# Methodology for Specifying and Testing Traffic Rule Compliance for Automated Driving

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

## Dissertation

vorgelegt von

**Felix Fabian Glatzki, M.Sc.**

aus Frankfurt am Main

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

| | |
|---|---|
| Tag der Einreichung: | 28.11.2022 |
| Tag der mündlichen Prüfung: | 17.01.2023 |

Darmstadt 2023

D 17

Glatzki, Felix Fabian: Methodology for Specifying and Testing Traffic Rule Compliance for Automated Driving
Darmstadt, Technische Universität Darmstadt
Tag der mündlichen Prüfung: 17.01.2023

Bitte verweisen Sie auf:
URN: urn:nbn:de:tuda-tuprints-235692
URI: https://tuprints.ulb.tu-darmstadt.de/id/eprint/23569

# Preface

This dissertation was written while I was working as a research assistant at the Institute of Automotive Engineering (FZD) of the Technical University of Darmstadt. The contents of this dissertation result from the research project PRORETA 5, which was carried out in cooperation with Continental AG.

A big thank you goes to my doctoral supervisor Prof. Dr. rer. nat. Hermann Winner. I would like to thank him not only for his support and the helpful technical discussions, but also for the trust he placed in me and the freedom he gave me in my research. The valuable exchange and the high standards not only contributed significantly to the success of this work, but also facilitated an enormous professional and human development.

Additionally, I thank Prof. Dr.-Ing. Krzysztof Czarnecki from the Waterloo Intelligent Systems Engineering Lab at the University of Waterloo for taking over the role as second examiner and the interest in my research.

I would like to thank the project partner Continental AG for the funding, the support in the project but also the always pleasant cooperation. Many thanks in particular to the staff involved in the technical exchange within the project meetings and the staff building up and providing the vehicle prototype.

Thanks also to all project members at the universities. In particular, I would like to thank Christoph Popp and Christoph Ziegler from the TU Darmstadt for the constant professional exchange and the outstanding collegiality within PRORETA. The collaboration has been instrumental in achieving the present milestone.

Furthermore, I would like to thank all employees of the Institute of Automotive Engineering. The working atmosphere and the professional as well as private exchange will remain in my good memory. A big thank you also goes to all the students I had the pleasure of working with during my time at the institute.

Last but not least, I would like to thank my family, who have supported me throughout my education as well as career and have given me advice and support in every situation. They enable me to live my life according to my interests, wishes and decisions. I am grateful for the great relationship with my parents and my sister and their support in all phases of my life.

Darmstadt, November 2022

# Table of Contents

# List of Symbols and Indices

## Latin formula symbols

| Symbol | Unit | Description |
|---|---|---|
| $\boldsymbol{a}$ | $\frac{\mathrm{m}}{\mathrm{s}^2}$ | Acceleration (2-dimensional) |
| $D$ | $\frac{\mathrm{m}}{\mathrm{s}^2}$ | Deceleration |
| $d$ | $\mathrm{m}$ | Distance |
| $\boldsymbol{p}$ | $\mathrm{m}$ | Position (2-dimensional) |
| $(s\,t)$ | - | Frenet coordinates |
| $t$ | $\mathrm{s}$ | Time |
| $T$ | - | Time interval |
| $v$ | $\frac{\mathrm{m}}{\mathrm{s}}$ | Speed |
| $\boldsymbol{v}$ | $\frac{\mathrm{m}}{\mathrm{s}}$ | Velocity (2-dimensional) |
| $\boldsymbol{x}$ | - | State |
| $(x\,y\,z)$ | - | Cartesian coordinates |

## Greek formula symbols

| Symbol | Unit | Description |
|---|---|---|
| $\psi$ | $\mathrm{rad}$ | Yaw angle |
| $(\varphi\,r)$ | - | Polar coordinates |
| $\tau$ | $\mathrm{s}$ | Duration |

## Calligraphic symbols and fraktur characters

| Symbol | Unit | Description |
|---|---|---|
| $\mathcal{A}$ | - | Behavioral attribute |
| $\mathcal{B}$ | - | Geometric representation of lane boundary |
| $\mathcal{C}$ | - | Vehicle outside contour |
| $\mathcal{D}$ | - | Set of motion-dynamic objects |
| $\mathcal{I}$ | - | Indication element |
| $\mathcal{L}$ | - | Lane |
| $\mathcal{N}$ | - | Set of roads |
| $\mathcal{O}$ | - | Motion-dynamic object |
| $\mathcal{P}$ | - | Pose |
| $\mathcal{R}$ | - | Road |
| $\mathcal{S}$ | - | Section |
| $\mathcal{T}$ | - | Trajectory |

## Accents and Operators

| Symbol | Description |
|---|---|
| $\exists$ | Exists |
| $\forall$ | For all |
| $\rightarrow$ | If ... then |
| $\leftrightarrow$ | Biconditional |
| $\neg$ | Negation |
| $\hat{}$ | Characteristic of an attribute |
| $\tilde{}$ | Condition |
| $\wedge$ | Logical and |
| $\vee$ | Logical or |

## Indices

| **Symbol** | **Description** |
|---|---|
| $E$ | Earth fixed Cartesion coordinate System |
| $F$ | Frenet coordinate System |
| $P$ | Polar coordinate System |
| $i$ | Loop variable |
| $j$ | Loop variable |
| $k$ | Loop variable |
| $l$ | Loop variable |
| $m$ | Loop variable |
| $s$ | $s$-direction |
| $t$ | $t$-direction |
| $x$ | $x$-direction |
| $y$ | $y$-direction |
| access | Accessible information |
| act | Actual value |
| action | Action |
| allow | Allowed |
| appr | Approach |
| arrive | Arrive |
| attr | Attribute |
| cond | Condition |
| cross | Crossing |
| ego | Ego vehicle |
| end | End |
| entry | Entry |
| exist | Existing information |
| exit | Exit |

| **Symbol** | **Description** |
|---|---|
| ext | Externally-reserved |
| fix | Fixed |
| fut | Future |
| interval | Condition of a time interval |
| lat | Lateral |
| leave | Leave |
| left | Left boundary |
| long | Longitudinal boundary |
| m | Moderate |
| max | Maximum |
| min | Minimum |
| occl | Occluded |
| presc | Prescribed |
| r | Reasonable |
| relevant | Relevant |
| right | Right boundary |
| scene | Scene representation |
| set | Planned (set) value |
| situ | Situation representation |
| start | Start |
| stop | Stop condition |
| thresh | Threshold |
| var | Variable |
| wet | Condition of a wet road |

# List of Abbreviations

| | |
|---|---|
| ADAS | Advanced Driver Assistance Systems |
| ADS | Automated Driving System |
| ASAM | Association for Standardization of Automation and Measuring Systems |
| BSSD | Behavior Semantic Scenery Description |
| BT-KAT-OWI | Bundeseinheitlicher Tatbestandskatalog für Straßenverkehrsordnungswidrigkeiten (transl.: Federal Catalog of Road Traffic Offences) |
| FMEA | Failure Mode and Effects Analysis |
| FTA | Fault Tree Analysis |
| GNSS | Global Navigation Satellite System |
| HAV | Highly Automated Vehicle |
| HAZOP | Hazard and Operability |
| INS | Inertial Navigation System |
| ISO | International Organization for Standardization |
| NHTSA | National Highway Traffic Safety Administration |
| ODD | Operational Design Domain |
| PerCollECT | Perception Sensor Collaborative Effect and Cause Tree |
| PET | Post Encroachment Time |
| RTK | Real-time Kinematic |
| STPA | System Theoretic Process Analysis |
| StVG | Straßenverkehrsgesetz (transl.: Road Traffic Act) |
| StVO | Straßenverkehrs-Ordnung (transl.: Road Traffic Regulations) |
| StVZO | Straßenverkehrs-Zulassungs-Ordnung (transl.: Road Traffic Licensing Regulations) |
| UNECE | United Nations Economic Commission for Europe |

# List of Figures

# List of Tables

# Kurzzusammenfassung

Die Einführung hochautomatisierter Fahrfunktionen verspricht einen Sicherheits- und Komfortgewinn, doch die Sicherheitsfreigabe bleibt weiterhin eine ungelöste Herausforderung. Hierbei besteht die Anforderung, dass die Einführung die Sicherheit im öffentlichen Straßenverkehr nicht mindert. Diese Dissertation befasst sich mit einem Hauptaspekt der Verkehrssicherheit: der Verkehrsregelkonformität. Auch ein automatisiertes Fahrzeug muss sich an die bestehenden Verkehrsregeln halten. Die entwickelte Methode ermöglicht die automatisierte Prüfung der Verkehrsregelkonformität von automatisierten Fahrfunktionen.

Im ersten Teil der Arbeit wird der Stand der Technik zur Beschreibung und Formalisierung von Verhaltensvorgaben analysiert. Eine besondere Herausforderung stellen hierbei die, je nach Verkehrsregion, unterschiedlichen Verkehrsregeln dar. Mit bestehenden Ansätzen ist für jede Verkehrsregion bzw. sogar für einzelne Verkehrsbereiche eine eigene Beschreibung und Formalisierung der Verhaltensregeln nötig. Dies zeigt die Notwendigkeit, neue Ansätze zur Abstraktion und Übertragbarkeit der Verhaltensvorgaben zu entwickeln, um den Aufwand der Prüfung der Verkehrsregelkonformität zu senken. Die Kriterien der Regelkonformität sind in die Verhaltensvorgabe innerhalb der Funktionsspezifikation zu integrieren. Das Ziel dieser Arbeit ist die Entwicklung einer Methode zur Formalisierung von Grenzen der Verkehrsregelkonformität, um basierend darauf Versagenskriterien für Gesamtsystemtests zu definieren und anzuwenden.

Hierfür werden als Grundlage bestehende Verkehrsregeln analysiert, um zu identifizieren, welche Verhaltensvorgaben vom statischen Verkehrsumfeld vorgegeben werden. Darauf aufbauend wird eine zwischen Verkehrsbereichen übertragbare, semantische Beschreibung, welche die Grenzen der Verkehrsregelkonformität an das statische Verkehrsumfeld knüpft, entwickelt. Die Methode umfasst die Ableitung von Verhaltensattributen, aus denen die semantische Verhaltensbeschreibung aufgebaut wird. Diese Verhaltensattribute konstruieren den Verhaltensraum, der die Grenzen des gesetzlich legalen Verhaltens beschreibt. Weiterhin werden Verfahren zur automatisierten Ableitung von Verhaltensattributen aus hochgenauen Karten entwickelt, um somit die Verhaltensanforderung aus einer Operational Design Domain zu extrahieren. Es wird untersucht, welche Funktionalitäten ein automatisiertes Fahrzeug zum Einhalten von Verkehrsregeln bereitstellen muss. Die Verhaltensattribute werden formalisiert, um quantifizierbare Versagenskriterien der Verkehrsregelkonformität zu erhalten, die in automatisierten Tests verwendet werden können. Abschließend wird aufbauend auf dem Stand der Technik eine Teststrategie für den Nachweis der Verkehrsregelkonformität vorgestellt. Durch die explizite Verfügbarkeit der Verhaltensgrenzen ergibt sich ein Vorteil in der Einflussanalyse möglicher Eingangsparameter für Tests.

Abschließend wird die entwickelte Methode auf bestehendes Kartenmaterial sowie auf Versuchsfahrten mit einem automatisierten Fahrzeugprototyp angewendet, um die praktische Anwendbarkeit des Ansatzes sowie den resultierenden Erkenntnisgewinn über die Prüfung der Verkehrsregelkonformität zu untersuchen. Der entwickelte Ansatz ermöglicht, die Verhaltensvorgabe hinsichtlich Verkehrsregelkonformität als wesentlichen Bestandteil der Funktionsspezifikation unabhängig vom Einsatzgebiet zu beschreiben. Es wird belegt, dass der Ansatz in der Lage ist, die Verkehrsregelkonformität eines automatisierten Fahrzeuges in verschiedenen Testszenarien innerhalb eines Anwendungsgebietes zu prüfen. Durch die Anwendung der entwickelten Methodik konnten Unzulänglichkeiten im untersuchten Versuchsträger hinsichtlich Regelverständnis und -einhaltung identifiziert werden.

# Abstract

The introduction of highly-automated driving functions promises to increase safety and comfort, but the safety validation remains an unsolved challenge. Here, the requirement is that the introduction does not reduce safety on public roads. This dissertation addresses one major aspect of road safety: traffic rule compliance. Even an automated vehicle must comply with existing traffic rules. The developed method enables automated testing of traffic rule compliance of automated driving functions.

In the first part of the thesis, the state of the art for describing and formalizing behavioral rules is analyzed. A special challenge is posed by the different traffic rules depending on the traffic region. With existing approaches, a separate description and formalization of the behavior rules is necessary for each traffic region or even for individual traffic areas. This shows the necessity to develop new approaches for the abstraction and transferability of the behavioral rules in order to reduce the effort of testing and ensuring traffic rule compliance. The rule compliance criteria are to be integrated into the behavior specification within the functional specification. The objective of this thesis is to develop a method to formalize the limits of traffic rule compliance, based on which fail criteria for system testing are defined and applied.

For this purpose, existing traffic rules are analyzed as a basis to identify which behavior constraints are imposed by the static traffic environment. Based on this, a semantic description that is transferable between traffic domains and that links the boundaries of traffic rule compliance to the static traffic environment is developed. The method involves deriving behavioral attributes from which the semantic behavior description is constructed. These behavioral attributes construct the behavior space that describes the boundaries of legally allowed behavior. Furthermore, methods for automated derivation of behavioral attributes from high definition maps are developed, thus extracting the behavioral requirement from an operational design domain. It is investigated which functionalities an automated vehicle has to provide to comply with the behavioral attributes. The attributes are then formalized to obtain quantifiable failure criteria of traffic rule compliance that can be used in automated testing. Finally, building on the state of the art, a test strategy for validating traffic rule conformance is presented. The explicit availability of the behavioral limits results in an advantage in the influence analysis of possible parameters for these tests.

