from and how they are linked to scenery. Subsequently, these findings will be analyzed in terms of a classification of behavioral demands.

GQ 1: In which traffic spaces is a motor vehicle allowed to be?

§ 2 of the StVO states that vehicles[122] must use the existing roadways. In this context, due to the right-hand driving requirement in Germany, the right-hand roadway must always be used if two roadways are present. In general, vehicles must always drive as far to the right as possible, regardless of specific situations such as oncoming traffic or being passed.

According to the RASt[123], a distinction is made between roads with one and two roadways. The roadways themselves are divided into one-way and two-way roadways. One-way roadways are classic one-way roads or structurally separated two-way roads. They can be single-lane or multi-lane. Multi-lane two-way roadways are also designed separately, whereby the traffic separation

---

[121] It is noticeable that traffic participants, with the exception of pedestrians, are classified and differentiated on the basis of the vehicle used. More intuitive would be the classification by traffic participant in the sense of a vehicle user. For example, the term bicycle is used instead of cyclist. This is not a translation error, but rather common practice in the automotive community. However, the different terms are considered synonymous in this work.

[122] This refers to vehicle users according to BMJ: Erläuterungen zur Straßenverkehrs-Ordnung (2019), p. 9.

[123] FGSV: Richtlinien für die Anlage von Stadtstraßen (RASt) (2006).

can, but does not have to, take place with the aid of a central strip. Special cases are extra-wide roadways, narrowing of the roadway at constraining points, or narrow two-way roadways with passing places. Elements separating the roadway from the side spaces are also important. Curbs, gutters and trough gutters provide both a visual and a geometric separation of the roadway from sidewalks, bicycle lanes or other spaces off the road. Visual separation is particularly important in the absence of lane or roadway edge markings.

Roadways, as described above, must be used by motor vehicles and may not be left in regular cases. Any situation in road traffic that does not require or enforce a deviation from this rule may be referred to as a regular case. Such deviations may be common practice and known as common-sense rules, so that, for example, if the roadway is blocked by a broken-down vehicle, the sidewalk is also used for further travel. Consequently, leaving the roadway is possible in special cases. Nevertheless, the focus in this work is placed on the regular case, but the special cases are included in further considerations if necessary.

As a first interim conclusion, it can be stated that motor vehicles are generally only allowed to be on roadways. However, this does not mean that it is permitted to be in the entire area of a roadway. Even without knowing the exact wording of the traffic regulations, it is known that, for example, restricted areas or even bicycle lanes on the roadway may not be used. Obviously, there is consequently a subset of spaces on roadways that need to be further differentiated. Nevertheless, it seems reasonable to first classify roadways as a whole as intended motion space. In this way, fragmentation of the roadway at the highest level is avoided. This offers the advantage of initially creating a clear separation from areas in the public traffic space that are definitely not passable. Based on this initial differentiation, further restrictions are then imposed. These further conditions or rules are developed with the help of the further guiding questions. As a result of the considerations for GQ 1, the following definitions are recorded:

Regular motion space In regular case, motor vehicles are only allowed to be and move in the space of roadways. This space is therefore referred to as regular motion space. The regular motion space represents a first distinction to non-drivable spaces in the public traffic space. A regular motion space can, but does not have to, include other spaces that shall not be used based on specific rules.

Non-regular motion space Spaces outside the regular motion space that shall never/ cannot be used by motor vehicles are referred to as non-regular motion spaces.

The fact that the regular motion space can include other spaces that may not be accessed has another advantage. For this consideration, a change of perspective is necessary. Until now, the drivable space has been analyzed and differentiated on the basis of traffic regulations. From the perspective of the DDT, however, there are physical limits or obstacles in addition to regulatory constraints. Thus, it may well be relevant whether or not a vehicle can reach certain areas without a physical obstacle. A concrete case would be, for example, a restricted area separating two lanes. A restricted area is an area on a roadway that, as a rule, may not be driven on or used.

Although the area may not be used, however, a vehicle is not physically prevented in any way from entering that area. In this case, the markings are only a visual indication that this area is restricted. Accordingly, during driving operations, (unintentional) entry into such areas cannot be ruled out, since there is no mechanism for obstruction other than the visual indication. Sidewalks or traffic islands, on the other hand, are spaces of non-regular motion space in which a vehicle is generally also not permitted to stay. By definition, they are not parts of the roadway. The associated curbs or elevations represent area boundaries that are physically more difficult or impossible to drive over. Spaces of non-regular motion spaces are consequently more difficult or not at all accessible for a vehicle, so that these spaces are also clearly separated in terms of driving physics. The above definitions therefore appear to be practicable from the perspective of the DDT with regard to the traversability of spatial boundaries.

GQ 2: What conditions are attached to the residence in traffic spaces?

In order to answer this question, only areas of regular motion space that are explicitly allowed to be driven on are considered below. Areas that are not allowed to be used per se do not have any conditions for a stay. For the analysis, conditions are accordingly sought that are tied to the residence in these spaces. For this purpose, a widespread road layout[124] is considered first: A two-lane road with bidirectional traffic. Both lanes have a preferred direction, which dictates a direction of movement for all traffic participants in the lanes. In countries where right-hand traffic is mandatory, this is always the right-hand lane in the direction of travel. In general, § 2 of the StVO states that driving on roads must be as far to the right as possible. In the case of several lanes in one direction, the lane that is furthest to the right and free must therefore always be selected. However, according to § 7 of StVO, this rule does not apply within urban areas. Initially, no further conditions besides that are attached to driving in the lane that fits the intended direction of travel. It can therefore be assumed that a permanent stay in urban areas is permitted when driving in lanes in the preferred direction. In the road layout considered, it is therefore clear that only the right-hand lane in the direction of travel may be used permanently. It is also clear that oncoming traffic is to be expected in the left lane, since this is the lane with preferred direction for the oncoming direction. Nevertheless, for the purpose of overtaking, passing or swerving, it may be permitted to use this lane against the preferred direction. In § 5 and § 6 of the StVO it is explicitly required that a return to the lane with the appropriate preferred direction must take place. Lanes that are used against their preferred direction must consequently not be used permanently and must therefore be exited again as soon as possible.

A conventional lane that is not explicitly designated for one type of traffic participant represents the motion space for multiple traffic participant types. However, there are also lanes that are explicitly designated for specific types of traffic participants. One example on German roads are bicycle protection lanes such as shown in Figure 3-1. These lanes are provided for bicycle traffic

---

[124] 94 % of all federal roads in Germany had this layout according to a statistic from 2021 published in BMDV: Längenstatistik der Straßen des überörtlichen Verkehrs (2021).

and are located directly next to the conventional lanes of other traffic participants. However, the bicycle protection lanes may be crossed when necessary, in particular to avoid oncoming traffic[125] or to park. Since this need is not permanent - for example, there will not always be oncoming traffic that needs to be evaded or there will not always be the need for parking - bicycle protection lanes are also spaces that may not be used permanently.

Figure 3-1: Example of a bicycle protection lane in Darmstadt, Germany.[126]

Basically, the following can be stated with respect to motor vehicles:
If a motor vehicle is authorized to stay in a space, then the conditions on the stay differ in the permitted permanence of that stay. The stay may be allowed permanently or non-permanently.

GQ 3: What behavioral rules shall a motor vehicle observe when driving in traffic spaces?

So far, it has been worked out whether a vehicle is allowed to stay in a certain space in traffic and what condition is attached to the duration of stay. Now it is necessary to identify further traffic rules that must be observed when using the regular motion space. Considering the DDT, it becomes obvious that basically two different areas have to be addressed in terms of regulations. One part of the DDT is the control of the movement of the vehicle, especially the driving speed. In this context, it is initially irrelevant how a potential interaction with other traffic participants or objects takes place. Basically, the movement must be realized for active participation in road traffic. Another part of the DDT is the interaction of the vehicle with other traffic participants, objects and infrastructure elements. These interactions also include the adaptation of the vehicle movement in the sense of a reaction to the environment, but only in an implicit form. Consequently, the analysis of the traffic rules to be observed can be divided into two further questions:

---

[125] BMJ: Straßenverkehrs-Ordnung (StVO) (2013), Appendix 3, Section 8, 22.

[126] Taken from VRM Redaktion: Anwohner zählen Verkehr auf Dieburger Straße (2022).

- **GQ 3.1:** Which traffic rules apply explicitly with respect to vehicle movement?
- **GQ 3.2:** Which traffic rules apply explicitly with regard to interaction with other traffic participants, objects and infrastructure elements?

Regarding GQ 3.1

With respect to vehicle movement, the StVO explicitly addresses only the speed of traffic participants. For each road there is a rule for the applicable driving speed. In most cases, this rule consists of a speed limit, but demands for a minimum speed are also possible. In urban areas, a speed limit of 50 km/h usually applies, so vehicles are not allowed to drive faster than 50 km/h in these areas. On German autobahn, a large part of the roads is even unlimited, so that no speed limit applies here at all. Where minimum speeds are required, traffic participants are obliged not to drive slower than the required speed[127a]. Exceptions are road, traffic, visibility or weather conditions that do not allow driving at the required speed. At the same time, such a demand prohibits the use of such a designated lane or road with vehicles that cannot or should not travel at such a speed. Here, a reference to prohibited spaces from GQ 1 becomes apparent.

In addition to the unconditional restrictions mentioned above, there may be conditional restrictions on driving speed[128]. The restrictions can relate to a specific time period, but also to environmental conditions such as rain[127b], snow or fog. Furthermore, restrictions are also possible depending on the visibility.

Apart from driving speed, there are no further explicit rules in the StVO regarding concrete restrictions on vehicle movement. Only implicit and unquantified rules, such as the instruction to avoid unnecessarily rapid acceleration of the vehicle, especially when driving off, are described in the sense of environmental protection in § 30 of the StVO. Concrete, quantitative limit values or ranges are not listed.

Regarding GQ 3.2

Interactions between traffic participants usually occur when there are potential points of conflict between these traffic participants. This means that at least two traffic participants want to use the same physical space to move. In such cases, road traffic regulations around the world usually provide priority rules to ensure that traffic can move as accident-free and efficiently as possible. In the StVO, the concept of priority is not precisely specified. For the considerations in this work, the following definition based on § 8 of the StVO is formulated:

Priority Whoever has priority[129] must not be significantly hindered or endangered by other traffic participants.

---

[127] BMJ: Straßenverkehrs-Ordnung (StVO) (2013), Appendix 2, Section 7. a: 52; b: 49.1.

[128] BMV and BMU: Allgemeine Verwaltungsvorschrift zur StVO (VwV-StVO) (2001), Zu §§ 39 bis 43.

[129] In Germany, the term *priority* is defined differently depending on specific situations. However, since the meaning of the terms is the same with regard to the present definition, no distinction of terms is introduced by the author. In this work, *priority* and *right of way* are considered synonymous.

The following cases are regulated in particular with regard to priority:

- Driving over intersections
- Driving over crosswalks
- Changing lanes

The mechanism of priority regulation is manifold, so that there are many different priority cases to be considered. The scenery plays a special role. Depending on the scenery, the number and driving direction of different traffic participants involved vary greatly. These variations must be taken into account when deriving the applicable priority rules. Concrete priority cases are not the focus of this chapter, but rather the different types of priority. Nevertheless, specific examples are provided to explain these types. In the following explanations, the vehicle from which perspective priority is considered is referred to as the ego-vehicle:

Ego-vehicle has priority: The ego-vehicle may have priority, so that other traffic participants must show consideration for the ego-vehicle and not obstruct it. A simple example is crossing an intersection straight while driving on a priority road. The ego-vehicle does not have to give priority to any other traffic participant. In return, the other traffic participants must give priority to the ego-vehicle in this situation.

Ego-vehicle must give priority: Other traffic participants have priority, so the ego-vehicle must not obstruct or endanger them. A simple example is a crosswalk. In this case, the ego-vehicle must give priority to pedestrians who (want to) cross the crosswalk and wait in front of the crosswalk if necessary.

Priority is not regulated: There are special cases where the right of way is not as clearly regulated as previously described. In these special situations, the traffic participants involved must agree on who has priority according to § 11 of the StVO. The traffic participants involved therefore decide for themselves who has priority. An example is a narrowing of the road with bidirectional traffic, where only one vehicle can pass. If priority in this case is not regulated by a traffic sign, the oncoming traffic participants must coordinate their actions. Usually, this communication takes place by means of adapted driving behavior (e.g. slowing down or stopping), hand signals, eye contact or headlight flashing. This is certainly a special challenge with regard to automated driving, but it is not discussed in detail in this work.

Interaction between traffic participants is not always regulated only in terms of priority. When overtaking, it must be clear beyond the right of way whether overtaking is permitted at all in the respective situation. The interaction between two traffic participants, which is referred to as overtaking, is defined in the explanations to the StVO as follows:

Overtaking is when one traffic participant passes another from behind who is moving in the same direction on the same roadway or is merely waiting due to traffic.[130]

This explicitly applies to the entire roadway, regardless of lane boundaries. Overtaking is generally permitted on German roads, which means that overtaking bans must be explicitly indicated.

In addition to interactions between traffic participants, there are also rules for interactions between traffic participants and objects or infrastructure elements. However, since these rules only apply when changing between individual spaces, these will be considered in the next part.

GQ 4: What behavioral rules shall a motor vehicle consider when moving between traffic spaces?

The regular motion space does not always consist of only one lane in the lateral direction. There can be several lanes with up to two preferred directions as well as additional lanes for cyclists. Marked crosswalks or stop lines, on the other hand, are infrastructure elements that divide the regular motion space in the longitudinal direction. A regular motion space can therefore contain further spaces that are subdivided in lateral and/or longitudinal direction. It is now examined which behavioral rules may occur during a transition from one space to another space. At first, it is only important to address different manifestations of the behavior rules for the transition between spaces. In the further course of the work, these will then be considered in more detail in some cases.

Basically, there are boundaries between two spaces that may or may not be crossed. Solid lines or curbs signal a prohibition to cross, while dashed lines or even unmarked guidelines represent a permission to cross. However, curbs can also be so high that it is physically impossible or difficult to drive over them. The same applies to other infrastructure elements that separate the non-regular motion space from the regular motion space. From the point of view of the DDT, this information is just as relevant as a prohibition, since the planning of the route or the planning of the driving trajectory directly depends on it.

In addition, however, conditions may be attached to a transition between two spaces. In general, for all lane changes and for all turning maneuvers according to § 7 and § 8 of the StVO, these actions must be announced in time with the help of the vehicle's turn indicators. A further example are parking lanes that are adjacent to conventional traffic lanes may only be used if parking is actually taking place in this area. Flowing traffic is not permitted in parking lanes. Marked crosswalks or intersections may not be blocked even if there is no existing obligation for a traffic participant to wait. Specifically, § 11 of the StVO states that in the case of stopped traffic, despite right of way or green light signal, it is not allowed to enter the intersection or junction if it would be necessary to wait in that areas. The same applies according to § 26 for driving into crosswalks.

---

[130] Translated from German: "Als Überholen gilt, wenn ein VT [(Verkehrsteilnehmer)] von hinten an einem anderen vorbeifährt, der sich auf derselben Fahrbahn in derselben Richtung bewegt oder nur verkehrsbedingt wartet", BMJ: Erläuterungen zur Straßenverkehrs-Ordnung (2019), p. 20.

Other conditions for entering spaces arise at intersections or signalized crossings. For example, a stop sign indicates that the vehicle must stop at the associated stop line before crossing it. On the other hand, a traffic light in red phase signals that the associated stop line may not be crossed.

In summary, there are the following characteristics of behavioral rules that must be observed and adhered to when transitioning between spaces:

- Permission
    - unconditional
    - conditional
- No permission
- Possibility of transition not given

3.2 Classification of Behavioral Demands

Based on the previously defined and discussed guiding questions, this section develops a classification of behavioral demands. The overall goal is not only to identify the behavioral demands on the basis of the scenery, but also to link the behavioral information obtained with the scenery. Besides the creation of the linkage itself, a suitable information structure has to be defined for this purpose. On the one hand, only the necessary information should be recorded and, on the other hand, redundancies should be avoided. In this way, the information content is kept as low as possible, so that the basis for an efficient linkage with the scenery is created. The following definitions are intended to support the process of information structuring with regard to information efficiency:

Necessary information in the context of behavioral demands is any information that constrains the possible behavior of a motor vehicle.

Redundancy in the context of behavioral demands exists if necessary information about the same part of the scenery is available more than once.

Based on the previously discussed guiding questions and the demand for information efficiency, a classification structure of the behavioral demands is developed in this chapter. Consequently, the classification should cover all previously elaborated behavioral demands in terms of redundancy-free and necessary information.

First, it is clarified what distinguishes necessary from unnecessary information. As presented in the previous chapter, behavioral rules are given by different scenery elements. An interpretation of the present scenery elements in combination with the applicable road traffic regulations allows the derivation of the explicit behavioral constraints. Since the result of this interpretation process represents the necessary information, neither the road traffic regulations nor the scenery is needed to describe this information. Nevertheless, the scenery elements play a crucial role in the derivation of the behavioral demands, since they indicate the applicable rules. For this reason, these scenery elements are defined as indication elements[131]:

Indication elements are elements of the scenery that define and indicate the behavioral demands considering the applicable road traffic regulations. It is possible that different scenery elements or different combinations of scenery elements result in the same behavioral demands.

Indication elements include traffic signs, but also other infrastructure elements such as lane topologies, markings, traffic signals or even intersection topologies. In addition, environmental conditions such as rain or time of day may be linked to indication elements with conditional behavioral demands. No indication element is part of the necessary information to describe the behavioral demands. The fact that different constellations of scenery elements lead to the same behavioral demands underlines the claim of freedom from redundancy. If indication elements were defined as necessary information, the result would be an arbitrarily large amount of redundant, behaviorally relevant information.[132] However, it should be noted that indication elements are not always sufficient to identify the behavioral demands in certain situations. For example, the information about driving in a 30 km/h zone would not be given directly if the AV starts driving in the zone itself. The associated indication elements are usually placed at the zone boundaries. This fact has to be considered in the following work steps as well.

Regardless of the indication elements, the examination of the four guiding questions from the previous chapter reveals different characteristics of behavioral demands. In the following, these different characteristics are classified and structured without violating the demand for necessary and redundancy-free information.

Restriction of residence

Based on GQ 1, it is evident that there are basic restrictions regarding the stay in public traffic spaces. In this context, motor vehicles are restricted regardless of their movement in their space of residence. If there is no restriction, a motor vehicle is initially allowed to freely reside in respective traffic spaces. If there are restrictions, an unconditional exclusion of motor vehicles from corresponding spaces may apply. It is clear from GQ 2 that residences in spaces may also be conditionally restricted in general.

Residence may be...

- *not restricted:* Motor vehicles are allowed to be in certain areas in the public traffic space without restriction.

---

[131] First published in Glatzki, F. et al.: Behavioral Attributes for a Behavior-Semantic Scenery Description (2021).

[132] Examples of redundant indication elements are shown in Figure 4-1 in Subsection 4.1.2.

- *conditionally restricted:* Motor vehicles are not allowed to be permanently in every area of the public traffic space. Some areas require a non-permanent stay and must therefore be left as soon as possible[133].
- *unconditionally restricted:* Motor vehicles are not allowed to be in certain areas in the public traffic space.

Restriction of driving speed

In addition to a potential (conditional) restriction of the residence, a motor vehicle may be restricted in its speed of movement according to GQ 3.1. In some cases, no restrictions are present. Existing restrictions may be conditional or unconditional, as in the case of residence restrictions. It is possible for a vehicle's speed range to be restricted both downward and upward.

Driving speed may be...

- *not restricted:* The movement of a motor vehicle in the public traffic space is not restricted in terms of minimum required and/or maximum permitted speed.
- *conditionally restricted:* The movement of a motor vehicle in the public traffic space is conditional restricted in terms of minimum required and/or maximum permitted speed depending on time periods, weather conditions etc.
- *unconditionally restricted:* The movement of a motor vehicle in the public traffic space is restricted in terms of minimum required and/or maximum permitted speed.

Restriction of space changes

The traffic space can be divided into different subspaces geometrically. Different lanes for different traffic participants, crosswalks or even intersection areas are examples of possible subspaces. From GQ 4 it can be seen that area changes, as before, residence and travel speed can be unrestricted, conditionally restricted and unconditionally restricted. In addition, it shows that physical restriction is also possible, not only prohibiting but actively preventing area changes.

Space changes may be...

- *not restricted:* Motor vehicles may complete space changes in the public traffic space without specific restrictions regarding the change.
- *conditionally restricted:* Motor vehicles may complete space changes in the public traffic space only under specific conditions.

---

[133] There are areas that have different residence restrictions due to other conditions. For example, the direction of travel of lanes in the Elbe Tunnel in Hamburg, Germany, is partially switched. In this case, the restriction alternates between *not restricted* and *unconditionally restricted*. However, this does not require a new class of restrictions, as the two existing classes can be combined for the representation of the relevant information.

- *unconditionally restricted:* Motor vehicles are not allowed to complete space changes in the public traffic space.
- *physically restricted:* Motor vehicles are physically incapable of completing space changes in the public traffic space.

Restriction of priority

From GQ 3.2, restrictions emerge regarding the interaction between traffic participants. Restrictions on the right of way of a motor vehicle are shown. The right of way can be unrestricted, so that other traffic participants do not have to be given priority. The reverse case also exists, where a considered motor vehicle must give priority to other traffic participants. In some cases, priority is neither unrestricted nor restricted, but simply not regulated. Compared to the previously identified restrictions, this case represents a new type of restriction.

Priority may be...

- *not restricted:* Motor vehicles do not have to give priority to other traffic participants in certain areas.
- *unconditionally restricted:* Motor vehicles have to give priority to other traffic participants in certain areas.
- *not regulated:* Priority is not regulated in certain areas, so that involved traffic participants have to agree on priority between each other.

Restriction of overtaking

A final constraint also arises from GQ 3.2, which is clearly distinct from the priority constraint. In terms of interaction between traffic participants, overtaking is constrained. Compared to the other constraints, this constraint represents the simplest case. There is only a distinction between *no restriction* and *unconditional restriction*.

Overtaking may be...

- *not restricted:* Motor vehicles are allowed to overtake in certain areas of the public traffic space.
- *unconditionally restricted:* Motor vehicles are not allowed to overtake in every area of the public traffic space.

3.3 Interim Conclusion

In this chapter, scenery-based behavioral demands were systematically identified using guiding questions. Important terms such as *traffic participant*, *priority* and *overtaking* were explained and defined. In addition, the new terms *regular motion space* and *non-regular motion space* for motor vehicles were introduced. The identified behavioral demands always result from a combination and interpretation of scenery elements - the *indication elements* - and applicable traffic regulations. The identified behavioral demands have different characteristics, so that in a second step a classification of the behavioral demands was performed. Considering a reduction to the relevant behavioral information, five different classes of behavioral demands result:

- Restriction of residence
- Restriction of driving speed
- Restriction of space changes
- Restriction of priority
- Restriction of overtaking

These results directly address and answer the first research question:

RQ 1: What behavioral demands result from the scenery of an ODD?

Nevertheless, it must be critically questioned to what extent these classes are transferable to other traffic regulations, i.e. to other countries. So far, the analyses have been carried out on the basis of the German road traffic regulations and a transferability has not been explicitly investigated. However, previous experience of the author of the present work indicates that transferability, possibly with minor adaptations, cannot be ruled out. As a potential basis for requirement and capability specification of AVs, transferability would be an important factor for uniform use of behavioral demands. This needs to be examined in further research. Another point that could be criticized is the lack of addressing of non-scenery based behavioral demands. In addition to the identified classes, there are other behavioral demands that, for example, constrain behavior with respect to potential collisions. The meaning of these behavioral demands for the overall approach of this work is addressed in Section 5.1.

Based on the results of this chapter, the presupposed link between scenery and behavioral demand from Section 1.1 is not refuted, but corroborates. It can be assumed that the scenery can still serve as a basis for deriving driving requirements and driving capabilities. To do so, however, it is necessary to represent the identified and classified behavioral demands in such a way that a holistic and systematic derivation becomes possible. Currently, the existing types of behavioral demand are known, but a concrete link to the scenery is not yet given. Only with the linkage of the scenery the holistic of the applicable behavioral demands for a considered scenery area results.

A map representation would provide that linkage and enables holistic analyses. Therefore, in the next chapter, a map representation of the scenery-based behavioral demands is elaborated.

4 Map Representation of Scenery-Based Behavioral Demands

In the scope of this chapter, a representation of the scenery-based behavioral demands is developed that enables the linkage to the scenery, which is fundamental for this work. In the first part, a novel concept for this purpose is presented. Based on this basic concept, goals and challenges are then derived that result for a transfer of this concept to a map representation. According to the defined goals, requirements for the map representation are identified, which serve as a basis for the development. Subsequently, the developed map representation - the *Behavior-Semantic Scenery Description* - is presented and applied to real-world sceneries.

4.1 Basic Concept[134]

The state of the art in Section 2.2 shows that there is no explicit and scenery-related representation of behavioral demands so far. This means that it is not yet possible to represent the valid rules of behavior based on the positions of a traffic participant in the traffic space. However, this is necessary so that driving requirements and driving capabilities can be derived for a potential trip of an automated vehicle. Consequently, a concept is sought that represents the behavioral demands based on the scenery-related position of the considered traffic participant. Therefore, the concept of *behavior space* and *behavioral attributes* is introduced in the following.

4.1.1 Behavior Space

The identified classes of behavioral demands can be further divided into two groups with respect to the areas of applicability. On the one hand, the behavior of traffic participants within a considered space is limited (residence, driving speed, priority and overtaking). On the other hand, the behavior of traffic participants is explicitly limited with regard to changes of space. Consequently, behavioral demands are always bound to spaces or to changes between these spaces in road traffic. It is therefore reasonable to use these spaces to represent behavioral demands. For this reason, the term *behavior space* is introduced:

Behavior space represents the restricted set of legally allowed behaviors of a traffic participant. The following applies:

---

[134] Parts of this section have already been published in Glatzki, F. et al.: Behavioral Attributes for a Behavior-Semantic Scenery Description (2021).

1. The behavior space is spanned by behavioral attributes that define all applicable behavioral demands of the behavior space.
2. The behavior space defines only the legal behavioral limits of a traffic participant, so that no explicit behavior is imposed on a traffic participant.
3. Behavior spaces may differ for different types of traffic participants.

Regarding 1.: In order to restrict the legally allowed behaviors, the behavioral limits must be specified. Due to the different types of behavioral demands, behavioral attributes are introduced for this purpose, which are derived and explained in the next section.

Regarding 2.: The behavior space only shows the behavioral limits. Within the defined behavioral limits, a traffic participant is allowed to behave and move freely.

Regarding 3.: In principle, it is possible that behavior spaces are defined for each traffic participant type. For a pedestrian, for example, a crosswalk has a completely different meaning than for a motor vehicle or a cyclist. However, in the context of this work, the focus will remain on motor vehicles.

The definition of the behavior space is initially kept very abstract and detached from geometry. In principle, it is at the user's discretion how coarse or fine granular the size of behavior spaces is designed. The behavior space may contain complete streets or just single lane sections. The larger a behavior space is designed, the higher the probability for multiple occupancies of the different behavioral attributes. For example, if the goal is to represent a road segment across the entire lane width, multiple lanes would require substructures describing these individual subspaces. Consequently, for a road with three lanes, at least three subspaces would be needed to represent the higher-level behavior space. It is not possible to dispense with the representation of the subspaces, otherwise the behavioral demands would become blurred and no clear behavioral limits could be defined. So what is the minimum necessary behavior space that must be represented?

The behavior space is described using the behavioral attributes. Consequently, a behavior space that is not described by further subspaces would be described by a set of the behavioral attributes. This means that no changes in the values of the behavioral attributes may occur within this behavior space. Each change would result in a new space section so that the assignment of information remains unique. Consequently, for a representation of behavioral demands in the form of behavior spaces, atomic behavior spaces must be defined:

Atomic behavior space is a behavior space in which the behavioral demands of the behavioral attributes do not change.

The typical atomic behavior space for motor vehicles is a longitudinal section of a traffic lane. Nevertheless, it is possible to create a behavior space smaller than the atomic behavior space. From the point of view of the behavior-relevant information, this results in redundancy, since the same sets of information are available several times. From a representation point of view, the representation of sub-atomic behavior spaces also results in disadvantages, since an unnecessarily large amount of information would have to be provided. In terms of information efficiency, a subdivision of atomic behavior spaces is consequently not desirable.

4.1.2 Behavioral Attributes

The behavioral attributes define the applicable behavioral demands for behavior spaces. For this reason, they represent the identified classes of behavioral demands. In principle, it would be possible to make each class a behavioral attribute separately. However, it is possible for individual classes to be merged when describing behavior spaces in order to store the behavioral information even more efficiently. The fewer behavioral attributes needed to describe behavior spaces, the greater the reduction in information content and overall complexity of the concept. Nevertheless, it is necessary that the behavioral attributes remain semantically independent. For example, it would not be practical to represent constraints on driving speed and overtaking in one behavioral attribute, since the constraints are fundamentally not dependent on each other.

The description of a behavior space requires a delimitation of the space itself in addition to the behavioral demands in the space. The identified classes *restriction of driving speed*, *restriction of priority* and *restriction of overtaking* are suitable for the inner description of the behavior space. In contrast, the other two classes *restriction of residence* and *restriction of space changes* refer to the behavior space boundaries. Via the behavioral space boundaries, both restriction in terms of space change and residence would be possible. From a behavioral point of view, there is no difference in not being allowed to enter a space because of restrictions on space change or residence. The prohibition would be semantically exactly the same. From this possible assignment of behavioral demands to behavioral space boundaries and behavioral space itself, the following behavioral attributes are defined and explained: *Speed*, *Boundary*, *Reservation* and *Overtake*.

Speed: This behavioral attribute includes all behavioral demands regarding restrictions on driving speed. Town signs as well as explicit speed signs are indication elements that cause these restrictions. Speed signs can be equipped with additional signs, so that the speed restrictions are provided with conditions. These conditional restrictions are also captured in the speed attribute. They include, for example, time-of-day restrictions, but also weather-dependent restrictions.

Boundary: This behavioral attribute represents the boundaries of the behavior space. Crossing the behavioral space boundaries is assigned with restrictions of the area changes and with restrictions of the residence. Crossing the boundaries can thus be *allowed*, *conditional*, *prohibited*, or *not possible*. Since the behavior space of a motor vehicle typically represents a longitudinal section of a lane, the boundary attribute is differentiated into longitudinal and lateral boundaries.

Crossing the longitudinal boundary is allowed without indication elements present. As soon as indication elements are present, however, restrictions may arise. A stop sign with associated stop line requires a crossing condition: The vehicle must stop before it is allowed to proceed. If a traffic signal with associated stop line is present, the stop line may not be crossed if the traffic signal shows red. Furthermore, it is not permitted to drive into intersections or crosswalks if there is traffic congestion and it is therefore not possible to drive through the areas. Crossing in these cases is therefore *conditional*[135]. Entering a one-way street against the direction of travel is not permitted. Similarly, there are lanes that are designated only for certain types of traffic. All spaces into which a motor vehicle is not allowed to enter are accordingly marked with a longitudinal boundary *prohibited*. In some cases, longitudinal entry into a behavior space may even be not possible, i.e., the vehicle is physically prevented from entering. An example of this would be a lane that ends for motor vehicles but allows bicyclists to continue. The two spaces may be separated by bollards or similar physical barriers, allowing only bicyclists to pass. In these cases, crossing the longitudinal boundary is *not possible*.

Lateral boundaries have in principle the same properties as longitudinal boundaries. Here, as well, the crossing is differentiated into *allowed*, *conditional*, *prohibited* and *not possible*. The lateral boundaries of behavior spaces typically correspond to the lane boundaries on roadways. No or dashed lane markings signal as an indication element that crossing the lateral boundary is *allowed*. Parking lanes require that entry is only allowed for the purpose of parking, so the associated lateral boundary is assigned *conditional*[135] accordingly. Solid lane markings or curbs may not be crossed and are modeled accordingly as lateral boundaries with the value *prohibited*. Especially high curbs, guard rails, fences or walls are physically not traversable for a motor vehicle. These indication elements therefore result in lateral boundaries where driving over them is *not possible*.

Reservation: In this attribute mainly the restrictions of the priority are covered. A reservation type is always defined. Behavior spaces in which the ego-vehicle itself has priority are called *own-reserved*. No other constraints exist for own-reserved behavior spaces.[136] An example is driving in a lane which is reserved for the driven direction and for which there are no further indication elements regarding priority. Behavior spaces in which the ego-vehicle must give priority to other traffic participants are called *externally-reserved*. In the case of externally-reserved, the traffic participant type and potential direction of origin of the traffic participants entitled to reservation are also specified. In Section 3.1 different traffic participant types were introduced. Regarding priority rules, the numerous types can be reduced to four classes, since priority rules are imposed only for these: motor vehicle, bicycle, pedestrian and rail vehicle. For example, passenger cars, motorcycles, trucks or even buses are included in the motor vehicle class in terms of priority. With these traffic participant classes and the direction of origin, externally-reserved behavior spaces are fully defined. In the case of a crosswalk, it would consequently be explicitly known that this behavior space is reserved for pedestrians already in this area or approaching it from the right

---

[135] The behavioral demand for the timely announcement of turning or lane change maneuvers with the help of the turn indicators is neglected in this work. This provides better clarity since this demand is present in many behavior spaces. However, the concept of the boundary attribute maps this demand effortlessly.

[136] The behavioral demand to drive as far to the right as possible is neglected in this work, since this rule does not apply in urban areas (Cf. Section 3.1, GQ 2.). However, the concept of the reservation attribute maps this demand effortlessly.

or left. Thus, the priority case is unambiguous and explicitly represented. Behavior spaces can furthermore be *equally-reserved*, addressing the case of unregulated priority from GQ 3.2. Since, as in the externally-reserved case, explicit interaction with other traffic participant types from certain directions of origin is addressed, these properties are also stored in the attribute. Thus, in the example of a lane narrowing, it would be explicitly specified with which traffic participants from which direction the ego-vehicle has to coordinate.

In addition, the reservation attribute is suitable for representing the conditional residence restrictions, since these are directly related to the priority regulation. If the ego-vehicle has to give priority to other traffic participants in a behavior space, it may additionally not permanently occupy this space. Therefore, the reservation type externally-reserved simultaneously addresses the necessity to leave the corresponding area as soon as possible. An example of this is the oncoming traffic lane or also a bicycle protection lane, both of which may only be used temporarily and not permanently.

Overtake: All behavioral demands regarding restrictions of overtaking are stored in this attribute. Overtaking is either permitted or prohibited. Typically, an overtaking prohibition is caused by a corresponding traffic sign. Another indication element for an overtaking prohibition is, for example, a crosswalk.

Figure 4-1 presents some indication elements that cause the defined behavioral attributes.

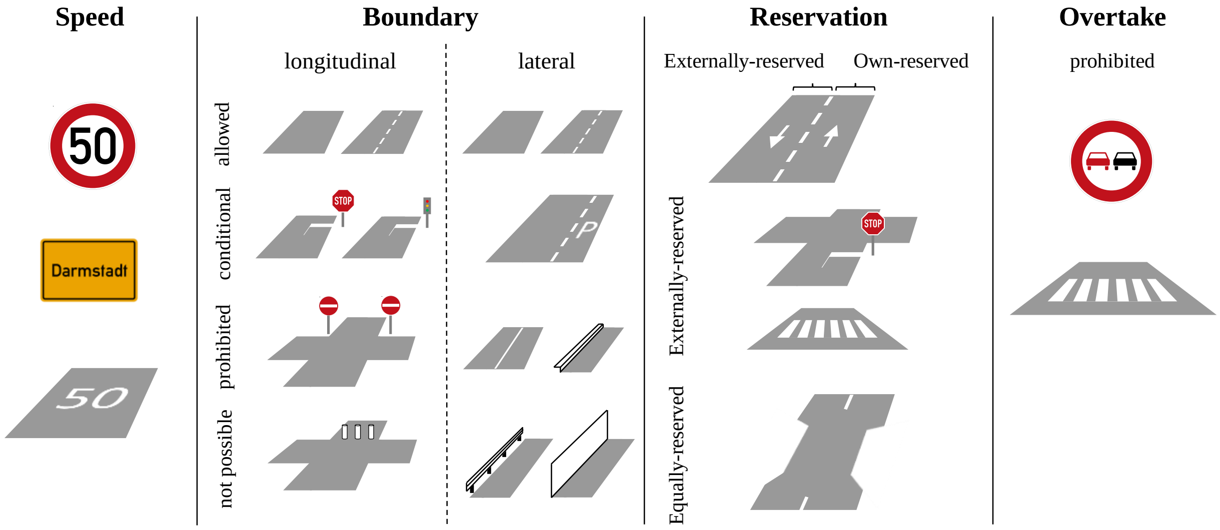


Figure 4-1: Example indication elements causing the behavioral attributes.©2021 IEEE

4.1.3 Application of the Basic Concept

To enhance the understanding of behavior space and behavioral attributes, an application example is presented below. For this purpose, three real X-intersections from the city of Darmstadt (Germany) are considered in Figure 4-2. The first image shows an intersection controlled by traffic lights. The second image shows an intersection with priority signage and the last image shows an uncontrolled intersection with a one-way road to the right. In Germany, uncontrolled intersections give priority to the traffic participants coming from the right, viewed from each direction arriving at the intersection. For all intersections, a left turning maneuver is considered, as depicted by the orange arrows. For the first case, the traffic lights of the first intersection are assumed to be inactive. In Germany, priority in the event of traffic signal failure or deactivation is typically regulated by traffic signs. These are present as a fallback level at almost every traffic signal system, so that the priority is clear. In this example, the behavior set is chosen respectively.

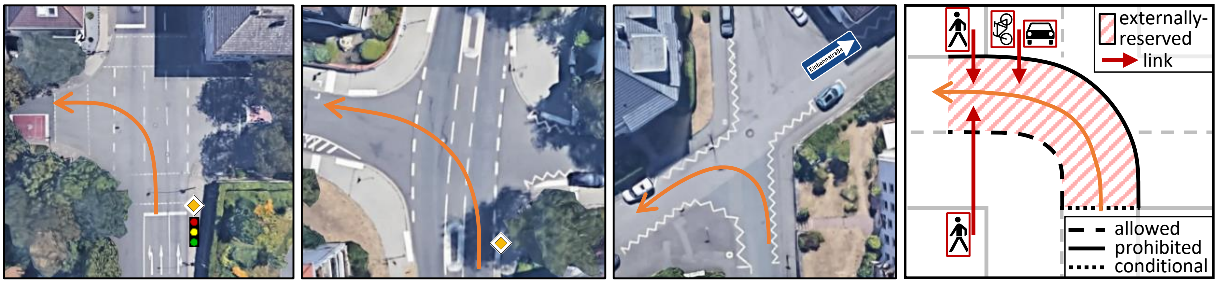


Figure 4-2: Example intersections and their behavior space representation.
Imagery and map data ©2021 Google/AeroWest.©2021 IEEE

On all three intersections, traffic signs indicate a speed limit of 30 km/h. So the first behavioral attribute *speed* is allocated with the value of *30 km/h*.

With the traffic light being inactive there is no restriction to enter the intersection regarding this indication element in the first example. For the second and third example, there generally exists an allowance to enter the intersection. Nevertheless, since all three behavior spaces represent a part within an intersection, the entry is restricted regarding stagnant traffic. A motor vehicle is not allowed to enter the intersection if it has extended stopping times within the intersection due to traffic obstruction. For example, crossing traffic would be blocked in the example intersections. Therefore, the *longitudinal boundary* attribute is set to a conditional restriction: *no stagnant traffic*.

For a left turn maneuver, it is allowed to drive over the left lateral boundary of the atomic behavior space (e.g. to avoid an obstacle). Of course, the behavioral attributes of the oncoming lane need to be respected in this case. It is not allowed for the vehicle to cross the right boundary while turning left. The left *lateral boundary* attribute is set to *allowed* and the right *lateral boundary* is set to *prohibited*.

The reservation is determined by the present traffic rules. For the first two examples, there is priority signage that gives priority to the left turning maneuver over traffic participants coming from left and right. Still, priority must be given to oncoming traffic participants, as well as pedestrians crossing the exit road parallel to the entry road. For the third intersection, because there is a one-way street to the right which applies as well for bicycles, it is not necessary to give priority to the right. Again, priority must be given to oncoming traffic participants and pedestrians crossing the road. For all intersections, there is enough space for two oncoming left turning traffic participants to turn at the same time. Therefore, the *reservation* attribute is set to *externally-reserved* for the traffic participant classes *pedestrians*, *bicycles* and *motor vehicles* with the respective *links* that indicate from where these traffic participants may come.

Finally, there is no overtaking prohibition. Contrary to popular belief, that overtaking at intersections is prohibited, the *overtake* attribute is set to *allowed* accordingly.

The resulting atomic behavior space is depicted in the last image of Figure 4-2 as an abstract representation. All three left turning maneuvers result in the same behavior space with the particularity that the first intersection has an additional behavior set for an active traffic light.

4.1.4 Interim Conclusion

In this section, behavior space and behavioral attributes were introduced for the representation of the behavioral demands identified and classified in Chapter 3. An application of this basic concept was demonstrated using examples. Thereby, the behavior space was initially only represented in an abstract way. Based on this representation, it was nevertheless possible to unambiguously assign the four behavioral attributes. However, a format that takes into account the structure of behavior spaces and explicitly represents or describes the information is missing. So far, the behavioral demands of the attributes have only been recorded in the form of text and image. Furthermore, there is also no explicit link to the scenery yet. The behavioral demands represented do result from the scenery, but the abstract representation does not ensure a linkage with the scenery. Of course, it would be quite possible to manually create individual visual representations of behavior spaces for different scenery sections, but this approach would not be practical. Moreover, in the case of multiple, existing behavior sets for a scenery section, multiple visualizations would be necessary. Thus, in Figure 4-2, two separate representations would be necessary for the intersection with traffic signals.

Another disadvantage of the representation shown is the representation of only single, isolated behavior spaces. With respect to the identification of the automated driving task, it is necessary to consider different behavior spaces in an overall context. In the third intersection image of Figure 4-2, not only the current atomic-behavior space is relevant for the behavioral decision of an automated vehicle, but also the following behavior spaces (not shown). For example, the narrowed road section behind the intersection after the left turning maneuver will be equally-reserved. This already needs to be considered by the automated vehicle while entering the intersection, so that it does not block the intersection while waiting for traffic participants to exit the narrowed section. A forward concatenation of the behavior spaces in the form of a route would elegantly solve this problem. Therefore, the information about the existence of the subsequent atomic behavior space needs to be represented.

In terms of a map representation of behavioral demands, the following can be stated:

- The behavior space provides a way to represent behavioral demands.

- The behavioral demands are differentiated and described on the basis of four behavioral attributes.
- The behavior space is so far only available in abstract form, without geometry and without explicit linkage to the scenery.
- Behavior spaces are only represented individually and in isolation.
- Multiple behavior space sets for a scenery section are not represented in one representation.
- Format and structure for a unified and explicit representation of behavior spaces and attributes are missing.

Based on these findings, the next chapter develops goals and challenges for a map representation of behavioral demands in form of behavioral spaces and behavioral attributes. The deficits mentioned will be explicitly addressed in order to create a suitable basis for deriving requirements and capabilities.

4.2 Goals and Challenges of the Map Representation[137]

This section deals with goals and resulting challenges for the development of a holistic map representation of behavioral demands. Since the term *map representation* is still somewhat abstract and not clearly defined, this term is first concretized. For this purpose, the findings from the previous chapters are recapitulated and put into context.

The focus of the map representation is on the behavioral demands that impose limits on the behavior of all traffic participants. Consequently, a central element is the **Behavior**.

The behavioral information is usually not explicitly available in the real world. It always requires an interpretation process that extracts the behavioral information from the combination of scenery elements and applicable traffic rules. This process of generating meaning is known in human language science as semantics. Kroeger gives the following example, which is very suitable in regard to the present work:
"[...] no one believes that speakers memorize every possible sentence of a language; this cannot be the case, because new and unique sentences are produced every day, and are understood by people hearing them for the first time. Rather, language learners acquire a vocabulary (lexicon), together with a set of rules for combining vocabulary items into well-formed sentences (syntax). The same logic forces us to recognize that language learners must acquire not only the meanings of vocabulary items, but also a set of rules for interpreting the expressions that are formed when

---

[137] Parts of this section have already been published in Lippert, M. et al.: Behavior-Semantic Scenery Description (BSSD) for Automated Driving (2022).

vocabulary items are combined. All of these components must be shared by the speech community in order for linguistic communication to be possible. When we study semantics, we are trying to understand this shared system of rules that allows hearers to correctly interpret what speakers intend to communicate."[138]

This example of semantics can be completely applied to the problem presented here. The scenery elements correspond to the vocabulary of a language. They can occur in almost arbitrary combinations, just like the words in sentences of a language. The behavior-relevant meaning of the combination of the scenery elements results thereby only with the help of a set of rules - the traffic rules. The same applies to the individual words, which can only be interpreted and finally given a meaning with the help of rules - the syntax. The understanding of the behavioral demands is also only gained through a correct interpretation of the scenery elements. For this reason, another key element of the intended representation is the **Semantics** related to behavior.

Knowing the behavioral meaning of the scenery is not yet sufficient in the context of automated driving. It is necessary to link the acquired knowledge to the operational environment of the vehicles. Therefore, the **Scenery** is obviously another key element for a map representation.