Finally, the developed method is applied to existing map material and to test drives with an automated vehicle prototype in order to investigate the practical applicability of the approach as well as the resulting gain in knowledge about traffic rule compliance testing. The developed approach allows to derive the behavioral specification with respect to traffic rule conformance as an essential part of the functional specification independent of the application domain. It is proven that the approach is able to test the traffic rule conformance of an automated vehicle in different test scenarios within an application domain. By applying the developed methodology, it was possible to identify defects in the investigated test vehicle with respect to rule understanding and compliance.

# 1 Introduction

The introduction of automated driving promises improvements in the quality of road traffic. By eliminating human errors, which are a main factor for traffic accidents, it may be possible to reduce the amount of traffic accidents and therefore improve traffic safety.[1] But a higher safety is not the only benefit.[2,3] We may see higher traffic efficiency due to cooperative and connected automated vehicles. Finally, the comfort of the user is increased, since the focus can be turned away from the driving task to other activities (e.g. reading, working, ...).

While the technical development of Highly Automated Vehicles (HAVs)[4] is quite advanced, there is still only a limited amount of HAV in a narrow operational domain on the road.[6,7] Apart from these, demonstration vehicles and testing fleets are in operation in real traffic.[8,9] For a broader introduction and acceptance, there are still unsolved challenges that need to be overcome.[10] One main challenge is the safety verification and validation of such systems. Wachenfeld and Winner[11] show that current approaches would take an infeasible economic effort to prove safety.

## 1.1 Motivation

One major part of road safety is adherence to the present traffic rules.[12] Current road traffic with humans being responsible for the vehicle's behavior relies on these rules. Agreeing to this rule set has proven to be viable and accepted. From this follows that for mixed traffic applications (HAV and humanly driven vehicles) HAV need to behave compliant with traffic rules. In order to ensure that HAV fulfill this requirement, it is necessary to specify and delimit which behavior is compliant and which is not. Generally, traffic rules are defined by traffic regulations (in Germany

---

[1] Aptiv Services US LLC et al.: Safety First for Automated Driving (2019), p. 6.

[2] Milakis, D. et al.: Policy and society related implications of automated driving (2017).

[3] Szimba, E. et al.: Assessing user benefits of automated driving (2020).

[4] vehicles fulfilling Level 3-5 of the SAE Levels of Driving Automation[5]

[5] SAE: J3131: Definitions for Terms Related to Automated Driving (2022).

[6] Honda Motor Co., Ltd.: Honda Receives Type Designation for Level 3 Automated Driving in Japan (2020).

[7] Mercedes-Benz Group AG: First internationally valid system approval for conditionally automated driving (2021).

[8] Waymo LLC: Waymo is opening its fully driverless service (2020).

[9] Lyft, Inc.: Lyft and Motional to Deploy Fully Self-Driving (2020).

[10] Casner, S. M. et al.: The Challenges of Partially Automated Driving (2016).

[11] Wachenfeld, W. et al.: The Release of Autonomous Vehicles (2016).

[12] Åberg, L.: Traffic rules and traffic safety (1998).

by the Straßenverkehrs-Ordnung (transl.: Road Traffic Regulations) (StVO)[13]) and are specific to a certain traffic area. Depending on the regulatory elements (e.g. traffic signs) in the vehicle environment, these rules are instantiated and restrict the allowed vehicle behavior. In operation, an HAV must understand these restrictions limiting the allowed behavior along the planned route in order to be able to comply with the traffic rules. Current approaches seek to describe and specify the rules individually for each traffic area or even sub-parts of traffic areas (e.g. for specific intersections). This creates high effort because the resulting descriptions are not transferable for an application in different traffic areas. Therefore, there is a need for abstraction and transferability of behavior specification and testing regarding traffic rule compliance for HAV.

## 1.2 Problem Statement and Research Needs

Automated driving functions employ safety-critical and safety-relevant electronic/electric components. The standard ISO 26262[14a] describes the development of such systems in the automotive context with regard to functional safety. During this process various safety analysis methods (such as Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Hazard and Operability) shall be applied.[14b] During the risk assessment of these methods a non-fulfillment of legal requirements is associated with the highest severity.[15] Therefore, ensuring compliance to the traffic rules becomes part of the safety development process. This is also supported by Ponn[16] who defines the term *relevant scenarios* as all scenarios[17] that *"contribute to the type approval of automated vehicles"*[16]. In the set of relevant scenarios, simple scenarios such as the start of a speed limit are included because *"an automated vehicle must comply with existing traffic regulations"*[16]. According to ISO 26262[14c], the development process follows the V-model. An overview of this process is given in Fig. 1-1.

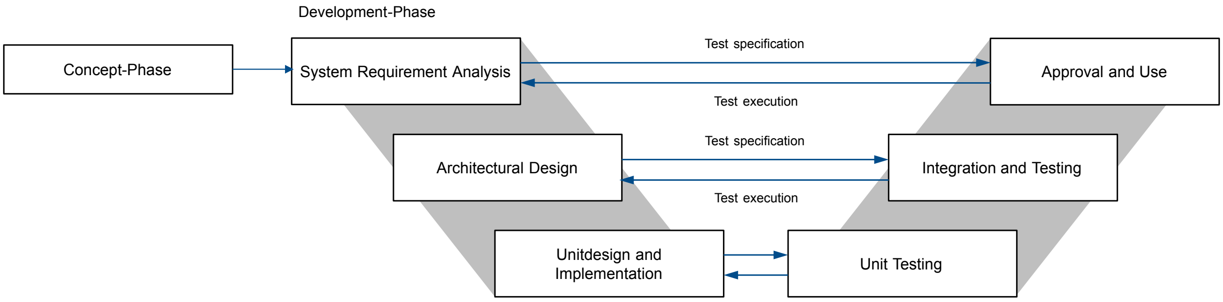


Figure 1-1: V-model development process (own illustration according to ISO26262[14c])

---

[13] Bundesministerium der Justiz: Straßenverkehrsgesetz (StVG) (2021).

[14] ISO: ISO 26262: Road vehicles - Functional safety (2018). a: -; b: Part 3, pp. 6-14; c: Part 3, p. vii.

[15] Bertsche, B.: Reliability in automotive and mechanical engineering (2008), p. 135.

[16] Ponn, T. et al.: Identify Relevant Scenarios for Type Approval of AV (2019), p. 3.

[17] The term *scenario* is defined in section 2.1.

The product development starts with the concept phase. In the concept phase the subject of development is defined (item definition). This means the functional range of the item and its relation to the operational environment including dependencies and interactions to other items are defined. Although it is not explicitly defined in ISO 26262 what the operational environment includes, a widely accepted term for the operational environment for HAV is defined in SAE J3106[18] with the Operational Design Domain (ODD):

*"Operating conditions under which a given driving automation system or feature thereof is specifically designed to function. Including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or road characteristics."*

This means that the ODD puts limitations on the road environment, the behavior of the HAV and the state of the Automated Driving System (ADS).[19] Based on the item definition, requirements on system level are derived. These requirements specify what the system needs to be capable of in terms of functionalities. Within the architectural design phase these functionalities are divided into interconnected sub-functions. In the unit design and implementation these domain-specific sub-functions are then developed. Along the right branch of the V the sub-functions are integrated into the system. Here, the functions are continuously tested against the stated requirements (verified and validated).

As stated, the traffic rule compliance must be taken into account and incorporated into this process from the beginning. This starts with considering the traffic rule-based behavior constraints coming from the environment defined in the description of the ODD as they directly influence the necessary functionality of the system. Subsequently, it must be derived what functionality the system and each sub-function need to provide in order to adhere to the behavior constraints. Conversely, the set requirements must then also be tested. From this follows the demand that the behavior constraints (both on system level and decomposed on sub-system level) are converted into test criteria, which rely on observable quantities.

A holistic view of traffic rule conformity over the product development cycle to achieve rule compliant behavior therefore is indispensable and has, to the knowledge of the author, not yet been presented in the current state of the art. This dissertation attacks this research gap and aims to provide methods to…

- … specify behavior constraints based on traffic rules.
- … derive functionalities on system and sub-system level to achieve traffic rule compliance.
- … develop test criteria and methods to verify these functionalities.

---

[18] SAE International: J3016: Taxonomy and Definitions for Terms (2018), p. 17.

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

The developed methods shall be applicable independent of the traffic area (urban, highway, ...). Consequently, the following research theses is formulated and analyzed in this work:

> *It is possible to describe the behavior constraints based on traffic rules - independent of the traffic area - and to use them for specification as well as testing of the system behavior within the development process of an HAV.*

## 1.3 Structure of the Dissertation

The dissertation is structured into 9 chapters. An overview of the structure is given in Fig. 1-2.

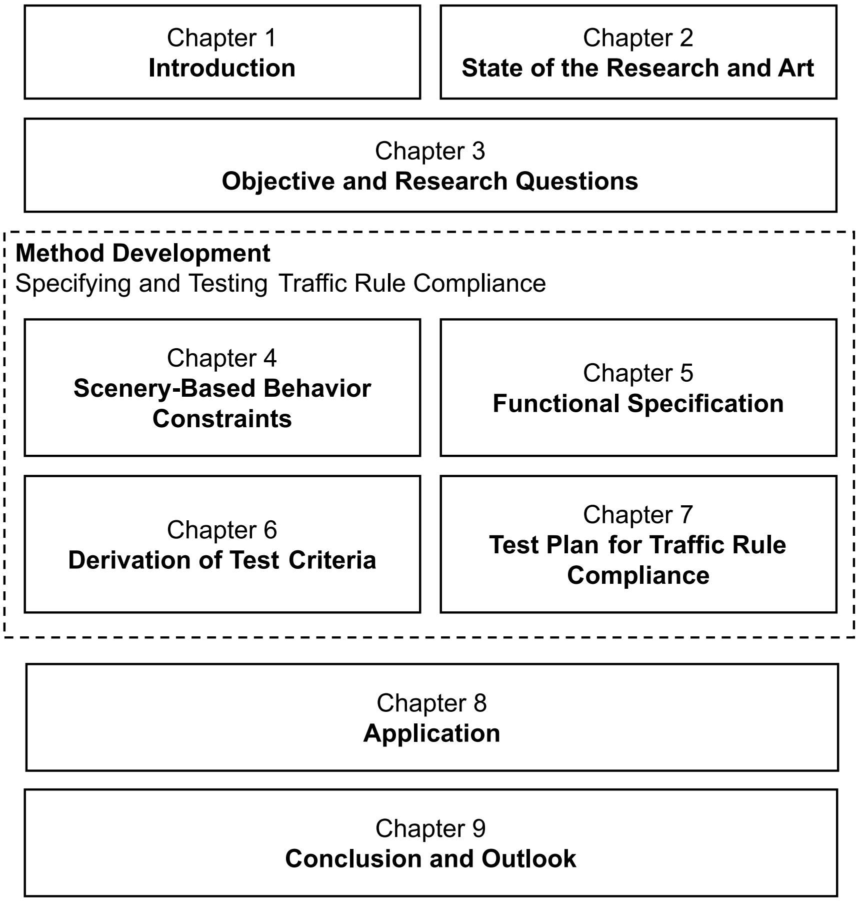


Figure 1-2: Structure of the dissertation

**Chapter 1** introduces the motivation of the dissertation and derives the research need. Finally, the structure of the dissertation is outlined.

In **Chapter 2** an overview of the current state of the art in relevant fields for the topic is given. This includes an overview of current development and release processes in the automotive industry. Existing approaches for the description of the ODD and the resulting behavior constraints for HAV are analyzed. Finally, an overview of the definition of traffic rules and how these are currently formalized and verified within the field of automated driving is outlined.

Based on the state of the art, **Chapter 3** details the identified research need from Chapter 1 resulting in the objective of a method to specify and test traffic rule compliance. An overview of the method is given and research questions that need to be answered in order to develop the method are identified.

**Chapter 4**, **5**, **6** and **7** cover the development of the method for specifying and testing traffic rule compliance for HAV. The identified research question from Chapter 3 are analyzed within these chapters:

- In **Chapter 4** the behavior constraints coming from the static traffic environment is analyzed and subsumed in a description as a basis for the functional specification and definition of the ODD.
- **Chapter 5** introduces a method to extract the behavior constraints from a given ODD and derives what functionalities an HAV needs to provide to fulfill this behavioral demand on system as well as subsystem level.
- In order to evaluate the necessary functionalities, **Chapter 6** quantifies the behavior constraints identified in Chapter 4 and derives pass-/fail criteria for the derived functionalities from Chapter 5.
- In a final step, methods to generate test cases based on the found results of the previous chapters are outlined in **Chapter 7**.

In **Chapter 8** the developed methodology is applied. For this, the different methods are applied to a real world use case. Based on map data, scenery-based behavior constraints are extracted automatedly, used as a basis for the specification and test case derivation and execution. In this course, the different applications are evaluated.

**Chapter 9** concludes the dissertation. An overview of the results is given, discussed and aligned with the expected benefits from Chapter 3. Finally, an outlook on open tasks and next steps is given.

# 2 Related Work

In this chapter, an overview of the relevant related work is given. The overview is subdivided into different topics of interest for this dissertation. First, relevant terms for this work are defined in section 2.1. Then, an overview of automotive safety as well as approaches specifically for ADSs are given in section 2.2. In section 2.3, current approaches to specify vehicle behavior in the application field of HAV is presented. Section 2.4 gives an overview of current approaches to describe the ODD of an HAV and analyzes how behavior constraints coming from traffic rules are incorporated into or facilitated by these approaches. Finally, section 2.5 gives an overview about current approaches to formalize traffic rules in order to make them machine readable.

## 2.1 Definition of Terms

In this section relevant terms that are used throughout this work are introduced and defined.

### 2.1.1 Scenery, Scene, Situation and Scenario

Since the surroundings of a vehicle directly influence the behavioral restrictions based on traffic rules, it is important to have clear definitions and a subdivision into terms that define these surroundings, also over temporal development. Ulbrich et al.[20] define the terms scene, scenario, scenery and situation as follows:

*"A **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)."*

*"A **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."*

*"The **scenery** subsumes all geo-spatially stationary aspects of the scene. This entails metric, semantic and topological information about roads and all their components like lanes, lane markings, road surfaces, or the roads' domain types. Moreover, this subsumes information*

---

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

*about conflict areas between lanes as well as information about their interconnections, e.g., at intersections. Apart from the before mentioned environment conditions, the scenery also includes stationary elements like houses, fences, curbs, trees, traffic lights, or traffic signs."*

*"A* ***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."*

### 2.1.2 Behavior[21]

Every traffic participant acts with a certain behavior, independently of being legally correct or not. Nolte et al.[22] define internal and external behavior of automated driving systems as a sequence of internal and external states. The internal behavior describes all internal processes that are necessary to fulfill the specified functions, while the external behavior represents actions and activities that directly influence other traffic participants. Czarnecki[23] further defines road user behavior as a change of state developing over time forced by external or internal factors. He describes the road user state as a composition of an externally observable state and an externally unobservable, internal state. The externally observable state contains the basic motion state, the physical form and the relationship between a road user and other objects. Furthermore, it includes activities of the road user as well as signal states. Since only the external states are perceptible by other traffic participants or observers and therefore externally measurable, the definition of external behavior as a change of the externally observable state serves as a basis for a derivation of the behavioral demand given by the scenery.

### 2.1.3 Local and General Traffic Rules

Traffic rules are subdivided into two types of rules. *General traffic rules* are rules that always must be observed by traffic participants independent of their location or state in the traffic environment. For example, section 1 of StVO[24] states that

*"a person using the road shall act in such a way as not to harm or endanger or, more than is unavoidable in the circumstances, to hinder or inconvenience any other person."*

This rule is valid for the whole traffic environment and thus, represents a general traffic rule. *Local traffic rules* give local instruction which are valid only for a certain section of the traffic

---

[21] This sub-section was taken from the publication: Glatzki, F. et al.: Behavioral Attributes for a Behavior-Semantic Scenery Description (BSSD) (2021).

[22] Nolte, M. et al.: Towards a skill- and ability-based development process (2017).

[23] Czarnecki, K.: Operational World Model Ontology - Part 2 (2018), p. 25.

[24] Bundesministerium der Justiz: Straßenverkehrsgesetz (StVG) (2021).

environment and thus, only need to be observed by traffic participants while they are within this section of the traffic environment. For example, in section 26 StVO[24] states that

*"at pedestrian crossings, vehicles, with the exception of rail-borne vehicles, must allow pedestrians as well as users of ambulance chairs and wheelchairs to cross the carriageway when they have clearly indicated their intention to do so. Vehicles may then approach only at a moderate speed; if necessary, they must wait."*

This rule is valid only at respective pedestrian crossings and thus, represents a local traffic rule.

## 2.2 Safety Validation in the Automotive Domain

As this dissertation contributes to the adherence of traffic rules by HAVs, it aims to contribute to the safety of such systems. Safety is defined as the *"absence of unreasonable risk"*[25a]. In order to assess safety and ensure the absence of unreasonable risk, industry as well as research have introduced and proposed several processes, methods and approaches. The following sections will introduce standards relating to safety in the automotive domain applied in industry (section 2.2.1) as well as current proposed approaches and techniques for the validation for ADSs by research institutions (section 2.2.2).

### 2.2.1 Standards

In this section a brief overview of current standards in the field of automotive safety is given. These standards give recommendations for processes to ensure the absence of unreasonable risk by detecting possible hazards and introduce methods to identify suitable measures to mitigate these hazards. Because within this dissertation the safety of the vehicle behavior is in focus, the field of cybersecurity is excluded. Here, ISO 21434[26] would be a relevant standard.

#### ISO 26262 - Functional Safety of Road Vehicles

The safety standard ISO 26262[25b] defines the process to ensure functional safety of safety-related systems containing electrical and/or electronic components in production road vehicles. Thus, the standard mainly targets risks arising from the functional failure of individual components. The process is aligned with the V-model, first considering the item on the overall level and then broken down into components. A hazard analysis and risk assessment (HARA) forms the basis for the evaluation. The results of this analysis are used to determine the Automotive Safety Integrity Level (ASIL) for the components of the system by combining the frequency of hazardous events with their severity and controllability. Based on the resulting ASIL, the required development

---

[25] ISO: ISO 26262: Road vehicles - Functional safety (2018), a: Part 1, p. 21; b: -.

[26] ISO: ISO 21434: Road vehicles - Cybersecurity engineering (2021).

steps and validation measures are given. The standard demands appropriate activities to ensure the fulfillment of the required steps, such as safety analyses (FMEA, FTA, etc.), repeatable tests and long-term tests with suitable pass/fail criteria as well as reviews. Additionally, ISO 26262 requires functional safety management.

### ISO 21448 - Safety of the Inteded Functionality

ISO 21448[27] gives guidelines to assuring the safety of the intended functionality which is *"the absence of unreasonable risk due to hazards resulting from functional insufficiencies of the intended functionality or its implementation"*. Thus, this standard has the goal to protect against potential hazards caused by the system without a functional fault. In a first step, potential safety hazards arising from functional insufficiencies of the system are identified. It has then to be demonstrated that these hazards are mitigated sufficiently by achieving an acceptance criterion during validation and safety demonstration. This criterion must respect applicable laws and regulations and consider an acceptable risk for the concerned population. Defining and achieving this criterion is mainly based on identifying triggering conditions for the system insufficiencies and improve the system to handle these triggering conditions. The main argumentation of the proof for safety of the intended functionality is that the system behaves safely within known scenarios and that the number of additional unknown and unsafe scenarios is sufficiently low.

### ISO/TR 4804 - Safety and Cybersecurity for Automated Driving Systems

ISO/TR 4804[28] is a guideline which aims to adapt and extend the processes and methods of introduced standards to be applicable to the field of HAV. Stahl[29] identifies the causes of limited applicability of the existing engineering standards (ISO 26262 and ISO 21448 SOTIF) as increased complexity and increasing usage of machine-learning based methods in ADS. ISO/TR 4804 gives a technical overview of the specification for the development of HAV based on existing publications and standards. Additionally, it provides a discussion of the verification and validation process of HAV consisting of three steps. In the first step, the defined specifications and requirements are verified by using test based approaches. In the validation step, a statistical argument is build that confirms the safety across both known and unknown scenarios, similar to ISO 21448. Finally, the standard demands observation of the system after introduction into the market. This means monitoring the performance of the system by field monitoring and provide any required updates such that safety and cybersecurity is ensured over the lifespan of the system. In this regard, robust processes including regression testing are needed in order to ensure that these updates do not introduce new risks.

---

[27] ISO: ISO/PAS 21448: Road vehicles - Safety of the intended functionality (2019).

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

[29] Stahl, T. N.: Safeguarding complex and learning-based automated driving functions via online verification (2022).

### ANSI/UL 4600

UL4600[30] outlines a generalized autonomous system standard framework using light autonomous road vehicles as concrete example. This framework helps to ensure thorough consideration of safety for an autonomous vehicles has been performed during the design process. Like ISO/TR 4084, UL4600 extends the safety considerations to be done throughout the system lifecycle. This is done by performing repeatable assessments of the thoroughness of a safety case. Rather than introducing processes, UL4600 sets out criteria to determine the acceptability of a safety case. The demanded safety case is goal-based. This means that a set of claims is backed by corresponding arguments which should be supported by evidence. As metrics, safety performance indicators are incorporated into the safety case. This facilitates the development by continuously monitoring the safety performance of the system and may be used to show the improvement of the system.

## 2.2.2 Approaches for the Safety Validation of Highly Automated Driving

As seen, with the current set of standards the safety validation of HAV still remains a challenge because of the open-world context of the system. Therefore, it is an active research topic. Within this section an overview of current approaches for the safety validation of HAV is given. The categorization of the approaches is largely based on the overview of safety-assessment approaches by Riedmaier et al.[31].

### Real-World Testing

Real-world testing, as the name suggests, evaluates the driving function under real-world conditions. This means that the HAV is tested in real traffic and the performance is compared to a reference (e.g. human driver). This approach is widely used for the release of systems up to level 2[32] of driving automation[31]. Although real-word testing provides a maximum degree of reality, it is still unsuitable for the release of systems with higher levels of automation. This is because an economically infeasible amount of driven kilometers would be necessary to state with sufficient confidence that the HAV is outperforming human drivers by a defined factor. Wachenfeld and Winner[33] have determined a distance of 6.6 Billion kilometers that would need to be driven in order to show that an interstate pilot is twice as safe as a human driver. Additionally, with every update of the system, retesting of the complete distance would be necessary. Therefore, real-world testing is a valuable approach to gain meaningful results during the development of ADS, however, it is not economically feasible as a sole release approach.

---

[30] Underwriters Laboratories: UL4600: Safety for the Evaluation of Autonomous Products (2022).

[31] Riedmaier, S. et al.: Survey on Scenario-Based Safety Assessment of Automated Vehicles (2020).

[32] according to SAE International: J3016: Taxonomy and Definitions for Terms (2018).

[33] Wachenfeld, W. et al.: The Release of Autonomous Vehicles (2016).

### Function-based Testing

In function-based testing, requirements are derived for individual functions of the system. These requirements are tested in simulation or on the test track in separated test cases. Current ISO standards and United Nations Economic Commission for Europe (UNECE) regulations are following this approach for Advanced Driver Assistance Systems.[31] For ADS a complete definition of requirements is nearly impossible because not every imaginable traffic situation is known during development and there is no human driver available that observes the behavior and intervenes in case of hazardous behavior. Additionally, predefined test cases for the individual subfunctions may lead to optimization of the system towards these test cases and thus, the performance within these test cases would potentially not resemble the performance of the real driving behavior. This poses strict requirements on the representativeness and completeness of the selected test cases.[34] Finally, there are high interdependencies between the functions in a complex system which results in difficulties of testing these functions individually. However, this is current subject of research in the upcoming dissertation of Klamann[35].

### Scenario-based Testing

A widely considered approach to overcome the challenges of previously presented approaches is scenario-based testing[36]. This approach was and is investigated in various large research projects (e.g. ENABLE-S3[37], pegasus[38], Verification Validation Methods[39]). The focus of the approach is laid on the relevant scenarios for the ADS, while parts without significant actions or events are omitted. This reduces the scope of the tests and thus, the test effort. Still, there are open issues that remain unresolved, mainly how an appropriate generation and selection process for relevant scenarios would look like. Riedmaier et al.[31] introduce a taxonomy for scenario-based testing which consists of scenario generation, scenario selection, scenario execution and AV assessment. During scenario generation, driving scenarios are collected either by knowledge-driven (e.g. Bagschik et al.[40], Klueck et al.[41]) or data-driven (e.g. Krajewski et al.[42], Jesenski et al.[43]) approaches in order to create a scenario database. In scenario selection, scenarios for the test execution are selected such that the parameter space is covered with test cases and challenging corner cases are identified. For the execution, different testing environments are available. A

---

[34] Wang, C.: Silent Testing for Safety Validation (2021), p. 14.

[35] Klamann, B.: Approaches for a Modular Safety Approval of Highly Automated Vehicles (2023).

[36] Schuldt, F. et al.: Effiziente systematische Testgenerierung für Fahrerassistenzsysteme (2013).

[37] https://enable-s3.eu/, accessed: 19.11.2022

[38] https://www.pegasusprojekt.de/en/home, accessed: 19.11.2022

[39] https://www.vvm-projekt.de/en/project accessed: 19.11.2022

[40] Bagschik, G. et al.: Wissensbasierte Szenariengenerierung (2018).

[41] Klueck, F. et al.: Using Ontologies for Test Suites Generation (2018).

[42] Krajewski, R. et al.: Data-Driven Maneuver Modeling for Safety Validation of Highly Automated Vehicles (2018).

[43] Jesenski, S. et al.: Generation of Scenes for the Validation of Highly Automated Driving Functions (2019).

report of the Association for Standardization of Automation and Measuring Systems (ASAM)[44] gives an overview of testing environments and how they are used throughout the scenario-based testing approach. Finally, during AV assessment, the performance of the HAV within executed test scenarios is evaluated against test criteria to evaluate safety. Section 2.2.3 gives an overview of evaluation criteria and safety requirements in current literature. In this dissertation, a main contribution to this step is made by defining and formalizing test criteria for the verification of traffic rule compliance of HAV.

### Silent Testing

The silent testing approach evaluates the function of the ADS in an open-loop simulation based on real sensor data in real traffic. The system may be evaluated directly during test drives on the vehicle or the sensor data is recorded and used as input to conduct the open-loop simulation after the test drive. In case of evaluation directly during test drives, the ADS has no influence on the vehicle behavior. A human driver or a validated driving function always controls the vehicle and thus, no risk is introduced with this approach. The behavior of the virtual (simulated) vehicle is compared to the performance of the human driver[45] or to criticality metrics[46] to evaluate the performance. Wang[47] identifies the detection of violation of traffic rules within his implementation of the VAAFO[45] approach as an open research question. The automotive manufacturer Tesla, for example, is using the silent testing approach.[48] New driving functions are evaluated on customer vehicles in field operation by letting them run in so called ”*shadow mode*”. Discovered incidents are reported to the developers to examine and improve the functions.

### Formal Verification

The goal of formal verification is to mathematically prove that the safety of the system is given within the complete ODD. There is no selection of scenarios, but predefined rules are brought into a mathematical form. If these mathematical relationships are implemented in the system, then the safety of the system is given. Thus, formal verification is not part of the scenario-based approach. Most of the works in the field of formal verification deal with the planning layer of an ADS. Relevant publications are presented in section 2.5 but for a complete safety validation, the perception would need to be formally verified as well.[49] Motion control is assumed to be well enough understood by the long research experience and is not verified within these approaches.

---

[44] ASAM Test Specification Study Group: Collaborative Testing for ADAS & AD (2022).

[45] Wachenfeld, W. et al.: VAAFO - A New Runtime Validation Method (2018).

[46] Koenig, A. et al.: Passive HAD as a concept for validating highly automated cars (2018).