Last, it is necessary to design the representation in such a way that the behaviorally relevant information is available for further processing. Both humans, such as developers, and machine functions or systems, such as algorithms, should be able to use this information. The relevant information must therefore be described accordingly. For this reason, the last central element of the map representation is the **Description**.

These core elements concretize the term *map representation*. Together, they give the intended map representation its name: The **Behavior-Semantic Scenery Description (BSSD)**.[139]

From the basics of behavior spaces and behavioral attributes, it is evident that the behavior space represents the behavioral demands in semantic form. So far, by using only single, isolated behavior spaces the behavioral demands are only represented for sub-parts of the scenery without putting them into context with each other. Additionally, there is no explicit linkage between the represented behavioral demands and the associated scenery. Thus, the main goal of the BSSD is defined as follows:
***Main Goal**: The BSSD shall semantically represent the behavioral demands in the overall context of a considered scenery and provide explicit linkage between demands and scenery.*

In general, the behavioral demands apply to a specific type of traffic participant. If this main objective is achieved holistically, the following hypothesis may be corroborated[140] and not be falsified:

---

[138] Kroeger, P. R.: Analyzing meaning (2019), p. 4.

[139] This term has already been introduced in Glatzki, F. et al.: Behavioral Attributes for a Behavior-Semantic Scenery Description (2021).

[140] Popper, K. R.: The logic of scientific discovery (1959).

***Hypothesis**: The BSSD represents the behavioral demand of the scenery for a specific traffic participant in semantic form.*

In this work, the scope is the BSSD for an automated motor vehicle. Thus, given considerations and examples address automated vehicles as a specific type of traffic participant. However, the BSSD can potentially be used for any type of traffic participant. In the following, the sub-goals and challenges to achieve the stated main goal of this chapter are identified and discussed. Subsequently, these will be used as a basis for deriving the requirements for BSSD.

Assignability: Currently, a description of individual atomic behavior spaces using behavioral attributes is possible based on a given scenery. At first, it is irrelevant whether the scenery is artificially generated or real. For the description of a behavior space, however, only the relevant scenery section is considered without establishing an explicit and traceable connection. For development, testing and operation of automated vehicles it is necessary to know the connection of the behavioral demand to a real scenery or a real route network. In this way, the derivation of driving requirements and capabilities within the ODD becomes possible. The following sub-goal and challenge arise:
***Sub-Goal:** The BSSD shall provide a traceable connection between real scenery and behavior spaces.*
***Challenge:** Each (atomic) behavior space is assigned to its corresponding scenery section.*

Connectivity: In addition to unambiguously assigning behavior spaces to the scenery, it is necessary to establish the connection between the behavior spaces themselves. Initially, each behavior space exists independently of others. If an ODD of automated vehicles is considered only within one atomic behavior space, information about a single atomic behavior space would be sufficient. Usually, the behavior space changes multiple times while moving through a road network due to changes in behavioral demands, for example, caused by traffic rules or various lane topologies. Thus, if an ODD contains multiple (different) atomic behavior spaces, the connection between them is essential. Even having only two different atomic behavior spaces requires an unambiguous connection, since both the entry into a new space and the associated driving in this space are linked to conditions. To fulfill these conditions, they must be known while being in the previous behavior space. Thus, the following sub-goal and challenge emerge:
***Sub-Goal:** The BSSD shall enable the navigation through the individual atomic behavior spaces comparable to a map.*
***Challenge:** The development of a suitable description structure that enables a concatenation of the individual behavior spaces.*

Consistency: When assigning the behavior spaces and connecting them to each other, the absence of contradictions is another decisive factor. There must be no duplications or multiple references within the description. The following sub-goal and challenge result:
***Sub-Goal:** The BSSD shall provide contradiction-free and unambiguous behavioral information for each part of the scenery.*

Challenge: *Prevent parts of the scenery that should be described in the same way from a behavioral perspective from being represented differently in the description.*

Generality: Different use cases of automated vehicles may require different ODD definitions and thus different associated sceneries to be navigated. To cover as many current and future use cases as possible, the BSSD should be generic. This means that an application is universally possible and in this way, every relevant scenery or ODD for the operation of AVs can be mapped. Completeness is difficult to prove in this respect, but the goal should nevertheless be pursued with a view to the future of automated and especially autonomous driving. Thus, the sub-goal and challenge are as follows:
Sub-Goal: *The BSSD shall be applicable to arbitrary ODDs of AVs.*
Challenge: *High complexity and great variety of possible ODDs significantly complicate a proof of generality.*

4.3 Requirements for the Map Representation[141]

Based on the previously mentioned goals and the resulting challenges in developing the BSSD, requirements for the description are derived in this section. First, the goal of assignability is considered. In order to unambiguously connect the scenery with the corresponding behavior spaces, the BSSD must first divide a scenery into individual parts that correspond to the atomic behavior spaces. An atomic behavior space usually corresponds to a lane segment, so the scenery must be broken down to the lane level. The first Requirement (Rq) is therefore:
Rq 1*: The BSSD shall divide the scenery into atomic behavior spaces.*

Once the scenery is divided into the individual parts corresponding to the atomic behavior spaces, the appropriate behavioral demands must be assigned. Thus, each individual part of the scenery shall have the four behavioral attributes allocated. The structure of an atomic behavior space as described in the basics has to be kept. Special attention has to be paid to the physical boundaries of the atomic behavior spaces, which have to be realized within the boundary attribute. These span the behavior space not only from a behavioral point of view but also from a geometric point of view. In summary the next requirement is:
Rq 2*: The BSSD shall represent the associated behavioral attributes of the atomic behavior spaces.*

The goal of connectivity demands that not only individual atomic behavior spaces, but all behavioral demands in the entire road network are represented holistically. For this purpose, the atomic behavior spaces must be interconnected. It must be ensured that all behavioral demands of the individual atomic behavior spaces remain unchanged while establishing the connections.

---

[141] This section has already been published in Lippert, M. et al.: Behavior-Semantic Scenery Description (BSSD) for Automated Driving (2022).

Consequently, no behavioral demands shall be added, nor may existing behavioral demands be removed or modified. As a result, there should be a navigable route network of atomic behavior spaces, so that the behavioral demands are explicitly given for each possible path within this network. Another constraint is the validity of the route network representation. The BSSD route network must represent the real route network, which is used to derive the BSSD, identically in the sense of navigability. This is the only way to enable later use of the BSSD for identifying route-based requirements and capabilities. Due to this endeavor, the following requirement is formulated:
Rq* 3: The BSSD shall connect behavior spaces logically and consistently to a valid representation of the navigable route network.*

In order to achieve the goal of consistency, ambiguities must be excluded. Consequently, there must not be different descriptions for the same information content. It is possible that different scenery sections require the same behavior space, although they differ in the scenery characteristics. In these cases, the different scenery sections must each be assigned the same behavior space so that the information content is unambiguous and thus consistent. Neither assignability nor connectivity must suffer from the consideration of this condition. The following requirement is defined to fulfill the consistency:
Rq* 4: If different sceneries impose the same behavioral demands, they shall always be represented by the same behavioral space.*

To meet the goal of generality, the BSSD should be as universally applicable as possible. This means that there should be no behavior space that cannot be represented by BSSD. Consequently, there must not be any real scenery or scenery section for which the behavior space cannot be represented or cannot be represented correctly. The final requirement is therefore:
Rq* 5: The BSSD shall represent the behavior space to any real scenery.*

4.4 Behavior-Semantic Scenery Description[142]

In the following, the elements necessary for a BSSD and their relationship to each other are derived from the identified requirements. With regard to an implementation, the structure of the BSSD should be as generic as possible and thus independent of the target format or target system. This ensures that the BSSD is utilizable in any use case and ODD. The aim is to achieve a description that represents all necessary elements and properties of the BSSD such that the requirements from Section 4.3 are met. Figure 4-3 represents the generic structure of the BSSD in an UML class diagram[143] resulting from the derived necessary elements and their relationship to

---

[142] This section has already been published in Lippert, M. et al.: Behavior-Semantic Scenery Description (BSSD) for Automated Driving (2022).

[143] Object Management Group: Unified Modeling Language Specification Version 2.51 (2017).

each other.

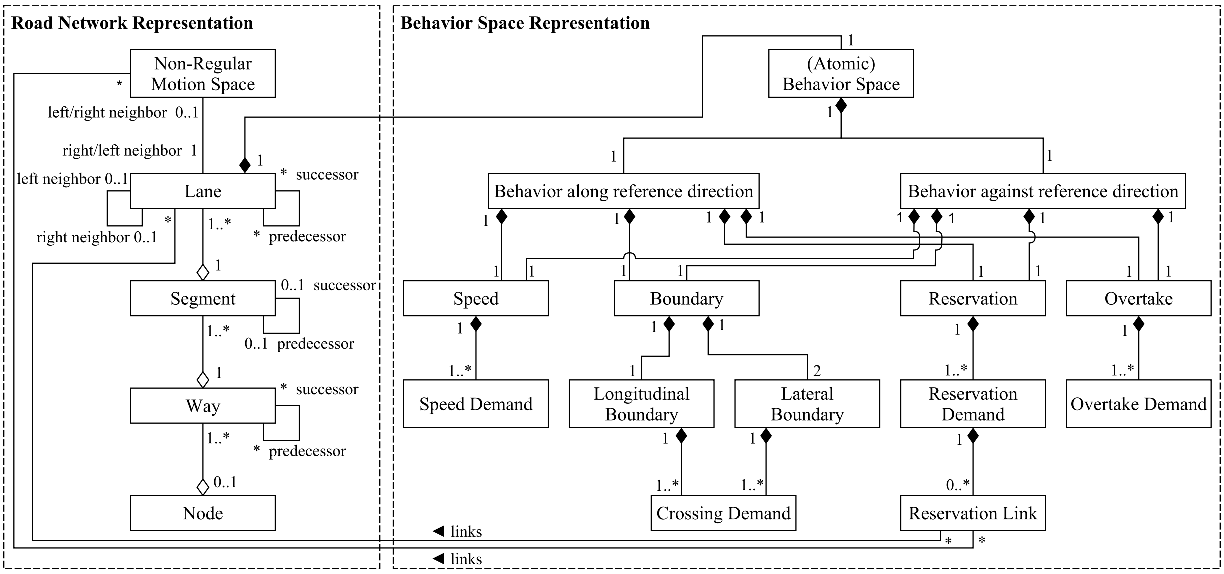


Figure 4-3: Structure of the Behavior-Semantic Scenery Description.
Legend: —— Association; —◇ Aggregation; —◆ Composition

4.4.1 Elements for the Road Network Representation

It follows directly from *Rq 1* that the basis for a BSSD is a (partial) route network that is decomposed according to atomic behavior spaces. In lateral extension, a lane represents the smallest possible road space onto which an atomic behavior space is represented. For this purpose, it must necessarily be possible to represent individual lanes. Lanes are the central elements of the road network representation onto which the atomic behavior spaces are mapped as the composition relation between the two representations in Figure 4-3 shows. In addition to a conventional lane for motor vehicles, a bicycle lane, for example, may also represent a lane. Such a lane is potentially used by a motor vehicle as well. Besides lanes within the regular motion space, elements of non-regular motion space have to be considered for the representation of reservation links (e.g. pedestrians coming from a sidewalk onto a pedestrian crossing).

Depending on the use case and ODD size, it may not be sufficient to represent individual atomic behavior spaces in isolation. They must be considered in the overall context of a road network so that *Rq 3* is satisfied to ensure connectivity. In terms of navigability, all possible driving options such as turning or driving straight ahead at intersections or junctions as they exist in reality must therefore be represented. Thus, for every point in the road network where multiple driving options follow, the available behavior spaces must be represented as well. Since geometry is not a part of the description of a behavior space, the BSSD in its plain form does not require any geometry for the representation of sceneries. In this case, further auxiliary elements besides lanes are necessary for a consistent route network representation. If the BSSD is integrated into a map containing geometric information, some of these auxiliary elements may be omitted, depending on the level of detail of the map. For example, the relationship of individual lane sections in a highly accurate map would be evident based on geometric adjacency alone, without the need to define further dependencies. Without geometry, on the other hand, further information is required that defines these dependencies between lane sections (e.g. *lane section 1 is the left neighbor of lane section 2* or similar information). Since a representation entirely without geometry requires the most auxiliary elements, this case is considered below. If geometric information is added, the corresponding auxiliary elements can simply be neglected. If they are beneficial for the application, however, it is still possible to use them.

Route networks can be described without geometry by a logically constructed topology following the topological graph theory. A road network is represented, as is common in navigation, using nodes and edges. The *nodes* represent traffic points where the traffic flow branches in different directions. In the scenery, these points correspond to intersections, traffic circles or junctions, for example. All connecting roads between the nodes are modeled as edges, which are called *ways*[144] in the following. Consequently, more than two ways are connected at nodes. Within nodes, again ways represent the possible connections between the incoming and outgoing ways adjacent to the nodes. Each way in a road network therefore may have arbitrarily many predecessors or successors. This ambiguity of nodes is explicitly desired, because in this way the different driving options at nodes are represented. However, for a lane-accurate representation of the scenery, the ways must be further subdivided into *lanes*. As soon as different lane topologies prevail within a way (e.g. transition to a different number of lanes), a subdivision of the lanes in longitudinal direction becomes necessary.

For lateral transitions between lanes (e.g. lane changes) the neighbors of a lane are specified. In order to ensure uniqueness in lateral transitions every lane has only one left and right neighbor at most. This results in a longitudinal segmentation of a way into a *segment* whenever any lane has a change in its behavior space. In order to enable the linkage of reservation receiving traffic participants lanes may have *non-regular motion space* as a left or right neighbor. In contrast to lateral neighbors, a lane may have any number of predecessors or successors in longitudinal direction. As with ways at nodes, this property allows the assignment of multiple driving options for diverging or separating lanes and the associated atomic behavior spaces.

An advantage of segmentation is the holistic representation of behavioral demands within a road segment. A segment represents the behavior space across the entire lane width. In this way, all behavioral demands for driving on the road section are explicitly available. The same principle applies to a way, which in turn consists of at least one segment.

In summary, depending on the integration of geometric information, the elements listed in Table 4-1 are necessary for mapping the BSSD to a road network.

---

[144] The term *way* is more appropriate than the term *edge* in the context of road networks for AVs or vehicles in general and more convenient to use than the term *connecting road*. Therefore, *way* is used in this work instead of the other terms.

Table 4-1: Necessary Elements for BSSD of a Road Network

Term	**Description**
Node	Area in which multiple ways interfere and incoming and outgoing ways are connected.
Way	Connecting road between and within nodes.
Segment	Section of a way in which the mapped behavior space is constant in longitudinal direction.
Lane	Section of a segment in which the mapped behavior space is constant (no change at all).
Non-regular motion space	Space outside the regular motion space that shall never be used by motor vehicles.[145]

The resulting structure of the road network representation within the BSSD is shown individually in Figure 4-4.

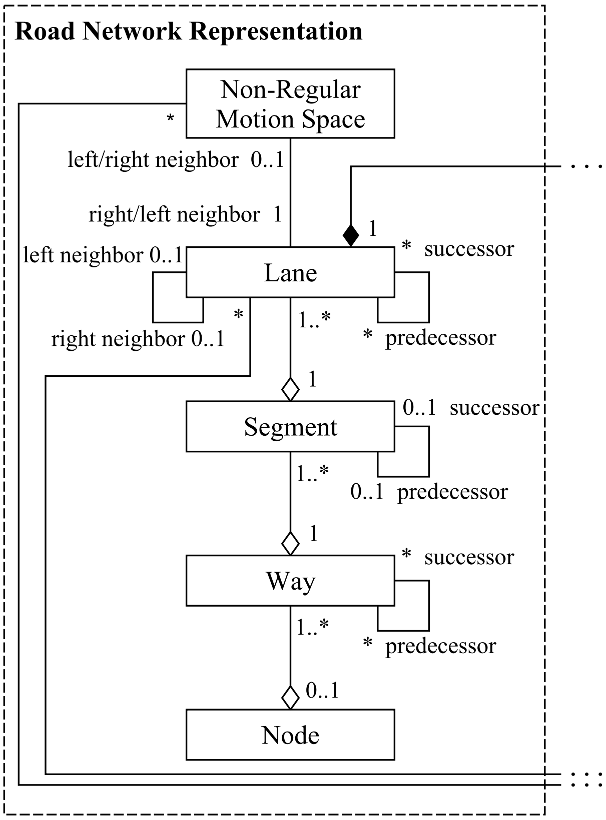


Figure 4-4: Structure of the BSSD road network representation.
Legend: —— Association; —◇ Aggregation; —◆ Composition

---

[145] Cf. definition in Section 3.1.

4.4.2 Elements for the Behavior Space Representation

After the atomic behavior spaces can be represented using the elaborated structure for a valid representation of road networks (*Rq 1* and *Rq 3*), a structure for mapping the behavioral demands onto the atomic behavior spaces has to be derived (*Rq 2*). This structure must additionally fulfill *Rq 4* to achieve consistency.

Due to the directionality of the behavioral demands, the atomic behavior space must always be able to represent both possible driving directions of an AV. Therefore, an *atomic behavior space* always consists of two additional elements, the *behavior along reference direction* and the *behavior against reference direction* (the reference direction may be selected as desired). Both directions must cover the same knowledge requirements about the possible behavioral demands: *What is the speed limit? What conditions apply when changing lanes or entering a new space? Which traffic participants must be given priority? Is overtaking allowed?*

As a result, for both considered driving directions, the behavioral attributes *speed*, *boundary*, *reservation* and *overtake* are each assigned exactly once. In turn, the behavioral attributes always belong to only one considered driving direction within an atomic behavior space. The behavioral demands describe the characteristic of the individual behavioral attributes in order to fulfill the mentioned knowledge requirements. They are stored as a part of the respective attribute.

***Speed Attribute*:** At least one *speed demand* element must be defined, specifying the maximum allowed driving speed within the atomic behavior space. Additional demand elements may be defined for speed limits under certain conditions such as time of day or weather. A required minimum speed may be added as well.

***Boundary Attribute*:** The behavioral demands are restricted to crossing conditions of the respective boundaries. An atomic behavior space always consists of one *longitudinal (entry) boundary* and two *lateral (exit) boundaries*. At least one or more *crossing demand* elements are assigned to each of the three boundaries. Conversely, each crossing demand element is part of a boundary element. An example for a double assignment of a longitudinal boundary is a stop line at a traffic light. In this case, different crossing demands apply for active or inactive traffic lights.

***Reservation Attribute*:** As introduced in Subsection 4.1.2, the reservation attribute covers all behavioral demands regarding priority and residence allowance rules. By abstracting the description of these demands, it is possible to apply the representation to all atomic behavior spaces independent of the type of road section (e.g. junction, road, roundabout) that is described. At least one *reservation demand* element is assigned to the reservation attribute. Dependent on the type of reservation (own, externally, equally) further elements are required. For the externally- and equally-reserved cases, the type of the reservation-entitled traffic participants must be represented. Additionally, there is the *reservation link* element, which indicates the origin and, if necessary, the destination direction of these traffic participants by directly referring the respective lane element.

Any number of reservation links can be defined for the reservation demand, which can address any number of lane or non-regular motion space elements.

***Overtake Attribute*:** The overtake attribute has at least one *overtake demand* element. As with the speed attribute, an overtake prohibition may be linked to different conditions, resulting in multiple overtake demands.

The resulting structure of the behavior space representation within the BSSD is shown individually in Figure 4-5. With the elaborated structure it is possible to assign a complete behavior space to each scenery section (*Rq 2*). The basis for the interconnection of the individual atomic behavior spaces (*Rq 3*) is the structure of the road network in Figure 4-4 derived in the previous chapter. The resulting overall structure in Figure 4-3 now represents not only each individual behavior space, but also their connections. Thus, the behavioral demands resulting from subsequent behavior spaces are represented and their sequence is directly accessible.

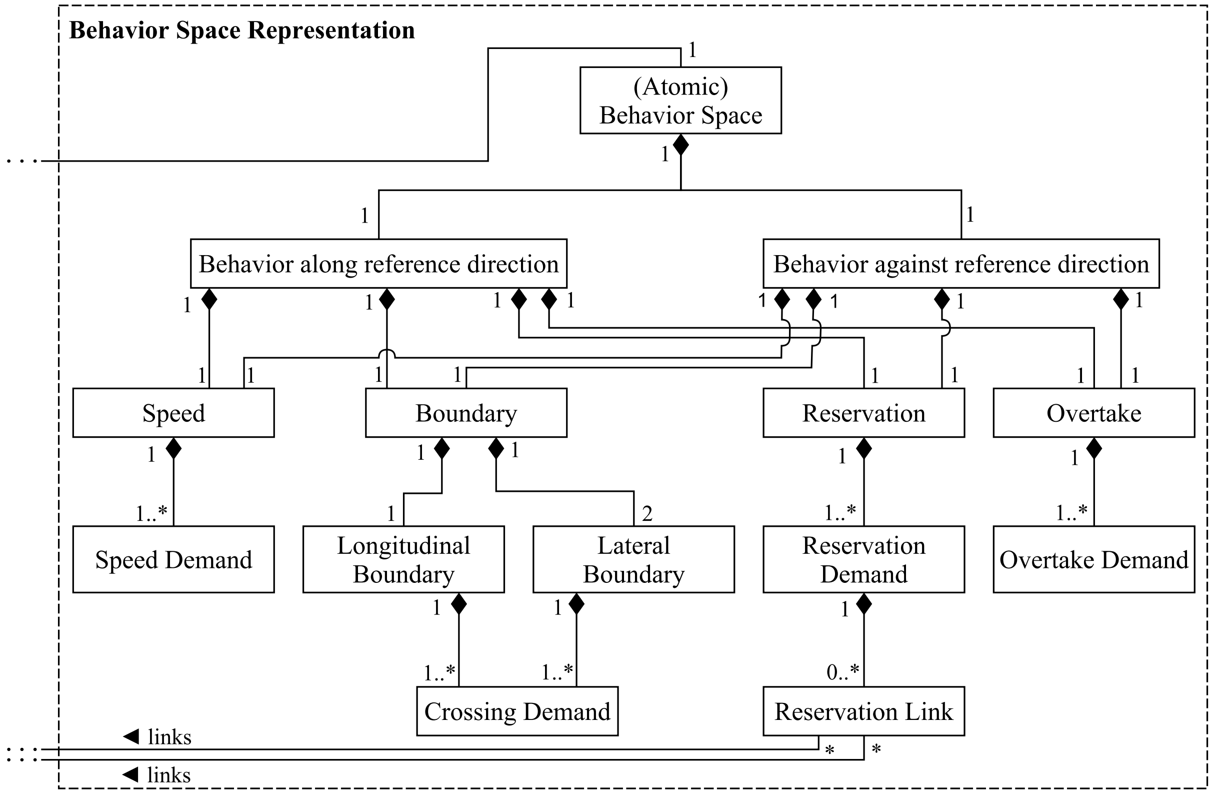


Figure 4-5: Structure of the BSSD behavior space representation.
Legend: —— Association; —◇ Aggregation; —◆ Composition

4.5 Application and Real World Examples[146]

In this section, the generic BSSD from the previous section is instantiated to describe real world sceneries. For this purpose, the BSSD is created using the map framework Lanelet2 as a basis[147]. Two real scenery sections in Darmstadt (Germany) are thereby considered and explained in the following. These examples demonstrate that despite striking differences in the two scenery sections, the resulting BSSD shows only few differences. The two examples additionally serve as an evaluation of the approach by checking the requirements specified in Section 4.3. The visualization of the scenery sections was done with JOSM[148] using the Lanelet2 map paint style. In addition, some of the BSSD information is visualized using the BSSD map style. Information boxes, arrows and pictograms were added manually to visually represent further information stored in the BSSD map implementation. The blue and black circles with respective numbering visually support the explanations in the following.

Before describing the examples themselves, the structure of the Lanelet2 framework and its impact on the BSSD implementation is first explained for further understanding. Lanelet2 builds on the map format OSM[147], which uses the elements *node*, *way*, *area* and *relation* in order to model a map[149]. Ways consist of nodes and correspond to *linestrings* in Lanelet2. Relations refer to *members* such as linestrings, nodes or relations and assign a *role*. The role defines the property or relationship of the member with respect to the relation.

Lanelet2 maps are augmented with BSSD information for the application of BSSD, while fully preserving the functionality of the original map. The core element of the Lanelet2 map format are *lanelets*, which are used as atomic components of road networks to build maps. They are modeled as relations and always reference two lateral boundaries in the form of linestrings with the roles *left* and *right*, within which directed movements take place and traffic rules do not change. Thus, for a motor vehicle, lanelets generally represent a lane section of a roadway. The representation of bicycle lanes or crosswalks as well as non-regular motion space is additionally possible.

The construction of a lane network for the BSSD is not necessary when using Lanelet2, since the map already provides the necessary information. Nevertheless, it must be ensured that the assignment of atomic behavior spaces, as shown in the generic UML representation of the BSSD (Figure 4-3), to this route network is possible. In case two successive behavior spaces have to be assigned to a single lanelet, this lanelet can be longitudinally split considering the design rules of Lanelet2. If the Lanelet2 map is to remain untouched, a lanelet can be artificially split using additional BSSD elements in OSM format. If an atomic behavior space contains two or more

---

[146] This section has already been published in Lippert, M. et al.: Behavior-Semantic Scenery Description (BSSD) for Automated Driving (2022).

[147] Cf. Subsection 2.2.4.

[148] JOSM: Extensible editor for OpenStreetMap (2021).

[149] These *nodes* and *ways* are different to the defined ones in Subsection 4.4.1, Table 4-1.

lanelets, they are referenced together without changing the format itself. The union of multiple lanelets would break the Lanelet2 format and make it unusable at this point. To represent the behavioral demands of the longitudinal boundary of behavior spaces, most lanelets also require additional linestrings. For example, if the number of lanes changes, as with merging lanes, there is typically no longitudinal linestring dividing the road segments. However, these can be added in a Lanelet2-compliant way without endangering the format. If such linestrings are already available, e.g. in the form of stop lines at the correct position, no new elements have to be created.

After introducing the basics of the Lanelet2 framework and its effects on the BSSD implementation, more detailed explanations regarding the BSSD implementation are provided considering concrete examples in the following. Figure 4-6 shows the aerial image and the corresponding Lanelet2 map with the BSSD extension of *Example A*. This example represents a T-junction within a 30 km/h speed zone. The priority road is a two lane one-way road and the secondary road is a two-lane road with bidirectional traffic. In order to explain the implemented structure, only one sequence of atomic behavior spaces is considered (yellow marking). Following the sequence in the marked direction (yellow arrow) is equivalent to a right turn maneuver. This sequence of behavior spaces is only one possible concatenation of all behavior spaces in this scenery section (e.g. alternative behavior spaces within the priority road are marked in transparent blue). In principle, it is possible to navigate through all adjacent behavior spaces. Consequently, instead of the turn maneuver, it would also be possible to continue straight ahead or to change lanes laterally. Depending on the selected concatenation and thus route, an analysis of the associated behavior spaces is possible. The atomic behavior space A (blue circle) is considered for a detailed explanation of the BSSD information. It must be noted that pedestrians that potentially cross the secondary road during that right turn maneuver only can cross the road in the considered behavior space. A fence (light green line) prevents the crossing in the preceding behavior spaces. A crossing in the successive behavior space would no longer be part of the turn maneuver resulting in different behavioral demands.

Atomic behavior spaces are directly mapped to their corresponding lanelet (black circle 1), as the behavioral demands change before and after this lanelet. The lanelet is defined as a member with the role *lanelet* of this *behavior space*, so that the scenery linkage is directly established. As further member, the behavior space has the relation *behavior* with the role *along* (black circle 2), which represents accordingly the behavior along the reference direction (the reference direction is defined by the lanelet). Besides the type of the relation, which is always defined, the behavioral demands of the attributes speed and overtake are directly stored within this relation (black circle 3). For behavior space A, the maximum allowed speed is 30 km/h and overtaking is not prohibited.

The behavioral demands of the remaining behavioral attributes boundary and reservation are modeled as relations. They are members of behavior with the respective role (*boundary_long*, *boundary_right*, *boundary_left* and *reservation*) as highlighted by the black circle 4. These elements in turn reference the Lanelet2 map information.

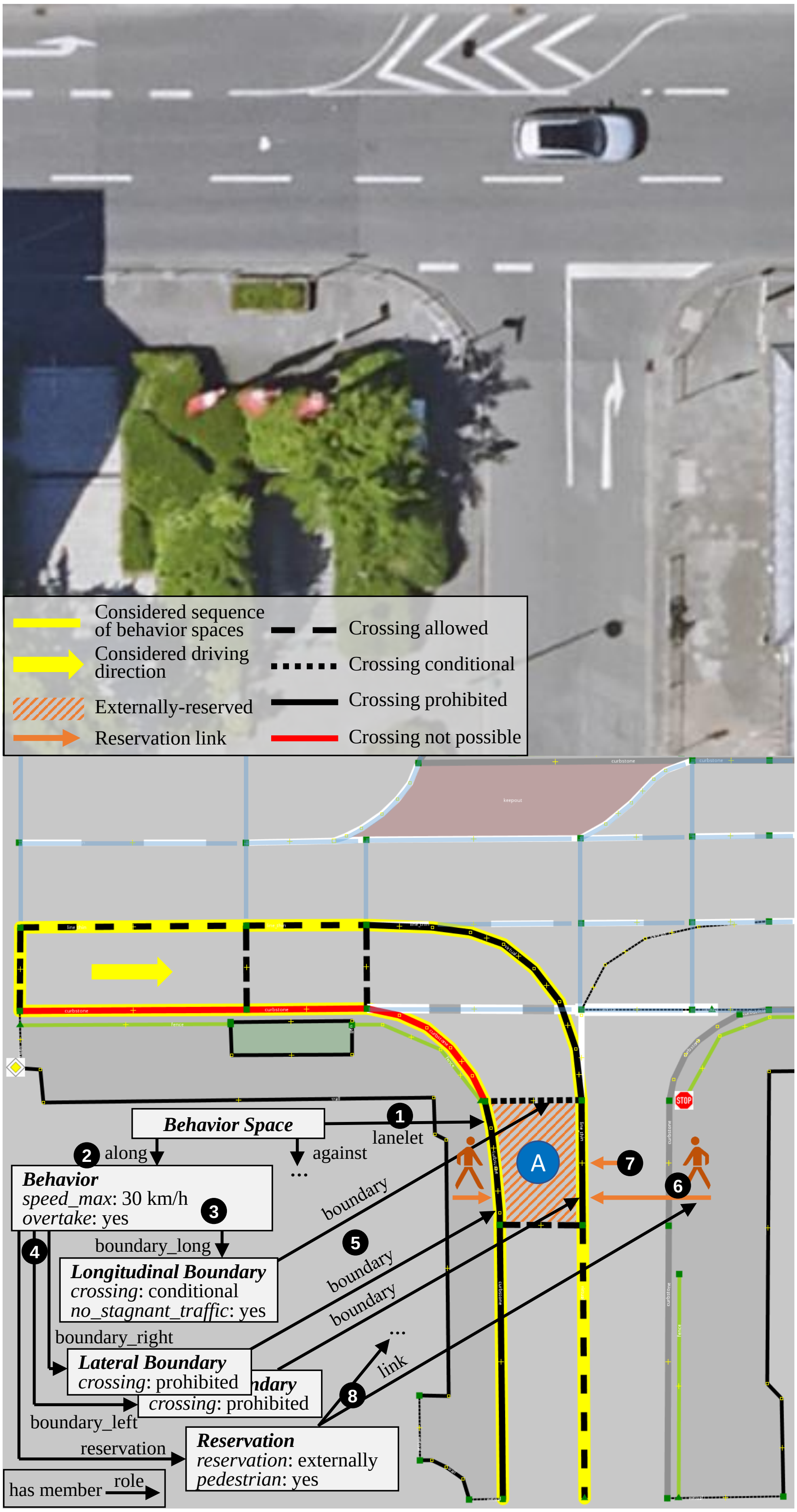


Figure 4-6: Example A: T-junction in Darmstadt, Germany.
Aerial image © Orthophoto Vermessungsamt Darmstadt 2021.

For example, the boundaries are directly linked to the linestrings of the lanelets or the newly created linestrings for the longitudinal boundaries (black circle 5). Likewise, the linking of lanelets, from which traffic participants with reservation claims may come, takes place. In this example, when entering the considered behavior space, priority must be given to pedestrians coming from the sidewalks to the left and right (black circle 6). That behavioral demand is a result of the turn maneuver since motor vehicles and bicycles generally have to give priority to pedestrians crossing the street while turning. Since crossing pedestrians might already be on the road in the lateral adjacent lanelet, this area has to be considered as a link as well (black circle 7). In general, all areas that have to be crossed by reservation entitled traffic participants must be considered and linked to the according reservation element. Thus, the reservation demand of the considered behavior space is *externally-reserved* for pedestrians with a reservation *link* to the corresponding Lanelet2 elements as highlighted by black circle 8 (sidewalks and adjacent lanelet, indicated by the orange arrows and pictograms). Only one of the three links is presented explicitly in this example for reasons of clarity.

A second real scenery section is considered in *Example B* in Figure 4-7.

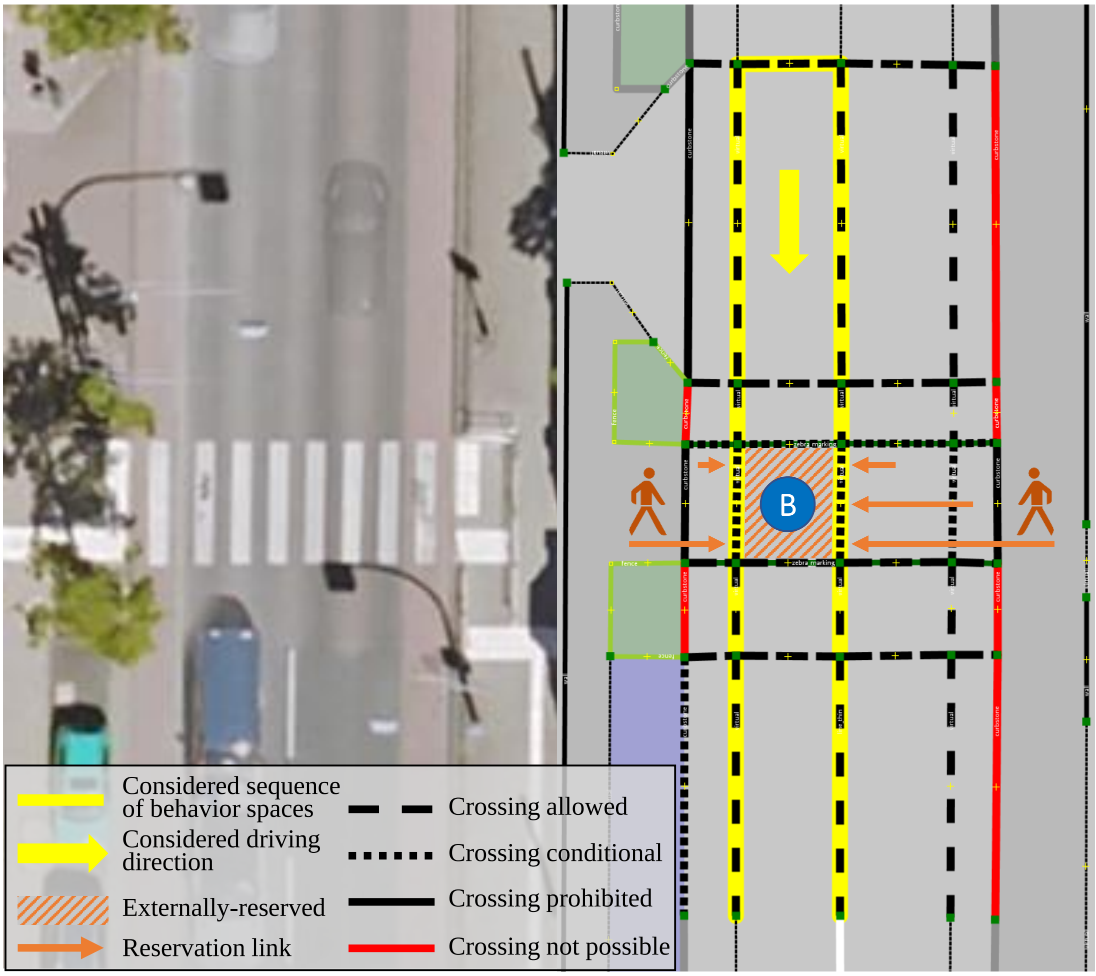


Figure 4-7: Example B: Two-lane road with crosswalk in Darmstadt, Germany.
Aerial image © Orthophoto Vermessungsamt Darmstadt 2021.

This example shows a two-lane road with bidirectional traffic in a 50 km/h speed zone, lateral adjacent bicycle protection lanes and a crosswalk. A parking area adjacent to one bicycle protection lane is found as well (blue colored area in the Lanelet2 map). In this example, the behavioral demands regarding the boundary elements of the behavior spaces are visualized considering a driving direction as indicated by the yellow arrow. Again, a certain sequence of atomic behavior spaces (yellow marking) and, in particular, the atomic behavior space B representing a lane section on the crosswalk is considered.

In order to demonstrate the benefits of the BSSD due to an usage of only four behavioral attributes to describe the behavioral demands, the presented atomic behavior spaces A and B are compared directly. The corresponding behavioral demands are shown in Table 4-2 and can be analyzed attribute-wise.

Table 4-2: Behavioral Demands of Example A and B

Attribute	**Behavior Space A**	**Behavior Space B**
Speed	*max*: 30 km/h	*max*: 50 km/h
Boundary	*long.*: conditional no stagnant traffic, *left*: prohibited, *right*: prohibited	*long.*: conditional no stagnant traffic, *left*: conditional no stagnant traffic, *right*: conditional no stagnant traffic
Reservation	*type*: externally-reserved, *object*: pedestrians	*type*: externally-reserved, *object*: pedestrians
Overtake	*permission*: yes	*permission*: no

The focus is placed on the behavioral demands regarding longitudinal boundary and reservation since lateral boundaries are less relevant considering the yellow marked sequence. In both examples the crossing demand of the longitudinal boundary is *no stagnant traffic*. This means that entering the behavior space is only allowed if the space can be passed without coming to a rest, no matter where this rule arises from. In *Example A* that demand results from being part of a turn maneuver at an intersection. The same demand in *Example B* results from being part of a crosswalk. Thus, a AV would have to check if sufficient driving space is available in the successive atomic behavior spaces before entering the considered space. Additionally, both examples have the same reservation demands. In both cases, AV entering this behavior space have to give priority to pedestrians coming from the sidewalks and areas that they have to pass by crossing the road as well. In both examples, AV must check the laterally adjacent areas for pedestrians potentially crossing the street. Furthermore, staying in the behavior spaces A and B is prohibited, meaning that this area must be left as soon as possible. This behavioral demand is also indicated by the external reservation. The attributes of speed and overtaking of *Example A* and *B* differ in their behavioral demands as well as the crossing demands of the lateral boundaries.

However, the equality of the behavioral demands of longitudinal boundary and reservation show that completely different sceneries may indeed be very similar in their demands. These similarities potentially result in reduced development and testing effort of AV, since the diversity at the behavioral level is reduced. A behavior planner would need to perform some of the same automated driving tasks in the examples shown, which would not have been apparent based on the scenery itself. Resulting from this, the test criteria for tests of the behavior planer would be the same for the equivalent demands on both sceneries and thus, reusable in between them in order to save effort. It would be even possible to perform an online check of compliance to this criteria during operation when localizing within the BSSD map. Additionally, capability-based route planning can consider the current skills of the AV with regard to the behavioral demands. In the first example, a route planer could decide to not turn right, if the vehicle does not have the skill to yield for pedestrians (no matter if this is principally the case or a function of the vehicle is degraded).

In both examples, concrete (navigable) sequences of atomic behavior spaces were considered. Nevertheless, for both scenery sections all behavior spaces are available in the sense of a complete BSSD. Thus, the decomposition of the scenery into atomic behavior spaces (*Rq 1*), the assignment of the corresponding behavioral attributes (*Rq 2*) and also the connection of the individual behavior spaces are addressed (*Rq 3*). The comparison of the two examples shows that behavior spaces of the BSSD can be very similar despite strongly different sceneries. The reservation dimension of both behavior spaces is identical. This shows, that even with completely different sceneries, *Rq 4* is addressed, so that different sceneries with the same behavioral demands are represented in the same way. While these examples do not prove that BSSD works for every conceivable (AV-relevant) scenery (*Rq 5*), they do not falsify the application of BSSD. In subsequent chapters, especially in Chapter 7, the BSSD is applied to further various sceneries. In advance to these chapters, it can be stated already that these sceneries also do not falsify the applicability of the BSSD. Thus, the hypothesis stated in Section 4.3 is corroborated based on current evidence.

4.6 Interim Conclusion

In this chapter, the basic concept of behavior space and behavioral attributes developed in Section 4.1 was transformed into a map representation. The deficits of the basic concept identified in Subsection 4.1.4 were explicitly addressed by deriving goals and challenges for the development of the map representation - the *behavior-semantic scenery description*. The goals and challenges served to define requirements for the structure of the BSSD. Based on the requirements, a generic structure of the BSSD was developed, which mainly consists of two fundamental building blocks:

- Road Network Representation
- Behavior Space Representation

With the help of this structure, the modeling of the road network is made possible independent of the intended implementation. An implementation without geometric information within a topological representation is possible as well as an implementation with the help of a map. The principle of linking road network and behavior spaces ensures a clear assignment of behavioral demands to the scenery in every case known so far. For both driving directions, the four behavioral attributes are stored within the behavioral spaces linked to the road network. Finally, the attributes are assigned the associated behavioral demands. For the description of the reservation, an additional interface to the road network was created, so that the linking of the reservation-authorized traffic participants to the scenery is enabled.

The generic structure was subsequently implemented in the Lanelet2 map format and demonstrated using real-world examples. Based on these examples, further examples that are shown in the course of the work and the previous experiences of the author, the requirements for the BSSD can be regarded as fulfilled. Only the goal of the generality is not to be considered as reached with the help of the limited number of sceneries. However, the fulfillment of this requirement is not falsified on the basis of the results. Based on the current state of knowledge, the hypothesis established at the beginning is thus also not falsified, but corroborated.

This provides the following basis for the remaining procedure of the work:

- The behavioral demands are explicitly available.
- The behavioral demands are directly linked to the scenery.
- The behavioral demands are navigable according to the associated road network.

Thus, this chapter addresses the second research question:

RQ 2: How to design a representation of behavioral demands as a basis for deriving route-based driving requirements?

In part, this question has already been answered by the results of this chapter. However, it remains to be proven whether the developed map representation is actually suitable for the derivation of route-based driving requirements. Thus, a route-based analysis of the behavioral demands is performed in the following chapter in order to systematically derive behavioral requirements based on them.

5 Route-Based Behavioral Requirements[150]

In this chapter, route-based behavioral requirements are systematically derived. A systematic derivation of behavioral requirements first requires an analysis of the intended process. With the help of the knowledge gained, it is then possible to identify the necessary process steps for the systematic derivation of requirements. Subsequently, the process steps are elaborated and applied to real-world sceneries. Before analyzing the necessary process steps, terms relevant to the further course of the work are clarified and refined.

5.1 Clarification and Refinement of Relevant Terms

With regard to the derivation of behavioral requirements and the subsequent definition of driving requirements and driving capabilities, further clarification and refinement of these terms is needed since Section 1.1 initially defined these terms only in very general terms.

Driving Requirements and Driving Capabilities

The derivation of requirements is based on the scenery of an ODD. At the same time, a definition and assignment of vehicle-related capabilities to these requirements must be ensured. This will allow a direct comparison between requirements and capabilities, which could be used, for example, to approve driving operations on the different sections of a route. The goal is thus to derive requirements and capabilities based on a clear differentiation of these terms. Only if the difference between these two terms is defined with sufficient distinctness, a link between capabilities and requirements becomes possible.

With the help of an analogy to the field of project management, the definition of requirements and capabilities becomes possible. The German Institute for Standardization (DIN) describes in the context of project management systems the requirement and target specification, which are to be found in the DIN 69901-5 as follows:

- The *requirement specification* describes the totality of the demands on the deliveries and services of a contractor within a (project) order as defined by the customer.[151]

---

[150] Parts of this chapter have already been published in Lippert, M.; Winner, H.: Behavioral Requirements for Automated Driving (2022).

[151] Summarized and translated from German: Das Lastenheft beschreibt die „vom Auftraggeber festgelegte Gesamtheit der Forderungen an die Lieferungen und Leistungen eines Auftragnehmers innerhalb eines (Projekt-) Auftrags.“, DIN 69901-5:2009-01: Projektmanagement - Projektmanagementsysteme - Teil 5: Begriffe (2009).

- The *target specification* describes the realization project developed by the contractor on the basis of the requirement specification specified by the customer.[152]

Accordingly, the requirement specification defines requirements for a desired solution, while the target specification represents the detailed realization of this solution. Thus, the requirement specification answers the question of ”what” and ”for what”, whereas the target specification answers the question of ”how” and ”with what”.

The requirement specification thus primarily describes the problem and the goal, so that neither technical solutions to the problem nor detailed steps for solving the problem are presented. The requirements to be derived from the present work are therefore to be presented in a solution-independent world. They are analogous to the requirement specification the demands for a desired solution. Based on these findings, the author of this work proposes the following definition for driving requirements:

Driving requirements describe requirements for the DDT that result from the ODD. They provide target descriptions of the autonomous overall system or subsystem and are presented in a solution-independent world.