[47] Wang, C.: Silent Testing for Safety Validation (2021), pp. 125-126.

[48] Templeton, B.: Tesla’s ”Shadow” Testing (2019).

[49] Buerkle, C. et al.: Towards Online Environment Model Verification (2020).

### 2.2.3 Evaluation Criteria

After various approaches for the safety validation of automated vehicles were presentend, within this section, a brief overview of evaluation criteria is given. Every test-based validation approach needs evaluation criteria on the basis of which the safety release is determined. A distinction is made between assessment on microscopic level (e.g. individual test cases) and on macroscopic level, i.e. whether the validation set as a whole meets certain criteria. Both criteria are derived from the requirements placed on the system.

#### Macroscopic Safety Requirements

Junietz et al.[50] define macroscopic safety requirements on the basis of an analysis of risk acceptance. They use the current safety in traffic as a reference. Concepts from other domains such as ALARP (as low as reasonably practicable), MEM (minimum endogenous mortality), GAMAB (French: *globalement au moins aussi bon*, generally at least as good as) are transferred to the domain of safety for automated driving. From these concepts, accident rates per milage are derived as requirement. The risk acceptance is dependent on the market share of automated vehicles. With an increasing market share, the safety requirement level rises as well. As these requirements cannot be proven before introduction of automated driving, Junietz et al.[50] suggest the monitoring of vehicles in the field. As this dissertation concerns the verification of traffic rule compliance during development of HAV macroscopic requirements are not suitable.

#### Microscopic Safety Requirements

For microscopic safety requirements different aspects exists which may be taken into account for the evaluation of a test case:[51]

- **Behavioral safety** addresses driving decisions and behavior.
- **Functional safety** addresses system faults or failures.
- **Crash safety** addresses the ability to protect passengers during a crash event.
- **Operational safety** addresses the interaction between vehicle and passenger.
- **Non-collision safety** addresses physical safety of people who might interact with the vehicle (e.g. electrical system or sensor hazards).

As this dissertation focusses on behavioral safety a more detailed introduction into requirements and criteria of this aspect is given. Since safety implies an absence of hazards, behavioral safety deals with hazard-free, visible actions of automated vehicles. Thus, traffic regulations provide an initial regulatory framework for behavior of HAV, which is extended by further legal constraints.[52]

---

[50] Junietz, P. et al.: Macroscopic Safety Requirements for HAD (2019).

[51] Waymo LLC: Waymo Safety Report (2021), p. 11.

[52] Lippert, M. et al.: Definition von Bestehens-/Versagenskriterien (2019).

Within this legal framework, an automated vehicle must be able to perform the driving tasks resulting from the driving scenarios at hand.[52] Wang[53] categorizes the criteria for the evaluation of the safety performance regarding behavioral safety into:

- Temporal Proximal Indicators
- Distance Proximal Indicators
- Intensity Based Indicators
- Other indicators

Temporal Proximal Indicators use the assumption that the closer vehicles are to each other, the nearer they are to a collision.[54] Various proximal measures have been proposed where Time-to-X (TTX) is the most commonly used indicator. For Distance Proximal Indiators, the main attribute for conflict determination is the distance available to avoid a collision.[54] Intensity Based Indicators reflect how difficult it is for an HAV or human driver to respond in order to avoid a collision.[53] Other indicators exist that do not fit into the aforementioned categories, e.g. combined indicators[55] or collision probability by predicting future motion of traffic participants[56]. Regarding criteria for traffic rule compliance, UNECE Regulation R79[57] states first quantified limits for behavior during lane changes. Other than that, to the knowledge of the author, there is no quantified traffic regulation (issued by an authority) available.

### 2.2.4 Approaches to Reduce Validation Effort

The extensive test demands are one of the main obstacles to the safety validation of HAV. This section provides a review of several approaches designed to reduce the validation effort.

#### Extreme Value Theory

Based on the probability distribution of more frequently occuring critical scenarios (e.g. near-crash), the extreme value theory is used to calculate the likelihood that rare events like accidents will occur. By performing this estimation, the required distance for safety validation can be reduced.[58] Asljung et al.[59] conclude that the required test effort can be reduced by a factor of 45 when using correct metrics and threshold values when applying extreme value theory. The difficulty in this approach lies within finding these metrics. Because no empirical data is

---

[53] Wang, C.: Silent Testing for Safety Validation (2021), pp. 24-25.

[54] Mahmud, S. S. et al.: Application of proximal surrogate indicators (2017).

[55] Huber, B. et al.: Evaluation of Traffic Situations based on Multidimensional Criticality Analysis (2020).

[56] Broadhurst, A. et al.: Monte Carlo road safety reasoning (2005).

[57] UNECE: Regulation R 79 (2021).

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

[59] Asljung, D. et al.: Using Extreme Value Theory for Vehicle Level Safety Validation (2017).

available before the introduction of HAV, there is no basis for validating the determined metrics. Theoretically, extreme value theory can be used in the scenario-based approach to reduce the number of test cases.

### Scenario Selection and Reduction Methods

Section 2.2.2 introduced knowledge- and data-driven approaches to create a scenario database. The selection of a appropriate test scenarios from this database is indispensible for a safety validation of HAV. The test suite needs to contain, in the best case, all relevant scenarios for the ADS. Selecting these relevant scenarios, however, is a challenge, but also introduces potential for reducing the validation effort as keeping non-relevant scenarios in the test suite increases the test effort. Menzel at al.[60] define three types of scenarios based on requirements emerging from different phases of the development process: functional, logical and concrete scenarios. Functional scenarios describe the scenario on a semantic level. Logical scenarios include a description on state-space level with parameter ranges. Concrete scenarios select concrete parameter values from the ranges such that the scenario is executable within a test case. Since there exist an infinite amount of possible parameter combinations from logical scenarios, it is essential that the parameter selection process results in sufficient coverage but also in feasible test suite. Ponn et al.[61] analyze different scenario selection approaches with regards to their advantages and disadvantages. They differentiate among others between Design of Experiments, Analytic Hierarchy Process, Ontology-based Scenario Selection, Data-Driven Scenario Selection and Scenario Selection on the Basis of Accident Databases. A more detailed introduction to the approach of Design of Experiments is given as it is used in Chapter 7. Within the approach of Design of Experiments, not all parameter combinations possible are chosen for testing but an intelligent selection is made. Among others, Schuldt[62] applies this concept. In his approach, first, relevant influence parameters are selected based on information sources. During systematic test case generation, dynamic analysis methods from software testing are used to determine the parameters. Equivalence partioning[63a] subdivides the test parameters into equivalence partitions. These partitions are derived based on the expectation that values within a partition should be treated similarly by the system. Boundary value analysis[63b] uses the equivalence classes to identify boundary values where each boundary is used to represent test coverage items. Finally, combinatorial test design techniques[63c] are used to systematically derive a subset of the test suite that covers the test model. Depending on the number of parameters that should interact (e.g. 2-wise testing demands that *”every possible pair of interesting values of any two parameters is included in some test case.”*[64]), this results in significant reduction of the test effort. An open research question that remains is what test coverage is necessary.

---

[60] Menzel, T. et al.: Scenarios for Development, Test and Validation of Automated Vehicles (2018).

[61] Ponn, T. et al.: Identify Relevant Scenarios for Type Approval of AV (2019).

[62] Schuldt, F.: Methodischer Test von automatisierten Fahrfunktionen (2017).

[63] ISO: ISO 29119: Software and systems engineering (2022), a: Part 4, p. 10; b: Part 4, p. 12; c: Part 4, p.15.

[64] Grindal, M. et al.: Combination testing strategies: a survey (2005).

Apart from the approaches presented by Ponn et al.[61], Amersbach[65] applies the functional decomposition approach (which is known from other fields (e.g. mathematics)) to the challenge of validation of HAV to reduce the approval effort. Automated driving functions are decomposed into six layers:

- Layer 0: Information Access
- Layer 1: Information Reception
- Layer 2: Information Processing
- Layer 3: Situational Understanding
- Layer 4: Behavioral Decision
- Layer 5: Action

A more detailed description of the interfaces as a basis for the formalization developed in this thesis is given in section 6.2.2. The idea behind the approach is not to optimize the scenario selection, but to reduce the test effort by omitting sub-spaces in the parameter space. This is achieved by testing the individual layers of decomposition individually and selecting only parameter ranges that are relevant to this functional layer. Amersbach quantifies the potential to reduce the validation effort by using this approach to a factor of around 20-130 depending on test coverage. A prerequisite to implement this approach is test criteria for the different decomposition layers. Naturally, test criteria will be formulated on system level. Klamann et al.[66] present a method to decompose safety requirements on system level such that the criteria is broken down on functional decomposition layers. They use proven methods such as FTA and System Theoretic Process Analysis (STPA) to fullfill this task.

## 2.3 Behavioral Description and Evaluation

Traffic rules regulate the behavior of traffic participants in order to ensure safe and flowing traffic. There exist multiple conventions on road traffic which are presented in the following. These conventions have the goal to unify traffic rules over different countries. In general, traffic rules are stated in textual form which results in vague behavioral limits with no quantified value. Various approaches in current literature pursue the goal to make these rules available and readable for ADSs. These approaches are presented after the introduction to traffic rules.

---

[65] Amersbach, C. T.: Functional Decomposition Approach (2020).

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

### 2.3.1 Traffic Rules

The Geneva Convention on Road Traffic[67] is an international treaty for the safety of road traffic by introducing uniform rules among the contracting parties. The convention addresses minimum mechanical and safety equipment needed for road vehicles. The convention has been ratified by 101 countries. The Vienna Convention on Road Traffic[68] replaces previous traffic conventions between signatory countries and marks the groundwork for establishing standard traffic rules among the contracting parties. It is ratified by 83 countries. It introduces rules of the road, such as signs and signals, instructions by authorized official as well as general rules. This includes rules for overtaking, passing of oncoming traffic, speed and distance between vehicles, general requirements governing maneuvers, change of direction as well as intersections and obligation to give way. In the course of the Conference on Road Traffic the Vienna Convention on Road Signs and Signals[69] was agreed as well. This treaty internationally harmonizes road traffic signs and is ratified by 67 countries. Not all countries in europe have joined the treaty (e.g. Andorra, Ireland) or have ratified the convention (e.g. Spain, UK). Additionally, in 1971 the European Agreement supplementing the Convention on road traffic[70] amends the provisions of the Vienna Convention on Road Traffic. Traffic signs are subdivided into 8 categories: Danger warning signs, priority signs, prohibitory or restrictive signs, mandatory signs, special regulation signs, information-, facility-, or service-signs, direction-, position-, or indication-signs and additional panels. Despite the standardization, there are differences in traffic signs, because the implementation can be country-specific, e.g. different color. But also the linked behavior rule can differ although traffic signs look similar. Tab. 2-1 compares two similar traffic signs for traffic-calmed areas in Germany and Austria. As can be observed by the linked rules, there results a different rule set from the two traffic signs. In addition to the conventions of the UNECE, there are other conventions of other countries (e.g. [71]). Outside of the respective conventions, there may be major differences between traffic signs. Especially relevant for this dissertation are the traffic laws in Germany. They give an example on how the regulations of the Vienna Convention are implemented country-specific. The traffic law in Germany is mainly handled by the following three laws:

- Straßenverkehrsgesetz (transl.: Road Traffic Act) (StVG)[72]
- StVO[73]
- Straßenverkehrs-Zulassungs-Ordnung (transl.: Road Traffic Licensing Regulations) (StVZO)[74]

---

[67] UNECE: Geneva Convention on Road Traffic (1949).

[68] UNECE: Vienna Convention on Road Traffic (1968).

[69] UNECE: Vienna Convention on Road Signs and Signals (1968).

[70] UNECE: European Agreement supplementing the Convention on road traffic (1971).

[71] U.S. Department of Transportation: Manual on Uniform Traffic Control Devices (2009).

[72] Bundesministerium der Justiz: Straßenverkehrsgesetz (StVG) (2021).

[73] Bundesministerium der Justiz: Straßenverkehrs-Ordnung (StVO) (2021).

[74] Bundesministerium der Justiz: Straßenverkehrs-Zulassungs-Ordnung (StVZO) (2021).

Table 2-1: Comparison of the rules resulting from the traffic sign ”traffic-calmed area” in Germany and Austria

| | **Germany** | **Austria** |
|---|---|---|
| **Sign** |  |  |
| **Rules** | • Max speed: Walking speed<br>• Pedestrians shall not be obstructed or endangered<br>• Parking is not allowed outside of marked areas<br>• When exiting, there is an obligation to wait for other road users | • Max speed: Walking speed<br>• Pedestrians and Bicyclists shall not be obstructed or endangered<br>• Vehicle traffic is prohibited (except: road service, fire department, ...)<br>• When exiting, there is an obligation to wait for other road users |

The StVG regulates the legal basis for the guidelines. The StVZO regulates formal and technical requirements for the registration of vehicles for use on public roads, paths and squares. The behavioral law for traffic participants is regulated in the StVO and therefore, it is the most relevant regulation for this dissertation. The StVO has three main components:

- General traffic rules
- Traffic signs and traffic devices
- Implementing and fine provisions

While the general traffic rules have to be respected everywhere while participating in road traffic, traffic signs and traffic devices impose traffic rules which are only valid locally (e.g. a speed limit because of a speed limit sign), see also section 2.1.3 for the definition of local and general rules in the context of this work. The last section defines the implementation and fine provisions of the defined rules.

### 2.3.2 Behavioral Specifications in the Field of Automated Vehicles

After introducing where traffic rules originate from, it becomes evident that the behavioral rules also need to be respected by HAV. For this, it is necessary that the ADS has a rule awareness as well as the ability to behave according to the detected rules. In current literature, there are various approaches to specify behavior for HAV which are presented in the following.