The target specification describes the product concept on a detailed level up to dimensions, functionality or design and therefore contains descriptions for problem solving and goal achievement. The capabilities to be derived in the present work are analogous to the target specification, are therefore solution-oriented, and consequently represent concrete solutions to the corresponding requirements. Furthermore, the capabilities always refer to an AV and thus represent the ”is capable of” of this system. Based on these further findings, the author of this work proposes the following definition for capabilities:

Driving capabilities are capabilities which are necessary to drive within the scenery of an ODD. They describe concrete solutions to achieve the goals of the corresponding driving requirements. They are vehicle-specific and represent the technical competence of an AV to fulfill the driving requirements. One or more driving capabilities always correspond to one driving requirement.

Local and Global Driving Requirements

As is already clear in the state of the art, the DDT is very versatile, complex and comprehensive. The DDT always results from two main aspects: Collision avoidance and traffic regulation compliance. It is intuitively clear that the task of collision avoidance is omnipresent. Collisions must be avoided at all times and in all places in road traffic. This also applies in the event that traffic rules for collision avoidance are briefly violated. Freedom from harm is therefore the top

---

[152] Summarized and translated from German: Das Pflichtenheft beschreibt das „vom Auftragnehmer erarbeitete Realisierungsvorhaben auf der Basis des vom Auftraggeber vorgegebenen Lastenhefts.“, DIN 69901-5:2009-01: Projektmanagement - Projektmanagementsysteme - Teil 5: Begriffe (2009).

priority and must always be ensured as far as possible. Compliance with traffic regulations is also a task that must always be ensured, except in special cases. However, there is a clear difference between this and collision avoidance. The concrete rules of behavior based on the traffic rules are in fact not equally valid everywhere. The dependence on the scenery which is demonstrated in this work clarifies that the DDT shows local differences with respect to the observance of traffic rules. These considerations lead to the conclusion that driving requirements can be distinguished into local and global requirements:

Local driving requirements are driving requirements that result from a specific scenery. They are scenery-dependent, not generally valid, and have a local scope.

Global driving requirements are driving requirements that do not result from a specific scenery. They are scenery-independent, generally valid and have a global scope.

The focus of the present work is on local driving requirements, since these are determined to a large extent by the scenery and are correspondingly dependent on concrete trips of an AV. Approaches to derive global driving requirements are also numerous, as already discussed in the state of the art[153]. In contrast, local requirements are often not considered in more detail and not systematically. For this reason, in this work, the term driving requirements without the addition of local or global refers exclusively to local driving requirements.

Behavioral Requirements

The relationship between ODD, scenery, and driving requirements from Subsection 1.1 suggests that driving requirements are first derived at the behavioral level. These behavioral requirements are then used as a subset for identifying the driving requirements at the remaining levels of the driving task. The definition of behavioral requirements from Subsection 1.1 is sufficient for understanding the following steps. Nevertheless, the definition is supplemented with respect to the distinction between local and global driving requirements:

Behavioral requirements describe local or global driving requirements for the observable behavior of an AV with regard to function specification. If not explicitly mentioned, the term behavioral requirement always refers to the local part of the driving requirements.

At this point, it is necessary to highlight the difference between behavioral requirements and behavioral demands. The two terms are closely related, but there are crucial differences:

- *Behavioral demands* describe the imposition of behavioral limits on participation in road traffic. Behavioral demands consequently directly address the behavior of traffic participants.

---

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

- *Behavioral requirements* describe the necessity of fulfilling behavioral demands in the context of a functional specification of AVs. Behavioral requirements therefore directly address the intended functionality of AVs.

Behavioral demands aim to limit the permitted behavior of traffic participants. Behavioral requirements aim to specify the function of an AV at the behavioral level.

5.2 Identification of Process Steps

The starting point of the analysis is the BSSD, which is completely derived for a specific route network. Thus, all behavior spaces in this route network are available. Each behavior space is fully described using the four behavioral attributes. Furthermore, the behavioral demands are directly linked to the scenery and the linkage of the behavioral spaces among each other is also available. The goal now is to use this behavioral information to derive behavioral requirements. To illustrate the problem, a simple example is considered below that reveals the process steps necessary to derive behavioral requirements. For this purpose, a potential trip of an AV is considered based on a route. As a reminder, the route, no matter how long, simple, or complex, is the core competency of an AV. Even the simplest AV imaginable must be able to handle at least one route from location A to location B. As routes are considered within the BSSD, this route must include a sequence of behavior spaces. Since the behavior spaces always correspond to lanes, it follows that the route must also be lane-accurate. Routes in general do not need to be specified lane-accurate, so a term distinction is needed. To avoid confusion with the general term *route*, the term *lane-accurate route* is introduced:

Lane-accurate route describes a particular way between two locations within a road traffic network at the lane level.

So what are the behavioral requirements for the trip as a result of concatenating behavior spaces within the lane-accurate route? For analysis, this potential trip is observed from behavior space to behavior space. It is assumed that the trip automation initially only has the information that is available based on the BSSD map. Let the section of the BSSD road network shown in Figure 5-1 be given. The section shows a two-lane one-way street with traffic flow from left to right from different points of view. The scenery layer shows the scenery with different trips of a vehicle. The resulting behavior spaces are shown in the BSSD layer. Finally, the topological layer shows the concatenation of the behavior spaces representing the trips drawn in the scenery layer. Due to different behavioral demands there are three segments with two behavior spaces each in the direction of the intended traffic flow. Segments are indicated in the figure with lowercase letters and behavior spaces with uppercase letters. The behavior spaces in segments a and c all have a speed limit of 50 km/h. Segment b has a speed limit of 30 km/h. For all behavior spaces, longitudinal entry is allowed and lateral exit is prohibited in the non-regular motion spaces. In segments a and b, a lateral change between the behavior spaces is prohibited, so that the lateral boundaries have the value prohibited. Only in segment c lateral switching between the behavior spaces is allowed. Furthermore, all behavior spaces are own-reserved and there is no overtaking prohibition.

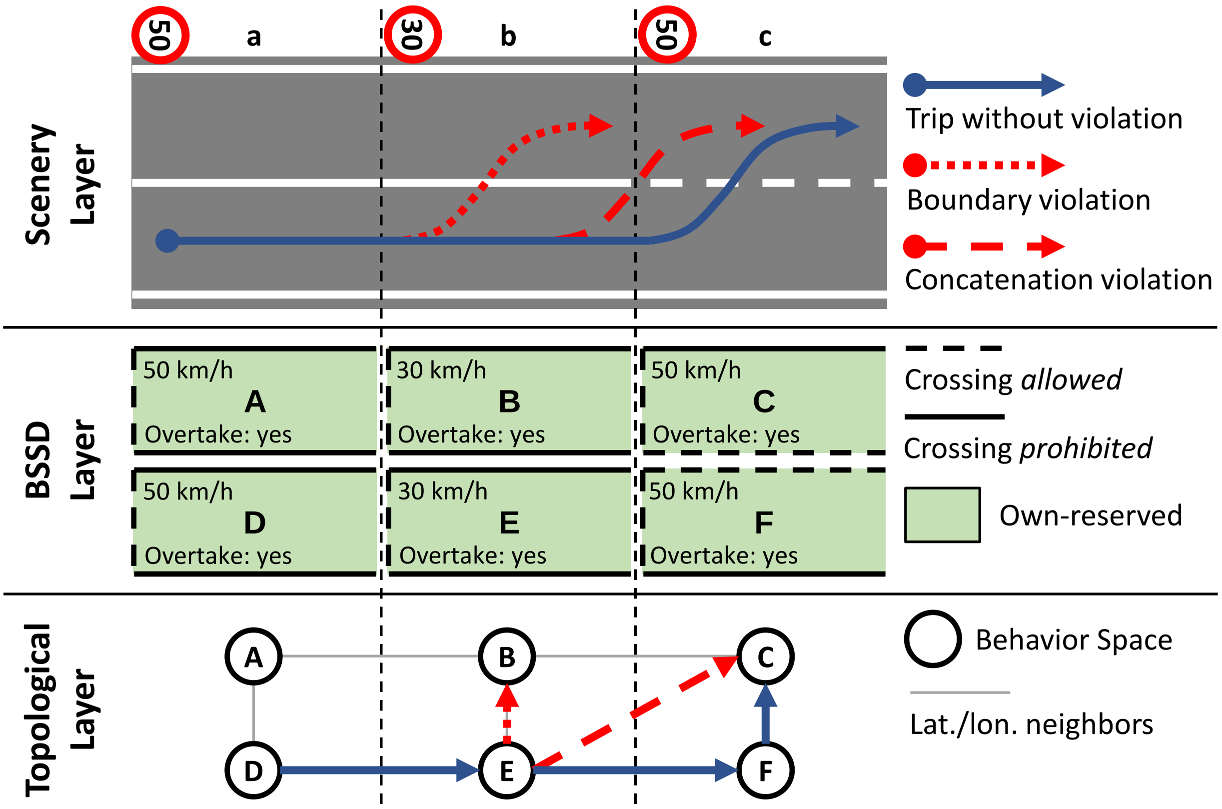


Figure 5-1: Example scenery section with layers of scenery, BSSD and topology.

First, a possible lane-accurate route must be identified within the BSSD segment. This route concatenates all the behavior spaces necessary for the trip so that there is a drivable concatenation of behavior spaces. It will be intuitively obvious that the lane-accurate route may only chain together behavior spaces that are actually direct geometric neighbors. Specifically, this means that the concatenated behavior spaces are longitudinally or laterally adjacent. Only in this way it is possible to obtain unambiguous information about the required behavior. During a real trip, of course, such binary transitions do not always occur without overlapping multiple behavior spaces. These cases are discussed in Section 5.3.2. In the shown BSSD section, for example, a trip from D to C is to be planned. A concatenation $\mathrm{D} \rightarrow \mathrm{E} \rightarrow \mathrm{C}$ would not be a correct concatenation, because E and C are not geometrically concatenated by longitudinal or lateral boundaries. The concatenation violation of $\mathrm{E} \rightarrow \mathrm{C}$ is depicted with the red dashed line that represents a corresponding trip in the scenery layer and the concatenation itself in the topological layer. An AV in this case would only have information about the behavior in E and C. The diagonal concatenation leads to the fact that the vehicle would have overlaps with the behavior spaces B and F in a real trip. However, these would not be considered due to the incorrect concatenation. The concatenation and corresponding trip of $\mathrm{D} \rightarrow \mathrm{E}$ is permissible and represented by the blue line.

Additionally, already during the planning of the lane-accurate route, there is a risk that traffic rules are disregarded or violated. Assuming that no special cases or situations occur during the trip, only boundaries that do not show prohibited or not possible as crossing demand may be crossed. In the shown example, there is only one way to get from behavior space D to behavior space C. First, there is a longitudinal crossing from D to E, because the lateral crossing to A is prohibited. Then, for the same reason, there is another longitudinal transition from E to F. Again, a concatenation of $\mathrm{E} \rightarrow \mathrm{B}$ would be a boundary violation (red dotted line). Finally, there is only the lateral transition from F to C, which is allowed in this case. Therefore, in the following, the lane-accurate route $\mathrm{D} \rightarrow \mathrm{E} \rightarrow \mathrm{F} \rightarrow \mathrm{C}$ represented by the blue lines in scenery and topological layer is considered in more detail.

However, crucial information is still missing for the analysis of concatenated behavioral demands. Looking at the lane-accurate route, it is noticeable that the behavior spaces are changed twice longitudinally and once laterally. But directly connected to the changes of the behavior spaces are also the crossing demands of the attribute boundary. Longitudinal and lateral boundaries can have different crossing demands and associated conditions. In order to get the resulting behavioral demands for entering a new space, the type of transition must be known. According to the transition, an assignment of the applicable crossing demands is possible. Considering this constraint, the concatenation is examined in the following with respect to the behavioral demands.

The lane-accurate route starts in behavior space D. The AV thus receives the information that it must not drive faster than 50 km/h and must not cross the lateral boundaries. For this behavior space, this information is sufficient because the vehicle will keep the lane and not exceed the maximum speed if the behavioral demands are met. Demands regarding collision avoidance, as announced in Section 5.1, are not considered further here. In the subsequent behavior space E, the behavioral demands only change in the speed attribute. Compared to behavior space D, the required speed limit is reduced by 20 km/h to 30 km/h. However, this information is only available in the BSSD road network in the behavior space of interest, in this case E. Without prior additional information, an AV would consequently enter behavior space E at the driving speed set in behavior space D. In a worst-case scenario, the vehicle would enter behavior space E at the speed limit set in behavior space D. The vehicle would then drive at the speed limit set in behavior space E. In extreme cases, the vehicle would be 20 km/h faster than the required speed limit. Only in behavior space E the vehicle would have the knowledge about the necessity of speed reduction, which could then be used to initiate a deceleration. From a behavioral point of view, this speed reduction obviously has to be done with sufficient distance or time before entering behavior space E. On the behavioral level, this results in a new demand that is not yet stored in this form in the BSSD. The reason for this additional demand lies in the kinematics of a moving vehicle. Consequently, there are kinematic dependencies between vehicle behavior and scenery-based, local behavioral demands, which must be taken into account in the derivation of the behavioral demands.

In the next behavior space F, the speed attribute changes again. The allowed speed limit is now back at 50 km/h, so the AV will stay below this limit when entering. Of course, the discrepancy between the maximum allowed speed and the driving speed of the vehicle when entering the behavior space is the same as in the case before regarding the speed reduction. However, there is no specific regulation requiring a minimum speed without further traffic signs. From a behavioral point of view, it is therefore not critical if the AV does not completely exhaust the given speed limit. Apart from that, the AV is not allowed to increase the speed in the behavior space beforehand anyway, because otherwise this speed limit might be exceeded. In this case, the early speed increase is only not allowed if the previous speed limit is already exhausted. Despite the existing kinematic dependency between speed and behavioral demand, there is no additional behavioral demand to the demands of the BSSD in the considered case. Thus, an analysis of all kinematic dependencies is basically required so that the behavioral requirements can be correctly derived.

Behavior space F now offers the possibility of a lateral space change compared to the previous spaces. To the right side, crossing the lateral boundary is still forbidden. The obvious consequence of this is that an AV has permission to leave this space in the lateral direction to the left. The related, indirect consequence is that the movement of the AV is no longer laterally limited when driving without a change of space. In the two behavior spaces D and E, the vehicle was forced to stay in the lane by the lateral constraints. In F, this constraint is now no longer present to one side. This means that it must be clearly defined for a trip whether the lane must be kept or may be left. In the present case, an additional behavioral demand must therefore be that the behavior space may be left laterally only for the purpose of changing lanes.

Based on the BSSD information, the lateral change from behavior space F to behavior space C is not restricted by any other behavioral attribute in the example considered - except for the speed limit. On closer inspection, however, it is noticeable that a vehicle performing a lateral change from F to C must take other road users into account. More specifically, the vehicle has to give priority to other road users coming from A and B. Although the target behavioral space of the lateral change is stored in BSSD as own-reserved, there still seem to be restrictions on the change with respect to priority. The reason for this is not initially important to this consideration and will be discussed and explained in Subsection 5.3.4. The takeaway from this, however, is that in addition to kinematic dependencies, the concatenated behavioral demands themselves must be examined.

Once all behavioral demands have been derived for a lane-accurate route, they must be transformed into behavioral requirements. In principle, this is just another semantic process. The behavioral demands are formulated as complete sentences so that they can be used for further work steps.

Based on the considerations made, the prerequisites and process steps necessary for deriving behavioral requirements are defined as follows and elaborated in the next section:

- **Prerequisite:** A complete and correct BSSD exists for the scenery section to be considered.
- **Step 1:** Identification of lane-accurate routes within the BSSD.
- **Step 2:** Identification of transitions between behavior spaces within lane-accurate routes.
- **Step 3:** Identification of applicable behavioral demands of individual behavior spaces based on the transitions.
- **Step 4:** Identification of behavioral demands based on concatenation.
    - **Step 4.1:** Analysis of change in behavioral demands.
    - **Step 4.2:** Analysis of the kinematic dependencies.
- **Step 5:** Formulation of the behavioral requirements based on the resulting behavioral demands.

5.3 Elaboration of Process Steps

The individual process steps are systematically worked through and elaborated in this section. Due to the similar information of behavioral demands and behavioral requirements, Step 5 is already completed in Step 3 and Step 4. This means that the behavioral requirements are already formulated on the basis of the separate behavioral demands. In this way, duplications of content are avoided and the traceability of the work steps is improved. This procedure is possible because it makes no difference whether the requirements are derived individually or collectively. However, it is important that the behavioral demand for which a requirement is derived is complete or finalized at this point.

5.3.1 Lane-Accurate Route

Based on the complete and correct BSSD, lane-accurate routes must first be identified. In contrast to conventional route planners, however, the desired route identification does not involve compliance with various optimization criteria. It is only concerned with generating a lane-accurate route in the first place that runs from a location A to a location B. The background to this is that the derivation of behavioral requirements relies on a route. What exactly the route looks like is not important. With regard to the development or even the operation of AVs, it is nevertheless useful to consider routes that are as realistic as possible. For this purpose, the classic optimization criteria can then be used, as they are also used in vehicle navigation.

Although initially there are no requirements for the course of the lane-accurate route, modeling rules must be observed. These modeling rules ensure that the route can be used to derive behavioral requirements in subsequent process steps. This means that within the lane-accurate route, all associated behavioral demands are fully and correctly available. For the trip of an AV, it must be clear at any time which behavioral demands are valid in the traveled sections. For this purpose, the following rules for concatenating behavior spaces are defined:

- ***Rule 1:*** *Only behavior spaces shall be concatenated with each other.*
- ***Rule 2:*** *Only behavior spaces that are direct neighbors shall be concatenated.*
- ***Rule 3:*** *Behavior spaces shall be concatenated only by lateral or longitudinal boundaries.*
- ***Rule 4:*** *The direction of the behavior spaces shall always coincide with the direction of the concatenation.*

Regarding Rule 1

In a BSSD, elements of non-regular motion space may be modeled in addition to behavior spaces. These elements are not intended for the trip of an AV. Elements such as curbs or green spaces should not be traveled and therefore should not be included in a route. In addition, behavioral information is not available for the elements of non-regular motion space, so concatenating these elements would result in an information gap within the lane-accurate route. An information gap contradicts the goal of ensuring that all necessary behavioral demands are available for a trip.

Regarding Rule 2

Information gaps within the route can also occur when the concatenated behavior spaces are not direct neighbors. If two behavior spaces are concatenated that are not direct neighbors, a vehicle within a trip would be in a kind of blind flight in the meantime. Thus, both for a real trip and for the derivation of behavioral requirements, this results in a definitional gap that precludes completeness of behavioral information.

Regarding Rule 3

Even concatenating directly adjacent behavior spaces is not always sufficient to ensure completeness of a trip's information. Behavior spaces that are adjacent via vertices do not qualify for direct concatenation. If a vehicle would travel this concatenation, it would traverse further behavior spaces due to the geometric dimensions. Thus, necessary behavioral demands would be missing, resulting in an information gap here as well. Thus, it has to be ensured that a real vehicle actually has the possibility to drive within the given lane-accurate route without leaving the concatenated behavior spaces. This can basically be ensured by concatenating behavior spaces only across their lateral and longitudinal boundaries. In this way, there is always a unique transition between the concatenated behavior spaces so that the behavior information is complete.

To ensure that a vehicle does not leave the concatenated behavior spaces during a trip due to geometry, further considerations are necessary. For example, even permissible lateral concatenation could cause the behavior spaces to be geometrically abandoned due to vehicle size. Thus, route identification would also need to consider the geometries and dimensions of both vehicle and behavior spaces. This problem quickly becomes complex when vehicle dynamics are added on top of that. Consequently, depending on the speed, it might not be possible to perform a lateral behavior space change without running into a non-concatenated behavior space during the change. For this reason, this problem is not discussed further in this section. Further considerations and possible solutions can be found in the next section.

Regarding Rule 4

Behavior spaces are always directional. For a geometric space in regular motion space there are always two behavior spaces[154]. Depending on the direction of travel, there are different behavior spaces which are valid for this direction. It is mandatory, therefore, that behavior spaces are always concatenated in the correct direction. This means that a concatenated behavior space is actually valid for the concatenated direction, i.e. for the direction of the lane-accurate route.

5.3.2 Transitions between Behavior Spaces

The transitions between the behavior spaces determine the relevance of the stored information. This means that depending on the type of transition, not every expression of a behavioral attribute has an influence on the resulting behavioral demands for the respective concatenation of behavior spaces. Before the relevance of the information is identified, the possible transitions between behavior spaces must first be known.

Each behavior space is represented by the four behavioral attributes *speed*, *boundary*, *reservation*, and *overtake*. Only the *boundary attribute*, in addition to limiting the possible behavior of an AV, also limits the physical dimensions of the behavior space itself. Consequently, this attribute gives the behavior space its physical geometric shape. The behavior spaces can be simplified as rectangles as shown in Figure 5-2. For clarity, spacings are drawn between the individual behavior spaces that do not exist in a real scenery. In reality, the behavior spaces correspond to lane sections, for example. Due to the directionality of the behavioral demands, a driving direction must be assumed for the consideration of the behavioral spaces (here from left to right). Since only the geometric shape is relevant for a consideration of the possible transitions between several behavior spaces, only the *boundary attribute* is visualized accordingly. A behavior space is always bounded by two lateral boundaries (right and left) and a longitudinal boundary. The longitudinal boundary is located at the beginning of the behavior space according to the direction of travel, i.e. at the left edge of the behavior space in the figure shown.

In principle, there are only two states for a considered vehicle within behavior spaces. The vehicle may or may not be completely within a behavior space. If the vehicle is in more than one behavior space, *overlapping* occurs. Overlapping is always initiated by a transition, which describes the moment when the vehicle crosses a boundary of the behavior space. After a transition, a vehicle can basically maintain the state of overlapping, for example by driving in two lanes at the same

---

[154] Cf. Subsection 4.4.2.

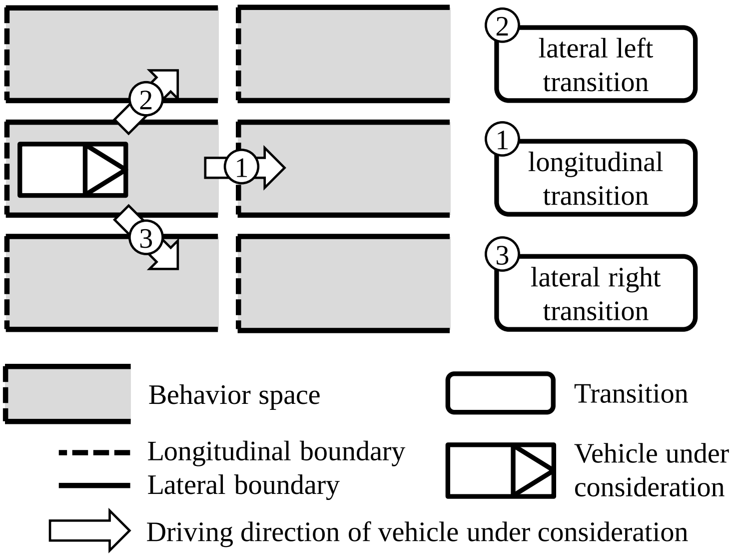


Figure 5-2: Transitions within BSSD.

time, or return completely to a single behavior space. Since a behavior space always consists of one longitudinal and two lateral boundaries, this results in three basic transitions: *longitudinal*, *lateral left* and *lateral right*.

In the figure, these transitions are shown in isolation. In reality, however, the transitions are not always isolated, since the vehicle has a spatial extension and cannot be modeled as a point. Considering a lane change, the vehicle could make an additional longitudinal transition during a lateral transition, resulting in overlapping four behavior spaces. In this case, there would actually be three boundaries involved: one lateral and two longitudinal. Furthermore, a behavior space could be geometrically very short or very narrow, so that a vehicle performs several lateral or longitudinal transitions simultaneously while passing through it (e.g., in the area of a crosswalk). This phenomenon of overlapping does not affect the derivation mechanism of behavioral requirements. Due to the dependence of the requirements on the transitions, the behavioral requirements can be derived based on the individual, decomposed transitions present. This is made possible by the unambiguous local separation of the behavior spaces. For each of the simultaneously driven behavioral spaces, the behavioral requirements apply according to the associated transitions. Since the vehicle cannot split up, the driving behavior must be selected in conformity with all the behavior spaces being driven on. This selection is a problem of the behavior planner of an AV and is thus not the focus of this work, which is why further considerations about it are neglected. As a result, a vehicle is assumed to be a point for the consideration of transitions.

5.3.3 Behavioral Demands of Individual Behavior Spaces

In order to obtain the relevant, applicable behavioral demands for a concatenation of behavior spaces, there must be a unique assignment of behavioral demands for each possible position of a vehicle within this concatenation. If a trip is considered along concatenated behavior spaces, the vehicle necessarily passes through the associated transitions. Consequently, it is necessary to identify which behavioral demands of all concatenated behavior spaces within the lane-accurate route are relevant and valid. For identification, an arbitrary concatenation of behavior spaces, in the following also referred to as *elements*, is traversed. The four rules for concatenating behavior spaces to a lane-accurate route identified in Section 5.3.1 are assumed to be fulfilled.

Let M_{BS} be the set of all behavior spaces within a BSSD. The concatenation of $n_{\mathrm{C}} \in \mathbb{N}$ behavior spaces is defined as the sequence $C = (E_i)_{i=1,2,\ldots,n_{\mathrm{C}}}$ while $E_i \in M_{\mathrm{BS}}$ and $(E_j, E_{j+1})_{j=1,2,\ldots,n_{\mathrm{C}}-1}$ are pairs of direct neighbors with the transition $T_{j,j+1}$ (Section 5.3.2) between them. Let D_i be the set of relevant behavioral demands of element E_i.

Figure 5-3 shows an example of a concatenation C with $n_{\mathrm{C}} = 6$ elements, corresponding transitions $T_{j,j+1}$ and resulting relevant behavioral demands D_i of the individual elements to visualize the following considerations. The example section of a BSSD road network with 12 behavior spaces could represent a three-lane one way road. However, the concrete scenery or BSSD representation is not important for the considerations. Here, in particular, the relation of the different terms should become clear in order to build up an overall understanding.

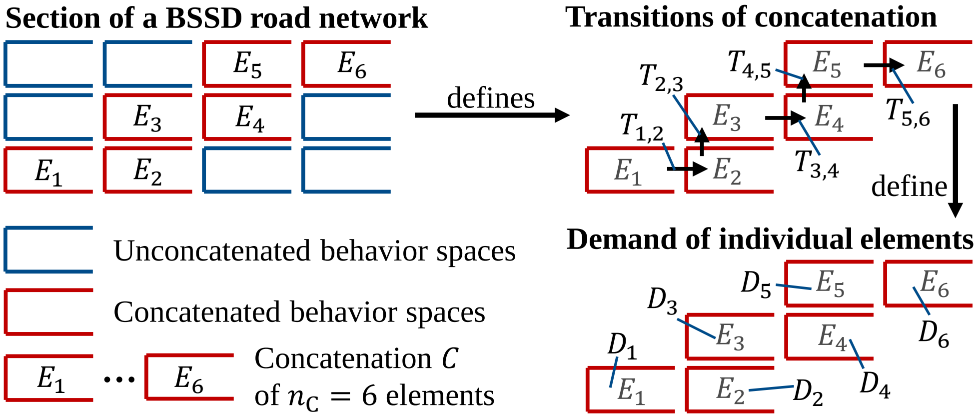


Figure 5-3: Visualization of an example BSSD road network section.

Starting in the first element E_1 of concatenation C, the behavioral demands of the *speed*, *reservation*, and *overtake* attributes of this element are relevant. In general, the first element is a special case because it is the only element of the concatenation that is not reached by a transition when traveling from first element E_1 to last element E_n with $n = n_{\mathrm{C}}$ (E_6 in the example). For this reason, no behavioral demand results from a transition, so the behavioral demands of the *boundary attribute* are irrelevant.

Proceeding from the first element, the remaining elements are now traversed in sequence. In doing so, the relevant behavioral demands are always determined for the next element, since equivalently to real driving, the demands must be known before entering the next element. For all further elements E_{j+1}, the relevant behavioral demands D_{j+1} depend on the transition $T_{j,j+1}$. This dependency is based on the definition of the BSSD, which links crossing demands to the longitudinal entry and to the lateral exit of a behavior space[155]. Accordingly, for a longitudinal transition from E_j to E_{j+1} (e.g., $T_{1,2}$ from E_1 to E_2), the longitudinal boundary of element E_{j+1} is relevant. For a lateral transition from E_j to E_{j+1} (e.g., $T_{2,3}$ from E_2 to E_3), in contrast, the lateral boundary of element E_j is relevant. Since a transition may occur to the right as well as to the left side, the two directions must be additionally distinguished accordingly. Regardless of the transition, the inherent attributes *speed*, *reservation* and *boundary* are relevant for each element E_{j+1}. Table 5-1 summarizes the relevant behavioral demands for all elements E_{j+1}.

Table 5-1: Relevant behavioral demands with respect to the transitions.

		Relevant Behavioral Demand D_{j+1} for Element E_{j+1} depending on the Transition $T_{j,j+1}$					
		$T_{j,j+1} =$ longitudinal		$T_{j,j+1} =$ lateral right		$T_{j,j+1} =$ lateral left	
Behavioral Demand		E_j	E_{j+1}	E_j	E_{j+1}	E_j	E_{j+1}
Speed			x		x		x
Boundary	Longitudinal		x				
	Lateral Right			x			
	Lateral Left					x	
Reservation			x		x		x
Overtake			x		x		x

The individual behavioral demands are examined below and formulated into behavioral requirements.

Speed Attribute

The speed attribute describes the behavioral demands regarding the allowed driving speeds of an AV. In urban traffic spaces, the behavioral demands are limited to the usual limitation of the maximum allowed driving speed. For this reason, the behavioral demands for a minimum required driving speed and the unlimited allowed driving speed are not considered further in this work.

Consequently, an AV is always required to respect a given speed limit. On the behavioral level of the DDT, this means that the driving speed must never be higher than defined in the corresponding speed limit. The first requirement regarding the speed attribute, in the following called Speed Requirement (SR), is thus:

> **SR1:** The AV shall not exceed the maximum permissible speed limit.

Further speed requirements result from the consideration of the concatenation of behavioral demands in the next subsection.

---

[155] Cf. Subsection 4.4.2.

Boundary Attribute

The boundary attribute contains behavioral demands that are linked to the lateral and longitudinal transitions. For this reason, there are the dependencies shown in Table 5-1 between transition and relevant behavioral demand. Regardless of the type of transition, it is possible to derive the behavioral requirements from the specific behavioral requirements of the behavior space. This derivation can be done independently of the transitions, since the transitions only determine the validity of the behavioral demands. In the following, the corresponding Boundary Requirements (BRs) are derived.

Allowed: This property of the boundary attribute does not restrict the driving behavior of an automated driving system. It merely instantiates the attribute and therefore does not result in a driving behavior requirement.

Stop: Boundaries with this behavioral demand shall not be crossed without further action. This attribute requires that an AV comes to a standstill at the boundary. The vehicle may only continue driving after it has come to a standstill. The following behavioral requirement is formulated:

> **BR1:** The AV shall stop at the boundary before proceeding.

No stagnant traffic: An AV may only enter areas with this behavioral demand if it is possible to drive completely through the area. The vehicle still has the option of stopping for a short time if the situation requires it. Nevertheless, it must be foreseeable that no longer stops will occur, as otherwise the flowing traffic of other road users will potentially be impeded. An example of this is turning left at intersections with oncoming traffic. If it is foreseeable that only a short stop is required when crossing the intersection to allow oncoming traffic to pass, this is still permissible. However, if it is clear that the traffic after the targeted area is stuck or the traffic is even already jammed in this area, then it is necessary to wait in front of the area at the boundary. The following behavioral requirement is therefore formulated:

> **BR2:** The AV shall not cross the boundary if the space cannot be passed through and exited completely without extended stopping times.

No red light: Behavior spaces that are controlled by traffic signals must not be passed through when the light is red. Specifically, passing through the associated boundary is not permitted during a red phase. When formulating the behavioral requirements, it is important to ensure that the possible vehicle behavior is not overly restricted. This means that the behavioral requirement must not be more restrictive than necessary. For example, it would be wrong to conclude that the vehicle must stop at the boundary when the traffic signal is red. This behavioral demand is only about the fact that the boundary must not be crossed. For this reason, for example, a slow approach until the phase changes to green would be just as possible as stopping at the boundary. The behavioral requirement is therefore:

> **BR3:** The AV shall not cross the boundary when the phase of the traffic light is red.

Parking only: There are behavior spaces that may only be entered for the purpose of parking. For this purpose, the intention to park must be present and parking must actually be performed in this area. The requirement is formulated restrictively:

> **BR4:** The AV shall not cross the boundary unless it parks in the space.

Prohibited: This behavioral demand states a clear prohibition on entering associated behavior spaces. From the point of view of traffic rules, crossing the boundary is prohibited, but there are special cases that justify crossing. For example, a lane change would be legitimate despite boundary attribute with the value prohibited, if a breakdown vehicle is passed as a result. In this way, the traffic flow is maintained. However, this and other special cases are not further specified here. Therefore, the behavioral requirement is:

> **BR5:** The AV shall not cross the boundary (except in special situations).

Not possible: For some boundaries, not only is crossing prohibited, but crossing is also physically impossible (e.g. a guard rail or a wall). For this reason, almost the same behavioral requirement applies to this behavioral demand as to the characteristic *prohibited*. The difference, however, is that this boundary must not be crossed, even in special cases, since otherwise a collision would inevitably occur. The following behavioral requirement is formulated:

> **BR6:** The AV shall not cross the boundary.

Reservation Attribute

The reservation attribute basically regulates the priority for a behavior space. However, it also contains behavioral demands regarding the duration of stay in behavior spaces. Three different reservation types are distinguished, for which Reservation Requirements (RRs) are derived below: own-reserved, externally-reserved, and equally-reserved.

Own-reserved: In behavior spaces declared as *own-reserved*, an AV has priority. This means that no constraints are imposed on the vehicle with respect to priority. Similar to the boundary attribute and the allowed value, the *own-reserved* expression is present only for an instantiation of the attribute. For this reason, no behavioral requirement is derived.

Externally-reserved: In externally-reserved behavior spaces, the AV does not have priority. Priority must be given to other road users. Specifically, this means that road users who have the right of way must not be impeded in their travel. As explained in Subsection 4.1.2 and Subsection 4.4.2, an externally-reserved space is always assigned information about type of authorized road users and direction of origin. Both road user type and direction of origin may vary depending on the scenery, which is why a generally applicable behavioral requirement is formulated first:

> **RR1:** The AV shall not obstruct traffic participants with reservation entitlement for the space.

In addition, the AV is not allowed to remain in externally-reserved behavior spaces for a longer time period than necessary. This means that the AV must vacate such behavior spaces as quickly as possible and move to equally- or own-reserved behavior spaces. An example of this is driving in the lane of oncoming traffic, which is only allowed temporarily for overtaking or passing. Once these maneuvers are completed, the AV must move back into an equally- or own-reserved behavior space that is usually the lane on which the AV drove before starting the maneuvers. The following second behavioral requirement is therefore formulated for the externally-reserved characteristic:

> **RR2:** The AV shall leave the space as soon as possible into an equally- or own-reserved space.

Equally-reserved: The expression *equally-reserved* also depends on the type of road user and the direction of origin. In equally-reserved behavior spaces, road users must communicate with each other. This means that priority is coordinated among the road users involved. In general, this behavioral demand can be seen as a request for cooperation. However, this statement is not precise and therefore not directly suitable as a behavioral requirement. For this reason, the cooperation behavior for the equally-reserved situations is considered again in more detail. If two oncoming vehicles meet at a narrow spot without a specific regulation, they must agree on priority. Usually, this is only the case if the vehicles would enter the narrow spot at the same time. Otherwise, the established common-sense rule is *first come, first served.* This rule is particularly widespread in North America and is anchored in the traffic regulations, where, for example, at four-way-stop intersections it yields *whoever stops first, drives first.* If this rule is adopted for all equally-reserved cases, the direct cooperation regarding priority is reduced to the few situations where traffic participants encounter each other at the same time. The following requirement is therefore formulated:

> **RR3:** The AV shall not obstruct equally entitled traffic participants arriving earlier in the space and shall coordinate priority with those arriving at the same time as the AV itself.

Overtake Attribute

The behavioral attribute overtake has only two different forms. Either overtaking is allowed or it is forbidden. If overtaking is allowed, there are no restrictions regarding the driving behavior. Nevertheless, the value *yes* is set in the BSSD for instantiation. For the value *no*, i.e. for an overtaking prohibition, the following overtake requirement is formulated:

> **OR1:** The AV shall not overtake.

Table 5-2 summarizes the resulting requirements with their Identification Numbers (IDs) of the individual behavior spaces.

Table 5-2: Requirements of individual behavior spaces.

Attribute	**Property**	**Behavioral Requirement**	**ID**
Speed	*limit*	The AV shall not exceed the maximum permissible speed limit.	SR1
Boundary	*allowed*	-	-
	stop	The AV shall stop at the boundary before proceeding.	BR1
	no stagnant traffic	The AV shall not cross the boundary if the space cannot be passed through and exited completely without extended stopping times.	BR2
	no red light	The AV shall not cross the boundary when the phase of the traffic light is red.	BR3
	parking only	The AV shall not cross the boundary unless it parks in the space.	BR4
	prohibited	The AV shall not cross the boundary (except in special situations).	BR5
	not possible	The AV shall not cross the boundary.	BR6
Reservation	*own-reserved*	-	-
	externally-reserved	The AV shall not obstruct traffic participants with reservation entitlement for the space.	RR1
		The AV shall leave the space as soon as possible into an equally- or own-reserved space.	RR2
	equally-reserved	The AV shall not obstruct equally entitled traffic participants arriving earlier in the space and shall coordinate priority with those arriving at the same time as the AV itself.	RR3
Overtake	*yes*	-	-
	no	The AV shall not overtake.	OR1

5.3.4 Behavioral Demands of Concatenation

For the derivation of the behavioral requirements an additional consideration of the concatenated sets of behavioral demands D_j and D_{j+1} is necessary. This concatenation may result in an additional set of behavioral demands $D_{j,j+1}$. The set of the total resulting behavioral demands for all successor elements E_{j+1} thus results in $D_{\text{res},j+1} = D_{j+1} \cup D_{j,j+1}$. For the first Element E_1 of a concatenation, simply $D_{\text{res},1} = D_1$ holds due to the lack of transition. Figure 5-4 shows the relationship of the different behavioral demands based on the introduced example of Figure 5-3. For clarity, the demands are shown directly in the elements of the concatenation to which they apply.

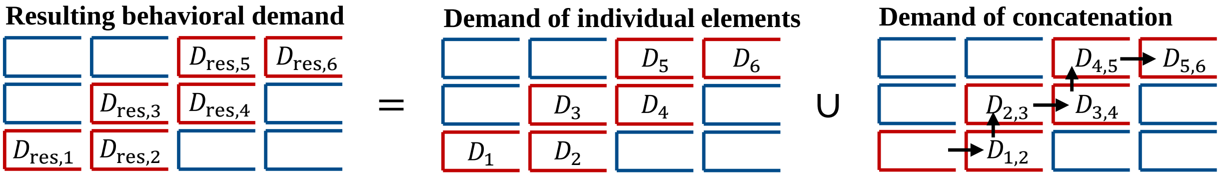


Figure 5-4: Visualization of relationship between behavioral demands $D_{\mathrm{res},i}$, D_i and $D_{j,j+1}$.

In the following, the behavioral demands and requirements resulting from concatenation are systematically derived. Due to the low complexity of the BSSD information, a systematic analysis of the concatenation is completely possible. The behavioral attributes are assumed to be independent from each other allowing them to be considered separately. Independent means that no new behavioral demands arise based on the combination of different expressions of the attributes among each other[156]. Conversely, this means that only changes within the attributes need to be considered for the analysis. For this reason, the analysis is performed separately for each attribute in the following. Step 4.1 and Step 4.2 are considered together in order to avoid multiple mentions and redundant descriptions. Selected examples further illustrate the considerations.

Speed Attribute

This attribute has few different characteristics. Basically, a maximum allowed driving speed may or may not exist. Conditions that link the speed limit to times of day or weather conditions are not of interest with regard to the analysis of changes in behavioral demand. It is only a question of the influence of different characteristics of the behavioral attributes in a transition between behavior spaces. For this reason, only the behavioral demands themselves are relevant, not conditions leading to them. From the perspective of the complete DDT, on the other hand, these conditions might become relevant again. For example, an AV might need to know the current time of day in order to determine the correct speed limit if it is temporally constrained.

Considering a transition $T_{j,j+1}$, there are only three cases that can potentially occur with respect to the involved speed limits $v_{\mathrm{lim},i}$ demanded by D_i of behavior space E_i:

- Case 1: $v_{\mathrm{lim},j} = v_{\mathrm{lim},j+1}$
- Case 2: $v_{\mathrm{lim},j} < v_{\mathrm{lim},j+1}$
- Case 3: $v_{\mathrm{lim},j} > v_{\mathrm{lim},j+1}$

In the first case, the speed limits in both behavior spaces are equal. Thus, there is no change in the behavioral attribute. Consequently, if an AV drives from behavior space E_j into E_{j+1}, it does not

---

[156] So far, no combinations of differently characterized behavioral attributes are known that lead to new behavioral requirements in these concrete constellations. For example, a change in the speed limit has no influence on the behavioral requirements for different properties of the reservation. Only the resulting behavioral requirements of both attributes have to be fulfilled. As the work progresses, it also becomes evident that there does not appear to be any influences between the behavioral attributes. However, if dependencies are identified in the future, they can be easily added.

need to adjust its driving behavior. It is assumed that the AV does indeed adhere to the behavioral rules and already complies with the speed limit in E_j and does not exceed it. Thus, for case 1, no additional behavioral demands result from concatenation.

In the second case, the speed limit in the following behavior space E_{j+1} is larger than in E_j. If the AV already behaves correctly in E_j, it undeniably underruns the speed limit when entering E_{j+1}. Since undercutting the speed limit is not bound to any official rule, no additional behavioral demands result from concatenation for case 2 either.

In the third case, the speed limit in the subsequent behavior space E_{j+1} is smaller than in E_j. Consequently, if the AV enters E_{j+1}, there is a possibility that the speed limit from D_{j+1} is exceeded. In principle, the AV can already move in E_j with a driving speed that is below the speed limit in E_{j+1}. Nevertheless, this case should not be considered as a normal case. Moreover, it is necessary to map all potentially necessary behavioral demands. In case 3, this results in an additional behavioral demand based on the kinematic dependence between driving behavior and behavioral demand due to concatenation. From a behavioral point of view, the AV must already comply with the required speed limit when entering E_{j+1}. This means that the driving speed must already be reduced before entering E_{j+1}. Of course, this only applies to the case that the AV in E_j actually drives faster than the speed limit from D_{j+1} allows. Nevertheless, due to the behavioral rules, this potential case must be taken into account.

The need for prior speed reduction is only part of the new behavioral demand. So far, this demand does not allow to say in which way the speed reduction has to be done. Since local behavioral requirements are the focus of this chapter, global behavioral requirements have not yet been considered. A behavioral demand that leads to a global behavioral requirement is mentioned in § 4 of the StVO. It formulates the following demand in the context of the distance regulation between road users: Whoever drives ahead must not brake hard without a compelling reason[157]. The explanations to the StVO list compelling reasons that justify heavy braking[158]. This explicitly addresses the delayed recognition of traffic situations. For example, the late recognition of the need to turn at an intersection or the late recognition of a parking space is explicitly not a compelling reason for hard braking. Furthermore, according to the explanations to the StVO, braking without cause is also present if the braking occurs too late and thus too violently. In this case, the braking itself is not without reason, but its intensity is. In the opinion of the author, the delayed recognition of the applicable traffic regulations on the one hand and the resulting heavy braking on the other hand, based on the explanations to the StVO, also does not represent a compelling reason for heavy braking. For this reason, a second behavioral demand is necessary in addition to the speed reduction: Speed reduction must not be achieved by heavy braking.

---

[157] Translated from German: "Wer vorausfährt, darf nicht ohne zwingenden Grund stark bremsen.", BMJ: Straßenverkehrs-Ordnung (StVO) (2013), p. 3.

[158] BMJ: Erläuterungen zur Straßenverkehrs-Ordnung (2019), p. 19.

Based on the additionally derived behavioral demands, the following behavioral requirements are formulated as a supplement to SR1 for the same behavior space:

SR1: The AV shall not exceed the maximum permissible speed limit.

SR1.1: The AV shall have completed a necessary driving speed adjustment prior to the entrance of the space.

SR1.2: The AV shall adjust the driving speed reasonably.

It can be seen that although these behavioral requirements apply to the behavior space E_{j+1}, they must be satisfied before entering this behavior space. Table 5-3 summarizes the behavioral requirements of the speed attribute.

Table 5-3: Behavioral requirements of the speed attribute.

Property	**Condition**	**Behavioral Requirement**	**ID**
Limit	-	The AV shall not exceed the maximum permissible speed limit.	SR1
	$v_{\text{lim},i} > v_{\text{lim},i+1}$	The AV shall have completed a necessary driving speed adjustment prior to the entrance of the space.	SR1.1
		The AV shall adjust the driving speed reasonably.	SR1.2

Boundary Attribute

The boundary attribute is basically analyzed in the same way as the speed attribute. However, there is a difference due to the characteristics of this attribute. Unlike all other attributes, the boundary attribute already addresses the transition between behavior spaces. The associated behavioral demands are directly linked to the corresponding transition, which is why an aspect of concatenation is already implied. Nevertheless, with respect to concatenation of multiple behavior spaces and with respect to kinematic dependencies of vehicles, further behavioral demands and requirements can be derived.

So far, the behavioral attributes have been examined strictly in terms of their characteristics. However, from the example in Section 5.2, it is clear that there are also general behavioral demands with respect to the boundary attribute. These behavioral demands arise directly as a result of concatenating behavior spaces into a lane-accurate route. For this reason, these general behavioral demands are considered first, followed by their various characteristics.

General: The behavior spaces from the BSSD provide information on behavioral constraints based on the scenery. With respect to the boundaries, it is possible that there are no restrictions at all or that they only apply conditionally. In order to be able to travel the concatenated behavior spaces within a trip, it is necessary that only these spaces are actually traveled. However, if concatenated behavior spaces do not contain crossing prohibitions for the lateral boundaries, exactly this information is missing for the compliance with the lateral boundaries of the behavior spaces. Nevertheless, it is possible that the behavior spaces have to be left laterally, even if the lane-accurate route is adhered to. Basically, two cases can be distinguished:

- *Purely longitudinally concatenated behavior spaces:* behavior spaces that are only longitudinally concatenated should also only be traversed longitudinally. In principle, therefore, these behavior spaces must not be left laterally. In this way, the AV is signaled that it must remain laterally within these behavior spaces. These rules also apply to lateral boundaries, which in principle (conditionally) permit driving over them. Nevertheless, it is possible that the lateral boundaries must be crossed during a trip. This can be the case, for example, if objects in the behavior spaces have to be passed and the lateral space is not sufficient for this. In these cases, it is necessary that information about the laterally adjacent behavior spaces is available. Otherwise, passing the lateral boundary would be unspecified. The exact specification of deviations from the lane-accurate route will not be further elaborated here. One way to account for this information is to re-plan the lane-accurate route. In this way, the required information of the lateral change would be available.
- *Laterally concatenated behavior spaces:* for laterally concatenated behavior spaces, the very nature of the concatenation itself dictates that lateral transitions are required. In these cases, the AV must be allowed to perform the lateral changes of the behavior spaces. However, this permission refers exclusively to the change request. Otherwise, it also applies in these behavior spaces that the behavior space is not to be left laterally without a valid reason.

It follows from both cases that the lateral boundaries of a behavior space may only be crossed for the purpose of a lateral change planned within the route. This ensures that all behavioral information required for the trip is available. Since this requirement is present in every concatenated behavior space uniformly, the ID is chosen to be *BR0*:

> **BR0:** The AV shall remain within the lateral boundaries except for route-based lateral changes of behavior spaces.

Allowed: Even on the basis of concatenation, no behavioral demand results for this expression compared to the individual consideration.

Stop: With respect to the kinematic dependency, further behavioral demands arise for stopping at boundaries. Similar to the speed attribute, it is necessary that an AV adjusts the driving speed in time before the boundary. Only if the speed is adjusted early it is possible to stop at the boundary. In this case, too, the speed adjustment must not be sudden, but must be designed appropriately. Further behavioral demands do not result from concatenating different expressions of the boundary attributes with the expression stop. The following behavioral requirements complementary to BR1 are formulated:

> **BR1:** The AV shall stop at the boundary before proceeding.

> > **BR1.1:** The AV shall adjust the driving speed reasonably in order to stop at the boundary.

No stagnant traffic: If a behavior space with this characteristic cannot be traversed without longer stopping times, an AV must not enter this space. As a consequence, the boundary of this space must not be crossed in this case. This results in similar behavioral demands based on kinematics as for the expression *stop*. The difference, however, is that stopping is not mandatory in the case of stagnant traffic. Accordingly, the driving speed does not necessarily have to be adjusted so that the AV comes to a stop. Heavy braking must also be avoided in this case. Therefore, the behavioral requirement BR2 is further complemented with BR2.1 based on this kinematic dependencies.

The entry condition *no stagnant traffic* refers to the complete range of the behavior space. This results in another behavioral demand regarding a specific combination of behavior spaces. If an AV must be able to traverse a behavior space without extended stopping times, then it follows that there must be sufficient driving space in the next behavior space. But what happens if the following behavior space also has the characteristic *no stagnant traffic*? In this space, too, the vehicle is not allowed to stop any longer. In this case, the AV would only be allowed to enter the first behavior space E_{j+1} if both E_{j+1} and the following behavior space E_{j+2} can be traversed without longer stopping times. For multiple chaining of behavior spaces with this characteristic, the same behavioral demand results analogously for all behavior spaces. The concatenation of two or more behavior spaces with the characteristic *no stagnant traffic* results in the additional behavioral requirement BR2.2. The overall behavioral requirements for the property *no stagnant traffic* are as follows:

> **BR2:** The AV shall not cross the boundary if the space cannot be passed through and exited completely without extended stopping times.
>
> > **BR2.1:** The AV shall adjust the driving speed reasonably in order not to cross the boundary in case of stagnant traffic.
> >
> > **BR2.2:** The AV shall not cross the longitudinal boundary of the space if the successive space(s) cannot be passed through and exited completely without extended stopping times.

No red light: For concatenated behavioral spaces controlled by traffic signals, there are very similar additional behavioral demands as for the characteristic *no stagnant traffic*. In the case of a red phase of the traffic signal, the boundary must not be crossed. For this purpose, it is necessary that an AV adjusts the driving speed in time and appropriately. Besides the behavioral demands from the kinematic consideration, there are no further demands. The following behavioral requirement results as supplement to BR3:

> **BR3:** The AV shall not cross the boundary when the phase of the traffic light is red.

> **BR3.1:** The AV shall adjust the driving speed reasonably in order not to cross the boundary in case of a red light.

Parking only: For the purpose of parking, it is also necessary from a kinematic point of view to adjust the driving speed in a reasonable manner. No other behavioral demands result. The requirement complementing BR4 is formulated analogously to the other requirements:

BR4: The AV shall not cross the boundary unless it parks in the space.

> **BR4.1:** The AV shall adjust the driving speed reasonably in order to park in the space.

Prohibited/ not possible: For both specifications, the boundary of the behavior space must not be crossed. Thus, similar behavioral requirements result from the kinematic consideration analogous to the previous considerations, which lead to the following behavioral requirements:

BR5: The AV shall not cross the boundary (except in special situations).

> **BR5.1:** The AV shall adjust the driving speed reasonably in order not to cross the boundary (except in special situations).

BR6: The AV shall not cross the boundary.

> **BR6.1:** The AV shall adjust the driving speed reasonably in order not to cross the boundary.

Table 5-4 summarizes the behavioral requirements of the boundary attribute.

Table 5-4: Behavioral requirements of the boundary attribute.

Property	**Condition**	**Behavioral Requirement**	**ID**
general	-	The AV shall remain within the lateral boundaries except for route-based lateral changes of behavior spaces.	BR0
stop	-	The AV shall stop at the boundary before proceeding.	BR1
	-	The AV shall adjust the driving speed reasonably in order to stop at the boundary.	BR1.1
no stagnant traffic	-	The AV shall not cross the boundary if the space cannot be passed through and exited completely without extended stopping times.	BR2
	-	The AV shall adjust the driving speed reasonably in order not to cross the boundary in case of stagnant traffic.	BR2.1
	same property in successive space(s)	The AV shall not cross the longitudinal boundary of the space if the successive space(s) cannot be passed through and exited completely without extended stopping times.	BR2.2
no red light	-	The AV shall not cross the boundary when the phase of the traffic light is red.	BR3
	-	The AV shall adjust the driving speed reasonably in order not to cross the boundary in case of a red light.	BR3.1
parking only	-	The AV shall not cross the boundary unless it parks in the space.	BR4
	-	The AV shall adjust the driving speed reasonably in order to park in the space.	BR4.1
prohibited	-	The AV shall not cross the boundary (except in special situations).	BR5
	-	The AV shall adjust the driving speed reasonably in order not to cross the boundary (except in special situations).	BR5.1
not possible	-	The AV shall not cross the boundary.	BR6
	-	The AV shall adjust the driving speed reasonably in order not to cross the boundary.	BR6.1

Reservation Attribute

For the attributes *speed* and *boundary* a distinction regarding longitudinal and lateral transition was not necessary. The behavioral demands and requirements resulting from concatenation were derived independently of the transition and are correspondingly valid for both types of transitions. However, the example in Section 5.2 shows that the type of transition of concatenation may well have an influence on the behavioral demands of *reservation*. For this reason, the *longitudinal* and *lateral* transitions are examined separately.

Own-reserved (longitudinal): Consideration of a single own-reserved behavior space revealed no constraints on driving behavior. Even in a longitudinal concatenation, no new behavioral demands emerge. With respect to the reservation attribute, longitudinal entry into a behavior space is consequently always possible without behavioral constraints.

Own-reserved (lateral): As exemplified in Section 5.2, lateral transitions into own-reserved behavior spaces result in further behavioral demands with respect to priority. In the example shown in Figure 5-1, a two-lane one-way street is considered. When changing lanes, priority must be given to traffic already in the target lane. There is no clear statement on this in the StVO, but traffic in the target lane must not be endangered in any way according to § 7[159]. According to the explanations to the StVO, this rule is violated if the road user changing lanes enters the safety distance of the other road user[160]. Basically, this rule leads to global behavioral requirements, i.e. requirements for collision avoidance. However, in the specific case of lateral behavioral space changes, it is the responsibility of an AV not to violate the safety distance of other road users. Thus, it is not a matter of maintaining its own safety distance from other road users, as is the case, for example, in a following maneuver. For this reason, the lateral change of behavior spaces can also be interpreted as a granting of safe continuation of other road users. Additionally, it should be noted that this regulation is closely linked to the scenery. The AV cannot come into the situation of this regulation in every scenery, so the requirement also has a strongly local character.

Also in the case of lateral change, the priority road users on the target lane should be indicated that they are not endangered. This indication can be made both by deceleration and acceleration of the driving speed. Even a constant driving speed is possible. For example, in order to indicate that the traffic behind in the target lane is not obstructed when approaching a slower-moving traffic participant longitudinally before changing lanes, acceleration or constant driving could be used. Analogously to the already discussed attributes, in case of a necessary speed adjustment, this must be done reasonably without sudden speed changes.

Last, it must be clarified to which types of road users this regulation applies. Lateral changes into behavior spaces with the characteristic *own-reserved* are, for example, lane changes in a one-way street or changing back from externally-reserved areas such as bicycle protection lanes or two-way

---

[159] BMJ: Straßenverkehrs-Ordnung (StVO) (2013).

[160] BMJ: Erläuterungen zur Straßenverkehrs-Ordnung (2019), p. 26.

traffic lanes. In all cases, no road users may be endangered who are basically driving in the same direction as the AV. Based on their direction of travel, these road users have the same right to the driving space as the AV. Therefore, the discussed consideration is aimed at road users who have the same right of reservation as the AV. In total, the following new behavioral requirements arise:

> **RR4:** The AV shall not endanger other traffic participants with the same reservation entitlement.
>
> > **RR4.1:** The AV shall indicate in advance by adjusting the driving speed reasonably that it does not endanger traffic participants with same reservation entitlement.

Externally-reserved (longitudinal): In an externally-reserved behavior space, the AV must always give priority to other traffic participants. In addition, the space must be left as quickly as possible into an equally- or own-reserved space. In order for the AV to give priority to other road users, it must approach the behavior space with reasonable driving speed. This may mean that the AV has to slow down or simply maintain an already low speed. In this way, the road users who have priority is given enough time to continue their journey unhindered. In addition, it is necessary to signal to the priority road users that they are granted priority. According to § 8 of the StVO, this can be done by driving with reduced speed[161]. Depending on the driving speed, the AV may have to reduce the speed for this purpose. But, this could be done as well by just maintaining an already low speed. As with the other attributes, care must be taken in the case of slowing down to ensure that the speed is not reduced abruptly. Consequently, the reasonable adjustment of driving speed is required both for the priority to be granted and for the corresponding communication with the road users involved. These demands can thus be transformed together into a single new behavioral requirement supplementing *RR1*:

> **RR1:** The AV shall not obstruct traffic participants with reservation entitlement for the space.
>
> > **RR1.1:** The AV shall indicate in advance by adjusting the driving speed reasonably that it will give priority to traffic participants who have priority.

Externally-reserved (lateral): For lateral transitions into externally-reserved behavior spaces, the same behavioral demands apply as for longitudinal transitions. Additionally, the rules of lateral transitions into own-reserved behavior spaces have to be considered. This can be explained using the example of overtaking in the oncoming traffic lane. If an AV wants to overtake a cyclist in front, then in most cases it has to change into the oncoming traffic lane. Obviously, according to an externally-reserved behavior space, it is necessary not to obstruct oncoming traffic. However, rear traffic also plays a role. Another road user from the traffic behind may have already started an overtaking maneuver to pass the AV and the cyclist. In this case, the AV must not endanger this road user by changing lanes. The following behavioral requirements are therefore formulated:

---

[161] BMJ: Straßenverkehrs-Ordnung (StVO) (2013).

RR1: The AV shall not obstruct traffic participants with reservation entitlement for the space.

> **RR1.1:** The AV shall indicate in advance by adjusting the driving speed reasonably that it will give priority to traffic participants who have priority.

RR4: The AV shall not endanger other traffic participants with the same reservation entitlement.

> **RR4.1:** The AV shall indicate in advance by adjusting the driving speed reasonably that it does not endanger traffic participants with same reservation entitlement.

Equally-reserved (longitudinal): As soon as an AV has to cooperate with other traffic participants, it is necessary to indicate this behavior in advance as well. As an example, a narrow road with two-directional traffic is considered. The narrow section is described by a behavior space with the characteristic *externally-reserved*. This means that all traffic participants who want to pass the narrow section must coordinate their priority with each other. In the first case, when the AV arrives later than other traffic participants, they must not be obstructed. In the second opposite case, the AV may enter the behavior space first. In the third case, where the AV and other traffic participants arrive at the same time, they must agree on the priority. Each of these cases requires an reasonably response from the AV. In all three cases, reasonable adjustments of driving speed are required. For the first and third cases, for example, this means decelerating, while in the second case it might be better to accelerate to indicate the priority situation. The AV must therefore adjust its speed in time for other road users to perceive its intention to cooperate - regardless of whether the aim is to avoid obstructing other traffic participants or to coordinate priority with them. Again, speed adjustments have to be in a reasonable way preventing high accelerations. Based on these behavioral demands, the following behavioral requirement results as a complement to RR3:

RR3: The AV shall not obstruct equally entitled traffic participants arriving earlier in the space and shall coordinate priority with those arriving at the same time as the AV itself.

> **RR3.1:** The AV shall indicate in advance by adjusting the driving speed reasonably that it is cooperating with other equally entitled traffic participants.

Equally-reserved (lateral): For lateral changes into behavior spaces with the characteristic *equally-reserved* the same behavioral demand applies as for a longitudinal change. Furthermore, the author of the present work is not aware of any scenery that yields further behavioral demands for a lateral change. Therefore, the same behavioral requirements as for the longitudinal transition are formulated:

RR3: The AV shall not obstruct equally entitled traffic participants arriving earlier in the space and shall coordinate priority with those arriving at the same time as the AV itself.

> **RR3.1:** The AV shall indicate in advance by adjusting the driving speed reasonably that it is cooperating with other equally entitled traffic participants.

Table 5-5 summarizes the behavioral requirements of the reservation attribute.

Table 5-5: Behavioral requirements of the reservation attribute.

Property	Transition	Behavioral Requirement	ID
own-reserved	longitudinal	-	-
	lateral	The AV shall not endanger other traffic participants with the same reservation entitlement.	RR4
		The AV shall indicate in advance by adjusting the driving speed reasonably that it does not endanger traffic participants with same reservation entitlement.	RR4.1
externally-reserved	longitudinal	The AV shall not obstruct traffic participants with reservation entitlement for the space.	RR1
		The AV shall indicate in advance by adjusting the driving speed reasonably that it will give priority to traffic participants who have priority.	RR1.1
	lateral	The AV shall not obstruct traffic participants with reservation entitlement for the space.	RR1
		The AV shall indicate in advance by adjusting the driving speed reasonably that it will give priority to traffic participants who have priority.	RR1.1
		The AV shall not endanger other traffic participants with the same reservation entitlement.	RR4
		The AV shall indicate in advance by adjusting the driving speed reasonably that it does not endanger traffic participants with same reservation entitlement.	RR4.1
	longitudinal/ lateral	The AV shall leave the space as soon as possible into an equally- or own-reserved space.	RR2
equally-reserved	longitudinal/ lateral	The AV shall not obstruct equally entitled traffic participants arriving earlier in the space and shall coordinate priority with those arriving at the same time as the AV itself.	RR3
		The AV shall indicate in advance by adjusting the driving speed reasonably that it is cooperating with other equally entitled traffic participants.	RR3.1

Overtake Attribute

Overtaking prohibitions generally apply to the entire roadway, so no distinction between longitudinal and lateral transitions is necessary. Thus, only the two different manifestations need to be considered.

Yes: If overtaking is allowed in a following area, there are no restrictions regarding overtaking with respect to this behavior space. Concatenation does not change this either.

No: As soon as a change into a behavior space with overtaking prohibition occurs, there are kinematic dependencies that lead to a further behavioral demand. Accordingly, an overtaking maneuver that is started before the prohibition must be completed no later than the entry into the behavior space with overtaking prohibition. This requirement is invalid if an overtaking ban already exists beforehand. The following additional behavioral requirement with respect to OR1 is formulated:

- **OR1:** The AV shall not overtake.
  - **OR1.1:** The AV shall have completed a potential overtaking maneuver prior to the entrance into the space.

Table 5-6 summarizes the behavioral requirements of the overtake attribute.

Table 5-6: Behavioral requirements of the overtake attribute.

Property	Transition	Behavioral Requirement	ID
yes	-	-	-
no	longitudinal	The AV shall not overtake.	OR1
		The AV shall have completed a potential overtaking maneuver prior to the entrance into the space.	OR1.1

5.4 Real-World Example

To demonstrate the presented method, the same real scenery section of Darmstadt (Germany) as considered in Section 4.5 is illustrated and analysed in Figure 5-5. The aerial view shows a T-intersection with a multi-lane one-way road running from left to right and a two-lane side road with two-way traffic. An abstract representation of the BSSD is shown as the second layer. Here, the dark frames show parts of the behavior spaces on this scenery section, which are marked with capital letters. Since there is always one behavior space per direction of travel (even against the one-way street) and these can also overlap in intersection areas, not all behavior spaces are shown for clarity (including the behavior space of the restricted area). The present segmentation of the behavioral spaces is based on changes in the behavioral demands in the longitudinal direction. If there are changed behavioral demands due to the scenery, a new segment is created. The behavior spaces are present in the BSSD unconcatenated, so that initially only information about the relative position of the behavior spaces to each other is known. Therefore, a possible concatenation of the behavior spaces is represented as the third level. The concatenation follows the path drawn in blue, which can potentially be followed by an AV. Non-concatenated behavior spaces are shown slightly transparent compared to the concatenated ones.

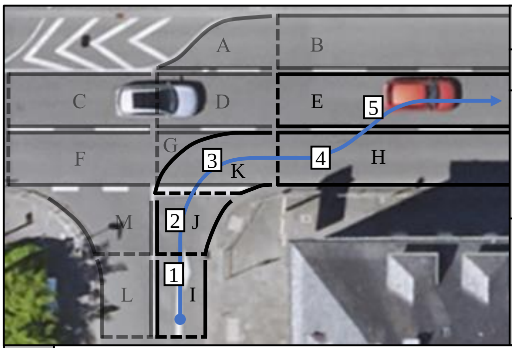
	E_i	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$
	$T_{i-1,i}$		*longitud.*	*longitud.*	*longitud.*	*lateral*
	D_i	S: *30 km/h* B: - R: *own* O: *yes*	S: *30 km/h* B: *allowed* R: *own* O: *yes*	S: *30 km/h* B: *stop* R: *ext.* O: *yes*	S: *30 km/h* B: *allowed* R: *own* O: *yes*	S: *30 km/h* B: *allowed* R: *own* O: *yes*
	$D_{i-1,i}$		S: - B: ✓ R: - O: -	S: - B: ✓ R: ✓ O: -	S: - B: ✓ R: - O: -	S: - B: ✓ R: ✓ O:
Behavioral Requirements of E_i	SR1: The AV shall not exceed the maximum permissible speed limit.	✓	✓	✓	✓	✓
	SR1.1: The AV shall have completed a necessary driving speed adjustment prior to the entrance of the space.	-	-	-	-	-
	SR1.2: The AV shall adjust the driving speed reasonably.	-	-	-	-	-
	BR0: The AV shall remain within the lateral boundaries except for route-based lateral changes of behavior spaces.	✓	✓	✓	✓	✓
	BR1: The AV shall stop at the boundary before proceeding.	-	-	✓	-	-
	BR1.1: The AV shall adjust the driving speed reasonably in order to stop at the boundary.	-	-	✓	-	-
	RR1: The AV shall not obstruct traffic participants with reservation entitlement for the space.	-	-	✓	-	-
	RR1.1: The AV shall indicate in advance by adjusting the driving speed reasonably that it will give priority to traffic participants who have priority.	-	-	✓	-	-
	RR2: The AV shall leave the space as soon as possible into an equally- or own-reserved space.	-	-	✓	-	-
	RR4: The AV shall not endanger other traffic participants with the same reservation entitlement.	-	-	-	-	✓
	RR4.1: The AV shall indicate in advance by adjusting the driving speed reasonably that it does not endanger traffic participants with same reservation entitlement.	-	-	-	-	✓
	OR1: The AV shall not overtake.	-	-	-	-	-
	OR1.1: The AV shall have completed a potential overtaking maneuver prior to the entrance into the space.	-	-	-	-	-

Figure 5-5: Example behavioral requirements of concatenated behavior spaces.
S: Speed Attribute; B: Boundary Attribute; R: Reservation Attribute; O: Overtake Attribute.
Aerial image © Orthophoto Vermessungsamt Darmstadt 2021.

Transitions $T_{i-1,i}$, behavioral demands of individual elements D_i and concatenated elements $D_{i-1,i}$ as well as resulting requirements of E_i are shown in the attached table. Since one column is considered for each element E_i in the table, the relationship of neighboring elements $(E_j, E_{j+1})_{j=1,2,\ldots,n_{\mathrm{C}-1}}$ from previous sections is reformulated into the mathematical equivalent $(E_{i-1}, E_i)_{i=2,3,\ldots,n_{\mathrm{C}}}$ to ensure a formally correct representation. Consequently, transition $T_{i-1,i}$ and behavioral demands $D_{i-1,i}$ of concatenation are not defined for $i = 1$.

As shown in the figure, the concatenation $C = (\mathrm{I}, \mathrm{J}, \mathrm{K}, \mathrm{H}, \mathrm{E})$ is considered, which consists of $n_{\mathrm{C}} = 5$ elements E_i with $i = 1, 2, \ldots, n_{\mathrm{C}}$ (number in white boxes corresponds to i). When this concatenation is followed, first a right turn is made coming from the minor road, and then a lane change to the left into the middle lane. According to these transitions, the behavioral demands D_i of the individual elements result. Along the concatenation, the demand of the *speed attribute* does not change, so that a maximum allowed speed of 30 km/h applies to all elements E_i. In the first element $E_1 = \mathrm{I}$ there is no behavioral demand based on the *boundary attribute* because there is no transition. In the third element $E_3 = \mathrm{K}$, there is a requirement that the AV stops before entering. The cause of this demand is a stop sign with associated stop line in the scenery. The other elements E_i have no demands concerning the entry (Crossing condition: *allowed*). Regarding the *reservation attribute*, there are no restrictive behavioral demands for the elements that are *own-reserved*, in these areas from an individual point of view no priority is to be given. Only element E_3 as representation of the intersection area is *externally-reserved*, so that certain other traffic participants shall not be obstructed and the space shall be left as soon as possible. Overtaking is allowed in every element E_i, so there is no restriction on behavior based on the *overtake attribute*.

From the transitions between the individual behavioral demands D_i, the behavioral demands $D_{i-1,i}$ from concatenation are derived. Since the demand for lane keeping is a basic demand for concatenation, it applies to all concatenated behavior spaces. However, for intended lateral changes of behavior spaces such as $T_{4,5}$ an exception applies for the transition process. For E_3, due to the *stop* condition, $D_{2,3}$ demands that the AV shall adjust its driving speed reasonably when approaching the longitudinal boundary. For the same behavior space, the demand of external reservation results in indicating to the reservation-entitled traffic participants that they have priority. For the lateral lane change in E_5, the concatenation results in two behavioral demands. Traffic participants with the same reservation claim to this behavior space - in this case bicyclists and motor vehicles traveling in the same direction - must not be endangered during the change and this must be indicated additionally.

For the resulting behavioral demands $D_{\mathrm{res},i} = D_i \cup D_{i-1,i}$ of the concatenated elements E_i, the behavioral requirements result as shown in the lower half of the figure. Although there is no restrictive requirement of the *overtake attribute* for the elements E_i, it is still instantiated for completeness. The distribution of requirements shows that the intersection entry and lane change have significantly more behavioral requirements than the remaining elements of the concatenation. Consideration of traffic participant type and direction of origin of the reservation-entitled traffic participants would further increase the complexity of the requirements. This is done in detail in the next chapter when it comes to the concrete specification of driving requirements.

5.5 Interim Conclusion

In this chapter, the behavioral requirements resulting from a route-based concatenation of behavior spaces were derived. It was shown that the behavioral requirements valid for a lane-accurate route depend on the transitions between the concatenated behavior spaces. The transitions define the applicable behavioral demands of the behavioral spaces, so that different behavioral requirements may apply to the same behavior space for different transitions. The concatenation results in further behavioral demands or behavioral requirements for the consideration of a trip of AVs, which are mainly determined by kinematic dependencies and interactions between the concatenated behavioral demands.

The following intermediate results are concretely available at the end of this chapter:

- Rules for concatenating behavior spaces into a lane-accurate route
- Possible transitions between concatenated behavior spaces
- Possible behavioral requirements of concatenated behavioral spaces based on transitions between behavioral spaces and concatenated behavioral demands
- Method for deriving route-based behavioral requirements based on BSSD

With the obtained results, it is possible to identify the behavioral requirements of lane-accurate routes. This addresses the following two research questions:

RQ 2: How to design a representation of behavioral demands as a basis for deriving route-based driving requirements?
RQ 3: How are driving requirements derived based on the behavioral demands of a scenery?

In this chapter, again, RQ 2 is only partially answered. However, the current state of work shows that the developed map representation of behavioral demands is suitable for a route-based derivation of behavioral requirements. Thus, RQ 3 is also partially answered. In order to answer the questions completely, the next chapter must show whether the higher-level driving requirements can be specified based on the behavioral requirements.

6 Matching of Route-Based Driving Requirements and Capabilities[162]

In this chapter, route-based behavioral requirements are used to derive driving requirements that can be matched with driving capabilities. For this purpose, the approach of matching driving requirements and capabilities is first considered. Based on the resulting findings, the route-based driving requirements and associated driving capabilities are derived. Finally, matching criteria are developed as a basis for identifying capability-based routes in the next chapter.

6.1 Concept of Matching

The main goal of this work is to identify routes that can be accomplished based on the driving capabilities of AVs. Consequently, the driving requirements of the route must not exceed the driving capabilities of the vehicles. In order to identify an exceeding of driving capabilities it is necessary that they can be matched with the driving requirements of the route. This matching determines whether the route can be mastered by an AV or not. In order to match, the requirements and capabilities must be compatible with each other. This means that for each driving requirement there must also be a corresponding driving capability. It is important that the driving capabilities of the AVs can be proven. According to the state of the art, the proof of driving functions is typically achieved with the help of tests. Therefore, it is assumed that test certificates exist for driving capabilities that have been tested and thus proven. If a driving capability has been successfully tested and proven, a test certificate exists for this driving capability. Whether the driving capabilities really meet the driving requirements is determined by the matching process. This process requires matching criteria that determine a match based on appropriate metrics. The following argumentation results from these considerations:

Let DR_i be the set of necessary driving requirements in order to drive in a concatenated behavior space E_i[163]. Furthermore, let $\bigcup_{m=1}^{n_{\mathrm{DC}}} DC_m$ be the superset of $n_{\mathrm{DC}} \in \mathbb{N}$ sets of driving capabilities of an AV that is proven with a corresponding superset of test certificate sets $\bigcup_{m=1}^{n_{\mathrm{DC}}} TC_m$ and compatible with DR_i. Then an AV shall only be allowed to drive in E_i if at least one set of proven driving capabilities DC_m matches the set of driving requirements DR_i. A match of DR_i and DC_m is determined with a matching process based on matching criteria.

Therefore, for matching to be possible, the following conditions must be met:

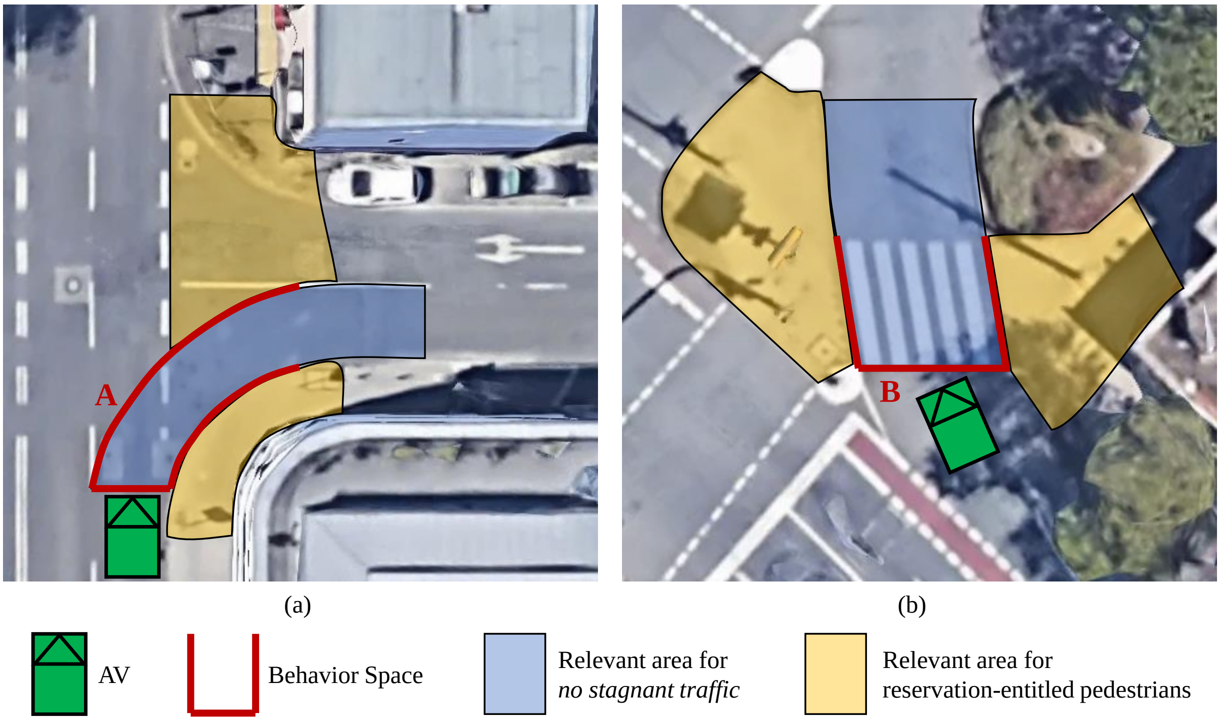
---

[162] Parts of this chapter have already been published in Lippert, M.; Winner, H.: Capability-Based Routes for Safe Automated Vehicles (2023).

[163] Cf. Subsection 5.3.3.

- For each set of driving requirements DR_i of a concatenated behavior space E_i, there is at least one compatible set of driving capabilities DC_m.
- The set of driving capabilities DC_m must be provable using tests in order to provide an associated set of test certificates TC_m for AVs.
- There are matching criteria for identifying matches between driving requirements of DR_i and driving capabilities of DC_m.

Examples are given below to illustrate the problems that can arise in defining driving requirements and driving capabilities under the above conditions. First, two different sceneries are considered, which have almost identical behavior spaces based on the BSSD. Consequently, from the behavioral requirements point of view, the two behavioral spaces should have the same driving requirements. Figure 6-1 shows two different scenery sections, each with a considered behavior space shown in red. In both figures, a fictitious AV is shown as an example that is supposed to enter the considered behavior spaces.



(a) (b)

Figure 6-1: Different scenery sections with almost identical behavior spaces.
Imagery and map data ©2022 Google/AeroWest.

Figure 6-1 a shows the behavior space for a right turn from a priority road. In contrast, Figure 6-1 b shows a separate turn lane with a crosswalk. In both cases, a speed limit of 50 km/h applies. The longitudinal entry into the behavior spaces is *conditional* with the value *no stagnant traffic*. The behavior space as well as a part of the following behavior space (entire area marked in blue) must be free of stagnant traffic to enter, otherwise longer stopping times cannot be avoided. The lateral boundaries are of the type *prohibited*, so that the behavior space must not be left laterally. For the *reservation* it is valid in both sceneries that only road users of the type *pedestrian* must be given priority. The areas from which the pedestrians entitled to reservation potentially come are shown in orange. The only difference between the two behavior spaces considered is the overtaking permission. Overtaking is allowed for the intersection area on the left, whereas overtaking is prohibited in a crosswalk. If both behavior spaces are considered as a concatenated element, the applicable behavioral requirements[164] result as shown in Table 6-1.

Table 6-1: Applicable behavioral requirements for behavior spaces A and B.

	Behavior Space	A	B
Behavioral Requirements	SR1: The AV shall not exceed the maximum permissible speed limit.	✓ 50 km/h	✓ 50 km/h
	BR0: The AV shall remain within the lateral boundaries except for route-based lateral changes of behavior spaces.	✓	✓
	BR2: The AV shall not cross the boundary if the space cannot be passed through and exited completely without extended stopping times.	✓	✓
	BR2.1: The AV shall adjust the driving speed reasonably in order not to cross the boundary in case of stagnant traffic.	✓	✓
	RR1: The AV shall not obstruct traffic participants with reservation entitlement for the space.	✓ pedestrian	✓ pedestrian
	RR1.1: The AV shall indicate in advance by adjusting the driving speed reasonably that it will give priority to traffic participants who have priority.	✓	✓
	RR2: The AV shall leave the space as soon as possible into an equally- or own-reserved space.	✓	✓
	OR1: The AV shall not overtake.	-	✓
	OR1.1: The AV shall have completed a potential overtaking maneuver prior to the entrance into the space.	-	✓

The behavioral requirements are supplemented based on the information from the behavior spaces. In this way, the concrete speed limit of 50 km/h is assigned to the requirement *SR1*. For *RR1* it results that the reservation-authorized road users are of type *pedestrian*. The link to potential pedestrian origin areas is not explicitly listed here, but is still present as described in Chapter 4. Figure 6-1 shows that in both scenery sections the pedestrians with priority come from areas to the right and left of the behavior spaces under consideration. Thus, without further consideration of geometry, the requirements of the two behavior spaces would be identical except for the overtaking requirement. For further considerations, behavioral requirements of the *boundary* attribute (BR0, BR2, BR2.1) and *reservation* attribute (RR1, RR1.1) are considered. The additional assumption is made that a driving capability is assigned to each individual requirement. This means that a

---

[164] Cf. Chapter 5.

driving capability exists for each requirement, which can be proven based on tests.

Since the behavioral requirements of the *boundary* and *reservation* attributes are identical, the following hypothesis is stated:

Hypothesis: *If an AV provably has the capabilities to drive in behavior space A, then it will also be capable of driving in behavior space B.*

This hypothesis is examined in the following. For behavior space A, complementary Driving Capabilitys (DCs) are formulated based on the behavioral requirements in Table 6-1:

- DC1: The AV is capable of remaining laterally within the behavior space.
- DC2: The AV is capable of not crossing the boundary of the behavior space when traffic is stagnant.
- DC2.1: The AV is capable of adjusting the driving speed reasonably to avoid crossing the boundary of the behavior space when traffic is stagnant.
- DC3: The AV is capable of avoiding obstructions of pedestrians with reservation entitlement for the behavior space.
- DC3.1: The AV is capable of indicating in advance by adjusting the driving speed reasonably that it will give priority to pedestrians who have priority.

These capabilities must be proven in appropriate tests. Intuitively, the proof could be provided by testing the AV in the real scenery of behavior space A or in an identical representation of it. What the tests specifically look like is not part of this work. Rather, it is interesting to investigate whether the proven capabilities in such a test are valid for behavior space B as well. For this purpose it is necessary to consider the different layers of the DDT. In order to remain as general as possible and independent of different system architectures of AVs, the considerations are aligned with the Sense-Plan-Act paradigm.

Considerations for DC1:

The capability of an AV to stay within the lateral boundaries of the behavior space is challenged by several scenery-specific factors. First, it is necessary for an AV to perceive the behavior space and, in particular, the lateral boundaries. If a highly accurate map is used for the driving task, this task is fairly trivial. Without the use of a map, however, an AV must use its own sensors to perceive the boundaries. As a result, an AV must be able to perceive different lane boundaries. Therefore, in the case of behavior space A, it would be necessary to identify the curb on the right side as the lane boundary. There is no marking on the left side, so an AV would have to independently estimate a virtual boundary. In order for the AV to plan to stay in the behavior space, it must perceive its own position. Based on its own vehicle position, the vehicle motion is usually planned with the help of a trajectory. This trajectory must be planned in such a way that the AV remains within the behavior space while following the trajectory. Deviations in both the perception of the boundaries and the vehicle position, as well as deviations in the vehicle dynamics controls, prevent the AV from driving through spaces that are arbitrarily narrow. Thus, the width of the behavior spaces has a direct impact on the capability DC1.

Considerations for DC2 and DC2.1:

The capability DC2 requires the automated vehicle to first detect the relevant area where no stagnant traffic shall be present upon entering the behavior space (blue area). In addition, the AV must have the information whether there is stagnant traffic at the time of a potential entry into the behavior space. Specifically, this means that other road users could prevent the AV from passing through the behavior space without longer stopping times. Thus, the capability DC2 is dependent on the geometric shape of the behavior space, as different geometries address different visibility zones of the AV.

In addition to DC2, the vehicle must be able to make appropriate speed adjustments in the presence of stagnant traffic to avoid crossing the boundary. Depending on visibility conditions, it may be necessary for the AV to adjust speed sooner or later. For example, in the case of occlusions, it may be necessary to reduce speed early to avoid violating the BR2 and BR2.1 requirements.

Considerations for DC3 and DC3.1:

Similar to the DC2 and DC2.1 capabilities, the driving capabilities for giving priority are dependent on specific scenery areas. Pedestrians crossing the orange areas that could be obstructed by the AV must be perceived. The AV must detect the areas to fulfill this capability and also detect pedestrians including their intentions to move.

Hypothesis Testing

Assuming the driving capabilities previously discussed would now be valid for behavior space A and proven with testing. Are these capabilities also valid for behavior space B, which has basically the same behavioral requirements?

Behavior space B differs significantly from behavior space A in the factors discussed as influencing driving capabilities. Most striking is the difference in geometry between the two behavior spaces. Behavior space A has a distinct curvature, while behavior space B is approximately straight. Moreover, A is clearly longer than B, but considerably narrower. Furthermore, the areas relevant for priority differ in their relative orientation to the behavior spaces. In addition, the lateral boundaries are also different. Figure 6-2 shows the geometric differences of the behavior spaces by superimposing both behavior spaces with their associated areas. Here, behavior space A serves as a mask for behavior space B.

The following differences potentially lead to the fact that the capabilities proven for behavior space A are not valid for B resulting in a falsification of the stated hypothesis:

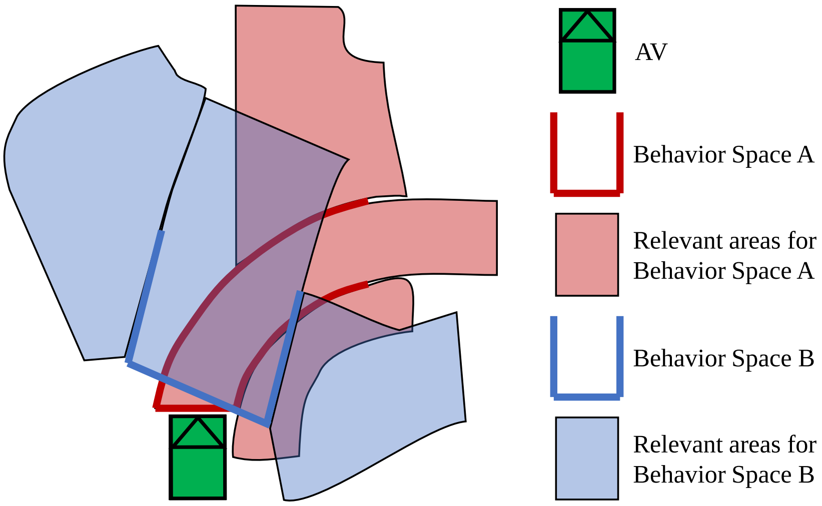


Figure 6-2: Matching behavior spaces A and B including associated relevant areas.

- With respect to capability DC1, the different widths of behavior spaces A and B are striking. Since there is a proof of the capability for the narrower behavior space A, it is reasonable to assume that the capability is therefore valid for behavior space B as well. This presumption can only be confirmed by giving clear constraints in the test certificate. It would therefore have to be proven that wider lanes are also covered by the tests. Additional difficulties may arise in the correct identification of the boundaries, as these differ between A and B.
- The areas within the behavior spaces[165] represent the areas to be monitored to identify stagnant traffic. Both direction and extent of the areas differ clearly, so it cannot be assumed that the capabilities DC2 and DC2.1 are directly transferable.
- The areas to the left and right of the behavior spaces[166] represent the areas to be monitored to identify the priority road users[167]. In particular, the areas on the left of the two behavior spaces do not have any overlap. On the right side, there is an overlap, but for the necessary range of behavior space B, it is only a small part. Thus, the test of areas for behavior space A cannot directly be used as a proof for behavior space B as well.

The differences described do not generally have to mean that a test of capabilities for behavior space A cannot also be evidence of capabilities for behavior space B. Whether the tests are also meaningful for behavior space B depends exclusively on the definition and execution of the tests. However, if the tests are exclusive to the requirements of behavior space A, then it can be assumed that the capabilities tested are not appropriate for major deviations in requirements. But what about minor to no deviations in driving requirements? To address this, two additional sceneries are considered in Figure 6-3, which are very similar to the behavior space A scenery. In both scenery sections, a right turn is considered as before. Due to the similarity of the behavioral

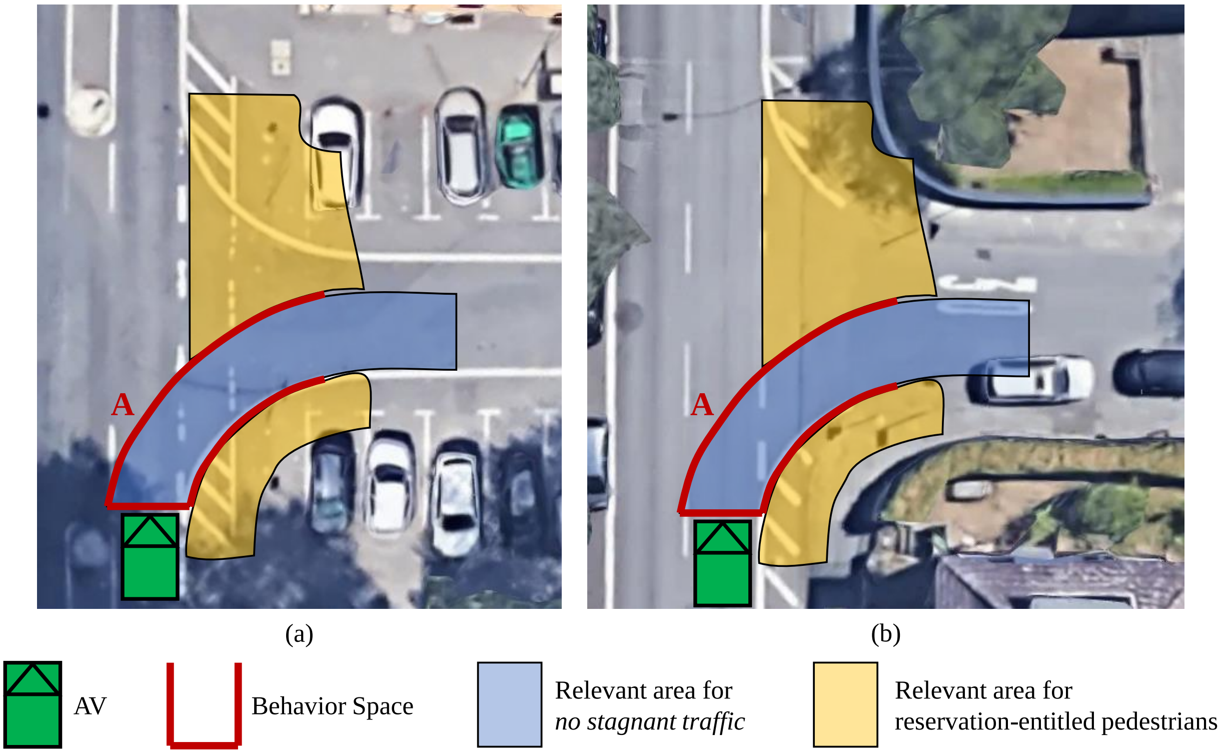
---

[165] Cf. blue areas in Figure 6-1.