Censi et al.[75] present a rule hierarchy as behavior specification for HAV. They claim that the behavior of an automated vehicle must not only be traffic rule compliant (local, general), but also has other constraints such as ethical, local culture, comfort etc. These rules may conflict with each other. They present a behavior specification method with so-called ”rulebooks”. Not all rules can be satisfied simultaneously. With the help of the rulebooks the different rules are arranged in a hierarchy (”rulebook = preordered set of rules”). A rule is a scoring function (there is a possibility of a more severe violation than another violation). This presents a way to specify and order overall behavior. Because safety is weighted highest, country- and culture-specific rules can be considered on the lower level. However, it does not deal with a representation of the individual rules, but refers to formalization in other works (see section below).

Perdomo Lopez et al.[76] present an approach to scenario interpretation at intersections. The interpretation module of a vehicle gives a proper meaning to the information of the surrounding environment. For this purpose, complex situations are reduced to so-called primary situations, these are based on the Vienna Convention on Traffic[77] as well as the German Directives for the Design of Urban Roads[78] and thus, specific for German intersections. The scenario is interpreted based on a linkage between primary situation, ego intention and information of the intersection state. Primary situations are define by potential conflicts with other road users. There are four primary situations (perpendicular conflict with VRU, conflict with a left-crossing and/or right-crossing lane, conflict with a parallel crosswalk, zebra crossing or bike lane and conflict with oncoming vehicle). With a flowchart the required behavior regarding priority for the intersection is mapped (depending on infrastructure, state of the traffic lights, ego target, etc.). This is based on target points that need to be approached under certain conditions. A speed is also prescribed at these points to avoid collisions or maintain priority. However, it is mainly about conflict avoidance and the method does not represent the totality of all traffic rules (no speed limit, no overtaking, no entry conditions (e.g. stagnant traffic in the intersection)). Additionally, it is only valid for intersections with up to 4 arms, some situations which demand the same behavior are depicted differently (e.g. pedestrian crossing and right turn at intersection), there is no clear distinction between different types of traffic participants (esp. VRU). If the approach shall be used in another traffic region, a completely different flow chart will be needed.

Similarly Zhao et al.[79] use flowcharts to model the behavior during lane change maneuvers. They use different types of areas (free area, forbidden areas and negotiation area), in order to subdivide the gap for lane changing. Based on this subdivision of areas, the lane change process is subdivided into three stages: *longitudinal spacing adjustment*, *right-of-way negotiation stage* and *action stage*. Again, the representation by using flow charts is specific to a certain scenario

---

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

[76] Perdomo Lopez, D. et al.: Scenario Interpretation based on Primary Situations (2017).

[77] UNECE: Vienna Convention on Road Signs and Signals (1968).

[78] Road and Transportation Research Association: Directives for the Design of Urban Roads (2012).

[79] Zhao, C. et al.: A Negotiation-based Right-of-way Assignment Strategy (2019).

and does not encompass all types of traffic rules (no speed limits, no overtaking prohibitions, etc.)

A different approach is introduced by Butz et al.[80] They abstract traffic situations by using zone graphs on the basis of which they perform morphological behavior analysis. Zone graphs are configured for one type of scenery (e.g. a 4-way intersection or roundabout) and an AV intent. A zone graph consists of different types of zones connected by different types of edges. There exist driving zones for the AV, position zones for other traffic participants or information zones that contain e.g. traffic signs. It is differentiated between dynamic and static zones. Static zones do not change over time, e.g. a pedestrian crossing. Dynamic zones are used to express the abilities of an AV (e.g. braking ability in front of the yield line). Thus, this approach is not a pure representation of rules but already considers the abilities of the ego vehicle. Traffic participants can be mapped to a zone. A zone threatens a driving zone when an object with priority could enter the driving zone from this zone. Using a zwicky-box, equivalence classes for the required behavior are derived. For example, when a pedestrian crossing is either blocked or threatened. the required behavior is to stop in front of it. Again, not all rules are represented with this approach (e.g. no speed limit or overtaking ban) and it remains open how the zone graph is derived.

### 2.3.3 Conclusion

In current approaches there are behavior frameworks that consider traffic rules, but either they are only regarded on a high level within a rule hierarchy or they are modeled by the usage of flow charts for a specific scenery or scenario. Butz et al.[80] introduce a promising approach by directly linking rule-related properties to zones of the scenery within a situation representation. Still, there is a lack of systematic and holistic derivation of behavior constraints resulting from the scenery and covering all types of traffic rules.

## 2.4 Operational Design Domain and Scenery Descriptions

As discovered in the previous section traffic rules are bound to local elements of the traffic environment. Therefore, the rules that need to be respected depend on the operational area of the HAV. As introduced in section 1.2, the ODD defines this area. Ultimately, traffic rules should be part of the description of the ODD or at least facilitate the derivation of the rules in order to evaluate the behavior constraints on the ADS. Therefore, current approaches to describe the ODD are presented in the following. Special attention will be paid to the form in which necessary behavior of the vehicle or at least whether the basis for the necessary behavior - in the form of traffic rules - is represented.

---

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

### 2.4.1 Standards for ODD-Description

Generally, there is not yet an agreed standard to describe the ODD, but there are standards under development (e.g. ISO/DIS 34503[81]). The Society of Automotive Engineers[82] gives a best practice for the description of the ODD. The framework presented therein for describing and defining an ODD uses a bottom-up approach. In the first step the road/route network in which the HAV will be deployed and that matches the intended use case is identified. A geographically bounded area limits the expected interactions and facilitates the identification of test cases. As the system evolves, the road network is adapted iteratively based on the functionality of the system. The next step is to characterize the fixed route network and infrastructure. This includes documenting key variables such as physical infrastructure and local weather as well as fixed zones (e.g. school, hospital) and the availability of connectivity (e.g. GNSS, Cellular). Then, operational constraints within the road network are identified: weather conditions, surface conditions and other road user (behaviors) as well as connectivity available. In the last step, the ODD narrative is formulated (this means conveying both direct as well as implied information) and thus, ADS capabilities are compared to the route network characterization and the operational constraints. In the last section, the best practice guide provides a lexicon with terminology that can be used for describing their ODD. While this section includes a short section for design elements and traffic control devices, it remains open what their constraints on the vehicle behavior are and how this knowledge should be incorporated into the comparison of capabilities of the ADS to the route network characterization. BSI PAS 1883[83] introduces a taxonomy to describe an ODD. This taxonomy consists of:

- Scenery (zones, drivable area, junctions, special structures, fixed road structures, temporary road structures)
- Environmental conditions
- Dynamic elements

The drivable area is characterized by type, geometry, lane specification, signs, edge and surface. Thus, first regulatory elements are provided. Still, there is only a listing of possible infrastructure and no consideration of related rules or resulting constraints on the behavior of an HAV. The ASAM develops a format for the description of ODD. Currently, there is only a concept paper[84] available. This paper introduces a language and format for an ODD description. The format is largely based on the approach of Irvine et al.[85] and Schwalb et al.[86]. The represented attributes are largely based on the SAE[82] and BSI[83] documents. There exists metrics for different user

---

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

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

[83] British Standards Institution: PAS 1883: (2020).

[84] ASAM: OpenODD: Concept Paper (2021).

[85] Irvine, P. et al.: A Two-Level Abstraction ODD Definition Language: Part I (2021).

[86] Schwalb, E. et al.: A Two-Level Abstraction ODD Definition Language: Part II (2021).

stories of potential users of the description format. Additionally, uncertainty representation is covered. Therefore, it presents a format to structure and store the ODD attributes introduced by aforementioned standards. Again, there is no explicit consideration of traffic rules and their resulting behavior constraints on the HAV.

### 2.4.2 ODD-Description Approaches

Apart from the activities in standard gremiums, the National Highway Traffic Safety Administration[87] published a framework for testing HAV. This framework also includes a taxonomy to describe the operational design domain which consists of:

- Physical infrastructure
- Operational constraints
- Objects
- Connectivity
- Environmental conditions
- Zones

Within the operational constraints speed limits as behavioral constraint are explicitly listed. Besides this no constraints on the behavior are explicitly dealt with in the framework. Czarnecki[88,89] presents an operational world model ontology. This ontology covers various elements and objects that may be present in the vehicle environment. Thus, it can be used to define the ODD of an HAV. In Part 1, Czarnecki defines a road structure ontology. This includes among others: road types, surface, geometry, cross-section design, facilities and junctions. Part 2 covers road uses, including vehicles and pedestrians and their behavior models. Apart from structuring road user types and classes, Czarnecki introduces behavioral factors that influence the behaviors of road users. There is a dedicated section for traffic rules, but it only introduces where traffic rules originate from (see also section 2.3.1), but neither categorizes or lists these rules nor analyzes the constraints on the vehicle behavior. Apart from traffic rules road user behavior is influenced by social norms, individual behavior factors and vehicle capabilities.

### 2.4.3 Scenery Description Approaches[90]

In addition to approaches to describe the ODD, there exist various approaches to describe the scenery in the field of automated vehicles. The scenery is a subset of the ODD. A widely used

---

[87] Virginia Tech Transportation Institue: Framework for Testable Cases and Scenarios (2018).

[88] Czarnecki, K.: Operational World Model Ontology - Part 1 (2018).

[89] Czarnecki, K.: Operational World Model Ontology - Part 2 (2018).

[90] This sub-section is taken and adapted from the publication: Glatzki, F. et al.: Behavioral Attributes for a Behavior-Semantic Scenery Description (BSSD) (2021).

approach to model and represent the scenery is to use ontologies. Bagschik et al.[91] introduce a 5-layer-model for the representation of driving scenes in order to develop an ontology-based scene creation for automated vehicles. In this model, the scenery is structured in the layers road-level, traffic infrastructure, temporary adaptions of the first two layers and environment. Traffic participants are added with regard to their possible maneuver-based behavior considering the given infrastructure and traffic rules. In a further work, Bagschik et al.[92] extend this ontology to generate functional scenarios. However, both publications do not explicitly examine the behavioral demand in this context, only possible maneuvers such as lane changes are considered. Scholtes et al.[93] add the digital infrastructure layer to the 5-layer-model, again not including behavioral components. Other approaches based on ontologies introduce a graph-based context representation including the scenery[94] or model road segments directly linking traffic regulations such as country specific speed limits[95]. Regele[96] introduces behavioral advises by considering explicit relations between lanes. Opposing traffic, for example, is linked directly with the advice *take special care during crossing over to the other lane*. Instead of using a scenery description indirectly to represent scenes, situations or scenarios, there is the use case for a pure representation of the scenery considering maps. In the context of HAV, OpenDRIVE[97] is a standardized file format developed for simulation applications, which require a precise description of road networks. This format structures roads, referred to a reference line with driving lanes and road features describing the scenery. Thus, it also includes traffic regulation elements such as traffic signs or lights, but without any link to the explicit behavioral information. Another precise description of road networks is presented by Poggenhans et al.[98]. They extend and generalize the map format Liblanelet[99] to a high definition map framework "Lanelet2". Lanelet2 describes traffic rules using regulatory elements, which refer to elements that define these traffic rules (e.g. traffic signs).

### 2.4.4 Conclusion[90]

Although there is no agreed standard, ODD description frameworks are doing well in capturing and structuring relevant elements of the road environment to delimit the operational area of an HAV. Still, the influence in form of behavior constraints is not yet represented in these frameworks. The related work shows that ontologies are a popular approach to model the scenery with its related elements. They are well suited to generate sceneries, but are not used for modeling

---

[91] Bagschik, G. et al.: Wissensbasierte Szenariengenerierung (2018).

[92] Bagschik, G. et al.: Ontology based Scene Creation (2018).

[93] Scholtes, M. et al.: 6-Layer Model for a Structured Description of Urban Traffic and Environment (2021).

[94] Ulbrich, S. et al.: Graph-based context representation (2014).

[95] Buechel, M. et al.: Ontology-based traffic scene modeling (2017).

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

[97] ASAM: OpenDRIVE (2020).

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

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

behavioral demands or requirements. Existing maps for HAV are not abstracted with regard to driving behavior, resulting in big amount of data with little information content regarding the automated driving task. Lanelet2[98] seems to be a promising approach, since the scenery is abstracted, amongst others, to regulatory elements. These regulatory elements provide the opportunity to represent traffic rules, but it remains unclear how this representation is performed. In addition, the explicit behavioral demand is not stated. For example, the regulatory element traffic light only references the respective traffic light and stop line. It does not explicitly state that it is not allowed to drive over the stop line during a red light. Also, Lanelet2 is well suited to describe the scenery as it is perceptible, for example as a ground truth for perception. The derivation of behavioral requirements for HAV is based on traffic rules, common sense rules or safety analyses. Additionally, expert knowledge might be used to complement resulting behavior sets. Besides requirement engineering, behavior sets including traffic rules are also used to verify the safety of trajectories that are generated by behavior planners. In fact, there is no approach to extract information about the behavioral demand from the scenery by providing a direct link between each other.

## 2.5 Formalization and Verification of Traffic Rules

Quantitative limits, which serve as test criteria, are necessary for evaluation. To the knowledge of the author, there is no literature covering the tests and especially test criteria for verifying traffic rule compliance. Though, there exist approaches to formalize traffic rules in order to verify the adherence to traffic rules during runtime of the ADS and with these also quantative limits are given. These approaches are presented in the following.

### 2.5.1 General Traffic Rules

Shalev Shwartz et al.[100] introduce the Responsibility-Sensitive Safety (RSS) model to ensure safety on traffic roads. In this approach, they formulate and formalize five “common sense” driving rules: “Do not hit someone from behind.”, “Do not cut-in recklessly.”, “Right-of-way is given, not taken.”, “Be careful of areas with limited visibility.” and “If you can avoid an accident without causing another one, you must do it.” The authors prove that following the formalized rules results in a collision-free traffic on roads. However, this assumes that all other road users are following these rules as well and that the perception input to the vehicle behavior planning is correct. Other parts of safety are not taken into account, for example module or component failures. Althoff and Dolan[101] propose an approach to formally verify the safety of HAV. By using reachability analysis, they consider all possible behaviors of mathematical models considering

---

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

[101] Althoff, M. et al.: Online Verification of Automated Road Vehicles (2014).

uncertain inputs and thus, predict the set of all possible occupancies of the HAV and other traffic participants. Safety is guaranteed with respect to the modeled uncertainties and behaviors if the occupancy of the HAV does not intersect that of other traffic participants at all times. Therefore, this approach covers the general rule after avoiding collisions with other traffic participants.