[166] Cf. orange areas in Figure 6-1.

[167] Cf. DC2 and DC2.1.

spaces to behavioral space A, the behavioral requirements are not listed again. Instead, the mask of behavior space A is superimposed over the two scenery sections using the same scale. It can be seen that both new scenery sections are covered appropriately. For the behavior spaces in both scenery sections, it can be assumed that the tested and proven capabilities for behavior space A are also valid in these sceneries.


(a)

(b)

Figure 6-3: Matching of behavior space A to similar scenery sections.
Imagery and map data ©2022 Google/AeroWest.

In the examples shown, it was only estimated whether driving requirements and driving capabilities match. The considerations indicate that the geometry of the different relevant areas plays a decisive role. To ensure that a match between requirements and capabilities is not identified on the basis of a rough estimate, matching criteria must be developed. Ideally, the application of these criteria allows a profound statement about the degree of match.

In summary, the matching of driving requirements and driving capabilities must not be based on behavioral requirements alone. Therefore, in addition to the behavioral level information, the physical layer of the scenery must be included. If the scenery is not explicitly addressed, driving requirements can only be differentiated at the behavioral level. Although this is the first step to assign different requirements to different behavior spaces, it is not in the sense of a targeted requirement specification. This is shown, among others, by the examples given, which prove that despite the same behavioral requirements, different scenery-related dependencies result in different driving requirements.

The variety of possible scenery combinations, potentially ignored without the physical scenery level, leads to a high test effort for the proof of the required capabilities. The added value of the intended approach of route-based requirements and capabilities would be lost. Without more concrete specification of behavioral requirements, an AV would need to demonstrate comprehensive driving capabilities that would already be sufficient for the majority of ODD. This would not solve the problem that an AV must always and everywhere have all capabilities for a defined ODD. In contrast, it seems much more efficient to extract the features that are crucial for the driving requirements from the scenery in order to enable a targeted specification and thus also a targeted proof of the driving capabilities.

6.2 Specification of Driving Requirements

Based on the findings in the previous section, the behavioral requirements identified in Chapter 5 are investigated with respect to the physical scenery features. The goal is to identify necessary specifications for the driving requirements that form a basis for matching with driving capabilities. For this purpose, the relevant scenery properties are divided into specification categories. The specification category serves as a container for the concrete specifications of behavior spaces. Driving capabilities are defined analogously to driving requirements so that the same specification categories can be assigned. In this way, matching is possible for each behavioral requirement. Based on the specification on the requirements side, it can be determined if it is within the proven specification of the driving capability. Finally, matching criteria are needed for the specification matching process. In the following sections, the necessary specification categories for the driving requirements are derived, the driving capabilities are formulated, and the matching criteria are developed. For better clarity and presentation of the methodical procedure of this and the following sections, the aforementioned steps are performed and described on the basis of the reservation behavioral requirements. For speed, boundary and overtake behavioral requirements, this procedure is followed analogously. A detailed documentation of this procedure and the associated results is provided in Annex A. The reservation behavioral requirements are chosen because they have a high complexity compared to other behavioral requirements. Therefore, they are particularly suitable for demonstrating the procedure. In the further course of the work, the demonstration of the capability-based route approach is also performed based on reservation requirements for the same reason.

Identification of Specification Categories

The reservation behavioral requirements are considered in the following from the DDT perspective. *RR1* and *RR1.1* require that reservation-authorized traffic participants shall not be obstructed and that this shall be indicated to the traffic participants. *RR3* and *RR3.1* require the same thing in principle, with the difference that it is not about obstruction but about cooperation. In *RR4* and *RR4.1* the same demands are also present, but with respect to a hazard. Because of the similarity of these requirements, it is possible to derive and use the same specification categories. The reservation requirement *RR2* requires that externally-reserved behavior spaces are exited as soon as possible when used. Since this requirement arises as a complement to *RR1* and *RR1.1*, the same specification categories are used as well. The analysis in the following refers to a considered behavior space with aforementioned requirements.

Probably the most obvious specification category is the type of traffic participant entitled to reservation. This information already exists explicitly within the behavior space in the BSSD, but must still be included in the specification. Otherwise, it would not be explicitly specified that a corresponding driving capability must meet this specification. Different road user types require different capabilities of an AV, as they must not simply be recognized as a dynamic object, but must necessarily be classified according to the reservation as well. Reservation requirements necessitate this classification, as it determines which traffic participants are entitled to a reservation.

The speed limit of the traffic participants entitled to reservation is also relevant for the specification of the requirements. The capability to perceive these traffic participants must be tested and demonstrated based on different speeds of movement. It may well make a difference whether traffic participants are potentially approaching at 30 km/h or 50 km/h. In this case, a different behavior is demanded of the complete automation chain, which must be explicitly demonstrated. For this purpose, it is additionally necessary to include the speed limit of the AV before entering the behavior space under consideration. Different relative speeds between AV and the other traffic participants require explicit proof and therefore explicit specification for the same reason.

The perception of traffic participants entitled to reservation is only successful if they are also sensed in the relevant areas of the scenery. For this purpose, the direction of origin of the traffic participants entitled to reservation is explicitly stored in the BSSD. Based on the BSSD map, the absolute positions of the linked areas are thus available. However, only the direction of origin is indicated by the BSSD and not the entire area of origin potentially to be monitored. It is necessary for the specification to define the position of these relevant origin areas. Thereby, the information about the road course from the respective direction of origin should not be lost, so that potential paths along which reservation-authorized traffic participants move can be represented.

According to the above mentioned requirements an AV shall not travel through the considered behavior space if any other traffic participant with reservation-entitlement is present. This applies both to traffic participants who are already in the behavior space under consideration and to traffic participants who want to enter the space. In addition, if an AV is in the space itself, it must leave the space as soon as possible. Differences in the fulfillment of these requirements arise from the geometry of the considered behavior space. Different lengths of the behavior space mean different distances that the AV must travel through. But also different curved shapes of the behavior space possibly influence the driving behavior of the AV. Therefore, it is necessary that these geometric properties are part of the requirements specification.

In addition to the geometry of the behavior space under consideration, the geometry of the preceding behavior space(s) is also relevant. Depending on which curvature is present in the previously concatenated behavior spaces, for example, the AV will approach the considered behavior space with a different orientation. Depending on the orientation, the relevant perceptual areas for the relevant traffic participants differ. However, since based on the requirement specification it is not yet specified how exactly the vehicle aligns in the behavior spaces, the orientation of the AV cannot be part of the requirement specification. Rather, the orientation of the behavior spaces must be considered. The design and proof of the specific driving capabilities can thus be unrestricted, so that the actual orientation of the AV in the behavior space is defined in the development process.

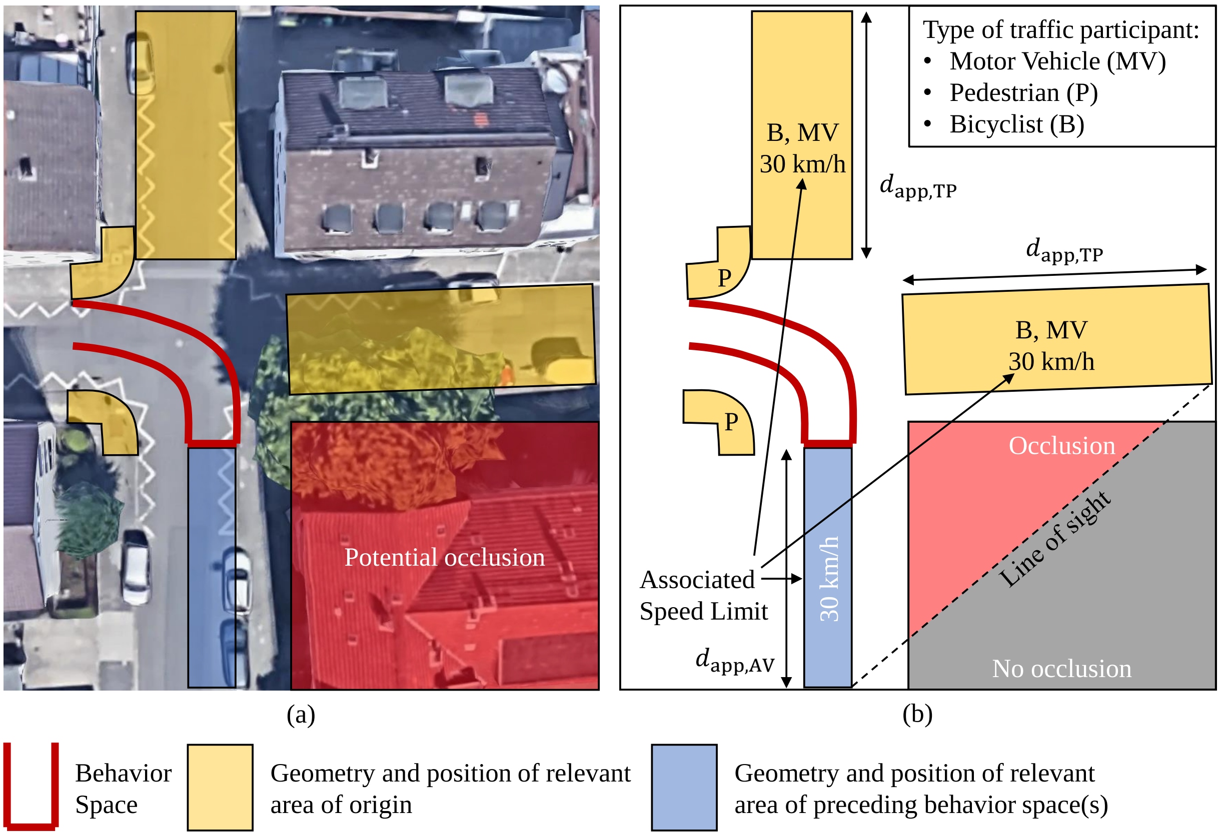
Finally, if the behavior space under consideration is highly curved, as is the case with behavior spaces for turning, occlusion may occur. Depending on the position of potentially present planted areas, walls or buildings, the area to be monitored might not be completely visible or only visible at a late stage. If such occlusion is present, the driving behavior must be adjusted so that the reservation requirements are not violated. For example, depending on the type of occlusion, it may be necessary for an AV to slowly move into the considered behavior space so that the relevant areas can be observed. These cases have to be specified explicitly, since an extra proof has to be provided accordingly.

Overall, the following specification categories result for all reservation requirements *RR1*, *RR1.1*, *RR2*, *RR3*, *RR3.1*, *RR4* and *RR4.1*:

- Type of relevant traffic participant
- Speed limit of relevant traffic participant
- Geometry and position of relevant area of origin
- Geometry and position of considered behavior space
- Geometry and position of relevant area of preceding behavior space(s)
- Speed limit of relevant preceding behavior space(s)
- Geometry and position of relevant area of occlusion

Application of Specification Categories

Figure 6-4 shows how the specification categories can be applied to specify reservation requirements for externally-reserved behavior spaces. Figure 6-4 a shows the aerial view of the X-intersection in a 30 km/h speed zone shown earlier. In Germany, the right-of-way rule ”right before left” applies at such intersections. This means that traffic participants coming from the right from the perspective of a vehicle entering the intersection have priority. Left-turners must generally give priority to oncoming traffic. When turning, there is the additional condition that pedestrians crossing the target road must also be given priority. In this example, left-turning is considered, represented by the behavior space marked in red. In addition, other information is shown that addresses the specification categories. In Figure 6-4 b, the concrete specifications of the specification categories are shown in isolation. The considered behavior space has the following specifications with respect to the behavioral requirements *RR1* and *RR1.1*.



(a) (b)

Figure 6-4: Reservation requirement specification example for externally-reserved behavior spaces. Imagery and map data ©2022 Google/AeroWest.

The *geometry and position of considered behavior space* is directly mapped (red) and can be used just as it is. Three different *types of traffic participants* must be considered for traveling in the considered behavior space. Motor vehicles and bicyclists from the adjacent arms of the intersection and pedestrians from the sidewalks must be considered. The priority motor vehicles and bicyclists all have their own *speed limit* of 30 km/h. Pedestrians generally do not have a *speed limit*, so it is not indicated accordingly. The orange highlighted areas represent the origin areas of the priority traffic participants. Figure 6-4 b shows the corresponding assignment of traffic participants, associated speed limits, and area of origin. The blue area marks the *preceding behavior space*, which limits the approach orientation of an AV to the considered behavior space. Also, the information of the *speed limits* is provided so that the maximum possible speed during the approach is specified. The other specification categories are considered in more detail below.

Geometry and position of relevant area of preceding behavior space(s)

The area highlighted in blue shows the geometry and position of the relevant area of preceding behavior space. Since there can be many preceding behavior spaces based on a route, a termination criterion must be defined to find the relevant area within the preceding behavior spaces. This means that the preceding behavior space(s) are only used for specification up to a certain distance starting from the considered behavior space and moving backwards. Without this termination criterion, it would be theoretically necessary to specify all preceding behavior spaces, since no information about the relevance is available. The preceding behavior space(s) are relevant if the DDT is performed in them with respect to the specified requirements. Thus, in this case, it is necessary to consider at what distance from the considered behavior space an AV potentially performs actions to cope with the required DDT at the earliest time. This requires a worst-case consideration for approaching the behavior space under consideration. In the considered reservation case, the AV may not cross the boundary of the behavioral space if reservation-entitled traffic participants are present. Thus, in principle, there are two ways in which an AV can approach the behavioral space. Either it decelerates to a standstill at the boundary or it approaches at a very low speed, so that ideally it does not have to stop. Since it is generally not possible to anticipate very far ahead in urban traffic, a very low deceleration to a standstill at the entry boundary of the considered behavior space is assumed. If a minimum deceleration is selected, the required stopping distance also leaves open the possibility of creeping up. The applicable speed limit is used as the initial speed of the AV, since this represents the maximum driving speed of the AV. The termination criterion for the relevant area of the preceding behavior space(s) is consequently calculated as the AV's approaching distance for stopping $d_{\mathrm{app,AV}}$ based on a minimum deceleration $a_{\mathrm{dec,min}}$ and the applicable speed limit $v_{\mathrm{lim,AV}}$ for the AV:

$$d_{\mathrm{app,AV}} = \frac{v_{\mathrm{lim,AV}}^2}{2\, a_{\mathrm{dec,min}}} \tag{6-1}$$

The approaching distance for stopping is shown in Figure 6-4 b.

Geometry and position of relevant area of occlusion

On the aerial view a potential occlusion is drawn in red. There is a building in this area, which could obscure an AV's view of one of the relevant areas previously identified. To identify if there is indeed occlusion, a line of sight is considered. In Figure 6-4 b, this line of sight is drawn. It runs from the outer, front corner of the relevant area of the preceding behavior space to the outer corner of the relevant area of origin. In general, the line of sight must be placed in such a way that the lateral extreme points of the areas are tangent to each other without intersecting the areas (even at other locations). The height of possible visual obstructions must be taken into account. Low fences or bridges are not necessarily a restriction for the line of sight. This ensures that the areas of occlusion relevant to the specification are covered. The result is colored in red in Figure 6-4 b. Since no occlusion is expected on the left side due to geometry conditions, this line of sight is not shown in the figure.

Geometry and position of relevant area of origin

Similar to the preceding behavior space(s), a termination criterion is also necessary for these areas so that the length of the areas can be specified. For identification, the sequence of the DDT must be considered. The AV requires the conservatively estimated approaching distance $d_{\mathrm{app,AV}}$ to stop at the boundary of the considered behavior space. Before the AV initiates the deceleration, it must have already perceived the reservation-authorized traffic participants in the orange areas. Therefore, it is assumed that the relevant orange area must be long enough that the relevant associated traffic participants are just entering the area at the beginning of the AV's deceleration. The traffic participants are relevant if they are entering the intersection area at the time of the completed stop of the AV and are therefore at the end of the orange area. This ensures that the AV can potentially grant priority in any case. The termination criterion for the orange areas is thus given by the approaching distance of the traffic participants $d_{\mathrm{app,TP}}$ covered during the AV's stopping maneuver. To calculate $d_{\mathrm{app,TP}}$, the duration of the approaching process $t_{\mathrm{app,AV}}$ of the AV is needed. The way travelled by the priority traffic participant during this time is then equal to the required quantity. $t_{\mathrm{app,AV}}$ is calculated either using $d_{\mathrm{app,AV}}$ or directly using the maximum allowed speed $v_{\mathrm{lim,AV}}$ of the AV and the minimum deceleration $a_{\mathrm{dec,min}}$:

$$t_{\mathrm{app,AV}} = \sqrt{\frac{2\, d_{\mathrm{app,AV}}}{a_{\mathrm{dec,min}}}} = \frac{v_{\mathrm{lim,AV}}}{a_{\mathrm{dec,min}}} \tag{6-2}$$

Finally, based on the speed limit $v_{\mathrm{lim,TP}}$ for the traffic participants under consideration, the approaching distance $d_{\mathrm{app,TP}}$ specifies the length of the orange areas as shown in Figure 6-4 b. In the rare case of different speed limits of different traffic participants, the maximum speed limit is selected to cover the relevant area in any case. $d_{\mathrm{app,TP}}$ results to:

$$d_{\mathrm{app,TP}} = v_{\mathrm{lim,TP}}\, t_{\mathrm{app,AV}} = \frac{v_{\mathrm{lim,AV}}\, v_{\mathrm{lim,TP}}}{a_{\mathrm{dec,min}}} \tag{6-3}$$

For the areas from which pedestrians are approaching, such as from a sidewalk as shown in Figure 6-4 a, a different method must be used to define the geometry. The main difference is that in such areas there is undirected traffic. This means that traffic participants in these areas do not have a clear preferred direction. In addition, there is no speed limit for pedestrians on the basis of which distances can be calculated. One possibility would be to assume a worst case maximum speed of pedestrians and then use this speed in all directions in the linked areas for dimensioning the areas. Since pedestrians are so-called vulnerable road users, their recognition is essential for an AV from a safety point of view. For this reason, the requirements regarding pedestrian priority play a minor role with respect to a route-specific analysis, since pedestrians should be recognized everywhere[168]. Therefore, the calculation of the specific areas will not be further elaborated here.

6.3 Specification of Driving Capabilities

What do the capabilities look like to enable matching? In Section 6.1, simple driving capabilities were given as an example, which are tailored exactly to the driving requirements. In this context,

---

[168] Except on German autobahn, which is strictly forbidden for pedestrians and also difficult to access.

a capability always meets exactly one requirement. The following generic example illustrates the relationship between requirement and capability:

- Driving requirement: *The AV shall/ shall not perform a certain action under certain conditions.*
- Driving capability: *The AV is capable of performing/ not performing a certain action under certain conditions.*

The advantage of this very direct matching is that the capabilities fit the requirements in every case. There is no need for reasoning that assigns different capabilities to requirements. This leads to the fact that the driving capabilities can be addressed by different vehicle-specific solutions. However, the proof of the capabilities must then be vehicle specific. In this way, driving capabilities are defined universally and uniformly without excluding specific technical solutions or developments. For this reason, this direct assignment appears not only intuitive but also practicable with regard to a uniform specification of driving capabilities.

The alternative to this approach is to further decompose the driving capabilities. It is possible to break down the driving requirements to subsets of the DDT. The result is a set of capabilities that contribute to the main capability being met at the behavioral level. Various approaches are suitable for decomposing the capabilities, as partly considered previously in Chapter 2. Basically, at the beginning of the decomposition, the decision has to be made how fine granular to decompose. In order to remain as abstract and generic as possible, the Sense-Plan-Act paradigm is suitable, since it only provides for a decomposition of the DDT on three layers. For a more detailed decomposition, which allows a deeper analysis of the capabilities, the six layers of functional decomposition according to Amersbach and Winner[169,170], for example, are suitable. Another possibility is to use skill graphs[171], which have already been introduced in Subsection 2.3.2[172]. In total, there are six skills that perform all subtasks of the DDT: *behavioral skill*, *planning skill*, *action skill*, *perception skill*, *data acquisition skill*, and *actuation skill*. The example modeling of the skill graphs is demonstrated using the behavioral skill *lane keeping*. This example is shown in Figure 6-5 and is analyzed below with respect to a suitability for the specification of driving capabilities in the present work. Due to the analogy of this skill to the behavioral requirement *BR0*, which also requires lane keeping, this example is especially suitable for the analysis.

The connecting arrows between each skill are labeled as *depends on* (solid line) and *may depend on* (dashed line) read in the direction indicated. The behavioral skill *lane keeping* thus depends on a total of 12 other skills. It is remarkable that the different skills also show up to three dependencies among each other. This shows a first, fundamental problem for the application in the matching

---

[169] Amersbach, C.; Winner, H.: Functional Decomposition: Reducing the Approval Effort for HAD (2017).

[170] Amersbach, C.; Winner, H.: Functional decomposition - Overcoming the parameter space explosion (2019).

[171] In this context, the terms *skill* and *capability* are understood to be synonymous.

[172] Jatzkowski, I. et al.: Automatic Construction of Skill Graphs for Online Monitoring (2021).

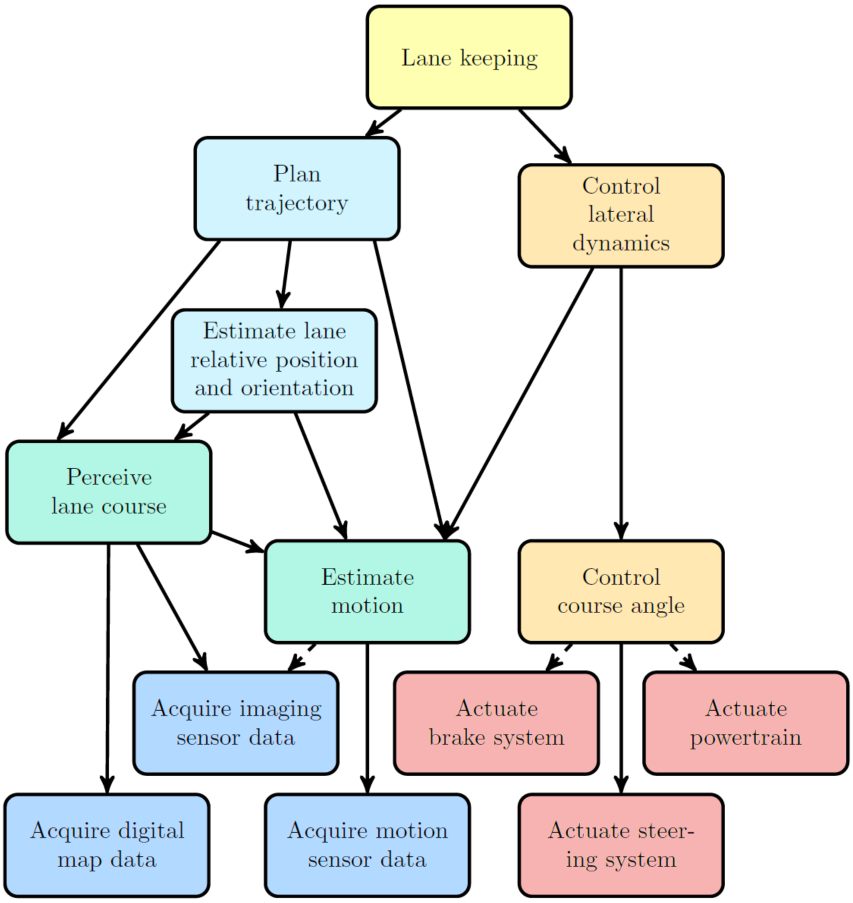


Figure 6-5: Example skill graph for the behavioral skill *lane keeping*.[173] Colour key: behavioral skill (yellow), planning skill (light blue), action skill (orange), perception skill (green), data acquisition skill (dark blue) and actuation skill (red). ©2021 IEEE.

process: Complexity. The dependencies are so diverse that verification of the individual skills becomes difficult. On the one hand, there is a need for many individual proofs due to the number of skills, and on the other hand, it is questionable to what extent the dependencies influence the individual proofs. Moreover, it is unclear how lane keeping requirements propagate within the graph. No approach is known so far that performs such an analysis. Thus, to partition the driving requirements specified in the present work into more finely granular driving capabilities, a far-reaching analysis would be required.

In addition, there is another problem that emerges with respect to the intended matching: arbitrariness. Considered for this purpose is the perception skill *perceive lane course*, which is directly dependent on the data acquisition skills *acquire digital map data* and *acquire imaging sensor data*. With these dependencies, an AV is already said to have certain capabilities. It is not clear, for example, whether an AV has only one dependency because it only requires one skill at the data acquisition layer, or whether the AV has additional skills that are not mapped. For the purpose of online monitoring of driving functions, this approach is compatible since the capabilities of the AV are already known. For the purpose of matching route-based requirements

---

[173] Directly taken from Jatzkowski, I. et al.: Automatic Construction of Skill Graphs for Online Monitoring (2021).

with capabilities, the resulting arbitrariness in the choice of individual sub-capabilities leads to problems. Specifically, this means that the partitioning of capabilities into sub-capabilities can only be done assuming a given system architecture of AVs. However, since the capabilities are intended to be universally verifiable, no concrete system architecture may yet be addressed in the definition.

The disadvantages of a decomposition of driving capabilities shown by the example of skill graphs are also present for the other approaches mentioned, such as sense-plan-act or also functional decomposition. The reason for this is that the addressed core problems of increasing complexity due to manifold dependencies and arbitrariness in the choice of partial capabilities also apply to these approaches. A solution to these problems is not known to the author of this work. However, if these problems are mitigated or even eliminated by appropriate approaches, capability decomposition would be another option for the matching process.

Due to the difficulties pointed out for the decomposition of driving capabilities, the method of driving capabilities analogous to driving requirements presented before is chosen in the present work. This is done by reformulating the requirements into capabilities as shown in Section 6.1 and at the beginning of this section. The specification categories defined in Section 6.2 are directly adopted for the generated capabilities. This offers the great advantage that it is already clear for the comparison between requirements and capabilities what exactly needs to be compared. With the help of this approach, the specification categories can be used directly for this purpose.

In order to ensure that the comparison between driving requirements and driving capabilities contributes to a statement about the drivability of the behavior spaces or the route, matching criteria must be defined that are as clear as possible. For this purpose, the aforementioned considered reservation requirements are chosen, which have a high potential for route-specific differences. Route planning based on requirements or capabilities that differ little would miss the purpose of demonstrating the intended approach. If all requirements were equal, capability-based routes would not differ from conventional routes. Thus, the reservation requirements *RR1* and *RR1.1* are selected. Reservation areas with respect to externally-reserved behavior spaces exhibit a wide variety due to many different combinations of scenery elements. For these requirements, the analogous Reservation Capabilitys (RCs) are formulated and the corresponding specification categories are assigned:

> **RC1:** The AV is capable of avoiding obstructions of traffic participants with reservation entitlement for the behavior space.
>
> **RC1.1:** The AV is capable of indicating in advance by adjusting the driving speed reasonably that it will give priority to traffic participants who have priority.

Specification categories:

- Type of traffic participant
- Speed limit of relevant traffic participant
- Geometry and position of considered behavior space
- Geometry and position of relevant area of origin
- Geometry and position of relevant area of preceding behavior space(s)
- Speed limit of relevant preceding behavior space(s)
- Geometry and position of relevant area of occlusion

In the next section, matching criteria are derived based on these driving capabilities and the associated driving requirements.

6.4 Matching Criteria

In this section, the matching criteria for driving requirements and driving capabilities are derived with respect to the reservation specifications. The specification criteria serve as a basis. This section provides the foundation for the identification of capability-based routes and its demonstration within this work.

For the matching between the driving requirements *RR1* and *RR1.1* and the driving capabilities *RC1* and *RC1.1*, each specification category is considered individually. To ensure that the capabilities meet the requirements, the matching criteria of all specification types must be met. To illustrate the reasoning, the already familiar X-intersection is considered again in Figure 6-6. The *geometry and position of considered behavior space* as well as the *geometry and position of relevant area of occlusion* will be neglected in the following. The remaining specification categories are sufficient for an evaluation of the overall approach in a first implementation, since sufficient variations are to be expected. Additionally, as noted in Section 6.2, areas reserved by pedestrians are not considered. The focus of the matching criteria is placed on areas of origin for motor vehicles, bicyclists and rail vehicles.

The specification categories of the reservation requirements have dependencies that must be considered in the nomenclature of the matching criteria. The following variables are introduced and partially shown in Figure 6-6 a:

- For each externally-reserved behavior space E_i, there exist $n_{\text{orig},i} \in \mathbb{N}$ areas of origin $(A_{\text{orig},i,k})_{k=1,2,\dots,n_{\text{orig}}}$ (orange areas).
- Each area of origin $A_{\text{orig},i,k}$ is associated with a set of traffic participant types $P_{i,k}$.

- For the set of traffic participant types $P_{i,k}$ assigned to an area of origin $A_{\mathrm{orig},i,k}$, there is a maximum speed limit $v_{\mathrm{lim,orig},i,k}$ (speed limits of road user types within an area rarely differ).

- The relevant speed limit $v_{\mathrm{lim,pre},i}$ of the AV for approaching the considered behavior space E_i is assigned to the relevant area of preceding behavior space(s) $A_{\mathrm{pre},i}$ (blue area).

Type of traffic participant

The matching criterion for the type of traffic participant is based on a nominal scale. This criterion is satisfied only if a successfully proven set of traffic participant types P_{proof} related to the associated proven area of origin matches the required set of traffic participant types $P_{i,k}$. The following matching criterion results:

$$P_{\mathrm{proof}} = P_{i,k} \tag{6-4}$$

Possible traffic participant types are *motor vehicle*, *pedestrian*, *bicyclist*, and *rail vehicle*. Therefore, the following closed set is defined for the road user types:

$$P \in \{\mathrm{motor\,vehicle}, \mathrm{pedestrian}, \mathrm{bicyclist}, \mathrm{rail\,vehicle}\} \tag{6-5}$$

Speed limit of relevant traffic participant

For the speed limit of relevant traffic participant types, the maximum speed limit within the set of traffic participant types $P_{i,k}$ is chosen. The following assumption is made: If an AV has a successful proof of granting priority to a traffic participant coming from $A_{\mathrm{orig},i,k}$ with a speed limit $v_{\mathrm{lim,orig,proof}}$, then it is able to grant priority even with equal or lower speed limits $v_{\mathrm{lim,orig},i,k}$ of traffic participants. The following matching criterion results:

$$v_{\mathrm{lim,orig,proof}} \geq v_{\mathrm{lim,orig},i,k} \tag{6-6}$$

Speed limit of relevant preceding behavior space(s)

For the speed limit within the relevant area of preceding behavior space(s) $A_{\mathrm{pre},i}$, the maximum speed limit $v_{\mathrm{lim,pre},i}$ among these behavior space(s) is chosen conservatively. The following assumption is made: If an AV has a successful proof of the required capabilities with a speed limit $v_{\mathrm{lim,pre,proof}}$ for approaching, then the proof is valid even for equal or lower speed limits $v_{\mathrm{lim,pre},i}$. The following matching criterion results:

$$v_{\mathrm{lim,pre,proof}} \geq v_{\mathrm{lim,pre},i} \tag{6-7}$$

Geometry and position of relevant area of preceding behavior space(s) and relevant area of origin

The matching criteria for the geometries and positions of the different areas are considered together. Basically, the relevant areas of origin must always be considered relative to the relevant area of preceding behavior space(s). This is because an AV approaches the considered behavior space within the area of preceding behavior space(s) and meanwhile already has to execute the DDT to grant priority. Accordingly, the relative positions of the relevant areas of origins to the AV's approach are crucial. As mentioned above, one way of matching successfully proven and required combinations of the relevant areas is to superimpose the areas based on an equal reference system. Thus, as shown earlier in Section 6.1 in Figure 6-2, an overlap of the matched areas can be identified. The same principle of this matching can be applied using a geometric parameterization of the relevant areas. The advantage here is a simpler and more efficient identification of the geometries of the areas as well as the matching itself. Therefore, with regard to the application of the matching criteria, a geometric parameterization of the relevant areas is performed.

For this purpose, the following assumption is made: *The relevant road areas can be approximated by rectangles.*

Intersections are scenery components that predominantly contribute to externally-reserved behavior spaces. In urban areas, intersections and junctions are designed so that the associated road arms are straight with sufficient distance to the intersection. This must be taken into account during the design and construction of roads by ensuring that all intersection accesses (in the sense of sufficient distance) are identifiable in good time[174]. The extensive implementation of this layout principle can be easily confirmed by looking at suitable aerial images, such as those from Google Earth[175]. Additionally, it is noticeable that the lane or road widths do not change significantly in the areas around the intersections. Based on these findings, the assumption made is retained. However, it must be assumed that there are exceptions that are not correctly represented due to this assumption. Any exceptions that occur within the application will be discussed in the evaluation.

With this assumption, the following simplifications result:

- The alignment of the relevant areas is determined by longitudinal and lateral offsets and a constant angle relative to each other.
- The geometry of the relevant areas need only be specified by a constant width. The length is no longer needed, since if the alignment - and thus the course - of the area is known, the length along this course can be chosen according to the associated speed limits for a proof. The proof thus confirms the driving capability regardless of the length of the area.
  Note 1: In the case of a non-rectilinear course of the areas, the length is relevant because the alignment changes along the course.

---

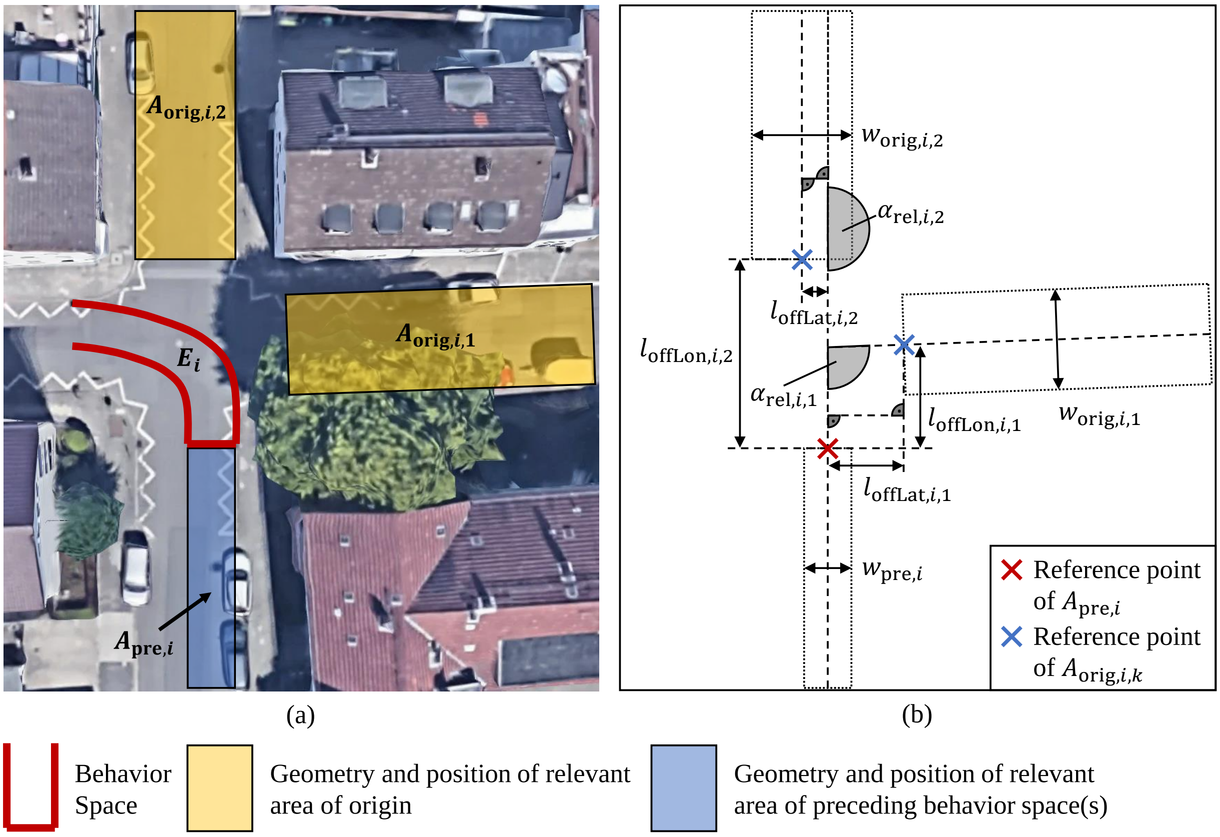
[174] FGSV: Richtlinien für die Anlage von Stadtstraßen (RASt) (2006), p. 109.

[175] Google LLC: Google Earth (2022).

> *Note 2*: This simplification does not apply to the identification of occlusion, since the complete geometry of the relevant area is required for this process.

Therefore, the relevant areas can be parameterized as shown in Figure 6-6 b. Each area is characterized by a width:

- Width $w_{\text{orig},i,k}$ of relevant area of origin $A_{\text{orig},i,k}$
- Width $w_{\text{pre},i}$ of relevant area of preceding behavior space(s) $A_{\text{pre},i}$



(a) (b)

Figure 6-6: Parameterization of relevant areas for externally-reserved behavior spaces.
Imagery and map data ©2022 Google/AeroWest.

The alignment of the areas is defined using reference points and relative angles. The reference points result from the geometric analysis of the scenery based on the BSSD map. They mark the end of the areas in the direction of the intersection. They form the crossing point between the virtual center line of an area and the transition line to the intersection area. All areas are positioned relative to the reference point of the relevant area of preceding behavior space(s) (red cross). In this way, all relevant areas are represented relative to the approach area of the AV. For this purpose, the reference points of these areas (blue cross) are defined using the longitudinal and lateral offsets $l_{\text{offLon},i,k}$ and $l_{\text{offLat},i,k}$ relative to reference point (red cross) and virtual centerline of $A_{\text{pre},i}$. The orientation of the areas is defined by a relative angle $\alpha_{\text{rel},i,k}$ describing the angle between the virtual centerlines of $A_{\text{pre},i}$ and $A_{\text{orig},i,k}$. With the help of this parameterization, a matching is made possible, for which the matching criteria are defined below.

Basically, all parameters are matched. Only if all required parameters are within the tested parameter spaces (index: proof), the capabilities are considered sufficient. The following assumptions are made:

- *Widths of the areas*: If the AV has a successful proof for a certain width, then this proof is also valid for smaller widths. This assumption results from the consideration that a smaller area to be observed or driven on within the proven range is equally covered as a subset.
- *Offsets and relative angles between the areas*: If the AV has a successful proof for a range of values of these parameters, then this proof is valid for all values within this range. Also in this case, the different parameters within the range of values are a subset of the proven values.

The following matching criteria result:

- Width of $A_{\mathrm{pre},i}$:

$$w_{\mathrm{pre,proof}} \geq w_{\mathrm{pre},i} \tag{6-8}$$

- Width of $A_{\mathrm{orig},i,k}$:

$$w_{\mathrm{orig,proof}} \geq w_{\mathrm{orig},i,k} \tag{6-9}$$

- Longitudinal and lateral offset between $A_{\mathrm{pre},i}$ and $A_{\mathrm{orig},i,k}$:

$$l_{\mathrm{offLon,proof,min}} \leq l_{\mathrm{offLon},i,k} \leq l_{\mathrm{offLon,proof,max}} \tag{6-10}$$

$$l_{\mathrm{offLat,proof,min}} \leq l_{\mathrm{offLat},i,k} \leq l_{\mathrm{offLat,proof,max}} \tag{6-11}$$

- Relative angle between $A_{\mathrm{pre},i}$ and $A_{\mathrm{orig},i,k}$:

$$\alpha_{\mathrm{rel,proof,min}} \leq \alpha_{\mathrm{rel},i,k} \leq \alpha_{\mathrm{rel,proof,max}} \tag{6-12}$$

6.5 Interim Conclusion

In this chapter, the concept of matching driving requirements and driving capabilities was first considered. For successful matching, at least one set of driving capabilities DC_m of an AV must satisfy the driving requirements DR_i applicable to a concatenated behavior space E_i. In this context, the set of driving capabilities DC_m must be proven with the help of a set of test certificates TC_m.

Based on an example application to real scenery sections, further specification needs of the behavioral requirements from Chapter 5 were identified. Therefore, specification categories were introduced that serve to concretize the behavioral requirements into driving requirements.

The specification categories specify the driving requirements with respect to selected BSSD information and geometric aspects of the associated scenery. In this way, not only the geometry-independent behavioral demands are used for specification, but also the geometric constraints given from the scenery are included. The development of the specification categories is thereby based on the influence of the behavioral and geometric information on the DDT of an AV. However, the derived specification categories are to be understood as a suggestion and not as final. On the basis of the examples shown, it is not apparent which specifications may still be required so that the DDT is addressed as completely as possible. This creates a need for further research that must be investigated in the future. Still, these findings finally answer RQ 2 and RQ 3:

RQ 2: How to design a representation of behavioral demands as a basis for deriving route-based driving requirements?
RQ 3: How are driving requirements derived based on the behavioral demands of a scenery?

Driving capabilities are derived equivalent to driving requirements and are given the same specification categories. In this way, matching between driving requirements and driving capabilities is directly enabled. The findings also show, that matching criteria are necessary for the matching. These criteria are intended to provide an unambiguous basis for decision-making on the fulfillment or non-fulfillment of the driving requirements. Based on the specification categories, the matching criteria for the reservation requirements were derived. Some assumptions and simplifications were made to facilitate the initial implementation of the concept and to enable a demonstration of the overall approach. Using this simple method ensures that capabilities and requirements can be matched and compared. However, this simple method can be questioned as there may be alternatives that are better suited for matching. This needs to be found out in further research by developing, testing and evaluating alternatives in terms of matching. This therefore creates a need for further research in order to further develop the overall matching approach. Nevertheless, this chapter additionally answers following research question in parts:

RQ 4: How are driving capabilities to be designed so that routes within an ODD can be determined based on a match of driving capabilities and driving requirements?

The derived requirements, capabilities and matching criteria are used as a basis for identifying capability-based routes in the next chapter. The suitability of requirement and capability specification as well as matching criteria is evaluated in a subsequent application to a real road network. This will enable a final answer to RQ 4 and the remaining research questions.

7 Capability-Based Routing[176]

In this chapter, an approach for identifying capability-based routes is developed and applied based on previous findings and work results. Capability-based routes are routes with driving requirements that do not exceed the driving capabilities of the AVs. Thus, the driving requirements of the scenery potentially lead to routes that deviate from conventionally planned routes. Therefore, a novel route search must be developed that takes into account this new criterion of *capability-exceeding* of AVs. Conventional route planners do not accomplish this so far, but are still suitable as a basis for this approach. In the following, a concept for the identification of capability-based routes is developed and implemented.

7.1 Concept of Capability-Based Route Search

A route planner searches for routes based on selected optimization criteria[177]. Conventional optimization criteria are the shortest or even the fastest route. For this purpose, the road network is typically divided into edges and nodes. Nodes are equivalent to intersections or junctions and represent the connection points of edges. Edges represent the individual road segments that are connected via the nodes. For the planning of routes within traffic networks, however, this division between nodes and edges is not always appropriate. In order to consider concrete turns or lane changes and thus lane-accurate paths within the network, this division is reversed. In so-called *edge based routing*, finer granular road sections (e.g. lane sections) become nodes and pairs of adjacent road sections become edges[178]. In this way, lane-accurate route planning is enabled. Depending on the selected criterion, the edges of the road network are weighted with different costs based on a cost function. From a starting node to a destination node, there are different paths depending on the network size, alternating nodes and edges. As a result, the combination of edges with the lowest total cost represents the optimal route with respect to the selected criterion.

Depending on the chosen instantiation, the BSSD road network does not necessarily consist of a graph that is suitable for routing. For the capability-based route search, a preprocessing is necessary to transform the BSSD road network into a graph. In this process, the lateral and longitudinal connections of the individual behavior spaces are explicitly represented as edges and the behavior spaces themselves as nodes. In this conversion process, the explicit BSSD informations are lost. However, this loss of information is intentional, since the road network

---

[176] Parts of this chapter have already been published in Lippert, M.; Winner, H.: Capability-Based Routes for Safe Automated Vehicles (2023).

[177] Cf. Section 2.4.

[178] Delling, D. et al.: Engineering Route Planning Algorithms (2009), p. 127.

should be reduced to the minimum necessary information for efficient route search. With the help of a cost function the explicit BSSD information is transferred into the edge weighting. The result is a routing graph that enables explicit routing based on the weighted edges without exceeding the driving capabilities of AVs. For the identification of capability-based routes, a classical route search algorithm is needed in addition to the weighted routing graph. This searches for the route with the lowest total costs within the weighted routing graph based on a starting point and a destination point. Since the route search algorithm is state of the art, the focus in this chapter is on the generation of the weighted routing graph. This is crucial for route identification since it defines the routing cost. The route search algorithm simply sums up the costs based on the routing graph and selects the edge combination with the minimum costs. The following modules are developed to create the routing graph:

- *Capability-Based Cost* module: Calculates the edge weights of the routing graph based on the matching results.
- *Matching* module: Matches driving requirements with existing driving capabilities.
- *Requirement Generation* module: Generates the driving requirements of the concatenated behavior spaces.