In order to participate in public traffic, an HAV must follow country-specific traffic rules besides collision avoidance and common sense rules. These traffic rules by law are mostly formulated vaguely, which challenges the application for HAV. Rizaldi and Althoff[102] formalize a subset of traffic rules from the Vienna Convention which apply to highway scenarios in higher order logic and show a pattern for deriving a procedure for each rule to verify whether a hybrid trace satisfies the rule. In another work, Rizaldi et al.[103] codify a part of the German overtaking traffic rules in linear temporal logic and present a verified checker for detecting the occurrence of an overtaking from a trace of a vehicle and determining a safe distance by considering the reaction time of the vehicle. Here, predicates found in the law text are assumed to be a core proposition (atomic proposition). Pek et al.[104] present an approach for verifying safety of lane change maneuvers, using formalized traffic rules according to the Vienna Convention on Road Traffic. They consider misbehavior of other traffic participants during lane changes and propose feasible solutions to avoid or mitigate a potential collision. Esterle et al.[105] propose a methodology for the formalization of traffic rules in a formal language using linear temporal logic. They formalized traffic rules for dual carriageways based on the StVO[106]. Here, the rules are divided into premises and conclusions. If the premises are fulfilled, then the conclusions must be adhered to. Such a premise may be ”always”. For example, it is always necessary to keep control of the vehicle and to observe the speed limit. Another premise might be ”on motorways”. On motorways, for example, stopping is not allowed. Opposed to introduce approaches, Maierhofer et al.[107] present an approach that is capable of formalizing based on a combination of legal sources and thus, is not only able to consider single rules from one rule set, but combine these rules in order to formalize for a specific use case (in this case: interstate). Still, the combination of legal sources need to be valid for this certain use case. In all of the presented works in this paragraph the formalization is directly performed on the basis of one or multiple traffic regulations of a specific traffic region and limited to German highway or motorway scenarios. Although some of the coded rules (e.g. speed limit) may be transferable to other traffic areas, a general applicability is not given. Again, only the planning layer of the vehicle is considered and the perception input as well as the vehicle control is not verified.

---

[102] Rizaldi, A. et al.: Formalising Traffic Rules for Accountability of Autonomous Vehicles (2015).

[103] Rizaldi, A. et al.: Formalising and Monitoring Traffic Rules for Autonomous Vehicles in Isabelle/HOL (2017).

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

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

[106] Bundesministerium der Justiz: Straßenverkehrs-Ordnung (StVO) (2021).

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

### 2.5.2 Local Traffic Rules

In their publication[108], Maierhofer et al. extend their previous work to priority rules at intersections. They define a suitable road network representation based on lanelets[109] for the formalization. Within this representation, the traffic signs are directly represented. Although the formalization may be adapted to different national requirements, the formalization still has to be performed over and over every time a new traffic area should be covered. Besides priority rules, no other traffic rules such as waiting in front of the intersection for stagnant traffic are covered. Additionally, the approach does not cover crossings, pedestrians, cyclists, railroad vehicles as well as buses and assumes that the ego vehicle has an unobstructed view over the intersection while the perception input is not verified. The formalization was evaluated using the inD dataset as well as manually-created test scenarios. Karimi & Duggirala[110] formalize rules at uncontrolled intersections in California, USA. They extract the rules from the California Driver Handbook[111], thus the basis is again directly legal text and transferability to other traffic regions is not ensured. The legal text is first brought in to a logical form, which then is converted to a semantic form. Within this form the rules are bound to so called boxes which are mapped to the scenery. For example, if the arrival box is reached, the condition *atTheIntersection()* is fulfilled. From these conditions, semantic rules such as *mustStopToYield()* are inferred. Therefore, this approach considers the local reference of traffic rules to the scenery. Still, it is specific to intersections in California without any traffic signs or dynamic signals. Additionally, other traffic rules than priority rules remain open (e.g. speed limits, entrance allowance) and are not holistically covered.

### 2.5.3 Conclusion

There exist various formalization methods (mainly based on logic approaches) for testing general traffic rules at runtime in the vehicle. Furthermore, there are approaches for specific traffic areas (e.g. specific intersections). However, there is a lack of an approach that is applicable to different traffic domains due to a lack of universal description of behavior constraints. Additionally, the procedures are not used as criteria within tests, but are directly checked during runtime (formal verification). This often assumes that the perception input is correct. So the criteria found in literature only verify the conformity of the planner with regard to the delivered input, but they do not check if the environment has been perceived correctly and whether there is awareness of the rules that are currently in place. In fact, there is no approach providing a testable interface for such awareness.

---

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

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

[110] Karimi, A. et al.: Formalizing traffic rules for uncontrolled intersections (2020).

[111] Department of Motor Vehicles: California Driver's Handbook (2022).

# 3 Objective and Research Questions

Based on the current state of the art, in this chapter, the objective of this dissertation is concretized. This includes a derivation of requirements and the presentation of the overall methodoloy to achieve the objective. From this, research questions that need to be answered to fulfill the requirements are deduced.

## 3.1 Scope and Requirements

The state of the art shows different methods to verify compliance to general traffic rules and to verify local traffic rules for individual traffic areas. However, no methodology exists that specifies and checks local traffic rules holistically, regardless of the area of application. The scope of this work is therefore the development of such a methodology. This includes, the record and description of the local traffic rules, the quantification and finally the test and evaluation of the compliance to these rules by an HAV. Therefore, the main objective of the developed methodology is to provide a process to prove compliance of an HAV to the local traffic rules within a certain, but arbitrary ODD. This means that the method should not restrict itself to a certain application domain or area. The first requirement to be fulfilled by the methodology therefore is:

**REQ 1.** *The methodology shall not be restricted to a specific operational design domain within the road traffic domain.*

As a first step, it is necessary to describe the resulting constraints on the behavior of an HAV. Because these constraints are bound to a geo-located space, a suitable representation form to capture the geographic locations is necessary. The standard format to represent geographic point locations are coordinates (latitude, longitude, altitude).[112] But not only the geographic location of single constraints is relevant, also the (geometric) relationship between different constraints is essential (i.e. which constraint follows, which constraint is adjacent). A map is *"a diagram or other visual representation that shows the relative position of the parts of something"*[113]. Therefore, the geo-located constraints shall be represented in a map which puts the position of the constraints in a relation with the local scenery as well as the position of constraints among each other. This results in the following requirement for the methodology:

**REQ 2.** *The methodology shall be able to describe the behavior constraints of a local scenery in a map.*

---

[112] ISO: ISO 6709: Standard representation of geographic point location by coordinates (2008).

[113] Merriam-Webster: "map" in merriam-webster.com (2022).

Resulting from REQ 1, this description format needs to be able to deal with an arbitrary ODD. In order to specify the scope of the system for a certain ODD, it is necessary to identify the local constraints of this ODD. This means to extract the behavior rules regarding local traffic rules from the scenery as it would be perceived by a human and reduce the information to an explicit description of the behavior constraints regarding local traffic rules specifically for the ODD under consideration. The methodology needs to provide a method to perform this step:

**REQ 3.** *The methodology shall extract the behavior constraints of a specific ODD to serve as part of the specification of the system.*

Applying the functional decomposition method by Amersbach[114] (see section 2.2) to the test process of HAV showed a reduction of the test effort. Therefore, the methodolgy developed in this dissertation aims to support the functional decomposition method and thus, profit from the benefit in effort reduction. This means that the methodology needs to provide methods to decompose the behavior constraints on system level to constraints on sub-system (decomposition) level. This results in the following requirement:

**REQ 4.** *The methodology shall support the functional decomposition approach in order to reduce the test effort.*

In order to make the specification testable, it is necessary to quantify and formalize the behavior constraints. This means that every identified constraint shall have a formal description resulting in quantifiable limits for the vehicle behavior based on local traffic rules. These boundaries serve as test criteria within the test process (see REQ 6).

**REQ 5.** *The methodology shall quantify the identified behavior constraints.*

In a final step, there needs to be evidence provided to verify the traffic rule compliance of an AV within a specific ODD. For this, from the specification, including the broken down functionalities to sub-system level, suitable test cases need to be provided. The last requirement of the methodology is:

**REQ 6.** *The methodology shall derive a test plan for the validation of local traffic rule compliance of an HAV.*

---

[114] Amersbach, C. T.: Functional Decomposition Approach (2020).

## 3.2 Methodology to Specify and Test Traffic Rule Compliance

In this section, based on the requirements from the previous section, the methodology to specify and test compliance to local traffic rules of HAV is derived. An overview of the methodology is depicted in Fig. 3-1.

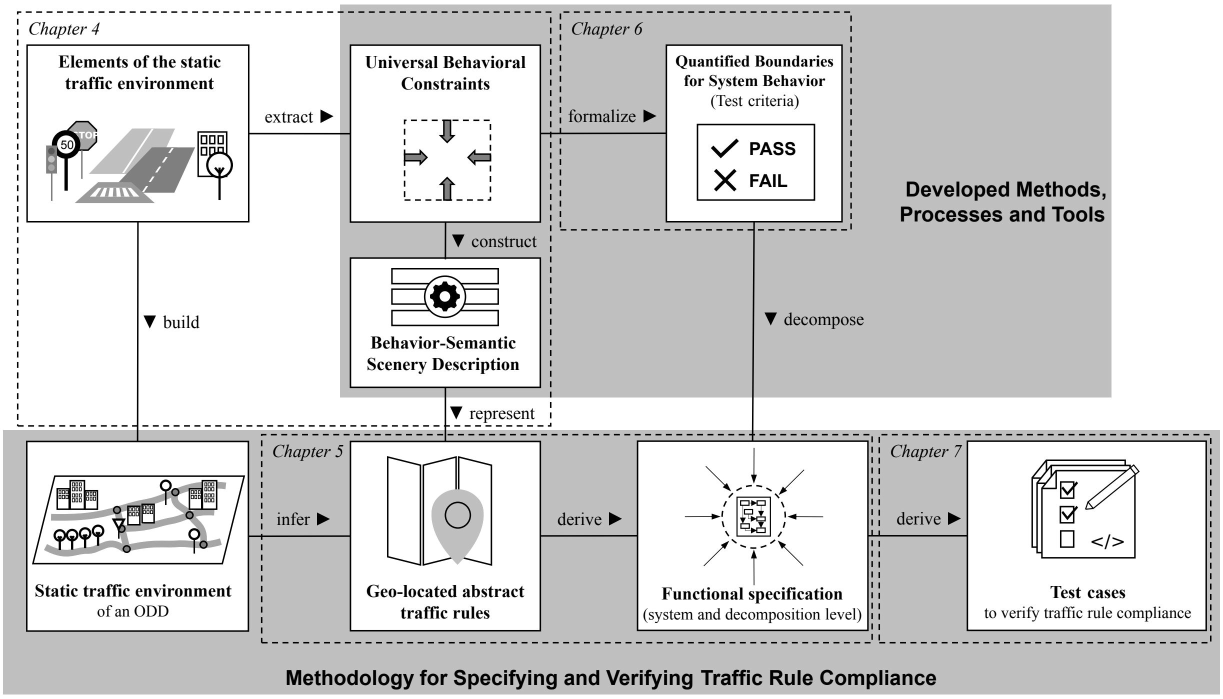


Figure 3-1: Overview of the Methodology.

The main objective of the methodology is to prove compliance to the geo-located traffic rules of an ODD under consideration. As identified, the static traffic environment instantiates these rules. Therefore, it is necessary to infer these rules from the environment. For this a suitable description format is necessary to represent the geo-located rules in a map (see REQ2). In order to fulfill REQ1, the rules need to be converted in an abstract format such that following steps of the methodology are applicable regardless of the application area. The format is constructed out of a representation of the behavior constraints that the elements of the static traffic environment may impose. Therefore, in a first step it is necessary to extract and analyze the constraints and abstract them in such a way that they are able to represent the behavioral limits of any given ODD (see REQ2). The description format is called Behavior-Semantic Scenery Description (see section 4.3), because it combines the behavior constraints in an explicit, semantic form with the geo-reference of the local scenery. With this representation of the geo-located abstract traffic rules, it is possible to derive the functional range of the system regarding local traffic rule compliance because the behavior limits based on local traffic rules are available. In an additional step, the behavior constraints are formalized to have test criteria for the specification of the system (see REQ4). These test criteria on system level (including the associated functionalities) are broken down on decomposition level in order to apply the functional decomposition approach by Amersbach[115] for a reduction of the test effort (see REQ5). Finally, a systematic methods to derive a test strategy are investigated in order to derive a test plan to show the applicability and benefit of the previously developed methods (see REQ6).

## 3.3 Derivation of Research Questions

Based on the defined objective and methodology of this dissertation in the previous sections, the research questions that need to be investigated in order to employ this methodology are derived in this section.

In order to construct abstract, universal behavior constraints, it is first necessary to identify what kind of constraints exist in general. For this the elements out of which the static traffic environment is constructed need to be analyzed with regards to the constraints on the behavior of an HAV. This leads to the first research question:

**RQ 1.** *What are the elements of the static traffic environment and what constraints on the behavior of an HAV do they have?*

Having identified what possibly could legally constraint the vehicle behavior, the next step is to derive a map description format that represents these constraints. The goal herewith is to find the minimal set necessary to describe these constraints while remaining universally applicable. This results in the following two research questions:

**RQ 2.** *How can the behavior constraints imposed by the local traffic rules be described in such a way that the description is universally applicable (unlimited area of application)?*

**RQ 3.** *How can the behavior constraints imposed by the local traffic rules be recorded in a map representation?*

As pointed out in section 3.2, the first step of the methodology is to infer the local traffic rules based on an ODD under consideration. This raises the following research question, which deals with finding a way from the representation of the scenery as a human would perceive it to the representation developed based on research question RQ2 and RQ3:

**RQ 4.** *How can the abstract behavior rules be inferred on the basis of a present scenery?*

---

[115] Amersbach, C. T.: Functional Decomposition Approach (2020).