7.1.1 Capability-Based Cost Module

The principle of finding an optimal route from origin to destination also applies to capability-based route search. A new optimization criterion is needed for the intended function of identifying routes that are feasible for AVs. This does not mean that the conventional criteria must be discarded. Even if a new criterion is used based on the new search function, the determined route should still be optimal with respect to conventional vehicle navigation. Accordingly, the route found should be the shortest or fastest possible despite further optimization criteria, for example. The basis of the new route planning should therefore be based on conventional route planning, so that these criteria and cost functions can be adopted. For the new criterion, however, a different or adapted cost function is required to weight the edges. In principle, there are two extreme forms of edge weighting. A weight can become minimal in the optimal case, i.e. theoretically assume a value of zero. The other extreme is an infinitely high weight assigned to edges that are maximally far from an optimum based on the evaluation of the cost function. Depending on the cost function, all other values are conceivable within these extremes. Negative costs are not allowed. From the previous findings, it is clear that the new cost function must be based on the previously presented matching of driving requirements and driving capabilities. Since the matching is performed for concatenated behavior spaces, it is suitable for *edge based routing*. The matching can either fail - driving capabilities are exceeded - or succeed - driving capabilities are not exceeded. Therefore, a cost function must be defined for the transitions between concatenated behavior spaces, following the matching concept from Section 6.1. The results of the cost function are as follows:

- If the set of driving requirements DR_i of a concatenated behavior space E_i based on the considered transition exceeds every set of driving capabilities DC_m of an AV, then it shall not be included in the AV's route.
- If the set of driving requirements DR_i of a concatenated behavior space E_i based on the considered transition does not exceed at least one set of driving capabilities DC_m of an AV, then it may be included in the AV's route.
- Precondition: a matching with the set of driving capabilities DC_m is allowed only if there is a set of test certificates TC_m for it, which proves the driving capabilities. In the following, it is assumed that only sets of driving capabilities that satisfy this precondition are used for matching. This eliminates the need to explicitly check the existence of test certificates.

Based on these requirements, the cost function to be defined must produce only two values. In the case of exceeding, the cost must be maximum so that the behavior space under consideration is excluded from the planning. In the case of a successful match, the cost must be minimal. In order to identify a successful match, the matching criteria of the specification categories of driving requirements and driving capabilities from Chapter 6 are applied. Thus, the matching cost function $c_{\text{match},i}$ for a concatenated behavior space E_i is defined as a function based on the set of driving requirements DR_i and all available, certified sets of driving capabilities $\bigcup_{m=1}^{n_{\text{DC}}} DC_m$ as follows:

$$c_{\text{match},i} = f\left(DR_i, \bigcup_{m=1}^{n_{\text{DC}}} DC_m\right) \tag{7-1}$$

The matching cost function has the following range of values according to the considerations:

$$c_{\text{match},i} = \begin{cases} 0 & \text{for not exceeding the driving capabilities} \\ \infty & \text{for exceeding the driving capabilities} \end{cases} \tag{7-2}$$

To avoid that the matching cost function $c_{\text{match},i}$ interferes with the conventional cost function $c_{\text{conv},i}$ in an undesired way, the cost functions have to be separated unambiguously. This means for the total cost function $c_{\text{tot},i}$:

- As long as driving capabilities are not exceeded, the total cost function c_{tot} is determined by the conventional cost function $c_{\text{conv},i}$.
- Once exceeding is identified, the total cost function $c_{\text{tot},i}$ is determined by the matching cost function $c_{\text{match},i}$.

Using the binary range of values of the matching cost function $c_{\text{match},i}$ (0 or ∞), these requirements can be realized via a simple addition of the cost functions. This results in the following total cost function $c_{\text{tot},i}$ for E_i:

$$c_{\text{tot},i} = c_{\text{conv},i} + c_{\text{match},i} \tag{7-3}$$

The total cost function yields the required results:

$$c_{\text{tot},i} = \begin{cases} c_{\text{conv},i} & \text{for not exceeding the driving capabilities} \\ c_{\text{match},i} = \infty & \text{for exceeding the driving capabilities} \end{cases} \tag{7-4}$$

Since the routing graph is generated and weighted in a preprocessing as described above, it is practical to remove edges with an infinite weight directly in this process. Thus, the route search algorithm does not have to visit these edges at all resulting in a more efficient calculation. This is taken into account in the implementation. For very large road networks with frequently updated data, an on-the-fly calculation of the edge weights within the iterations of the routing algorithm would also be suitable. This way, the entire road network would not always have to be preprocessed. Since the road network considered for the implementation in this work is rather small, this approach is not pursued further.

7.1.2 Matching Module

For each behavior space that is potentially to be driven in, the *matching* module must be run through. In this module, the driving requirements of the behavior spaces are matched with the certified driving capabilities using the matching criteria defined in Subsection 6.4.

Depending on the characteristics of the behavior spaces, several instances of the specification categories are possible. This case occurs as soon as a behavior space has multiple reservation elements or multiple areas of origin, as shown in Figure 6-6, for example. Independent of this ambiguity is the matching with respect to the area of preceding behavior space(s). For each externally-reserved behavior space, the width and speed limit for this area are checked accordingly[179]. All other specification categories are checked for each individual area of origin[180]. This means that the matching of multiple areas of origin must also be performed for multiple instances of the specification categories. Altogether, the set of reservation requirements $DR_{\text{reserv},i}$ consists of several subsets - reservation requirements regarding the area of preceding behavior space(s) $DR_{\text{reserv,pre},i}$ and regarding the associated areas of origin $\bigcup_{k=1}^{n_{\text{orig},i}} DR_{\text{reserv,orig},i,k}$:

$$DR_{\text{reserv},i} = DR_{\text{reserv,pre},i} \cup \left(\bigcup_{k=1}^{n_{\text{orig},i}} DR_{\text{reserv,orig},i,k} \right) \tag{7-5}$$

According to the previous chapter, $DR_{\text{reserv,pre},i}$ and $DR_{\text{reserv,orig},i,k}$ are defined as:

$$DR_{\text{reserv,pre},i} = \{v_{\text{lim,pre},i}, w_{\text{pre},i}\} \tag{7-6}$$

$$DR_{\text{reserv,orig},i,k} = \{P_{i,k}, v_{\text{lim,orig},i,k}, w_{\text{orig},i,k}, l_{\text{offLon},i,k}, l_{\text{offLat},i,k}, \alpha_{\text{rel},i,k}\} \tag{7-7}$$

---

[179] Cf. equations (6-8) and (6-7).

[180] Cf. equations (6-4), (6-6), (6-9), (6-10), (6-11) and (6-12).

Equivalently, the certified capabilities $DC_{\text{reserv},m}$ are defined as:

$$DC_{\text{reserv},m} = DC_{\text{reserv,pre},m} \cup \left(\bigcup_{k=1}^{n_{\text{orig},m}} DC_{\text{reserv,orig},l,k} \right) \tag{7-8}$$

Based on the previous chapter, $DC_{\text{reserv,pre},m}$ and $DC_{\text{reserv,orig},m,k}$ are defined for matching as:

$$DC_{\text{reserv,pre},m} = \{v_{\text{lim,pre,proof},m}, w_{\text{pre,proof},m}\} \tag{7-9}$$

$$\begin{aligned} DC_{\text{reserv,orig},m,k} = \{&P_{\text{proof},m,k}, v_{\text{lim,orig,proof},m,k}, w_{\text{orig,proof},m,k}, \\ &l_{\text{offLon,proof,min},m,k}, l_{\text{offLon,proof,max},m,k}, \\ &l_{\text{offLat,proof,min},m,k}, l_{\text{offLat,proof,max},m,k}, \\ &\alpha_{\text{rel,proof,min},m,k}, \alpha_{\text{rel,proof,max},m,k}\} \end{aligned} \tag{7-10}$$

The matching of reservation requirements and capabilities is divided into two cases. In the first case, the externally-reserved behavior space has $n_{\text{orig}} = 1$ areas of origin. In this case, a matching set of reservation capabilities $DC_{\text{reserv},m}$ that satisfies both $DR_{\text{reserv,pre},i}$ and $DR_{\text{reserv,orig},i,1}$ is sufficient. This set can contain multiple areas of origin as long as one matching subset $DC_{\text{reserv,orig},m,k}$ is available. In the second case, the externally-reserved behavior space has $n_{\text{orig}} > 1$ areas of origin. If a matching set of reservation capabilities $DC_{\text{reserv},m}$ with the same number of areas of origin is found, the matching is complete. However, it is possible that there are several sets of reservation capabilities $DC_{\text{reserv},m}$, where only one matching subset of area of origin $DC_{\text{reserv,orig},m,k}$ is identified. If the different sets in sum fulfill the required areas of origin and the area of preceding behavior space(s) is also fulfilled, then the matching is successfully completed. As long as $DR_{\text{reserv,pre},i}$ and $DC_{\text{reserv,orig},m,k}$ are treated in pairs, this form of matching is possible. For example, if a behavior space at an X-intersection requires granting priority to oncoming traffic and traffic from the right, then this requirement can be satisfied with two sets of reservation capabilities. One set contains the priority situation for oncoming traffic and one set contains the priority situation for traffic from the right. For both sets the requirements of the area of preceding behavior space(s) must be fulfilled.

Based on the previously defined sets and subsets, the driving requirements are matched with the driving capabilities. Since the matching criteria defined in Subsection 6.4 are applied directly for matching, it is not further explained here. However, before the matching criteria can be applied as described, the concrete set of driving requirements DR_i for a concatenated behavior space E_i in the BSSD road network must be identified. Since only reservation requirements are considered, $DR_i = DR_{\text{reserv},i}$ yields.

7.1.3 Requirement Generation Module

In the following, the conceptual procedure for the generation of the concrete set of driving requirements of a concatenated behavior space E_i is described. In the first step, a general preprocessing is performed to ensure that the correct behavioral information of the BSSD is used. Subsequently, the reservation requirements are derived. All process steps are based on the generic structure of the BSSD[181], so that an implementation is possible independent of the selected BSSD instantiation. However, due to the geometric dependencies of the driving requirements, an instantiation with geometry information must be selected (e.g. high-definition map formats).

Preprocessing

1. Creation of the superset DR_i.
2. Identification of the reference direction of the behavior space E_i.
3. Identification of the behavior set matching the considered routing direction (*behavior along/ against reference direction*).
4. Selection of the identified behavior set as basis for all downstream process steps for the identification of the concrete driving requirements of the behavior space E_i.

Reservation Requirements Generation For each element of *reservation demand* with reservation type *externally-reserved*:

1. Creation of the set $DR_{\mathrm{reserv},i}$ and corresponding subset $DR_{\mathrm{reserv,pre},i}$.
2. Identification of the relevant preceding behavior space(s).
3. Identification of the relevant speed limit $v_{\mathrm{lim,pre},i}$ of the preceding behavior space(s) directly from the *speed demand* element of the *speed attribute* element. Add result to $DR_{\mathrm{reserv,pre},i}$.
4. Calculation of a rectangle approximation for the area of preceding behavior space(s) $A_{\mathrm{pre},i}$.
5. Identification of the width $w_{\mathrm{pre},i}$ of the area of preceding behavior space(s) using the rectangle approximation. Add result to $DR_{\mathrm{reserv,pre},i}$.
6. Identification of the lane segments of the *reservation link* elements directly from the *reservation demand* element of the *reservation attribute* element.
7. Identification of contiguous lane segments as individual areas of origin $(A_{\mathrm{orig},i,k})_{k=1,2,\ldots,n_{\mathrm{orig}}}$.
8. Creation of one subset $DR_{\mathrm{reserv,orig},i,k}$ for each area of origin $A_{\mathrm{orig},i,k}$.
9. Identification of the set of reservation-entitled traffic participant types $P_{i,k}$ within each area of origin $A_{\mathrm{orig},i,k}$. This information is taken directly from the *reservation demand* element of the *reservation attribute* element. Add result to $DR_{\mathrm{reserv,orig},i,k}$.

---

[181] Cf. Section 4.4.

10. Identification of the maximum speed limit $v_{\mathrm{lim,orig},i,k}$ of the traffic participant types within the areas of origin. This information could be taken from another BSSD layer for the corresponding traffic participants or from map data of the selected map format. Add result to $DR_{\mathrm{reserv,orig},i,k}$.
11. Calculation of a rectangle approximation for all areas of origin $(A_{\mathrm{orig},i,k})_{k=1,2,\ldots,n_{\mathrm{orig}}}$.
12. Identification of the width $w_{\mathrm{orig},i,k}$ of all areas of origin based on the rectangle approximation. Add result to $DR_{\mathrm{reserv,orig},i,k}$.
13. Calculation of center lines and reference points of all approximated rectangles.
14. Calculation of each relative angle $\alpha_{\mathrm{rel},i,k}$ of the center lines of the areas of origin to the center line of the area of preceding behavior space(s). Add result to $DR_{\mathrm{reserv,orig},i,k}$.
15. Calculation of the longitudinal offset $l_{\mathrm{offLon},i,k}$ and lateral offset $l_{\mathrm{offLat},i,k}$ between the reference points of each area of origin and the area of preceding behavior space(s). Add result to $DR_{\mathrm{reserv,orig},i,k}$.

7.2 Implementation

The implementation of the described concept of capability-based route planning is based on the BSSD instantiation presented in Section 4.5. The high-definition map framework Lanelet2[182] was chosen as the basis. Besides providing a map format, another advantage of this framework is the availability of a comprehensive C++ software library for handling Lanelet2 map data[183]. The following software modules are used from this library as a basis for capability-based route planning:

- *lanelet2_core*: Basic module for handling Lanelet2 maps as well as all related primitives like points, linestrings, or lanelets. In addition, extensive functions for geometric calculations are provided.
- *lanelet2_io*: Module for reading and writing Lanelet2 maps.
- *lanelet2_traffic_rules*: Module for interpreting selected traffic rules in Lanelet2 maps such as passability or speed limits of lanelets based on country and road user type. This module is used in this work as input for the generation of a routing graph, since traffic passable lanelets must be known for this purpose.

---

[182] Poggenhans, F. et al.: Lanelet2: A high-definition map framework for the future of automated driving (2018).

[183] FZI Forschungszentrum Informatik: Lanelet2 GitHub repository (2018).

- *lanelet2_routing*: Module for route search within Lanelet2 maps. This module generates a routing graph based on conventional optimization criteria such as shortest or fastest path. Within the routing graph the optimal route is subsequently searched. It is possible to modify and extend the cost function as desired. To ensure that only passable lanelets are used from the point of view of traffic rules, the *lanelet2_traffic_rules* module is included in addition to the cost function to generate the routing graph. Thus, a basic function is already given, which generates routes that are correct from the traffic point of view based on the conventional optimization criteria.

For the handling of the BSSD data within the Lanelet2 framework the *BSSD data handler* is used, which was developed especially for this purpose. When reading the maps, this handler parses the BSSD data and makes it available to the software environment according to the generic BSSD structure from Section 4.4. In this way, arbitrary queries regarding all BSSD information are made possible. The modules *capability-based cost*, *matching* and *requirement generation* conceptualized in the previous section are implemented as part of the *lanelet2_routing* module. The following program sequence with required input and generated output results in the implemented software for capability-based route search:

Input: Necessary data and information for processing a route query

- File path of the BSSD map instantiated in Lanelet2 format
- List with set(s) of certified driving capabilities as described in the concept
- IDs of the behavior spaces of origin and destination with any number of intermediate destinations

Output: Result of route query in different formats

- Route as a list with sequence of behavior space IDs (only if route search is successful)
- Route as BSSD map (only if route search was successful)
- Routing graph (independent of route search result)

Program sequence: Processing of the route query based on the defined input

1. Loading the Lanelet2 part of the map using the *lanelet2_io* module
2. Loading the BSSD part of the map using the *BSSD data handler*
3. Initializing the traffic rules in the Lanelet2 part of the map to identify traffic passable lanelets of the linked behavior spaces using the *lanelet2_traffic_rules* module
4. Initializing the *capability-based cost* module as part of the *lanelet2_routing* module
5. Generation of the routing graph using the *lanelet2_routing* module including the *capability-based cost* module

- 5.1. Generation of edges in the routing graph for each passable lateral and longitudinal transition between behavior spaces (corresponds to concatenated behavior space)
- 5.2. Calculation of the costs of each edge using the *capability-based cost* module
  - 5.2.1. Calculation of conventional costs using the *lanelet2_routing* cost function
  - 5.2.2. Generation of the driving requirements using the *requirement generation* module
  - 5.2.3. Matching driving requirements and capabilities using the *matching* module
  - 5.2.4. Calculation of matching costs based on the matching results
  - 5.2.5. Calculation of total costs
- 5.3. Weighting all edges with the total costs
- 5.4. Removal of all edges with an infinitely high weight

6. Search for a route with minimum total costs using the *lanelet2_routing* search algorithm
7. Output of routing graph and route if route search is successful

8 Application and Evaluation[184]

In this chapter, the previously described concept of capability-based route search is demonstrated and evaluated using the developed implementation. For this purpose, a real road network of the city of Darmstadt in Germany is available. Before the routing graph can be generated and finally the route search can be applied, the driving requirements of this road network are first derived in isolation using the requirement generation module. Based on an analysis of the requirement specification bandwidth of the road network, different sets of driving capabilities are defined for the route search. Subsequently, the complete program sequence of the capability-based route search is run for different combinations of the capability sets and different start and destination points. The obtained results are then presented and critically discussed. In the following sections, the mentioned contents are addressed one by one.

8.1 Road Network

For the demonstration of capability-based route search based on a BSSD map, a road network specifically selected for this purpose is used. The road network covers large parts of Darmstadt's city center and includes both large, multi-lane roads and small residential streets. In doing so, the network connects specific intersections that were selected based on their different characteristics in terms of behavioral demands and geometry. These intersections therefore form the key component of the network for the following application.

The road network was first modeled in Lanelet2 map format using the open source tool JOSM[185]. For modeling, georeferenced aerial images from the land registry of Darmstadt in TrueDOP format were used. The fully rectified aerial images ensure a perpendicular view of the earth's surface. Building tilts are eliminated during the production of the images so that almost every area of the ground is visible. A ground sampling distance of $8\,\mathrm{cm}$ ensures high accuracy for analysis and modeling of the road network in this work. Accordingly, each pixel represents $64\,\mathrm{cm}^2$ $(8 \cdot 8\,\mathrm{cm}^2)$ of the ground, resulting in a sharp image. In the modeling process, the selected intersections were modeled in high detail so that high quality data is available to the implementation of capability-based route search at the crucial locations. This also provides a more sound basis for the discussion of results following the application. The remaining part of the road network is modeled in less detail and is used solely for interconnecting the selected intersections. This ensures that the

---

[184] Parts of this chapter have already been published in Lippert, M.; Winner, H.: Capability-Based Routes for Safe Automated Vehicles (2023).

[185] JOSM: Extensible editor for OpenStreetMap (2021).

route search always has to make a selection from different possible routes. Nevertheless, this interconnection network is modeled using real roads and intersections. However, not all lanes are always modeled, so that some road sections can only be driven in one direction. Thus, the complete road network consists of real road sections, which are partly incomplete and thus do not offer the same route options as the complete road network. Furthermore, not all existing roads are covered in the selected urban area, so the results of usual route planners based on complete road data for conventional optimization criteria may additionally differ from those calculated here. Figure 8-1 shows the modeled road network. The detailed modeled intersections are shown in magenta and the connecting network in yellow. Black arrows mark one-way streets that can only be accessed in the directions shown.

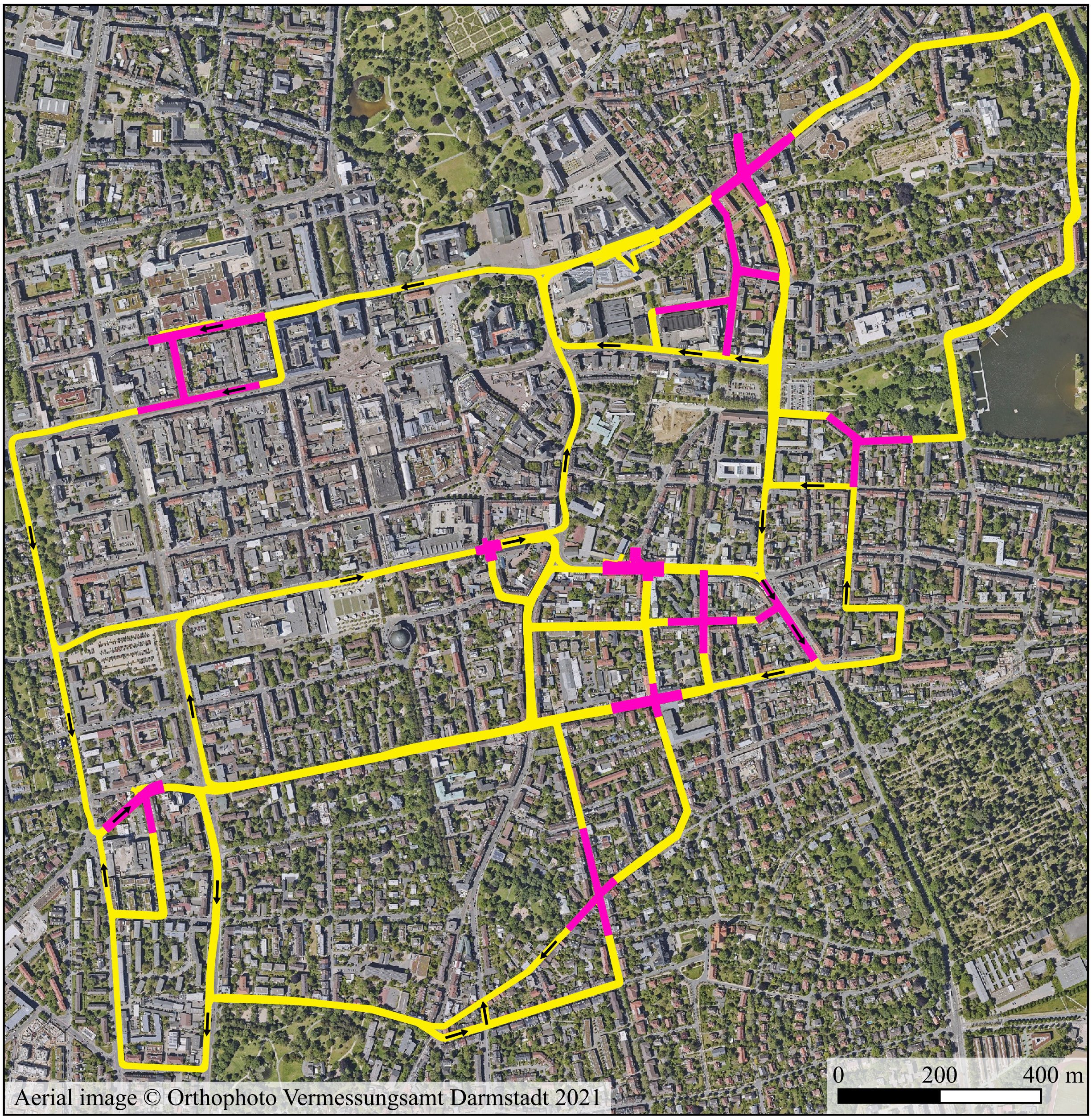
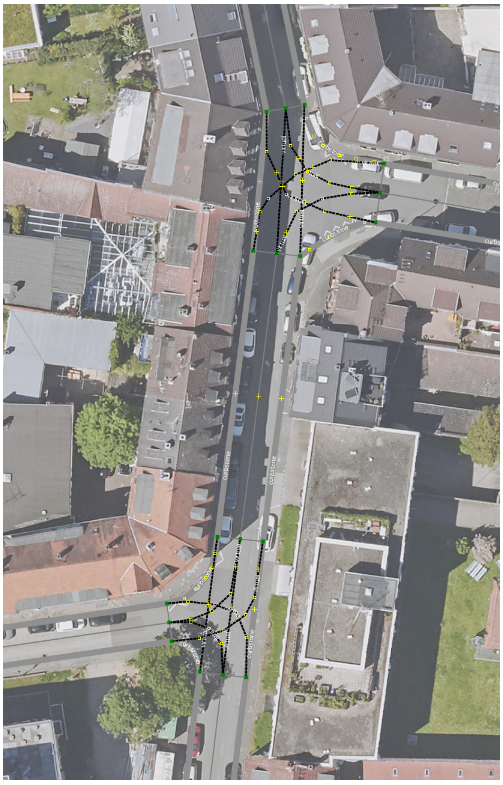


Figure 8-1: Overview of the modeled road network in Darmstadt, Germany. Detailed modeled intersections are visualized in magenta, the connecting network in yellow and one-way streets are marked with arrows.

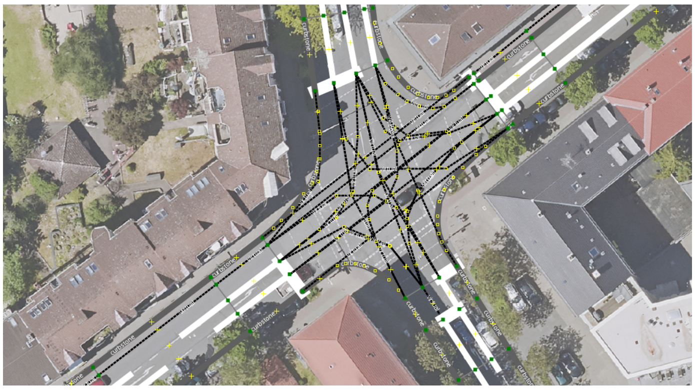
Based on the modeled Lanelet2 map of the road network, the BSSD map was derived. For this purpose, the structure and information required for the BSSD were derived in a partially automated way using a custom developed tool. The partial automation requires a manual completion of the BSSD map, which is also done with the tool JOSM. In particular, the selected intersections were completed in this way.

A total of 14 intersections modeled in detail are available in the presented road network. The intersections differ in terms of traffic guidance for different traffic participants, priority control and geometry as shown in Figure 8-2. They can be roughly grouped into the following classes (Quantity of modeled classes in brackets):

- Uncontrolled X-intersection in residential areas (2)
- Uncontrolled T-intersection in residential areas (3)
- Traffic sign controlled T-intersection in city areas (3)
- Traffic sign controlled T-intersection with bicycle (protection) lanes (2)
- Traffic sign controlled T-intersection with rail traffic (2)
- Traffic light controlled X-intersection without protected left turn (1)
- Traffic light controlled X-intersection with protected left turn and bicycle lanes (1)



(a) Uncontrolled intersections



(b) Traffic light controlled intersection

(c) Traffic sign controlled intersection

Figure 8-2: Examples of detailed modelled intersections in Darmstadt, Germany.
Aerial images © Orthophoto Vermessungsamt Darmstadt 2021.

Figure 8-2 shows four of the mentioned intersections as examples. The Lanelet2 map paint style in JOSM is used to visualize the modeling. Figure 8-2 a shows two uncontrolled T-intersections in residential area. Figure 8-2 b shows the traffic light controlled X-intersection with protected left turn lanes. Additionally, there are designated bicycle lanes. However, they only have to be taken into account, when making a left turn with inactive traffic light. Finally, Figure 8-2 c shows a traffic sign controlled T-intersection with a bicycle lane. Noticeable is the wide and multi-lane priority road, which requires a large area to be observed when entering from the road coming from the south. Particularly noticeable at all four intersections are the different angles between the intersection arms.

8.2 Preparatory Analysis

In the following, the driving requirements of the road network are analyzed. The goal is the definition of driving capability sets as a basis for routing. For this purpose, the requirement generation module is applied to each behavior space in the network in order to compute the reservation requirements. Based on the results, driving capabilities will be defined to enable the demonstration of capability-based routing.

8.2.1 Generated Driving Requirements

Essentially, the capability-based route search program sequence is run through to step 5.2.2, where the driving requirements for each behavior space are determined. For analysis, the reservation requirements of the externally-reserved behavior spaces of the detailed modeled intersections are first visualized. In this process, the areas of preceding behavior space(s) and areas of origin are shown in pairs. The rectangular approximations of the areas are used for visualization, with the coordinate origin of the scenery placed in the reference point of area A_{pre}. Width, position and orientation correspond to the determined specifications from the requirement generation module. The length of the areas is set to 30 m for visualization purposes, since the length is not specified due to the rectangle approximation, as described in Subsection 6.4. Figure 8-3 shows the visualized reservation requirements grouped by the speed limits $v_{\mathrm{lim,pre}}$ of area A_{pre} and $v_{\mathrm{lim,orig}}$ of area A_{orig}. All areas are shown in transparent colors. The areas A_{pre} are shown uniformly in blue. The areas A_{orig} are colored according to the associated sets of reservation-entitled traffic participants P. For yellow areas, priority is to be given to motor vehicles and bicyclists, for green areas to bicyclists only, and for red areas to motor vehicles, bicyclists, and rail vehicles. Both the different speed limits $v_{\mathrm{lim,pre}}$ and $v_{\mathrm{lim,orig}}$ as well as the different required sets of reservation-entitled traffic participants P potentially provide a basis for defining different driving capability sets.

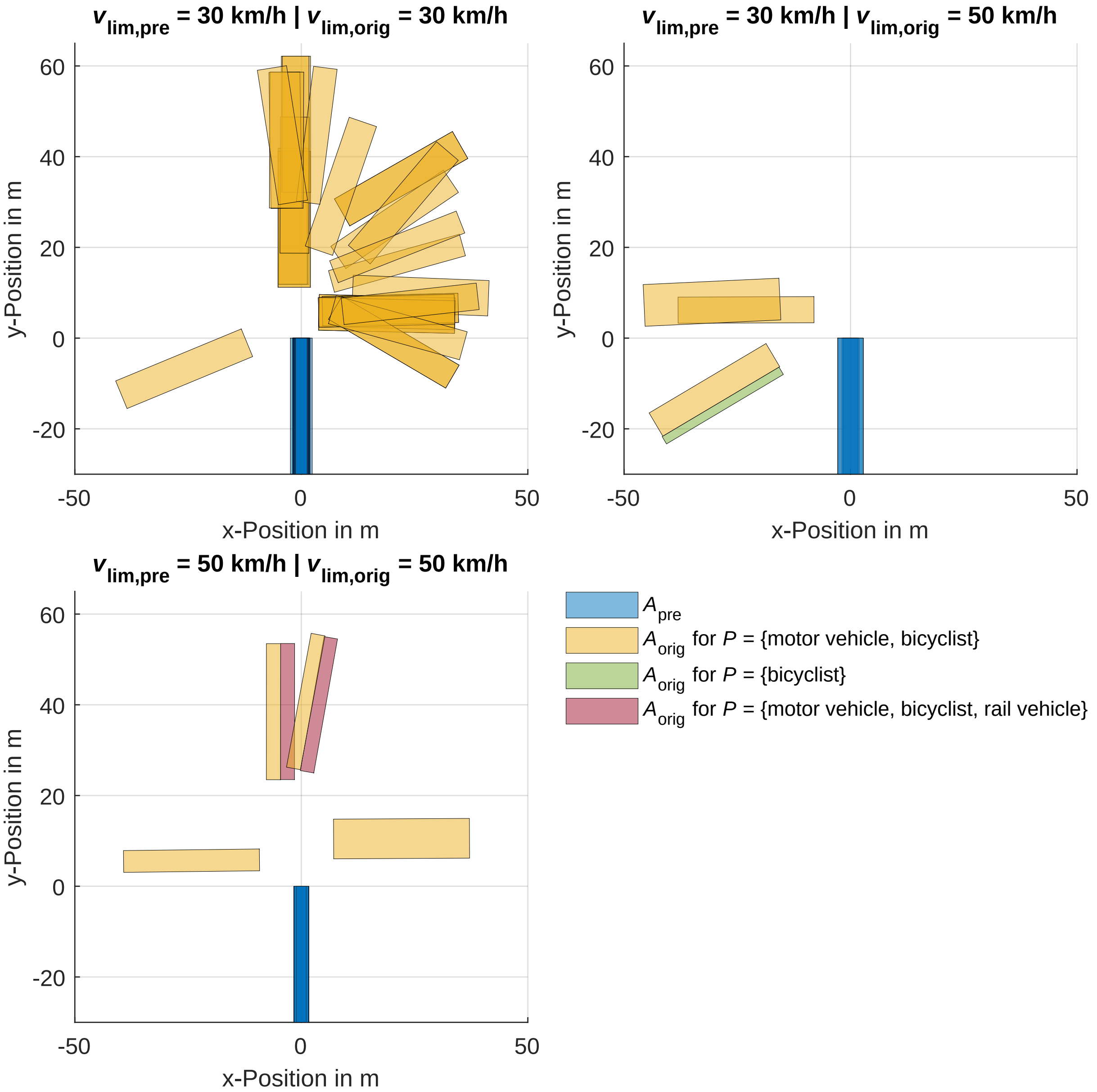


Figure 8-3: Visualization of the reservation requirements for externally-reserved behavior spaces in the road network. Top left: areas of preceding behavior spaces and areas of origin with a 30 km/h speed limit. Top right: areas of preceding behavior spaces with a 30 km/h speed limit and areas of origin with a 50 km/h speed limit. Bottom left: areas of preceding behavior spaces and areas of origin with a 50 km/h speed limit.

A total of 33 externally-reserved behavior spaces are shown, 7 of which have more than one area of origin. This results in a total of 42 areas of origin. The majority of the behavior spaces are located in 30 km/h speed zones shown in Figure 8-3 top left. Position and orientation of the areas of origin show that the priority traffic participants do not necessarily come only directly from the front ($\alpha_{\mathrm{rel}} = 180°$) or directly from the right ($\alpha_{\mathrm{rel}} = 90°$). For one behavior space, priority must be granted from the left based on a traffic sign. In addition, the lateral and longitudinal offsets of the areas of origin differ significantly. There are also clear geometric differences in the other two groups shown at the top right and bottom left in Figure 8-3. In addition, there are other sets P of reservation-entitled traffic participants that result in different areas of origin A_{orig}.

In addition to the geometric differences of the areas of origin, different widths of the areas of preceding behavior spaces are also visible.

The visualized reservation requirements are now considered quantitatively with respect to their geometric specification parameters. Figure 8-4 shows the concrete parameter values of the individual pairings of area A_{pre} and associated area A_{orig} of the behavior spaces based on a data set ID. Behavior spaces with multiple areas A_{orig} receive individual, consecutive IDs for each area A_{orig} accordingly. If multiple sets belong to one behavior space, they are represented with the same symbol. As soon as the symbol changes with ascending ID, this indicates a new behavior space. Thus, the behavior spaces with ascending IDs are alternately represented with a circle ($\circ$) or an asterisk ($*$). The data set is sorted according to the maneuvers described by the behavior spaces. Green marks right turns, blue marks driving straight ahead and red marks left turns.

At many intersections, priority needs not be given to motor vehicles, bicyclists, or rail vehicles when turning right[186]. However, in the present road network, priority must be given for five right-turn maneuvers. In this case, the traffic participants who must be given priority come exclusively from the left ($\alpha_{\text{rel}} \approx 270°$). For straight ahead maneuvers, traffic participants who must be given priority come exclusively from the right ($\alpha_{\text{rel}} \approx 90°$). For left-turn maneuvers, the traffic participants with priority come from the right and/or the front, although the directions can no longer be clearly separated here. Overall, the specification parameter α_{rel} offers a wide range of values for defining different driving capabilities.

In addition to the relative angles, the longitudinal and lateral offsets l_{offLon} and l_{offLat} of the areas A_{orig} in particular have a wider range of values. The specification parameters differ widely from each other. However, the values are strongly dependent on the relative angle α_{rel}. For example, areas with around $90°$ tend to be placed on the right, i.e. in the positive x-range, and areas with around $270°$ tend to be placed on the left. This is reflected especially in the lateral offsets l_{offLon} and l_{offLat}. Overall, it can be seen that depending on the intersection, not only angles but also the distances of the intersection arms can differ significantly. Therefore, these specification parameters are also suitable for variable capability definition within the present road network.

In contrast, the widths w_{pre} of the area A_{pre} and w_{orig} of the area A_{orig} are in a smaller range of values. This is due to the limited number of lanes, which are used for approaching an intersection area on the one hand and serve as possible areas of origin on the other hand. Since lanes usually do not exceed a certain width, the variations in the two parameters w_{pre} and w_{orig}, in absolute terms, remain small. Relatively considered, however, it is also possible to define different areas of driving capability for these parameters.

---

[186] Consideration of pedestrian priority has been excluded for further implementation in Section 6.2 and Section 6.4.

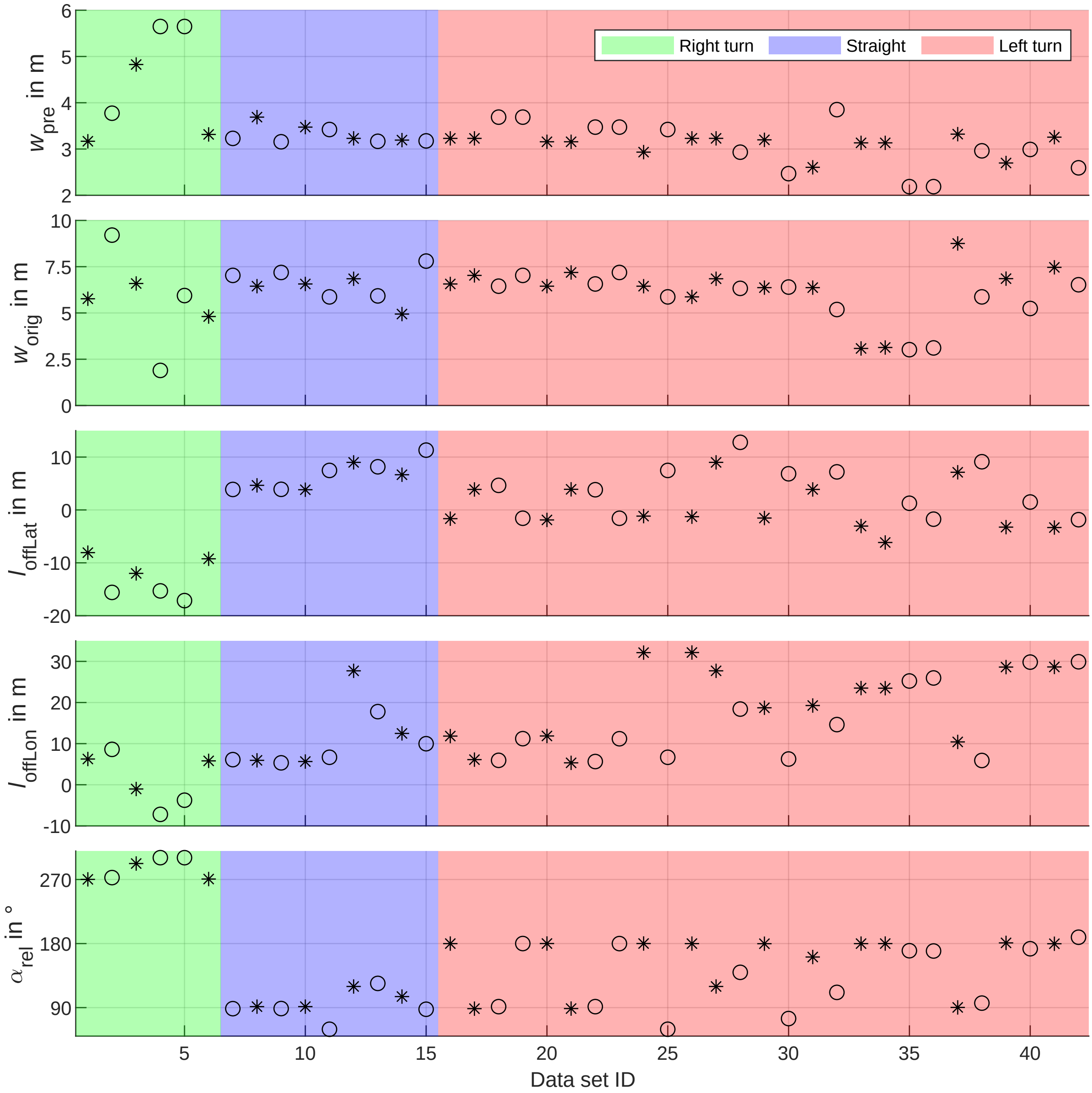


Figure 8-4: Specification parameter of the reservation requirements in the road network. Behavior spaces are alternately represented with $\circ$ and $*$. Same markers for multiple consecutive set IDs represent the same behavior space.

8.2.2 Definition of Driving Capabilities

Specific sets of reservation capabilities are now defined as the basis for the routing application. These capabilities are exemplary and serve to demonstrate the approach developed in this work. Since many intersections do not require priority to be granted when turning right, the capabilities are defined based on the parameter values presented for straight and left turns. Therefore, when traveling on the road network under consideration, some intersections do not result in reservation requirements. However, as soon as an intersection is to be crossed straight ahead, it may be necessary to give priority from the right in 30 km/h speed zones. Therefore, the first capability set $DC_{\mathrm{reserv},1}$ is designed to grant priority from the right ($\alpha_{\mathrm{rel,proof,min|max}} = 80° \,|\, 100°$). This set is valid for reservation-entitled road user types motor vehicle and bicyclist and speed limits of 30 km/h. As shown in the considered data, right is not necessarily equal to right. Thus, $DC_{\text{reserv},1}$ is extended by a second capability set $DC_{\text{reserv},2}$, which includes an additional angle range for traffic from the right ($\alpha_{\text{rel,proof,min}|\text{max}} = 50° \,|\, 70°$). In order to use the road network even more efficiently, another capability set $DC_{\text{reserv},3}$ is defined, which specifically includes granting priority from the front ($\alpha_{\text{rel,proof,min}|\text{max}} = 170° \,|\, 190°$). Compared to the previously defined capability sets, the longitudinal and lateral offsets differ. This is necessary because the offsets depend on the angular orientation of the areas, as described before. Last, the capability set $DC_{\text{reserv},3}$ is extended to a new set $DC_{\text{reserv},4}$ so that rail vehicles are covered in addition to motor vehicles and bicyclists. Additionally, the covered speed limits are increased to 50 km/h. The resulting driving capability sets including the defined specification parameters are summarized in Table 8-1.

Table 8-1: Specified reservation capabilities (MV: motor vehicle | B: bicyclist | RV: rail vehicle).

Parameter	$DC_{\text{reserv},1}$	$DC_{\text{reserv},2}$	$DC_{\text{reserv},3}$	$DC_{\text{reserv},4}$	**Unit**
$v_{\text{lim,pre,proof}}$	30	30	30	50	km/h
$w_{\text{pre,proof}}$	4	4	4	4	m
P_{proof}	$\{\text{MV}, \text{B}\}$	$\{\text{MV}, \text{B}\}$	$\{\text{MV}, \text{B}\}$	$\{\text{MV}, \text{B}, \text{RV}\}$	–
$v_{\text{lim,orig,proof}}$	30	30	30	50	km/h
$l_{\text{offLon,proof,min}\|\text{max}}$	3 | 10	3 | 10	10 | 30	10 | 30	m
$l_{\text{offLat,proof,min}\|\text{max}}$	3 | 10	3 | 10	−10 | 0	−10 | 0	m
$\alpha_{\text{rel,proof,min}\|\text{max}}$	80 | 100	50 | 70	170 | 190	170 | 190	°

8.3 Routing Results

Based on the defined driving capabilities, the capability-based route search is applied to the present road network. In order to demonstrate the functionality of the implemented route search, the start and destination points are defined with respect to diverse route options. For this purpose, the route planning should have different route options that require different driving capabilities. The focus will be on the intersections modeled in detail, so *all other (non-magenta) intersections* in the road network will be handled *without* a capability-based matching. Route sections without the modeled intersections therefore always represent the shortest path based on the conventional optimization criterion. The following route requests are performed (driving capability set m corresponds to $DC_{\text{reserv},m}$):

- Route 1: Shortest route without driving capability sets
- Route 2: Shortest route with driving capability set 1
- Route 3: Shortest route with driving capability set 1 and 2
- Route 4: Shortest route with driving capability set 1, 2 and 3
- Route 5: Shortest route with driving capability sets 1, 2, 3, and 4

Figure 8-5 shows the road network with selected start and destination points and the calculated routes. For a clear representation of the different routes, the road network is shown twice. The presented road network is colored yellow and the detailed modeled intersections within it are highlighted in magenta. Start and destination points are shown with corresponding markers.

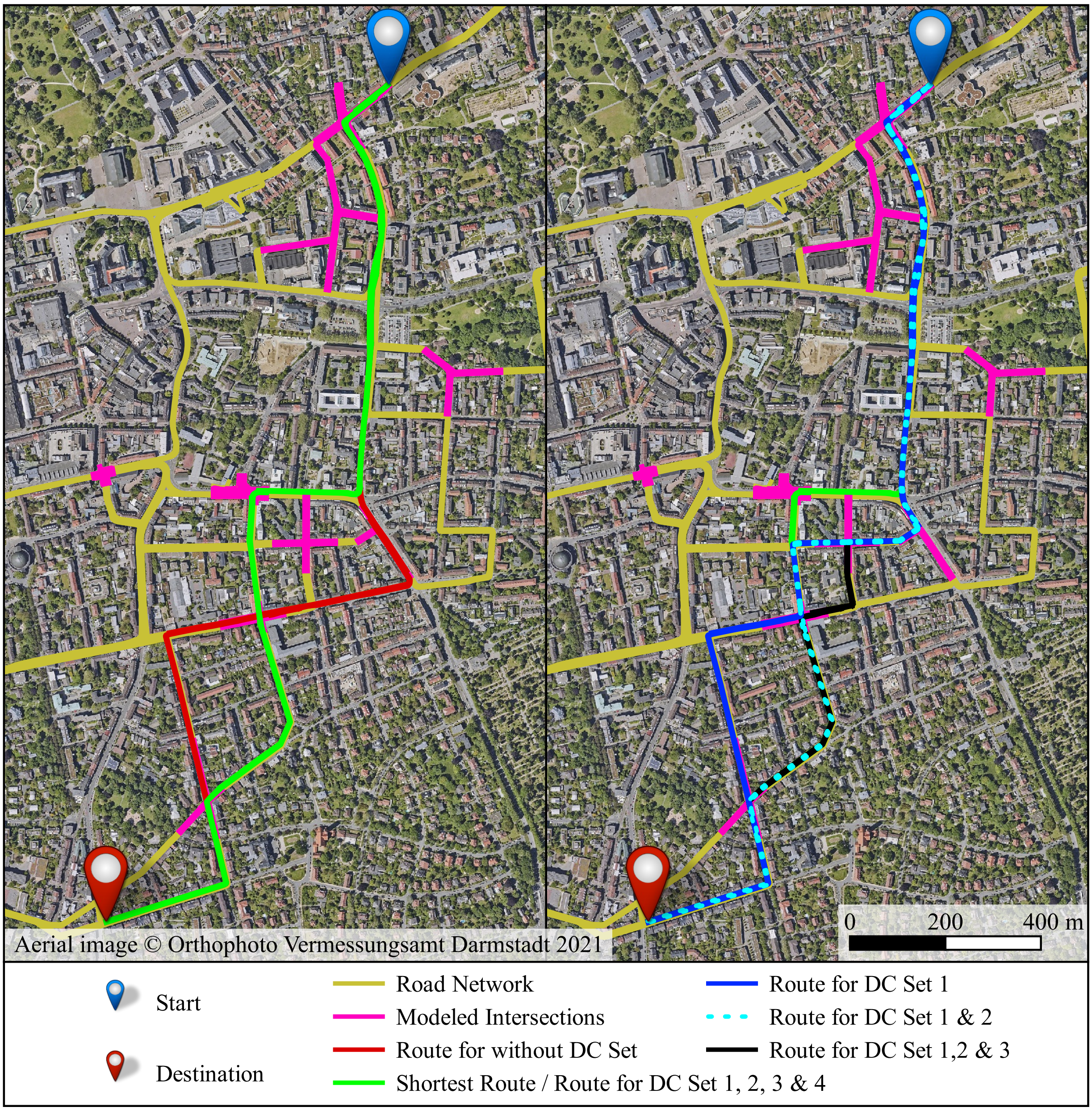


Figure 8-5: Routing results for the defined driving capability sets.

As a reference for the calculated routes, the shortest route based on the conventional optimization criterion *shortest path* of the Lanelet2 algorithm is shown in green.

Route 1: This route is colored red and is partially below the green route as it follows the same course in these sections. The red route only contains behavior spaces that have no driving requirements in terms of reservation. Thus, all externally-reserved behavior spaces are excluded in the generated routing graph. The route therefore only passes through intersections where the AV has priority. At almost all intersections, routing is therefore straight ahead or to the right. Of particular note is the first intersection in the route where a left turn is made. This is possible without the appropriate capability sets because protected left turns are provided at this intersection (green turn arrow at the traffic signal). The last intersection on the route is in a residential area where the right-before-left rule applies. Nevertheless, it is allowed to cross this intersection because the intersection arm on the right in the direction of the route is a one-way street[187]. Since the one-way street is for both motor vehicles and bicyclists and leads away from the intersection, no priority needs to be given.

Route 2: The blue route is based on driving capability set 1, which gives priority to motor vehicle and bicyclists in 30 km/h speed zones from the right. Therefore, the priority road within this route is exited into a residential area, as this path is shorter than that described in the red route. When turning right from the priority road, priority does not need to be granted and priority in the residential area is covered by the capability set. Finally, the residential area is exited by a right turn at an intersection with traffic signals. From this point on, the blue route again coincides with the red route.

Route 3: If the driving capabilities of the blue route are extended by capability set 2, an even shorter route succeeds. The dotted route colored in cyan avoids a detour at the end of the route by crossing the penultimate intersection with traffic lights straight ahead. This crossing requires no special capabilities, but a left turn is made at the intersection after it. However, the associated behavior space requires that priority can be granted from the right from a previously uncovered angular area. The new capability set 2 gained adds this missing angular range to the overall driving capabilities.

Route 4: If the previous driving capabilities are extended by set 3, the even shorter black route is found. The new capability set now allows driving in externally-reserved behavior spaces that require granting priority from the front. This enables left turns at many intersections. Accordingly, compared to Route 2 or 3, it is now possible for the AV to make a left turn in a residential area as well as at a major intersection. Despite the intersection being controlled by a traffic signal, the AV must yield priority from the front because left turns are not protected. Thus, although this intersection is geometrically similar to the first intersection in the route, different driving capabilities are required despite the traffic signal.

---

[187] Cf. marked one-way streets in Figure 8-1.

Route 5: With the driving capabilities available, Route 4 is not far from the shortest route shown in green. In order for the shortest route to be mastered by the AV, further driving capabilities are lacking. Part of the green route is on a road with rail traffic. The left turn required with this Start-Destination combination must also cross rail traffic. This means that in addition to motor vehicles and bicyclists, the AV must also give priority to rail vehicles from the front. Furthermore, both the associated behavior space and the linked areas of traffic participants with priority are in a 50 km/h speed zone. Driving capability set 4 covers these new requirements, so that this part of the network can also be driven on. If the AV possesses all defined capability sets, it is thus able to travel the shortest route.

8.4 Discussion of the Overall Approach

The overall goal of this work is to develop an approach for identifying routes for which the driving requirements do not exceed the driving capabilities of AVs. In this chapter, the developed overall method was applied using an implementation of capability-based route planning with respect to the BSSD reservation attribute. The results are analyzed and critically reviewed below.

With the application of the implemented route planning, it is shown that the identified routes are dependent on driving requirements and driving capabilities. Based on the reservation requirement specifications developed in this thesis, the route planning performs a comparison with the driving capabilities defined for the road network at hand. It is shown that the route planning only calculates routes with driving requirements that do not exceed the available driving capabilities. The performed variation of the available driving capabilities supports this result. Nevertheless, the demonstration initially only shows that capability-based routes can be identified based on the available specifications, but not whether these routes do not exceed the actual available driving capabilities of a real AV. Therefore, possible sources of error that lead to the falsification of the specified requirements and thus to an incorrect matching are first shown. Subsequently, general uncertainties of the overall approach are highlighted, which potentially prevent or complicate a real-world application of the approach.

8.4.1 Map-Based Errors

A digital map is necessary for the derived approach. Regardless of map format, it is possible that the map data is incorrect. The following sources of error can be mentioned with respect to capability-based route planning:

Geometry: The geometry of the scenery represents an essential part of the specification. Positional and angular errors or errors in the modeled geometric shapes potentially lead to an incorrect requirements specification. For example, relative angular errors between two modeled crossing arms will result in an incorrect specification of relative angles between areas of preceding behavior space(s) and areas of origin. Relative positioning errors between different scenery elements lead to erroneous offsets or even erroneous widths. The above-mentioned resulting specification errors also potentially arise in the case of an incorrectly modeled shape of, for example, a road section.

Labeling: Almost all elements of the map are labeled with information. Incorrect information in the map potentially results in incorrectly derived and thus incorrectly labeled BSSD information. For example, an incorrect label of a lane boundary may cause crossing to be allowed even though it is actually prohibited. But also wrong speed limits or priority regulations lead in the end to a incorrect specification.

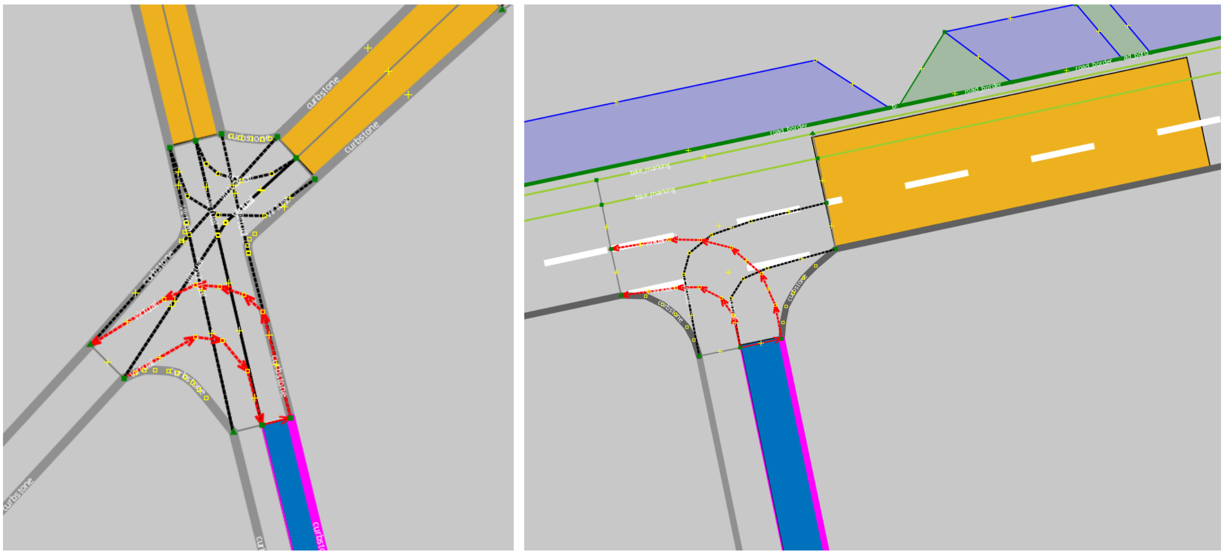
Data actuality: Maps are created based on a snapshot. As soon as changes occur in the real world, these must also be applied to the map. For example, a construction site can change the course of a road significantly. For the roadworks section, the specifications made may then no longer be valid. But even small changes, such as the addition of a traffic signal at an intersection, significantly changes the specification.

In the road network modeled in this work, there are no noticeable geometry or label errors. This was verified using the highly accurate and georeferenced aerial imagery. In addition to the aerial imagery, the accuracy of the labeled information was partially verified with the help of on-site inspections and publicly available map data. However, especially with regard to the actuality of the data, errors cannot be completely excluded.

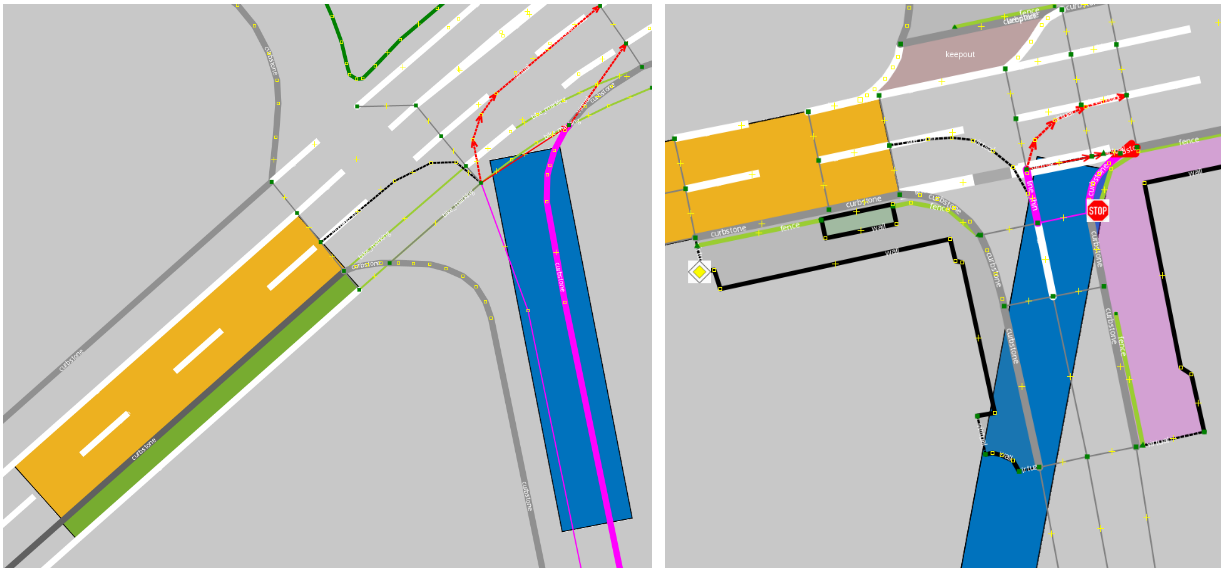
8.4.2 Model-Based Errors

The aforementioned sources of error related to the maps used are independent of the specification approach chosen in this work. However, errors also arise based on the models used. For the purpose of developing an initial implementation, the simple assumption was made that the areas to be specified (A_{orig}, A_{pre}) are rectangles. However, based on this assumption, errors may occur if the mentioned areas deviate significantly from a rectangular shape in reality. For this purpose, Figure 8-6 shows examples of such deviations and the resulting specification errors based on the presented road network. Depicted in each case is a considered behavior space (red) for turning and the corresponding resulting areas A_{pre} (blue) and A_{orig} (orange, green). Additionally, the reference behavior space for calculating A_{pre} is shown (magenta), so that the origin of the deviations becomes clear.

Figure 8-6 a shows examples of an essentially error-free specification. The identified areas represent the real world almost perfectly. In contrast, significant deviations between modeled areas and the map can be seen in Figure 8-6 b. Angle as well as width differ significantly. This is due on the one hand to the rectangle assumption and on the other hand to the chosen implementation method. The rectangles are determined based on the adjacent longitudinal boundaries of the linked behavior spaces. This is done by simply constructing a straight line centered through the longitudinal linestrings at the beginning and end of the behavior space, which serves as basis for the calculation for the relative angles as well. The averaged length of the longitudinal linestrings, i.e., the averaged width of the behavior space based on the beginning and end, is specified as the width of the rectangle. Behavior spaces with significantly different widths at the beginning and end are thus approximated incorrectly - both in width and angle. The deviations become larger the shorter the behavior space used for the calculation, as shown in the right image in Figure 8-6 b.



(a) No deviations



(b) Significant deviations

Figure 8-6: Examples for possible deviations due to rectangle assumption. Red: considered behavior space E_i; magenta: reference behavior space of A_{pre}; blue area: A_{pre}; orange/green area: A_{orig}.

The routing results presented are based only on intersections where there is little to no deviation of the rectangle approximation from reality. Nevertheless, based on the deviations shown here, it can be concluded that the method used to approximate the rectangle can be significantly improved. For the initial demonstration of the overall approach, however, these deviations are of secondary importance, which is why no optimization of the implementation was performed. Even if a different modeling method is chosen, there will always be deviations in behavior spaces such as in Figure 8-6 b due to the rectangle assumption. For a higher accuracy of the approximation, it is possible to assume other shapes as a basis for the specification. However, it should be noted that the specification of driving requirements is always a trade off. On the one hand, the real world should be approximated as closely as possible so that the specification is as close to reality as possible. On the other hand, the level of abstraction of the driving requirements should be high enough that common test certificates can be created for similar behavior spaces. Thus, the closer the specification is to the real world, the more difficult it becomes to harmonize similar behavior spaces. Furthermore, a detailed modeled world requires many more specification parameters than shown in this work. This is another drawback to modeling the real world in too much detail.

8.4.3 General Uncertainties

In addition to the aforementioned sources of error that directly lead to a faulty specification, there are uncertainties in the overall approach that need to be critically questioned. Uncertainties refer to circumstances that may cause capability-based route finding to be infeasible in the manner presented in this work, regardless of implementation.

Completeness: The approach presented specifies driving requirements and driving capabilities based on scenery-based behavioral demands. Potentially necessary information can be lost in each of the steps required for derivation. Each step is subject to certain constraints, assumptions, and, in some cases, simplifications that may contribute to this loss of information. However, the problem of completeness is a commonly known problem in the context of AV development. Thus, although the presented approach is systematically structured, it cannot be spoken of as being complete without further ado.

Specification: The choice of specification parameters represents another uncertainty. The result shows that based on the identified parameters, a match between requirements and capabilities is possible. The resulting routes also show that the specification can cover different requirements. Nevertheless, it has not been conclusively clarified whether the identified specification parameters are suitable, on the one hand, for mapping the real requirements of the routes and, on the other hand, for providing proof with test certificates. This requires simulation or real-world tests which, if applicable, falsify the selected specification and identify possibilities for further or other parameters.

Matching criteria: The matching criteria are subject to a number of assumptions. For example, for all specified widths of the different areas, it is assumed that the proof of a certain width automatically implies the proof of lower widths. This is an assumption made for the demonstration of the overall approach sought in this work. While it is based on DDT considerations, it has not been demonstrated that the assumptions apply to a real-world proof. For this reason, not only the suitability of the specification, but also the suitability of the matching criteria must be proven for a realization.

8.4.4 Resulting Challenges

The discussion of possible errors and uncertainties in the overall approach allows conclusions to be drawn about challenges that must be mastered for realization. Based on the previous discussion, these are addressed and summarized below.

Map creation and update: A correct map is essential for the realization of capability-based route search. Particularly important is the fidelity of the geometry, the labeled context knowledge (e.g., types of geometry elements), and the actuality of the data.

Proof of specification: The suitability of the identified requirement and capability specifications must be proven. This will require performing and evaluating tests in simulations and the real world. The specification is falsified if an AV successfully tested for a particular driving capability set is unable to drive a route segment with equally specified driving requirements. Based on the results, it may be necessary to adjust the specifications.

Proof of matching criteria: The suitability of the identified marching criteria must be proven. This requires demonstrating that an AV with certified capability sets is actually capable of driving the route segments identified as non-exceeding. If route sections identified as passable exceed the driving capabilities of the AV, the matching criteria are falsified and must be revised.

Creation of test certificates: A general challenge becomes the creation and proof of test certificates for capability sets. The tests must prove that an AV actually possesses the capabilities that are certified using the test certificates. This challenge is closely coupled with the proof of specification and matching criteria.

8.5 Conclusion on Research Questions

In the previous chapters, the research questions RQ 1, RQ 2 and RQ 3 have already been addressed and answered. Based on the results and findings of the implementation as well as application, this section answers the remaining research questions including the still partially open research question RQ 4.

RQ 4: How are driving capabilities to be designed so that routes within an ODD can be determined based on a match of driving capabilities and driving requirements?
Chapter 6 already showed that driving capabilities can be defined equivalently to driving requirements and specified based on corresponding specification categories. The application in this chapter additionally shows that this type of design is fundamentally suitable for a route-based

match between requirements and capabilities - at least for the implemented reservation specification. The remaining specifications have to be investigated in the future. Additionally, the approach presented is only one way to enable the matching. Further approaches need to be explored in the future to ensure that driving requirements, driving capabilities, and associated matching criteria are optimal with respect to matching.

RQ 5: Is the developed method applicable?
The applicability of the overall method is demonstrated in this chapter using the driving requirements and capabilities of the BSSD reservation attribute. For this purpose, a route network was modeled and driving capability sets were defined. Based on this, RQ 5 can thus be answered positively. Nevertheless, it becomes clear that the practicality of the method still needs to be extensively investigated. For this purpose, certified capability sets should be used that have been certified at least in an extensive simulation, but better in real tests. Trials and tests with a real AV are therefore essential to answer the applicability comprehensively.

RQ 6: How is the developed method to be evaluated?
This chapter also answers RQ 6. Sources of error and uncertainties of the overall approach are identified based on the application. The implementation has weaknesses in specification accuracy due to assumptions and simplifications made. However, since the implementation and application are for the purpose of demonstrating the overall method, these weaknesses are not critical to the evaluation. Furthermore, for the application, only intersections where the specification is nearly error-free were considered. Based on the identified sources of error and uncertainty, the discussion of results identifies challenges for the realization of the entire method. These challenges need to be addressed in further research in order to answer RQ 6 with respect to a real-world application. However, in the context of this thesis, this research question is answered with this chapter.

Using the findings gained based on the research questions RQ 1 - RQ 6 the superordinate main research question RQ 0 of the present work is addressed and answered in the following, concluding chapter.

9 Conclusion and Outlook

The present work deals with the drivability of routes within an ODD of AVs. Routes are the basis for any driving mission of an AV, regardless of the use case. Therefore, an AV must be provably able to drive at least one route. For this purpose, it is necessary to actively integrate routes already in the development process. This offers the advantage that driving requirements and driving capabilities of AVs can be specified purposefully for the intended use. Ideally, this also ensures that AVs do not drive routes in operation that are not feasible on the basis of the driving capabilities. An analysis of the relationships between route and the resulting driving requirements as well as required driving capabilities shows that achieving this goal is possible. Therefore, the following main research question is addressed in this work:

RQ 0: How to identify routes with driving requirements that do not exceed the driving capabilities of AVs?

Based on addressing six defined, subordinate research questions, new findings compared to related work are obtained that contribute to answering this research question:

- The scenery, as a key component of the ODD, defines the local behavioral demands that directly constrain the observable behavior of AVs. Thereby, the behavioral demands demonstrably result from a combination of the scenery and the applicable traffic rules. They are identified and classified in the work.

- In related work, there is no approach to explicitly link behavior and scenery. Therefore, to provide a basis for route-based derivation of driving requirements, a generic map representation is developed that accomplishes just that. It is shown that the behavioral demands can be explicitly linked to the scenery using the developed BSSD. For this purpose, the BSSD is instantiated using the map format Lanelet2. A significant advantage of the introduced behavior spaces is the complexity reduction of the scenery. All behavior-relevant information is extracted and explicitly represented using only four behavioral attributes. All other information from the scenery, such as infrastructure or other traffic facilities, does not need to be carried along for behavior specification.

- It becomes apparent that for route-based requirement derivation, concatenated behavior spaces must be considered. A method that enables this derivation is presented. Based on lane-accurate routes within the BSSD, explicit behavioral requirements that can be assigned to the route are derived. This represents an innovation over previous related work.

- To provide meaningful comparability of driving requirements and driving capabilities, behavioral requirements alone are not sufficient. It turns out that driving requirements related to parts of the DDT of AVs can differ significantly despite very similar behavior spaces and thus similar behavioral requirements. The key finding from this is that behavioral requirements need to be specified in terms of concrete scenery properties. Thus, specification categories are derived and assigned to the behavioral requirements. Each behavioral requirement is specified by the assigned specification categories with respect to the associated scenery, resulting in concrete driving requirements. Based on related work, this demonstrates for the first time that the derivation of route-based driving requirements is possible.

- Another finding is that driving capabilities must be defined to match the driving requirements. Furthermore, matching criteria are necessary for a meaningful matching. An approach to defining driving capabilities and matching criteria is presented with respect to a demonstration of capability-based route planning. Other approaches are conceivable. Nevertheless, based on the related work, this is the first approach that enables route-based matching of requirements and capabilities.
- The application of the overall approach developed demonstrates that capability-based routes can be identified within a real road network. Weaknesses of the approach and implementation are highlighted in an evaluation. The key finding is that the overall method is generally applicable, with practicality for real-world AVs yet to be demonstrated. Challenges to this end are outlined.

Overall, the research objectives are achieved. Based on the elaborated findings, the following remaining research needs are derived for a practical implementation of the overall method:

- *Transferability*: The approach was developed based on the German road traffic. Thus, for an application in other countries, the transferability of the BSSD to the traffic regulations and existing traffic infrastructure applicable there must be intensively examined.
- *Suitability of specification categories and matching criteria*: Based on a real road network, a basic suitability based on the behavioral attribute *reservation* has already been demonstrated. However, it remains unclear whether the specifications and matching criteria are also suitable for use with a real AV. For this purpose, further research has to be conducted in order to, on the one hand, develop specifications that have not been considered so far and, on the other hand, to provide evidence for their practical suitability. A necessary adaptation of specification categories and matching criteria is not to be excluded.
- *Test certificates*: capability-based route planning requires certified evidence of the driving capabilities of AVs. So far, no work is known that provides such certification. Consequently, a further research need is to develop a method to produce these test certificates for AVs.

Overall, the present work makes a unique and new contribution to the targeted functional specification of AVs and thus necessary identification of routes for which the driving requirements do not exceed the driving capabilities of AVs. The identification of capability-based routes for AVs is potentially possible, but needs further elaboration in light of the research needs outlined.

A Specification of Speed, Boundary and Overtake Requirements

A.1 Speed Requirements

The specification of requirements from the speed attribute are largely obvious and intuitive, so a detailed description is not provided here. For specification, it is necessary that the speed limit is quantified in the associated requirements. This means that for each behavior space, the value of the speed limit must be specified within the driving requirements. For *SR1*, these are the speed limits directly from the behavior spaces. *SR1* is thus specified for each individual behavior space, so that for different speed limits of the behavior spaces the specification differs accordingly.

Under a certain condition, the two requirements *SR1.1* and *SR1.2* result from the concatenation. Consequently, these requirements are not valid for every behavior space in a lane-accurate route. The following necessary condition must be met for this[188]:

- The speed limit $v_{\mathrm{lim},j}$ of D_j in E_j is greater than the speed limit $v_{\mathrm{lim},j+1}$ of D_{j+1} in E_{j+1}.

Since an AV need not exhaust the speed limit completely, this condition is only necessary and not sufficient. Thus, although the case of a mandatory speed reduction need not occur, this requirement is defined based on the scenery. From a requirements point of view, there is no alternative to this, since all possible cases based on the route must be considered. The formulation of sufficient requirements is only possible if the driving behavior of the AV is already known. However, this contradicts the principle of requirements that must be formulated as independently as possible from a problem solution.

As soon as the above condition for a concatenated behavior space is met, the requirements *SR1.1* and *SR1.2* are valid and consequently need to be specified further. For this purpose, only the change of the speed limit upon entering the considered behavior space is specified: $v_{\mathrm{lim},j} \rightarrow v_{\mathrm{lim},j+1}$.

The following specification categories result for the speed requirements:

- *SR1*:
  - Speed limit $v_{\mathrm{lim},i}$ of considered behavior space E_i
- *SR1.1*, *SR1.2*:
  - Change of speed limit $v_{\mathrm{lim},j} \rightarrow v_{\mathrm{lim},j+1}$ for the transition into the considered behavior space E_{j+1}

---

[188] Cf. Section 5.3.4.

A.2 Boundary Requirements

In the following, the behavioral requirements resulting from the behavioral attribute *boundary* are examined. The subsections are named according to the property of the concatenated behavioral attributes[189]. A closer look at the behavioral requirements of the property *parking only* is omitted, since this property plays a minor role in the context of capability-based routes.

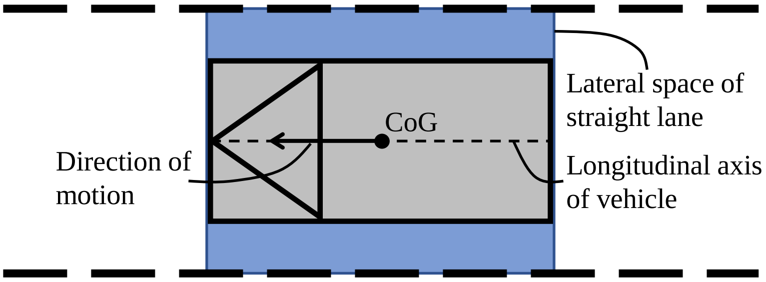
General

BR0 states that AVs must stay within the lateral boundaries of the behavior spaces as long as no lateral transition is planned. In principle, these requirements apply to any behavior space in a lane-accurate route. Consequently, what is sought are the scenery-specific properties of behavior spaces, which may vary for different behavior spaces. Additionally, these properties must address parts of the DDT, otherwise they would not be relevant. Intuitively, the first distinguishing feature between behavior spaces can be the distance between lateral boundaries. This distance is similar to the width of the lane described by the boundaries of the behavior spaces. The smaller the width of the behavior spaces, the more difficult the driving task is to remain within the boundaries. This relationship is intuitively obvious, not only by comparison with a human driver. Human drivers generally slow down their driving speed so that narrow driving spaces can be navigated without collision. It can be directly concluded that the driving task is more difficult due to the narrow lane width available. In order to cope with the driving task, speed is typically reduced, since slower travel allows more precise driving. An AV is also faced with this problem, as it must drive accurately in addition to perceiving the limitations accurately. Due to deviations in both perception and driving dynamics control, lanes must not become too narrow, otherwise they can no longer be driven on without crossing the boundaries. In an ideal world, the smallest possible width of lanes would be given by the width of the AV itself. However, due to uncertainties in driving automation, this is not realistic. Reid et al.[190] investigate this problem to derive requirements for AV localization. Their research shows that lane width is not the only factor influencing the lane keeping task. Depending on the curvature of the lane, more restrictive requirements arise in the form of reduced space available for a vehicle. Figure A-1 illustrates the curvature-related change in available space within a constant-width lane. It is assumed that the AV drives without side slip angle. The side slip angle is the angle between the longitudinal axis of the vehicle and the direction of motion of the vehicle's Center of Gravity (CoG). If a vehicle is moving without a side slip angle, it is therefore always aligned in the direction of motion. In concrete terms, this means, that the vehicle is always aligned tangentially to the driven curve when cornering. This condition is visualized in the figure by drawing the longitudinal axis of the vehicle and the direction of motion of the CoG.

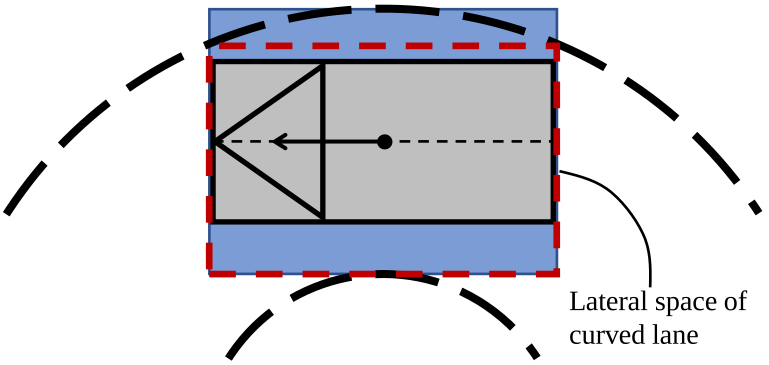
---

[189] Cf. Table 5-4.

[190] Reid, T. G. R. et al.: Localization Requirements for Autonomous Vehicles (2019).



(a) Straight lane



(b) Curved lane with same actual width as in (a)

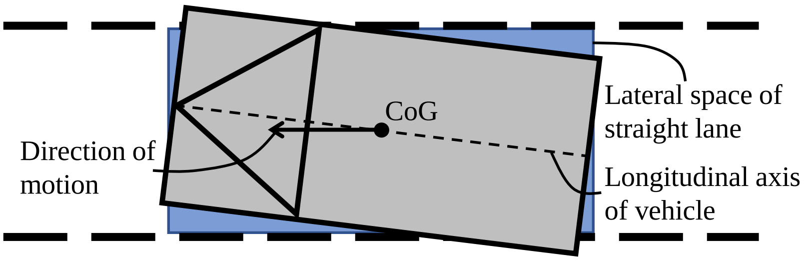
Figure A-1: Available lateral space within a straight and a curved lane.[191]

Figure A-1 a shows a traffic lane without curvature. To illustrate the available space, a fictitious AV with a blue bounding box in the lane is shown. The bounding box exemplarily limits the lateral space in which the vehicle is allowed to move without crossing the lateral boundaries. In the lateral direction, the available space is obviously limited by the lateral boundaries of the lane, as these may not be crossed. In the longitudinal direction, the bounding box is bounded by the length of the AV. Figure A-1 b shows the same vehicle with the same blue bounding box as in Figure A-1 a. However, in this example, the lane is curved, so the blue bounding box that previously fit within the lane now extends well beyond the edges. A new bounding box is drawn in red, representing the available lateral space of the AV within the curved lane. Due to the curvature, this bounding box is significantly smaller and thus requires higher precision of the entire automation chain. The width of the bounding box is referred to as the effective width of the lane. The effective width can maximally be equal to the actual width of a lane. The greater the curvature of a lane, the smaller the effective width, while the vehicle length remains the same.

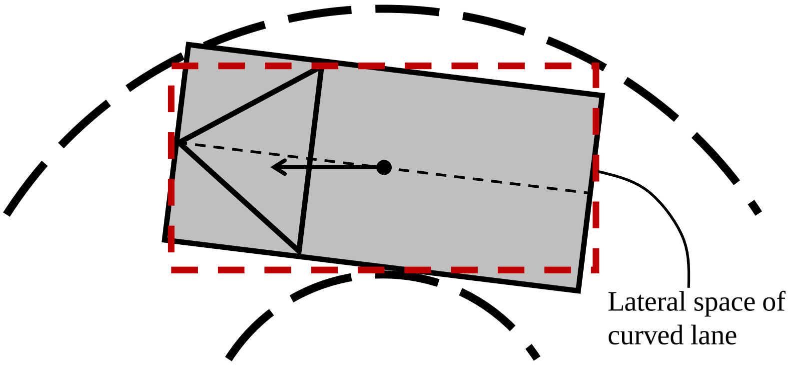
The introduced bounding box works well for the case where the AV drives without side slip angle. This way, it is ensured that the effective width of the lane is represented by the width of the bounding box. But what happens when the AV traverses a curve or even a straight line with a side slip angle? Because of the angle between vehicle longitudinal axis and direction of motion of the CoG, the relative available lateral space becomes smaller. A consideration of two extreme cases in Figure A-2 illustrates this relationship.

---

[191] Adapted from Reid, T. G. R. et al.: Localization Requirements for Autonomous Vehicles (2019).



(a) Straight lane



(b) Curved lane with greater actual width than in (a)

Figure A-2: Relative available lateral space considering side slip angle.[192]

As before, Figure A-2 a considers a straight lane and Figure A-2 b considers a curved lane. In both cases, however, the minimum theoretically drivable lane width for the same fictitious AV is now selected. For the straight lane, this means that the lane and thus the blue bounding box are as wide as the vehicle itself. It follows directly from this that the AV must drive parallel to the lane, i.e. without a side slip angle, so that it does not leave the lane. As shown in the figure, any change in the side slip angle would result in the lane boundaries being overrun. The red bounding box for the curved lane represents the optimum space usage of the fictitious AV within a curve. For optimum space usage, it is necessary for the box to be tangent to the curve resulting in an effective width equal to vehicle width. In this example, the AV must therefore drive without a side slip angle again so that the lane boundary is not overrun. The two examples show that driving in lanes is most space-efficient when driving without a side slip angle. Driving with certain side slip angles is vehicle-specific and not dependent on the scenery. For the specification of *BR0*, the side slip angle-free consideration is therefore the appropriate choice, since this represents the optimum with respect to the lateral space usage. For this reason, this case is chosen as the specification basis for *BR0* in the following.

The relevant parameters of effective width w_{eff}, actual width w_{act} and curvature $\kappa = 1/r$ of the behavioral space or lane, where r is the radius of the curve, are shown in Figure A-3.

The effective width w_{eff} describes the lateral space available in a curved lane for an AV with a length l_{AV} driving without side slip angle. In the absence of curvature ($\kappa = 0$), $w_{\text{eff}} = w_{\text{act}}$

---

[192] Adapted from Reid, T. G. R. et al.: Localization Requirements for Autonomous Vehicles (2019).

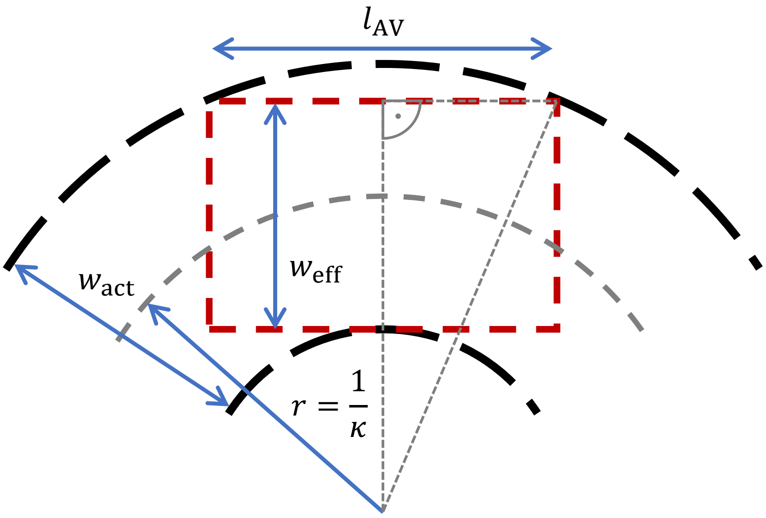


Figure A-3: Relevant parameter for the calculation of the effective lane width.[193]

yields. The relationship between the above parameters can be represented using Pythagoras[194]:

$$\left(\frac{l_{\mathrm{AV}}}{2}\right)^2 + \left(\frac{1}{\kappa} - \frac{w_{\mathrm{act}}}{2} + w_{\mathrm{eff}}\right)^2 = \left(\frac{1}{\kappa} + \frac{w_{\mathrm{act}}}{2}\right)^2 \tag{A-1}$$

Solving for w_{eff} results in:

$$w_{\mathrm{eff}} = \sqrt{\left(\frac{1}{\kappa} + \frac{w_{\mathrm{act}}}{2}\right)^2 - \left(\frac{l_{\mathrm{AV}}}{2}\right)^2} + \frac{w_{\mathrm{act}}}{2} - \frac{1}{\kappa} \tag{A-2}$$

The dependence of the effective width w_{eff} on the vehicle length l_{AV} is actually not desirable for a specification that is as independent of the vehicle as possible. Nevertheless, the preceding considerations prove that vehicle geometry cannot be dispensed with entirely. Without the vehicle geometry, it would be necessary to provide the curvature and effective width profiles over the entire length of the behavior space. In the sense of matching requirements and capabilities, this approach would not be useful, since most of these profiles will differ in reality. Thus, to further specify *BR0*, the effective width w_{eff} of the behavior spaces is used as derived in Equation A-2. Since in reality the effective width is not constant over the length of the behavior space, the minimum value is chosen as the value for w_{eff}.

Nevertheless, in addition to the effective width of the behavior space, the maximum curvature κ_{max} must also be provided for the specification. The reason for this is that different combinations of actual width and curvature of behavior spaces can result in the same values for the effective width[195]. In some cases, this results in narrow behavior spaces without curvature having the same

---

[193] Adapted from Reid, T. G. R. et al.: Localization Requirements for Autonomous Vehicles (2019).

[194] Reid, T. G. R. et al.: Localization Requirements for Autonomous Vehicles (2019).

[195] Cf. Equation A-2.

effective width as wider lanes with curvature. A proof of capabilities for the requirements of lane keeping could be provided on the basis of the effective width, for example, only for lanes without curvature. However, whether this would also enable an AV to drive through curved behavior spaces would not be demonstrated. Therefore, in addition to the effective width, the maximum curvature $\kappa_{\max}$ of behavior spaces is also included for specification. In this way, each behavior space is uniquely distinguishable and specified.

In addition, it is necessary to also specify the speed limit of the behavior space under consideration, since higher driving speeds lead to larger deviations in positioning accuracy. This means that a combination of curvature and width of the behavior space cannot necessarily be traveled at any speed. Again, the speed limit is a necessary condition, not a sufficient one. An AV does not have to travel as fast as the speed limit indicates, but the possibility still exists. If the speed limit is to be fully exploited, it must necessarily represent a specification category for the driving requirements.

Another way to distinguish the *BR0* requirement for different behavior spaces is the type of lateral limits. The lateral boundaries of behavior spaces correspond to lane boundaries and can vary greatly depending on the scenery. Lane boundaries can be unmarked or marked with different line types. In addition, lanes are also often delineated by a curb of a sidewalk. These and other different types of the boundary represent another distinguishing feature for the *BR0* requirement. This is only true in the case where the boundaries of the behavior space are perceived by the AV itself. For example, if a highly accurate map is used, the type of boundary is irrelevant for the fulfillment of the DDT. Nevertheless, it is one of the specifications of the driving requirements because they are formulated as universally as possible. Whether and how an AV meets these specifications is not relevant at this point.

Overall, the following specification categories for *BR0* emerge:

- Effective width $w_{\mathrm{eff},i}$ of considered behavior space E_i
- Maximum curvature $\kappa_{\mathrm{max},i}$ of considered behavior space E_i
- Speed limit $v_{\mathrm{lim},i}$ of considered behavior space E_i
- Type of lateral boundaries of considered behavior space

Stop, prohibited and not possible

BR1 and *BR1.1* require stopping at the longitudinal boundary of the behavior space with appropriate deceleration. To do this, the AV must first identify the appropriate boundary. Regardless of whether this happens with or without a high-precision map, the type of boundary is relevant for a complete specification, as in *BR0*.

Stopping itself is a basic global requirement for AVs that applies regardless of scenery. Stopping relative to objects, or as in this case relative to a stop line, is also a basic global requirement. Nevertheless, for *BR1* and *BR1.1*, it must be demonstrated that an AV meets these requirements.

From a behavioral perspective, the stop line must not be crossed before stopping. Differences in these requirements depending on the scenery result in the different speed limits that apply in the area in front of the stop line. Different speeds driven before the stop line require different behaviors due to different stopping distances. It can be assumed that AVs fulfill these requirements anyway, as soon as they are able to handle the corresponding speed limits. Nevertheless, proof of compliance with the requirements for different speeds becomes necessary. For this reason, the applicable speed limit in the area before the stop line is included as another specification of these requirements.

BR5 and *BR5.1* for boundary property *prohibited* as well as *BR6* and *BR6.1* for boundary property *not possible* require similar behavior. Although an AV is not obliged to stop at these boundaries, it must not (or only in special cases) cross them. These behavioral requirements therefore lead to the same specification categories as for *BR1* and *BR1.1*. In these cases, too, the boundary must be identified and held at a given speed, or at least not crossed. It should be noted that planning a lane-accurate route generally excludes transitions with the requirements from the behavioral demands *prohibited* and *not possible*, since they are prohibited or not possible, respectively. Nevertheless, for the sake of completeness, specification categories are assigned.

For the behavioral requirements *BR1*, *BR1.1*, *BR5*, *BR5.1*, *BR6*, and *BR6.1*, the following specification categories result in total:

- Type of associated boundary
- Speed limit of relevant preceding behavior space(s)

No stagnant traffic

BR2, *BR2.1* and *BR2.2* essentially require that an AV must not travel through the associated behavior space if it cannot pass through and leave it without extended stopping times. Differences in these requirements arise from the geometry of the behavior space. Different lengths of the behavior spaces mean different distances that the AV must travel through. Depending on the lane-accurate route, an AV must perceive different areas in order to identify congested traffic. The area of the behavior space itself and the area of the following behavior space(s) are crucial. In these areas, there must not be any congested traffic and there must be sufficient space in the subsequent behavior space(s) for the AV to clear the critical area. Therefore, it is necessary that these geometric properties are part of the requirements specification. Especially for requirement *BR2.2* multiple concatenated behavior spaces with the property *no stagnant traffic* must be considered.

In addition to the geometry of the behavior space under consideration and the successive behavior space, the geometry of the preceding behavior space(s) is also relevant. Depending on which curvature is present in the previously concatenated behavior spaces, for example, the AV will approach the considered behavior space with a different orientation. Depending on the orientation, the relevant perceptual areas for the stagnant traffic differ. However, since based on the requirement specification it is not yet specified how exactly the vehicle aligns in the behavior spaces, the orientation of the AV cannot be part of the requirement specification. Rather, the orientation of the behavior spaces must be considered. The design and verification of the specific driving capabilities can thus be unrestricted, so that the actual orientation of the AV in the behavior space is defined in the development process.

Furthermore, if the behavior space under consideration is highly curved, as is the case with behavior spaces for turning, occlusion may occur. Depending on the position of potentially present planted areas, walls or buildings, the area to be monitored might not be completely visible or only visible at a late stage. If such occlusion is present, the driving behavior must be adjusted so that the requirements of *no stagnant traffic* are not violated. For example, depending on the type of occlusion, it may be necessary for an AV to slowly move into the considered behavior space so that the entire area can be observed. However, the specific solution to this problem is not part of the requirements specification, so it is not discussed further.

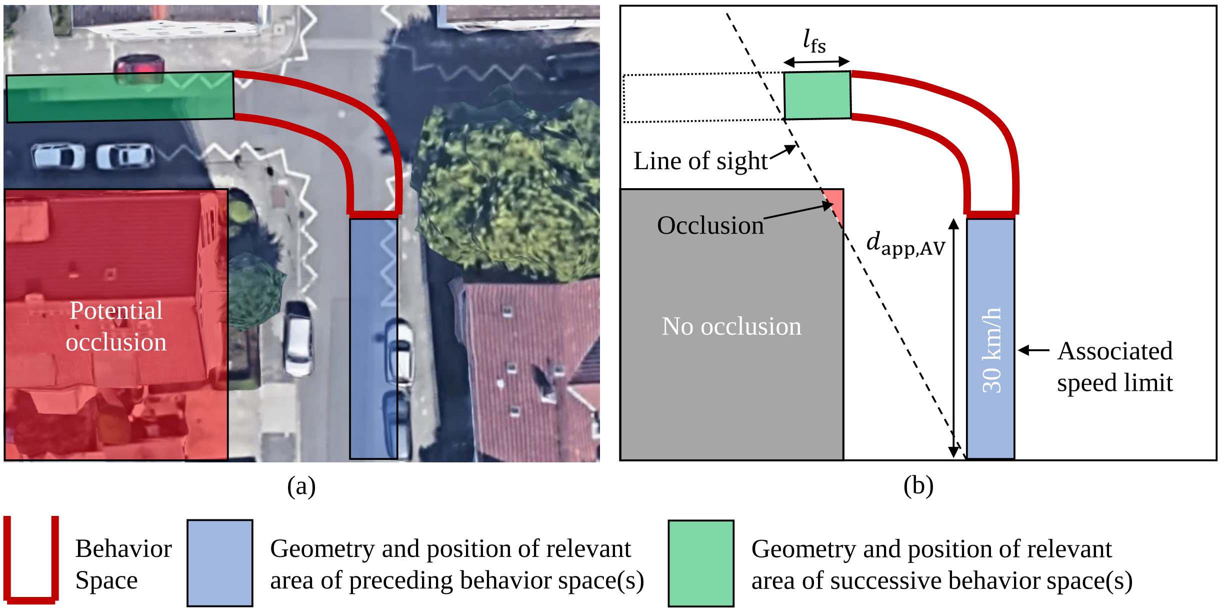
Last, the applicable speed limit of the relevant preceding behavior space(s) is also relevant for these requirements, since observing the traffic in the relevant areas may be challenging in different ways at different driving speeds. As for the case before, the speed limit has to be considered when approaching the behavior space under consideration.