In order to support the functional decomposition approach, it needs to be investigated, how the abstract behavior constraints on system level can be decomposed to necessary functionalities on decomposition level. This results in the following research question:

**RQ 5.** *What conclusions can be drawn from the behavior constraints on system level for the functional specification at the sub-system level (decomposition level)?*

In order to use the inferred behavior rules for the test of HAV with regards to traffic rule compliance, they need to be converted into pass/fail criteria. This means, formalizing the rules into quantifiable expressions. This investigation is performed by answering the following research question:

**RQ 6.** *How can identified behavior constraints of local traffic rules be converted into concrete pass/fail criteria for system and sub-system tests?*

With the knowledge resulting from the analysis of the previous questions, test cases that detect defects which result in violating the traffic rules need to be created. The process of test case generation and benefit of the previous knowledge within this process is evaluated with the investigation of the following research question:

**RQ 7.** *How can a test plan for the validation of local traffic rule conformity be defined?*

Finally, the practical applicability of the developed approaches must be given. This is pursued with the analysis of the following research question within a real world use case:

**RQ 8.** *Is the developed methodology practically applicable?*

# 4 Scenery-Based Behavior Constraints

In this chapter the first two research questions (RQ1, RQ2) are addressed and the description method for the scenery-based behavior constraints is derived. This includes the following steps:

- Identification of elements of the static traffic environments and analysis of their resulting contraints on vehicle behavior based on local traffic rules (section 4.1)
- Abstraction of the behavior constraints in order to describe the traffic environment from behavioral perspective (section 4.2)
- Development of a description format to explicitly represent the behavior constraints of a scenery (section 4.3)

The research within this chapter to address these research questions has been conducted together with Moritz Lippert. While the author of this dissertation focussed on the work to identify and abstract the behavior constraints (section 4.1 and 4.2), Moritz Lippert's focus was the development of the description format to record these constraints (section 4.3).

## 4.1 Analysis of the Static Traffic Environment

This section addresses research question RQ1:

*What are the behavior-relevant elements of the static traffic environment and what effect do they have on the legal behavior specification of an automated vehicle?*

In order to analyze the behavior constraints of the static traffic environment, it is first necessary to identify how this environment is built up. The 6-Layer Model by Scholtes et al.[116] (see also section 2.4) provides a structure to perform this analysis by structuring various elements of the traffic environment into layers. The first three layers subsume the space in which various types of objects (pedestrians, vehicles, ...) may move. The first layer (Road Network and Traffic Guidance Objects) subsume elements that define *where* and *how* traffic participants may move. The base for any movement of an HAV is the roadway. On the roadway, road markings and delimitations such as curbstones are applied in order to further subdivide the traffic space. In addition traffic signs give indication which spaces shall be used and which rules need to respected while doing this. In the second layer (Roadside Structures) further elements of the road surroundings are added such as buildings, vegetation and walls or fences. The third layer (Temporary Modifications of Layer 1 and Layer 2) describes, as the name says, all temporary modifications of elements of Layer 1 and 2. All objects within this layer are of the same class as Layer 1 or Layer 2 objects. The

---

[116] Scholtes, M. et al.: 6-Layer Model for a Structured Description of Urban Traffic and Environment (2021).

difference is that these objects are only used for temporary modifications (e.g. a construction sign with corresponding traffic signs and road markings). Higher layers (4-6) describe the dynamic content of the traffic environment and therefore, are disregarded in the following. In the following, contained elements within the first three layers are identified and analyzed regarding the constraints on the rule-base behavior constraints. For this, the German Directives for the Design of Urban Roads[117] and the StVO[118] are taken into consideration and design elements of the static road traffic environment are extracted from these sources. For each element, the behavioral constrains are determined, resulting in a list of all constraints based on German traffic environments. Because Layer 3 elements are either of the class of Layer 1 or Layer 2, a separate analysis for Layer 3 is omitted. In the following sections all identified constraints are printed in italic. The process to identify behavior constraints is summarized in Fig. 4-1. Within the following sections not every single identified element is listed and explained, but only at least one example per identified constraint. The explanations would otherwise become too long.

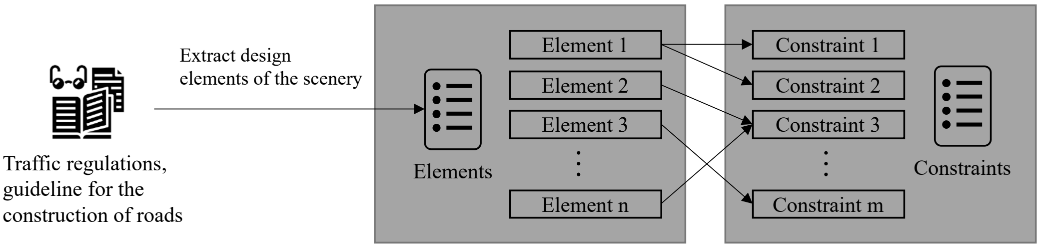


Figure 4-1: Process to extract behavior constraints from the design elements.

## 4.1.1 Extract Behavior Constraints

### Layer 1: Road Network and Traffic Guidance Objects

Even without any further elements the roadway itself may put constraints on the behavior of an HAV. Section 2 paragraph 1 of the StVO states that vehicles need to use the roadway. If there is more than one roadway within one road, vehicles are forced to drive on the right of these roadways. This directly puts constraints on the allowed *driving direction* within certain sections of the scenery. Indirectly this also limits the performance of *u-turns* and restricts the *entrance into roadways* from certain directions. The road layout itself without any other elements may also give *right of way* to traffic participants coming from a certain direction. At two intersecting roadways without any further infrastructure, the rule ”right-before-left” advises that traffic coming from the right has priority. Additionaly, in general while turning at such intersecting roadways *turn indication* needs to be activated.

The main part of rules is instantiated by traffic signs as these have the purpose to affect or control the traffic. On road level, road markings further subdivide the roadway into lanes. These

---

[117] Road and Transportation Research Association: Directives for the Design of Urban Roads (2012).

[118] Bundesministerium der Justiz: Straßenverkehrsgesetz (StVG) (2021)

delimitations of the traffic space come with rules that specifiy the *crossing of boundaries*. A solid lane marking, for example, prohibits driving over the boundary while a dashed lane marking allows driving over the boundary. At the same time lane markings may also impose restrictions regarding *parking*. There are also forms of lane markings that restrict certain spaces for the *usage* of any vehicles (restriced area). Other markings give the *right of way* to certain types of traffic participants. For example, at a pedestrian crossing, pedestrians will have the right of way. Therefore, vehicular traffic will need to yield for pedestrians. Additionally, roadmarkings may also limit the *usage* of certain lanes based on the type of traffic participant. For example, there are special lanes for buses and trams.

Traffic signs in the form of plates introduce further rules. Placed at intersections they overwrite the *validity of rules* based on the road layout regarding the *right of way*. For example a ”priority” road sign gives priority to traffic following the road over the intersection, it is not necessary to yield to the right anymore. Conversely, the sign ”give priority” advises to yield to traffic coming from the left and right. A stop sign, in addition, states that the vehicle needs to come to a full stop before entering the intersection, constraining the *continuing* of vehicles. Furthermore, traffic signs may prohibit the *entrance into certain roads* (e.g. ”no entry” sign or ”prohibition of motor vehicle” sign) as well as the *driving direction* (e.g. ”one way road” or ”direction arrows”). Speed limit signs constrain the allowed *driving speed*. Certain signs (e.g. tunnel ahead) require the *vehicle lighting* to be turned on. Finally there are zone signs (such as ”city-entry” sign or ”highway” sign). These sign mark the beginning (and their corresponding end sign the end) of certain zones. In this zone multiple constraints are imposed on the vehicle. First of all the *entrance* into these zones may be limited. For example, on the highway only vehicles able to drive at least 80 km/h are allowed.

### Layer 2: Roadside Structures

Especially in urban areas there are other elements that occur in the road environment, even if they do not have a direct rule restricting the behavior of the vehicle. The Directives for the Design of Urban Roads[119] subdivide these elements into the following categories:

- Kerbs and channels
- Speed reduction measures
- Greenery
- Street furniture

Kerbs and channels often constitute the delimitation of the roadway. Therefore, there is a clear prohibition on *crossing these boundaries* (except for parking). Speed reduction measures may either be different types of speed bumps, but also narrowing of the roadway with a center island, whereby again boundaries are introduced that cannot be driven over. In some cases even greenery (trees, hedges, etc.) is placed within the roadway, which then restricts the *lane usage*. Outside of

---

[119] Road and Transportation Research Association: Directives for the Design of Urban Roads (2012)

the road they are used to restrict the *crossing of boundaries*. Street furniture includes barriers, civil engineering equipment, installations, etc. These restrict the motion space because they cannot be driven over (*boundary crossing* not possible). However, certain areas of the street may also be selectively *unusable* for vehicles of a certain height because of cables, for example.

Table 4-1 presents an excerpt of the elements of the traffic environment and which rule constraints these may impose.

Table 4-1: Resulting behavior constraints from road elements[120]

| | **Constraints on...** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Traffic Element** | Right of Way | Road Entrance | Lane Usage | Driving Direction | Overtaking | Driving Speed | Boundary Crossing | Vehicle Lighting | Turn Indication | Continuing (stop) | U-Turns | Parking | Validity of other rules |
| Road Network (Roadway, Curbstones, ...) | x | | | x | | | x | x | x | | x | | |
| Traffic Signs | x | x | x | x | x | x | x | x | x | x | x | x | x |
| 201 Andreas cross | x | | | x | | | | | | | | x | |
| 205 Give priority | x | | | | | | | | | | | x | |
| 206 Stop. Give priority | x | | | | | | x | | | x | | | |
| 208 Priority of oncoming traffic | x | | | | | | | | | | | | |
| 209 Prescribed direction of travel | | | x | | | | | | | | | | |
| ⋮ | | | | | | | | | | | | | |
| 301 Priority | x | | | | | | | | | | | | |
| 306 Priority road | x | | | | | | | | | | | x | |
| 308 Priority over oncoming traffic | x | | | | | | | | | | | | |
| 310 Town sign | | | | | | x | | | | | | | x |
| 330 Highway | | x | | x | x | x | | | | | x | | x |
| 331 Motor road | | x | | x | x | x | | | | | x | | x |
| ⋮ | | | | | | | | | | | | | |
| 600 Barrier | | x | | | | | x | | | | | | |
| Parking and loading areas | | x | x | | | | x | | | | | x | |
| Public transport facilities | x | | | | | | x | | | | | x | |
| Speed reduction measures | | | | | | | x | | | | | | |
| Greenery | | | x | | | | x | | | | | | |
| Street furniture | | | x | | | | x | | | | | | |

---

[120] Own representation based on StVO[118] and German Directives for the Design of Urban Roads[119]

### 4.1.2 Structuring Behavior Constraints[121]

Four key questions are used to further structure the traffic environment based on the identified behavior constraints. With this structuring, it is possible to reduce the stated constraints into an abstract set of rules coming from the static traffic environment in the next section. While there exist many restrictions on parking allowance, finding and selecting an allowed space for parking is highly different from fulfilling the driving task in moving traffic. Therefore, a separate representation of available parking spaces in a separate data format is assumed and thus, constraints regarding parking not considered from now on in this dissertation.

**A. In which spaces is the vehicle allowed to move?**

In general, the motion space for motor vehicles is the roadway. This space is called the regular motion space. It is defined from the perspective of motor vehicles. A bike path also serves as a regular motion space, but only for bicycles. Based on traffic rules, it is not allowed for motor vehicles to leave the regular motion space (by the constraint of *crossing boundaries*). A typical example would be a sidewalk where motor vehicles are not allowed to move (constraint on *lane usage*). In common sense, it is widely accepted to leave the regular motion space in special cases. For example, when the road is blocked by a broken down car. Outside of the regular motion space, no rules are stated for the vehicles (since they are not allowed to be there). For that reason, a cautious behavior and slow driving speeds are necessary in these spaces.

**B. What conditions are tied to the residence allowance in these spaces?**

As identified, it is possible to subdivide the regular motion space, based on conditions tied to the residence in these spaces. On the one hand, there are spaces in which motor vehicles are allowed to move permanently. This space is usually characterized by driving lanes pointing in the driving direction of motor vehicles. On the other hand, there are spaces, which are not allowed for permanent use. A typical example is oncoming traffic lanes. It is allowed to use these lanes temporarily such as for overtaking, but these lanes cannot be permanently used (by the restriction on *right of way*). Additionally, there are parts of the regular motion space that are reserved for certain types of traffic participants (e.g. bus lane, pedestrian crossing) (restriction on *usage of lanes*). Finally, there are spaces, which are not allowed for use at all. This may be indicated by the restriction on the *usage of lanes* (e.g. restricted area) or restriction on *boundary crossing* (e.g. solid lane marking)

**C. Which behavior rules needs the vehicle to fulfill while driving in these spaces?**

Every identified driving space has rules associated with it. A rule that applies independent of the presence of other traffic participants is the speed limit (restriction on *driving speed*). In

---

[121] This sub-section is taken and adapted from the publication: Glatzki, F. et al.: Behavioral Attributes for a Behavior-Semantic Scenery Description (BSSD) (2021)

addition to the speed limit, the interaction with other traffic participants needs to be considered. In particular, this interaction is regulated by priority rules. Priority may be given to objects coming from a certain direction (e.g. at intersection) and/or certain object types (e.g. pedestrians at crosswalks). At certain sceneries, different traffic participants may also have the same priority right (e.g. two oncoming vehicles turning left at an intersection). Besides the restriction on *right of way*, restrictions on *overtaking* describes an important aspect of vehicle interaction. Overtaking may be prohibited at certain road sections explicitly by traffic signage, but it may also be prohibited implicitly by other traffic rules (e.g. pedestrian crossing). Finally, certain spaces may require turned on low beams, e.g. in tunnels.