Overall, for the requirements *BR2*, *BR2.1* and *BR2.2* the following specification categories are applicable:

- Geometry and position of considered behavior space(s)
- Geometry and position of relevant area of preceding behavior space(s)
- Speed limit of relevant preceding behavior space(s)
- Geometry and position of relevant area of successive behavior space(s)
- Geometry and position of relevant area of occlusion

Figure A-4 shows a possible specification of the requirements *BR2* and *BR2.1* comparing aerial image (a) and extracted specification (b). On the aerial image, the considered behavioral space (red) is shown for a left turn at an X-intersection. Thus, the *geometry of considered behavior space* is mapped. The *speed limit of preceding behavior space* is specified as 30 km/h in Figure A-4 b since the intersection is within a 30 km/h speed zone. The other specification categories are considered in more detail below.

Geometry and position of relevant area of preceding behavior space(s)
The area highlighted in blue shows the geometry and position of relevant area of preceding behavior space. Since there can be many preceding behavior spaces based on a route, a termination criterion must be defined to find the relevant area within the preceding behavior spaces. This means that the preceding behavior space(s) are only used for specification up to a certain distance starting from the considered behavior space and moving backwards. Without this termination criterion, it



(a) (b)

Figure A-4: Boundary requirement specification example for *no stagnant traffic*.
Imagery and map data ©2022 Google/AeroWest.

would be theoretically necessary to specify all preceding behavior spaces, since no information about the relevance is available. The preceding behavior space(s) are relevant if the DDT is performed in them with respect to the specified requirements. Thus, in this case, it is necessary to consider at what distance from the considered behavior space an AV potentially performs actions to cope with the required DDT at the earliest time. This requires a worst-case consideration for approaching the behavior space under consideration. In the case of stagnant traffic, the AV may not cross the boundary of the behavioral space. Thus, in principle, there are two ways in which an AV can approach the behavioral space. Either it decelerates to a standstill at the boundary or it approaches at a very low speed, so that ideally it does not have to stop. Since it is generally not possible to anticipate very far ahead in urban traffic, a very low deceleration to a standstill at the stop line is assumed. If a minimum deceleration is selected, the required stopping distance also leaves open the possibility of creeping up. The applicable speed limit is used as the initial speed of the AV, since this represents the maximum driving speed of the AV. The termination criterion for the relevant area of the preceding behavior space(s) is consequently calculated as the AV's approaching distance for stopping $d_{\text{app,AV}}$ based on a minimum deceleration $a_{\text{dec,min}}$ and the applicable speed limit $v_{\text{lim,AV}}$ for the AV:

$$d_{\text{app,AV}} = \frac{v_{\text{lim,AV}}^2}{2\,a_{\text{dec,min}}} \tag{A-3}$$

The approaching distance for stopping is shown in Figure A-4 b.

Geometry and position of relevant area of successive behavior space(s)

The green highlighted area in Figure A-4 a shows the successive behavior space. In addition to the considered behavior space, this behavior space must also be free of stagnant traffic to a certain extent. Specifically, an AV traveling through the considered behavior space must have sufficient free space in the successive space to clear the *no stagnant traffic* area. Consequently, it is not necessary to use the entire behavioral space marked in green in the aerial view to specify the requirements. In Figure A-4 b, the relevant space is shown with a reduced length. The length l_{fs} corresponds to the length of the free space required for the AV. This length is calculated using the vehicle length l_{AV} of the AV and an additional safety margin l_{sm}. As for the specification category of effective width, the vehicle geometry is required in this case, otherwise no concrete specification is possible. The safety margin is equivalent to conventional safety distances that are maintained, for example, when stopping in a queue of vehicles. The length of the free space and thus the stopping criterion for the successive behavior space is consequently given by:

$$l_{\mathrm{fs}} = l_{\mathrm{AV}} + l_{\mathrm{sm}} \tag{A-4}$$

Geometry and position of relevant area of occlusion

On the aerial view a potential occlusion is drawn in red. There is a building in this area, which could obscure an AV's view of one of the relevant areas previously identified. To identify if there is indeed occlusion, a line of sight is considered. In Figure A-4 b, this line of sight is drawn. It runs from the outer, front corner of the relevant area of the preceding behavior space to the outer corner of the relevant area of the successive behavior space. In general, the line of sight must be placed in such a way that the lateral extreme points of the areas are tangent to each other without intersecting the areas (even at other locations). The height of possible visual obstructions must be taken into account. Low fences or bridges are not necessarily a restriction for the line of sight. This ensures that the areas of occlusion relevant to the specification are covered. The result is colored in red in Figure A-4 b. In this case, the building on the left side of the road is only a small visual restriction at the beginning of the approach of an AV to the considered behavioral space.

No red light

BR3 and *BR3.1* require that when a traffic signal is in the red phase, it is not allowed to enter the associated behavior space. Intuitively, it is clear that the traffic signal itself is a crucial scenery element for specifying the requirements. An AV must know the phase of the traffic signal to meet these requirements. If a traffic signal is not equipped with a communication interface, an AV must perceive the phase itself without external information. Thus, different types of traffic lights can cause the AV to be subjected to different tests. For example, traffic lights can additionally differ in orientation such as vertical or horizontal, but also in the type of mounting such as standing or hanging. The type of traffic light has to be taken into account for specification accordingly. On top of that, the relative position of the traffic signal to the associated boundary (stop line or virtual (non existent) line) is relevant. Different positions potentially lead to different testing of the AV's capabilities. Finally, the geometry and position of the preceding behavior space must also be considered, as was already necessary for the requirements of *no stagnant traffic*.

Besides this specification categories, other categories can be assigned that have already been derived for other requirements such as the type of boundary and the speed limit before entry of the the behavior space under consideration.

Overall, the following specification categories result for the requirements *BR3* and *BR3.1*:

- Type of traffic light
- Position of traffic light
- Type of associated boundary
- Geometry and position of relevant area of preceding behavior space(s)
- Speed limit of relevant preceding behavior space(s)

A.3 Overtake Requirements

The requirements *OR1* and *OR1.1* are not requirements that specify overtaking per se. These requirements simply require that overtaking is not allowed in areas where overtaking is prohibited and that potential overtaking is completed before entering these areas. For the latter requirement, the speed limit both before and in the no overtaking area is relevant to demonstrating the appropriate capabilities. Higher speed limits potentially require higher speeds during overtaking, so potentially the distance traveled during overtaking is also increased. In addition, the speed limit may decrease in the area of the overtaking ban. Even under the circumstances of speed adjustment, the requirements of overtaking shall not be violated.

The following specification categories result for the *OR1.1* requirement:

- Speed limit of relevant preceding behavior space(s)
- Change of speed limit

Bibliography

Althoff, M. et al.: CommonRoad: Composable benchmarks for motion planning on roads (2017)
Althoff, Matthias; Koschi, Markus; Manzinger, Stefanie: CommonRoad: Composable benchmarks for motion planning on roads, in: 2017 IEEE Intelligent Vehicles Symposium (IV), pp. 719–726, 2017

Amersbach, C. et al.: Functional decomposition - Overcoming the parameter space explosion (2019)
Amersbach, Christian; Winner, Hermann: Functional decomposition - A contribution to overcome the parameter space explosion during validation of highly automated driving, in: Traffic Injury Prevention, Vol. 20, pp. S52–S57, 2019

Amersbach, C. et al.: Functional Decomposition: Reducing the Approval Effort for HAD (2017)
Amersbach, Christian; Winner, Hermann: Functional Decomposition: An Approach to Reduce the Approval Effort for Highly Automated Driving, in: 8. Tagung Fahrerassistenz, Lehrstuhl für Fahrzeugtechnik mit TÜV SÜD Akademie, 2017

Anderson, J. M.; Kalra, N.; Stanley, K. D.; Sorensen, P.; Samaras, C.; Oluwatola, T. A.: Autonomous Vehicle Technology: A Guide for Policymakers (2016)
Anderson, James M.; Kalra, Nidhi; Stanley, Karlyn D.; Sorensen, Paul; Samaras, Constantine; Oluwatola, Tobi A.: Autonomous Vehicle Technology: A Guide for Policymakers, RAND Corporation, 2016

Armand, A. et al.: Ontology-based context awareness for driving assistance systems (2014)
Armand, Alexandre; Filliat, David; Ibañez-Guzman, Javier: Ontology-based context awareness for driving assistance systems, in: 2014 IEEE Intelligent Vehicles Symposium Proceedings, pp. 227–233, 2014

Armand, A. et al.: Digital Maps for Driving Assistance Systems and Autonomous Driving (2017)
Armand, Alexandre; Ibanez-Guzman, Javier; Zinoune, Clément: Digital Maps for Driving Assistance Systems and Autonomous Driving, in: Watzenig, Daniel; Horn, Martin (PUB): Automated Driving: Safer and More Efficient Future Driving, Springer International Publishing, 2017

ASAM: OpenDRIVE (2021)
ASAM: OpenDRIVE, URL: https://www.asam.net/standards/detail/opendrive/, 2021, visited on 11/06/2022

ASAM: OpenODD (2021)
ASAM: OpenODD, URL: https://www.asam.net/standards/detail/openodd/, 2021, visited on 11/06/2022

ASAM: OpenSCENARIO (2022)
ASAM: OpenSCENARIO, URL: https://www.asam.net/standards/detail/openscenario/, 2022, visited on 11/06/2022

Bagschik, G. et al.: Wissensbasierte Szenariengenerierung für Betriebsszenarien auf Autobahnen (2018)
Bagschik, G.; Menzel, T.; Körner, C.; Maurer, M.: Wissensbasierte Szenariengenerierung für Betriebsszenarien auf Autobahnen, in: 12. Workshop Fahrerassistenzsysteme und automatisiertes Fahren, 2018

Bagschik, G.: Systematischer Einsatz von Szenarien für die Absicherung automatisierter Fahrzeuge (2022)
Bagschik, Gerrit: Systematischer Einsatz von Szenarien für die Absicherung automatisierter Fahrzeuge am Beispiel deutscher Autobahnen, Dissertation, Technische Universität Braunschweig, 2022

Bagschik, G. et al.: Ontology based Scene Creation for the Development of Automated Vehicles (2018)
Bagschik, Gerrit; Menzel, Till; Maurer, Markus: Ontology based Scene Creation for the Development of Automated Vehicles, in: 2018 IEEE Intelligent Vehicles Symposium (IV), pp. 1813–1820, 2018

Bagschik, G. et al.: A System's Perspective Towards an Architecture Framework for Safe AVs (2018)
Bagschik, Gerrit; Nolte, Marcus; Ernst, Susanne; Maurer, Markus: A System's Perspective Towards an Architecture Framework for Safe Automated Vehicles, in: 2018 21st International Conference on Intelligent Transportation Systems (ITSC), pp. 2438–2445, 2018

Bast, H. et al.: Route Planning in Transportation Networks (2016)
Bast, Hannah; Delling, Daniel; Goldberg, Andrew; Müller-Hannemann, Matthias; Pajor, Thomas; Sanders, Peter; Wagner, Dorothea; Werneck, Renato F.: Route Planning in Transportation Networks, in: Kliemann, Lasse; Sanders, Peter (PUB): Algorithm Engineering: Selected Results and Surveys, Springer International Publishing, 2016

Benda, H. von et al.: Klassifikation und Gefährlichkeit von Straßenverkehrssituationen (1983)
Benda, Helga von; Hoyos, K. G.; Schaible-Rapp, Agnes: Klassifikation und Gefährlichkeit von Straßenverkehrssituationen, in: FORSCHUNGSBER BAST, 1983

Bender, P. et al.: Lanelets: Efficient map representation for autonomous driving (2014)
Bender, Philipp; Ziegler, Julius; Stiller, Christoph: Lanelets: Efficient map representation for autonomous driving, in: Intelligent Vehicles Symposium Proceedings, 2014 IEEE, pp. 420–425, 2014

BMDV: Längenstatistik der Straßen des überörtlichen Verkehrs (2021)
BMDV: Längenstatistik der Straßen des überörtlichen Verkehrs, URL: https://www.bmvi.de/SharedDocs/DE/Artikel/StB/bestandsaufnahme-strassen-ueberoertlich.html, 2021, visited on 05/23/2022

BMJ: Erläuterungen zur Straßenverkehrs-Ordnung (2019)
BMJ: Erläuterungen zur Straßenverkehrs-Ordnung, 2019

BMJ: Straßenverkehrs-Ordnung (StVO) (2013)
BMJ: Straßenverkehrs-Ordnung (StVO), 2013

BMV and BMU: Allgemeine Verwaltungsvorschrift zur StVO (VwV-StVO) (2001)
BMV and BMU: Allgemeine Verwaltungsvorschrift zur Straßenverkehrs-Ordnung (VwV-StVO), 2001

Bock, J. et al.: Data basis for scenario-based validation of HAD on highways (2018)
Bock, Julian; Krajewski, R; Eckstein, L; Klimke, J; Sauerbier, J; Zlocki, A: Data basis for scenario-based validation of HAD on highways, in: 27th Aachen colloquium automobile and engine technology, pp. 8–10, 2018

BSI: PAS 1881:2022: Assuring the operational safety of automated vehicles – Specification (2022)
BSI: PAS 1881:2022: Assuring the operational safety of automated vehicles – Specification, 2022

BSI: PAS 1883:2020: ODD taxonomy for an automated driving system - Specification (2020)
BSI: PAS 1883:2020: Operational design domain (ODD) taxonomy for an automated driving system (ADS) - Specification, 2020

Buechel, M. et al.: Ontology-based scene modeling, situational awareness and decision-making for AVs (2017)
Buechel, Martin; Hinz, Gereon; Ruehl, Frederik; Schroth, Hans; Gyoeri, Csaba; Knoll, Alois: Ontology-based traffic scene modeling, traffic regulations dependent situational awareness and decision-making for automated vehicles, in: 28th IEEE Intelligent Vehicles Symposium, pp. 1471–1476, 2017

Butz, M. et al.: SOCA: Domain Analysis for Highly Automated Driving Systems (2020)
Butz, Martin; Heinzemann, Christian; Herrmann, Martin; Oehlerking, Jens; Rittel, Michael; Schalm, Nadja; Ziegenbein, Dirk: SOCA: Domain Analysis for Highly Automated Driving Systems, in: 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC), pp. 1–6, 2020

Cambridge University Press & Assessment: Meaning of route in English (2022)
Cambridge University Press & Assessment: Meaning of route in English, URL: https://dictionary.cambridge.org/dictionary/english/route, 2022, visited on 07/14/2022

Censi, A. et al.: Liability, Ethics, and Culture-Aware Behavior Specification using Rulebooks (2019)
Censi, Andrea; Slutsky, Konstantin; Wongpiromsarn, Tichakorn; Yershov, Dmitry; Pendleton, Scott; Fu, James; Frazzoli, Emilio: Liability, Ethics, and Culture-Aware Behavior Specification using Rulebooks, URL: https://arxiv.org/pdf/1902.09355, 2019

Colwell, I. et al.: An AV Safety Concept Based on Runtime Restriction of the ODD (2018)
Colwell, Ian; Phan, Buu; Saleem, Shahwar; Salay, Rick; Czarnecki, Krzysztof: An Automated Vehicle Safety Concept Based on Runtime Restriction of the Operational Design Domain, in: 2018 IEEE Intelligent Vehicles Symposium (IV), pp. 1910–1917, 2018

Czarnecki, K.: ADS High-Level Quality Requirements Analysis - Driving Behavior Safety (2018)
Czarnecki, Krzysztof: Automated Driving System (ADS) High-Level Quality Requirements Analysis - Driving Behavior Safety, Waterloo Intelligent Systems Engineering (WISE) Lab, University of Waterloo, 2018

Czarnecki, K.: Operational Design Domain for Automated Driving Systems (2018)
Czarnecki, Krzysztof: Operational Design Domain for Automated Driving Systems - Taxonomy of Basic Terms, Waterloo Intelligent Systems Engineering (WISE) Lab, University of Waterloo, 2018

Czarnecki, K.: Operational World Model Ontology for Automated Driving Systems - Part 1 (2018)
Czarnecki, Krzysztof: Operational World Model Ontology for Automated Driving Systems - Part 1: Road Structure, Waterloo Intelligent Systems Engineering (WISE) Lab, University of Waterloo, 2018

Czarnecki, K.: Operational World Model Ontology for Automated Driving Systems - Part 2 (2018)
Czarnecki, Krzysztof: Operational World Model Ontology for Automated Driving Systems - Part 2: Road Users, Animals, Other Obstacles, and Environmental Conditions, Waterloo Intelligent Systems Engineering (WISE) Lab, University of Waterloo, 2018

Delling, D. et al.: Engineering Route Planning Algorithms (2009)
Delling, Daniel; Sanders, Peter; Schultes, Dominik; Wagner, Dorothea: Engineering Route Planning Algorithms, in: Lerner, Jürgen; Wagner, Dorothea; Zweig, Katharina A. (PUB): Algorithmics of Large and Complex Networks: Design, Analysis, and Simulation, Springer Berlin Heidelberg, 2009

Dijkstra, E. W.: A note on two problems in connexion with graphs (1959)
Dijkstra, E. W.: A note on two problems in connexion with graphs, in: Numerische Mathematik, Vol. 1, pp. 269–271, 1959

DIN 69901-5:2009-01: Projektmanagement - Projektmanagementsysteme - Teil 5: Begriffe (2009)
DIN 69901-5:2009-01: Projektmanagement - Projektmanagementsysteme - Teil 5: Begriffe, 2009

Erz, J. et al.: Ontology That Reconciles the ODD, Scenario-based Testing, and AV Architectures (2022)
Erz, Jannis; Schütt, Barbara; Braun, Thilo; Guissouma, Houssem; Sax, Eric: Towards an Ontology That Reconciles the Operational Design Domain, Scenario-based Testing, and Automated Vehicle Architectures, in: 2022 IEEE International Systems Conference (SysCon), pp. 1–8, 2022

Esterle, K. et al.: Formalizing Traffic Rules for Machine Interpretability (2020)
Esterle, Klemens; Gressenbuch, Luis; Knoll, Alois: Formalizing Traffic Rules for Machine Interpretability, in: 2020 IEEE 3rd Connected and Automated Vehicles Symposium (CAVS), pp. 1–7, 2020

Fastenmeier, W. et al.: Autofahrer und Verkehrssituation (1995)
Fastenmeier, Wolfgang et al.: Autofahrer und Verkehrssituation. Neue Wege zur Bewertung von Sicherheit und Zuverlässigkeit moderner Strassenverkehrssysteme, 1995

Fastenmeier, W.: Die Verkehrssituation als Analyseeinheit im Verkehrssystem (1995)
Fastenmeier, Wolfgang: Die Verkehrssituation als Analyseeinheit im Verkehrssystem, in: MENSCH FAHRZEUG UMWELT, 1995

FGSV: Richtlinien für die Anlage von Autobahnen (RAA) (2008)
FGSV: Richtlinien für die Anlage von Autobahnen (RAA), 2008

FGSV: Richtlinien für die Anlage von Landstraßen (RAL) (2012)
FGSV: Richtlinien für die Anlage von Landstraßen (RAL), 2012

FGSV: Richtlinien für die Anlage von Stadtstraßen (RASt) (2006)
FGSV: Richtlinien für die Anlage von Stadtstraßen (RASt), 2006

Fricke, J. et al.: Towards Knowledge-based Road Modeling for Automated Vehicles (2021)
Fricke, Jenny; Plachetka, Christopher; Rech, Bernd: Towards Knowledge-based Road Modeling for Automated Vehicles: Analysis and Concept for Incorporating Prior Knowledge, in: 2021 IEEE Intelligent Vehicles Symposium Workshops (IV Workshops), pp. 49–56, 2021

FZI Forschungszentrum Informatik: Lanelet2 GitHub repository (2018)
FZI Forschungszentrum Informatik: Lanelet2 GitHub repository, URL: https://github.com/fzi-forschungszentrum-informatik/Lanelet2, 2018, visited on 11/01/2022

Geyer, S. et al.: Unified ontology for generating test and use–case catalogues for vehicle guidance (2014)
Geyer, Sebastian; Baltzer, Marcel; Franz, Benjamin; Hakuli, Stephan; Kauer, Michaela; Kienle, Martin; Meier, Sonja; Weißgerber, Thomas; Bengler, Klaus; Bruder, Ralph; Flemisch, Frank; Winner, Hermann: Concept and development of a unified ontology for generating test and use–case catalogues for assisted and automated vehicle guidance, in: IET Intelligent Transport Systems, Vol. 8, pp. 183–189, 2014

Glatzki, F. et al.: Behavioral Attributes for a Behavior-Semantic Scenery Description (2021)
Glatzki, Felix; Lippert, Moritz; Winner, Hermann: Behavioral Attributes for a Behavior-Semantic Scenery Description (BSSD) for the Development of Automated Driving Functions, in: 2021 IEEE International Intelligent Transportation Systems Conference (ITSC), pp. 667–672, 2021

Google LLC: Google Earth (2022)
Google LLC: Google Earth, URL: https://earth.google.com/, 2022, visited on 07/14/2022

Gruber, T. R.: A translation approach to portable ontology specifications (1993)
Gruber, Thomas R.: A translation approach to portable ontology specifications, in: Knowledge Acquisition, Vol. 5, pp. 199–220, 1993

Gyllenhammar, M. et al.: Towards an Operational Design Domain for Safety Argumentation of ADS (2020)
Gyllenhammar, Magnus; Johansson, Rolf; Warg, Fredrik; Chen, Dejiu; Heyn, Hans-Martin; Sanfridson, Martin; Söderberg, Jan; Thorsén, Anders; Ursing, Stig: Towards an Operational Design Domain That Supports the Safety Argumentation of an Automated Driving System, in: 10th European Congress on Embedded Real Time Software and Systems (ERTS 2020), 2020

Haklay, M. et al.: OpenStreetMap: User-Generated Street Maps (2008)
Haklay, M.; Weber, P.: OpenStreetMap: User-Generated Street Maps, in: IEEE Pervasive Computing, Vol. 7, pp. 12–18, 2008

Hamilton, A. et al.: Semantic-based approach for route determination and ontologyupdating (2013)
Hamilton, A.; González, E.J.; Acosta, L.; Arnay, R.; Espelosín, J.: Semantic-based approach for route determination and ontologyupdating, in: Engineering Applications of Artificial Intelligence, Vol. 26, pp. 1174–1184, 2013

Hülsen, M. et al.: Traffic intersection situation description ontology for advanced driver assistance (2011)
Hülsen, Michael; Zollner, J. Marius; Weiss, Christian: Traffic intersection situation description ontology for advanced driver assistance, in: 2011 IEEE Intelligent Vehicles Symposium (IV 2011), pp. 993–999, 2011

IEC: IEC 61025:2006 - Fault Tree Analysis (FTA) (2006)
IEC: IEC 61025:2006 - Fault Tree Analysis (FTA), 2006

ISO: ISO 21448:2022: Road vehicles - Safety of the intended functionality (2022)
ISO: ISO 21448:2022: Road vehicles - Safety of the intended functionality, 2022

ISO: ISO 26262:2011: Road vehicles - Functional safety (2011)
ISO: ISO 26262:2011: Road vehicles - Functional safety, 2011

ISO: ISO 34502:2022: Road vehicles - Scenario based safety evaluation framework (2022)
ISO: ISO 34502:2022: Road vehicles - Test scenarios for automated driving systems - Scenario based safety evaluation framework, 2022

ISO: ISO/DIS 34503: Road Vehicles - Taxonomy for operational design domain (2022)
ISO: ISO/DIS 34503: Road Vehicles - Test scenarios for automated driving systems - Taxonomy for operational design domain, 2022

ISO: ISO/TR 4804:2020: Road vehicles - Safety and cybersecurity for automated driving systems (2020)
ISO: ISO/TR 4804:2020: Road vehicles - Safety and cybersecurity for automated driving systems - Design, verification and validation, 2020

ISO/SAE: ISO/SAE 21434:2021: Road vehicles - Cybersecurity engineering (2021)
ISO/SAE: ISO/SAE 21434:2021: Road vehicles - Cybersecurity engineering, 2021

Jatzkowski, I. et al.: Automatic Construction of Skill Graphs for Online Monitoring (2021)
Jatzkowski, Inga; Menzel, Till; Bock, Ansgar; Maurer, Markus: A Knowledge-based Approach for the Automatic Construction of Skill Graphs for Online Monitoring, in: 2021 IEEE Intelligent Vehicles Symposium (IV), pp. 142–149, 2021

JOSM: Extensible editor for OpenStreetMap (2021)
JOSM: Extensible editor for OpenStreetMap, URL: https://josm.openstreetmap.de/, 2021

Junietz, P. et al.: Evaluation of Different Approaches to Address Safety Validation of Automated Driving (2018)
Junietz, Philipp; Wachenfeld, Walther; Klonecki, Kamil; Winner, Hermann: Evaluation of Different Approaches to Address Safety Validation of Automated Driving, in: 2018 21st International Conference on Intelligent Transportation Systems (ITSC), pp. 491–496, 2018

Karimi, A. et al.: Formalizing traffic rules for uncontrolled intersections (2020)
Karimi, Abolfazl; Duggirala, Parasara Sridhar: Formalizing traffic rules for uncontrolled intersections, in: 2020 ACM/IEEE 11th International Conference on Cyber-Physical Systems (ICCPS), pp. 41–50, 2020

Klamann, B. et al.: Defining Pass-/Fail-Criteria for Particular Tests of Automated Driving Functions (2019)
Klamann, Björn; Lippert, Moritz; Amersbach, Christian; Winner, Hermann: Defining Pass-/Fail-Criteria for Particular Tests of Automated Driving Functions, in: 2019 IEEE Intelligent Transportation Systems Conference (ITSC), pp. 169–174, 2019

Kroeger, P. R.: Analyzing meaning (2019)
Kroeger, Paul R.: Analyzing meaning, Textbooks in Language Sciences, Language Science Press, 2019

Leveson, N. G.: STPA: A New Hazard Analysis Technique (2012)
Leveson, Nancy G.: STPA: A New Hazard Analysis Technique, in: (PUB): Engineering a Safer World: Systems Thinking Applied to Safety, The MIT Press, 2012

Lippert, M. et al.: Behavior-Semantic Scenery Description (BSSD) for Automated Driving (2022)
Lippert, Moritz; Glatzki, Felix; Winner, Hermann: Behavior-Semantic Scenery Description (BSSD) of Road Networks for Automated Driving, URL: https://arxiv.org/abs/2202.05211, 2022

Lippert, M. et al.: Capability-Based Routes for Safe Automated Vehicles (2023)
Lippert, Moritz; Winner, Hermann: Capability-Based Routes for Development, Testing and Operation of Safe Automated Vehicles, in: Conference Proceedings of the 27th International Technical Conference on the Enhanced Safety of Vehicles (ESV), 2023

Lippert, M. et al.: Behavioral Requirements for Automated Driving (2022)
Lippert, Moritz; Winner, Hermann: How to Derive Behavioral Requirements for Automated Driving from a Behavior-Semantic Scenery Description, in: 14. Uni-DAS e.V. Workshop Fahrerassistenz und automatisiertes Fahren, pp. 217–229, 2022

Maierhofer, S. et al.: Formalization of Intersection Traffic Rules in Temporal Logic (2022)
Maierhofer, Sebastian; Moosbrugger, Paul; Althoff, Matthias: Formalization of Intersection Traffic Rules in Temporal Logic, in: 2022 IEEE Intelligent Vehicles Symposium (IV), pp. 1135–1144, 2022

Maierhofer, S. et al.: Formalization of Interstate Traffic Rules in Temporal Logic (2020)
Maierhofer, Sebastian; Rettinger, Anna-Katharina; Mayer, Eva Charlotte; Althoff, Matthias: Formalization of Interstate Traffic Rules in Temporal Logic, in: 2020 IEEE Intelligent Vehicles Symposium (IV), pp. 752–759, 2020

Neidhardt, E. et al.: Route Planning Based on Street Criteria for Autonomous Driving Vehicles (2021)
Neidhardt, Eric; Suske, David: Route Planning Based on Street Criteria for Autonomous Driving Vehicles, in: 2021 5th International Conference on Vision, Image and Signal Processing (ICVISP), pp. 45–48, 2021

Nilsson, N. J.: Principles of artificial intelligence (1982)
Nilsson, Nils J: Principles of artificial intelligence, Springer Science & Business Media, 1982

Nolte, M. et al.: Skill- and ability-based development process for self-aware automated road vehicles (2017)
Nolte, Marcus; Bagschik, Gerrit; Jatzkowski, Inga; Stolte, Torben; Reschka, Andreas; Maurer, Markus: Towards a skill- and ability-based development process for self-aware automated road vehicles, in: 2017 IEEE Intelligent Transportation Systems Conference, pp. 1–6, 2017

Object Management Group: Unified Modeling Language Specification Version 2.51 (2017)
Object Management Group: Unified Modeling Language Specification Version 2.51, URL: https://www.omg.org/spec/UML/2.5.1/, 2017, visited on 05/23/2022

Ollier, G. et al.: Using Operational Design Domain in Hazard Identification for Automated Systems (2022)
Ollier, Guillaume; Razafindrabe, Diana; Adedjouma, Morayo; Gerasimou, Simos; Mraidha, Chokri: Using Operational Design Domain in Hazard Identification for Automated Systems, in: 2022 18th European Dependable Computing Conference (EDCC), pp. 109–112, 2022

OpenStreetMap Contributors: OpenStreetMap (2022)
OpenStreetMap Contributors: OpenStreetMap, URL: https://www.openstreetmap.org/, 2022

Pek, C. et al.: Using online verification to prevent autonomous vehicles from causing accidents (2020)
Pek, Christian; Manzinger, Stefanie; Koschi, Markus; Althoff, Matthias: Using online verification to prevent autonomous vehicles from causing accidents, in: Nature Machine Intelligence, Vol. 2, pp. 518–528, 2020

Perdomo Lopez, D. et al.: Scenario Interpretation based on Primary Situations at Urban Intersections (2017)
Perdomo Lopez, David; Waldmann, Rene; Joerdens, Christian; Rojas, Raúl: Scenario Interpretation based on Primary Situations for Automatic Turning at Urban Intersections, in: VEHITS 2017, pp. 15–23, 2017

Poggenhans, F. et al.: Lanelet2: A high-definition map framework for the future of automated driving (2018)
Poggenhans, Fabian; Pauls, Jan-Hendrik; Janosovits, Johannes; Orf, Stefan; Naumann, Maximilian; Kuhnt, Florian; Mayr, Matthias: Lanelet2: A high-definition map framework for the future of automated driving, in: 2018 IEEE Intelligent Transportation Systems Conference, pp. 1672–1679, 2018

Popper, K. R.: The logic of scientific discovery (1959)
Popper, Karl R.: The logic of scientific discovery, 1959

Queiroz, R. et al.: GeoScenario: An Open DSL for Autonomous Driving Scenario Representation (2019)
Queiroz, Rodrigo; Berger, Thorsten; Czarnecki, Krzysztof: GeoScenario: An Open DSL for Autonomous Driving Scenario Representation, in: 2019 IEEE Intelligent Vehicles Symposium (IV), pp. 287–294, 2019

Regele, R.: Using Ontology-Based Traffic Models for More Efficient Decision Making of AVs (2008)
Regele, Ralf: Using Ontology-Based Traffic Models for More Efficient Decision Making of Autonomous Vehicles, in: Fourth International Conference on Autonomic and Autonomous Systems, 2008, pp. 94–99, 2008

Reid, T. G. R. et al.: Localization Requirements for Autonomous Vehicles (2019)
Reid, Tyler G. R.; Houts, Sarah E.; Cammarata, Robert; Mills, Graham; Agarwal, Siddharth; Vora, Ankit; Pandey, Gaurav: Localization Requirements for Autonomous Vehicles, in: CoRR, Vol. abs/1906.01061, 2019

Reschka, A.: Fertigkeiten- und Fähigkeitengraphen für automatisierte Fahrzeugen (2017)
Reschka, Andreas: Fertigkeiten- und Fähigkeitengraphen als Grundlage des sicheren Betriebs von automatisierten Fahrzeugen im öffentlichen Straßenverkehr in städtischer Umgebung, Dissertation, Technische Universität Braunschweig, 2017

Reschka, A. et al.: Ability and skill graphs for vehicle guidance systems (2015)
Reschka, Andreas; Bagschik, Gerrit; Ulbrich, Simon; Nolte, Marcus; Maurer, Markus: Ability and skill graphs for system modeling, online monitoring, and decision support for vehicle guidance systems, in: 2015 IEEE Intelligent Vehicles Symposium (IV), pp. 933–939, 2015

SAE: SAE J3016: Taxonomy and Definitions of Terms for Automation Systems (2021)
SAE: SAE J3016: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, 2021

SAE ITC: AVSC Best Practice for Describing an Operational Design Domain (2020)
SAE ITC: Automated Vehicle Safety Consortium (AVSC) Best Practice for Describing an Operational Design Domain: Conceptual Framework and Lexicon (AVSC00002202004), 2020

Scholtes, M. et al.: Structured Description and Categorization of Urban Traffic and Environment (2021)
Scholtes, Maike; Westhofen, Lukas; Turner, Lara Ruth; Lotto, Katrin; Schuldes, Michael; Weber, Hendrik; Wagener, Nicolas; Neurohr, Christian; Bollmann, Martin Herbert; Körtke, Franziska; Hiller, Johannes; Hoss, Michael; Bock, Julian; Eckstein, Lutz: 6-Layer Model for a Structured Description and Categorization of Urban Traffic and Environment, in: IEEE Access, Vol. 9, pp. 59131–59147, 2021

Schönemann, V. et al.: Scenario-Based Functional Safety for Automated Valet Parking (2019)
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: Advances in Information and Communication Networks, pp. 53–64, 2019

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

Schuldt, F. et al.: Effiziente systematische Testgenerierung in virtuellen Umgebungen (2013)
Schuldt, Fabian; Saust, Falko; Lichte, Bernd; Maurer, Markus; Scholz, Stephan: Effiziente systematische Testgenerierung für Fahrerassistenzsysteme in virtuellen Umgebungen, 2013

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, URL: http://arxiv.org/pdf/1708.06374v6, 2017

Statistisches Bundesamt (Destatis): Verkehrsunfälle - Grundbegriffe der Verkehrsunfallstatistik (2022)
Statistisches Bundesamt (Destatis): Verkehrsunfälle - Grundbegriffe der Verkehrsunfallstatistik, 2022

Stolte, T. et al.: Safety goals and functional safety requirements for actuation systems of AVs (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), pp. 2191–2198, 2016

Stolte, T. et al.: Hazard analysis and risk assessment for an automated unmanned protective vehicle (2017)
Stolte, Torben; Bagschik, Gerrit; Reschka, Andreas; Maurer, Markus: Hazard analysis and risk assessment for an automated unmanned protective vehicle, in: 28th IEEE Intelligent Vehicles Symposium, pp. 1848–1855, 2017

Taha, A.-E. et al.: Route Planning Considerations for Autonomous Vehicles (2018)
Taha, Abd-Elhamid; Abu Ali, Najah: Route Planning Considerations for Autonomous Vehicles, in: IEEE Communications Magazine, Vol. 56, pp. 78–84, 2018

Thorn, E. et al.: A Framework for Automated Driving System Testable Cases and Scenarios (2018)
Thorn, Eric; Kimmel, Shawn; Chaka, Michelle: A Framework for Automated Driving System Testable Cases and Scenarios, Report No. DOT HS 812 623, National Highway Traffic Safety Administration, Washington, DC, 2018

Ulbrich, S. et al.: Terms Scene, Situation, and Scenario for Automated Driving (2015)
Ulbrich, Simon; Menzel, Till; Reschka, Andreas; Schuldt, Fabian; Maurer, Markus: Defining and Substantiating the Terms Scene, Situation, and Scenario for Automated Driving, in: 2015 IEEE 18th International Conference on Intelligent Transportation Systems (ITSC 2015), pp. 982–988, 2015

Ulbrich, S. et al.: Context representation, environment modeling and information aggregation for AD (2014)
Ulbrich, Simon; Nothdurft, Tobias; Maurer, Markus; Hecker, Peter: Graph-based context representation, environment modeling and information aggregation for automated driving, in: Intelligent Vehicles Symposium Proceedings, 2014 IEEE, pp. 541–547, 2014

VRM Redaktion: Anwohner zählen Verkehr auf Dieburger Straße (2022)
VRM Redaktion: Anwohner zählen Verkehr auf Dieburger Straße, URL: https://www.main-spitze.de/lokales/darmstadt/anwohner-zaehlen-verkehr-auf-dieburger-strasse-1901929, 2022, visited on 10/01/2022

Wachenfeld, W. et al.: The Release of Autonomous Vehicles (2016)
Wachenfeld, Walther; Winner, Hermann: The Release of Autonomous Vehicles, in: Maurer, Markus; Lenz, Barbara; Winner, Hermann; Gerdes, J. Christian (PUB): Autonomous Driving: Technical, Legal and Social Aspects, Springer, 2016

Waymo: Waymo Safety Report (2021)
Waymo: Waymo Safety Report, 2021

Zhao, L. et al.: Ontology-Based Driving Decision Making: Feasibility at Uncontrolled Intersections (2017)
Zhao, Lihua; Ichise, Ryutaro; Liu, Zheng; Mita, Seiichi; Sasaki, Yutaka: Ontology-Based Driving Decision Making: A Feasibility Study at Uncontrolled Intersections, in: IEICE Transactions on Information and Systems, Vol. E100.D, pp. 1425–1439, 2017

Zhao, L. et al.: Fast decision making using ontology-based knowledge base (2016)
Zhao, Lihua; Ichise, Ryutaro; Sasaki, Yutaka; Liu, Zheng; Yoshikawa, Tatsuya: Fast decision making using ontology-based knowledge base, in: 2016 IEEE Intelligent Vehicles Symposium (IV), pp. 173–178, 2016

Zhao, L. et al.: Ontology-based decision making on uncontrolled intersections and narrow roads (2015)
Zhao, Lihua; Ichise, Ryutaro; Yoshikawa, Tatsuya; Naito, Takeshi; Kakinami, Toshiaki; Sasaki, Yutaka: Ontology-based decision making on uncontrolled intersections and narrow roads, in: 2015 IEEE Intelligent Vehicles Symposium (IV), pp. 83–88, 2015

Ziegler, J. et al.: Making Bertha Drive - An Autonomous Journey on a Historic Route (2014)
Ziegler, Julius; Bender, Philipp; Schreiber, Markus; Lategahn, Henning; Strauss, Tobias; Stiller, Christoph; Dang, Thao; Franke, Uwe; Appenrodt, Nils; Keller, Christoph G.; Kaus, Eberhard; Herrtwich, Ralf G.; Rabe, Clemens; Pfeiffer, David; Lindner, Frank; Stein, Fridtjof; Erbs, Friedrich; Enzweiler, Markus; Knöppel, Carsten; Hipp, Jochen; Haueis, Martin; Trepte, Maximilian; Brenk, Carsten; Tamke, Andreas; Ghanaat, Mohammad; Braun, Markus; Joos, Armin; Fritz, Hans; Mock, Horst; Hein, Martin; Zeeb, Eberhard: Making Bertha Drive - An Autonomous Journey on a Historic Route, in: IEEE Intelligent Transportation Systems Magazine, Vol. 6, pp. 8–20, 2014

Own Publications

Lippert, Moritz; Winner, Hermann:
Capability-Based Routes for Development, Testing and Operation of Safe Automated Vehicles, in: Conference Proceedings of the 27th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Yokohama, Japan, 2023.

Lippert, Moritz; Glatzki, Felix; Winner, Hermann:
Behavior-Semantic Scenery Description (BSSD) of Road Networks for Automated Driving, submitted to the IEEE for possible publication in IEEE Access, URL: https://arxiv.org/abs/2202.05211, 2022.

Lippert, Moritz; Winner, Hermann:
How to Derive Behavioral Requirements for Automated Driving from a Behavior-Semantic Scenery Description, in: 14. Uni-DAS e.V. Workshop Fahrerassistenz und automatisiertes Fahren, pp. 217-229, Berkheim, Germany, Uni-DAS e.V., ISBN 978-3-941543-65-2, 2022.

Glatzki, Felix; Lippert, Moritz; Winner, Hermann:
Behavioral Attributes for a Behavior-Semantic Scenery Description (BSSD) for the Development of Automated Driving Functions, in: 2021 IEEE International Intelligent Transportation Systems Conference (ITSC), pp. 667-672, Indianapolis, IN, USA, IEEE, DOI: 10.1109/ITSC48978.2021.9564892, 2021.

Stolte, Torben; Graubohm, Robert; Jatzkowski, Inga; Maurer, Markus; Ackermann, Stefan; Klamann, Björn; Lippert, Moritz; Winner, Hermann:
Towards Safety Concepts for Automated Vehicles by the Example of the Project UNICARagil, in: 29th Aachen Colloquium, pp. 1561-1594, Aachen, ISBN 978-3-00-064871-7, 2020.

Lippert, Moritz; Klamann, Björn; Amersbach, Christian; Winner, Hermann:
Definition von Bestehens-/Versagenskriterien für das partikuläre Testen von automatisierten Fahrfunktionen, in: 9. Tagung Automatisiertes Fahren, München, Germany, DOI: 10.25534/tuprints-00009663, 2020.

Klamann, Björn; Lippert, Moritz; Amersbach, Christian; Winner, Hermann:
Defining Pass-/Fail-Criteria for Particular Tests of Automated Driving Functions, in: 2019 IEEE Intelligent Transportation Systems Conference (ITSC), pp. 169-174, Auckland, New Zealand, IEEE, DOI: 10.1109/ITSC.2019.8917483, 2019.

Supervised Theses

Abali, Emre: Definition von Anforderungen und Sicherheitszielen für automatisierte Fahrzeuge und deren Ableitung auf Modulebene. Master Thesis No. 772/20, 2020

Aghadavoodi, Erfan: Entwicklung und Implementierung einer Funktion zur Identifikation von sicheren Halteorten für fahrerlose Fahrzeuge. Bachelor Thesis No. 1399/22, 2022

Berghöfer, Moritz: Entwicklung eines Konzepts zur Integration der verhaltenssemantischen Szeneriebeschreibung in hochgenaue Karten. Master Thesis No. 839/21, 2022

Glatzki, Felix: Szenarienbasierte Beschreibung von Anwendungsfällen für das urbane automatisierte Fahren. Master Thesis No. 741/19, 2019

Hildebrand, Jannik: Entwicklung eines Frameworks zur automatisierten Generierung der BSSD-Erweiterung für lanelet2-Karten. Master Thesis No. 837/21, 2022

Hildebrand, Jannik: Entwicklung eines Tools zur Extraktion von kartenbasierten Merkmalen für die Kategorisierung von Streckenabschnitten. Bachelor Thesis No. 1338/19, 2019

Hoppen, Fabian: Entwicklung einer Methodik zur Identifikation von sicheren Orten für Nothaltemanöver fahrerloser Fahrzeuge. Master Thesis No. 771/20, 2020

Hülsmann, Robert: Formal Falsification Criteria as a Basis for Behavior Planning based on Reinforcement Learning Algorithms. Master Thesis No. 792/20, 2021

Krämer, Eric: Erweiterung und Implementierung eines fähigkeitsbasierten Routenplaners für das automatisierte Fahren. Bachelor Thesis No. 1372/20, 2021

Kurun, Dersim: Entwicklung einer Methodik zur Kategorisierung von GNSS-Empfangsbedingungen für ein automatisiertes Forschungsfahrzeug. Bachelor Thesis No. 1376/20, 2021

Müller, Matthias: Experimentelle Untersuchung der Auswirkung von Vertikalanregungen bei der horizontalen Ladungssicherungsprüfung. Master Thesis No. 719/18, 2019

Navaratnam, Thanush: Entwicklung eines Tools zur Visualisierung einer verhaltenssemantischen Szeneriebeschreibung von Streckenabschnitten. Bachelor Thesis No. 1373/20, 2021

Schmidt, Marvin: Entwicklung einer Verhaltensbeschreibung für automatisierte Fahrzeuge in semantischer und formalisierter Form. Master Thesis No. 778/20, 2020

Schumacher, Max: Homologation eines Hydraulischen Untersuchungswerkzeuges für Ladungssicherungskonzepte. Master Thesis No. 760/19, 2020

Smits, Leonard: Entwicklung einer Methode zur Generierung und Durchführung von Testfällen für die Verhaltens- und Trajektorienplanung automatisierter Fahrzeuge. Master Thesis No. 836/21, 2022

Smits, Leonard: Entwicklung eines Routensuchalgorithmus mit Erweiterung für einen Anforderungs- und Fähigkeitsvergleich automatisierter Fahrzeuge. Bachelor Thesis No. 1337/19, 2019