### D. Which behavior rules does the vehicle need to consider during changes between spaces?

While entering a new driving space (e.g. lane change), of course, the vehicle needs to respect the rules associated with the space that it enters. Besides that, the change into this space itself needs to be allowed. In general, it is possible to enter a space in longitudinal or lateral direction. Lateral lane limits that prohibited the entrance into a space are, for example, solid lane markings. In longitudinal direction, the entrance into a space may also be tied to a condition. For example, at intersections with a stop sign the vehicle is required to stop at the stop line before entering the intersection or while turning left or right the respective turn indicator needs to be active to perform the maneuver. Therefore, the restrictions on *usage of a lane, entering a road, crossing boundaries, continuing, turn indication* and *performing u-turns* are closely related with crossing the boundary of a certain road space.

In order to describe the identified behavior-relevant characteristics of the scenery, it is necessary to identify a structure that is able to record these characteristics. This structure will then contain the behavior constraints for a motor vehicles operating within the described scenery. This means that no explicit behavior of the vehicle is demanded, but rather the delimitation of the legally possible vehicle behavior is given. Within these limits, the vehicle may behave without further restrictions. Therefore, we call this delimited set of legally allowed behaviors the behavior space. The behavior space is derived from the scenery and its linked traffic rules. It enfolds the legally allowed behavior for the vehicle and is a subset of the state space which describes all possible vehicle behaviors. The behavior space itself is constructed out of different dimensions, which we call behavioral attributes. A planned behavior lying within the behavior space (and thus adhering to the behavioral attributes) is per definition rule-conformant. Fig. 4-2 highlights this relation.

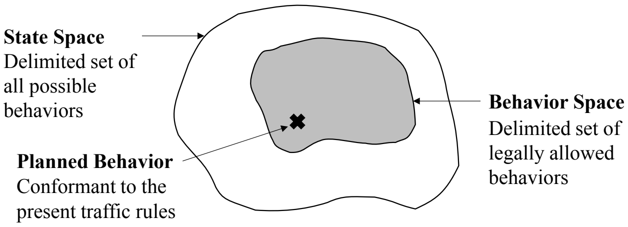


Figure 4-2: Relation between state space, behavior space and planned behavior

## 4.2 Behavioral Attributes[122]

This section addresses research question RQ2:
*How can the local traffic rules be described in such a way that the description is universally applicable (unlimited area of application)?*

The behavioral attributes determine the limits of the allowed behavior and thus, span the behavior space. The goal of the behavioral attributes is to capture all possible rule types identified in section 4.1 and abstract them to such a degree, that the respective element that sets the rule is not represented, but rather the associated behavior rule itself. Elements that set a rule are called indication elements. Based on the investigated key questions, four behavioral attributes are introduced to describe the behavior space. Each of these attributes has underlying properties. The attributes with their respective properties are assigned to what is called an atomic behavior space. The atomic behavior space is a segment of the road network within which the behavioral attributes do not change. In most cases, this will be a longitudinal sub-section of a lane. In Fig. 4-3 exemplary indication elements for every behavioral attribute are given.

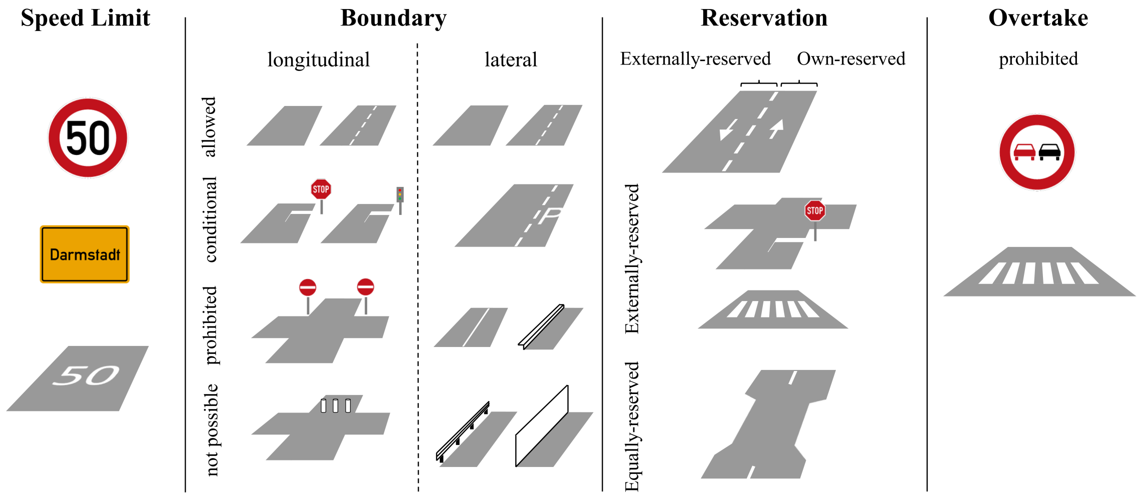


Figure 4-3: Exemplary indication elements for each behavioral attribute

### 4.2.1 Speed Limit

This attribute defines the maximum allowed speed within the atomic behavior space. A vehicle moving within this space is not allowed to drive faster than this speed. The speed limit may be indicated by traffic signs or road markings but can also be bound to the type of the road (e.g. urban road, highway). For example, a town entrance sign may also serve as an indication element for a speed limit. In addition to the speed limit itself, there might be a time restriction for this

---

[122] This section was taken from the publication: Glatzki, F. et al.: Behavioral Attributes for a Behavior-Semantic Scenery Description (BSSD) (2021) and supplemented by section 4.2.5 and 4.2.6

limit and other conditions, which apply for the speed limit to be valid (e.g. a separate speed limit for a wet road). Therefore, there is the possibility to define a value for different time intervals and for other special conditions within this behavioral attribute.

### 4.2.2 Boundary

This attribute describes the related behavior rules for crossing the boundaries of an atomic behavior space. Crossing of boundaries may be allowed, conditionally allowed, prohibited or not possible. It is differentiated between longitudinal and lateral boundaries. The longitudinal boundary specifies the rule regarding entering a lane in longitudinal direction, while the lateral boundaries specify the rule while leaving a lane in lateral direction (to the left and to the right). To cross a longitudinal boundary between two atomic behavior spaces without any further indication elements while driving in the correct driving direction of these lanes is allowed. With additional indication elements, this allowance may change. For example, a stop sign and its matching stop line leads to a conditionally allowed boundary, with the condition to stop at the stop line. Particularly interesting are traffic lights, because of their dynamic indication. Boundaries with traffic lights are also conditionally allowed to cross, with the condition to not violate a red light. In addition, we are able to cover traffic light outages by specifying one boundary attribute for active traffic lights and a separate one for non-active traffic lights. If the driving maneuver assigned to the space after the boundary requires to operate the turning indicator, this is represented as a boundary condition as well. In lateral direction, the indication elements for the crossing rule will be the lane boundaries. Examples for allowed crossing rules of a lateral boundary are dashed lane marking as well as no lane marking between lanes. A solid-lane marking as well as a curbstone, for example, indicates a prohibited crossing of the lateral boundary. It is not allowed to cross these boundaries. It might sound reasonable to soften the prohibition to cross a boundary if there is a special situation and special care is taken, but since we strictly represent the traffic rules, we remain with the official strict prohibition. Nevertheless, it would be possible to modify this property based on agreed common sense rules in the future. A dashed lane marking to delimit parking spaces is an example for a conditional crossing of the lateral boundary. It is only allowed to cross this boundary if the goal to park there exists. Finally, walls, guardrails, trenches, etc. indicate a boundary that is not possible to cross.

### 4.2.3 Reservation

The reservation defines the conditions that need to be fulfilled in order to enter and/or remain in this area from a priority point of view. As the name of this attribute suggest, every atomic behavior space is treated as a space that is reserved for a certain (or multiple) class(es) of traffic participants. This class of traffic participants shall not be obstructed in its driving mission within this area by other classes of traffic participants. In addition, only if the traffic participant has a reservation for this area, it is allowed to move permanently in the atomic behavior space. For example, it is not allowed to drive permanently in oncoming lane direction, because this space is reserved for traffic participants driving in the correct direction. From a motor vehicle point of view, the reservation conditions depend on type and link of the reservation. The reservation type defines, with respect to the driving direction if a lane area is reserved for specific traffic participant classes. Possible traffic participant classes are motor vehicles, bicycles, pedestrians and railed vehicles, because each of this class may have an individual reservation right. A reservation type may be own-reserved (for the traffic participant class under consideration, here: motor vehicle), externally-reserved (for other traffic participant classes) or equally-reserved (if there is no clear priority rule between two different traffic participant classes). Own-reserved behavior spaces, for example, are driving lanes pointing in the driving direction of motor vehicles as well as priority roads leading over intersections. Externally-reserved behavior spaces are, for example, oncoming traffic lanes as well as non-priority roads leading over intersections. Externally-reserved motion spaces may be indicated by various traffic signs (e.g. stop sign, yield sign). Equally-reserved motion spaces are, for example, two overlapping left turn lanes in oncoming direction or narrowed roads without a clear priority rule. If the reservation is not of the type own-reserved, the link identifies the areas from which the reservation entitled traffic participants may come.

### 4.2.4 Overtake

This attribute defines the permission to overtake other traffic participants on a given lane. Overtaking takes place when two traffic participants are traveling in the same direction on the same roadway with different speeds and the faster vehicle passes the slower vehicle. It does not matter whether the two vehicles are in the same lane or not. Overtaking may be prohibited or allowed. The typical indication element for the prohibition of overtaking is the “overtaking prohibited” traffic sign, but there are also other scenery elements that result in an overtaking prohibition. For example, overtaking at crosswalks is prohibited.

### 4.2.5 Lighting

While the publication from Glatzki et al.[123] focusses mainly on the behavior resulting from behavior planning algorithms in form of a planned respectively driven trajectory, for completeness an attribute for lighting is listed here. This attribute defines the required state of the low beams of the vehicle. Certain section (e.g. in tunnels) require the vehicle to have the low beams turned on. In the course of this dissertation, this attribute will not further be considered, since it is a basic function that is already handled by current state of the art vehicles[124].

---

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

[124] ADAC: Lichtassistenten: Diese Systeme sorgen für mehr Sicherheit (2021).

### 4.2.6 Example

Fig. 4-4 introduces an example for the usage of the behavioral attributes to describe the behavior constraints of the scenery. The exemplary road section shows a two-lane road with one lane per driving direction. The speed limit is reduced from 50 km/h (section ①) to 30 km/h (section ②) before a pedestrian crossing (section ③).

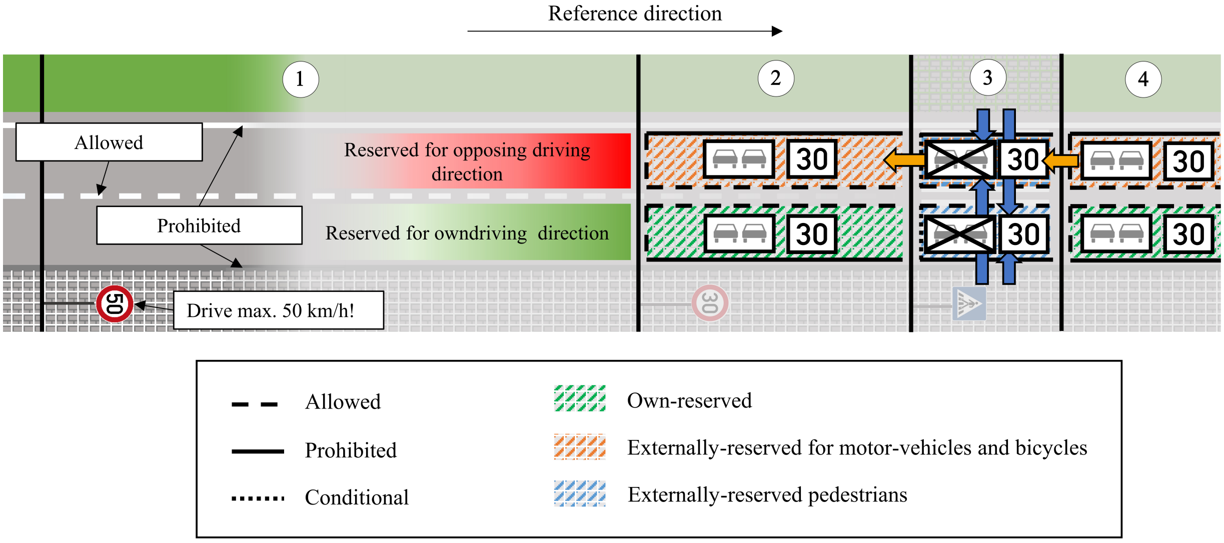


Figure 4-4: Exemplary scenery section with derived attributes

On the left hand side of the road layout, constraints are addressed using natural language (not employing behavioral attributes yet). The solid lane boundary and the curb are not allowed to be crossed and the speed limit sign advises to drive a maximum of 50 km/h. The right hand side of the road layout is abstracted by using the behavioral attributes. It becomes clear, that the opposing driving direction is reserved for oncoming traffic. The area of the pedestrian crossing is reserved for pedestrians that want to cross the road as well. Here, overtaking is not allowed. The longitudinal boundary entering the pedestrian crossing is conditional. This is because there shall not be any stagnant traffic that leads to stopping on the pedestrian crossing before entering it. This example highlights how the behavioral attributes extract and describe the behavior constraints of the local scenery. However, there is no method to describe the relation between the atomic behavior spaces and the relation to the geometric road layout yet. This method is introduced in the next section.

## 4.3 Behavior-Semantic Scenery Description[125]

In this section the BSSD to represent the behavior constraints imposed by the local traffic rules in a map is derived. The section addresses research question RQ3:

---

[125] This sub-section was taken from the publication: Lippert, M. et al.: Behavior-Semantic Scenery Description (BSSD) (2022)

*How can the behavior constraints imposed by the local traffic rules be recorded in a map representation?*

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. However, the main goal of BSSD is to semantically represent the behavioral demands in the overall context of a considered scenery. Here, the behavioral demands apply to a specific type of traffic participant. If this main objective is achieved holistically, the following hypothesis may be corroborated and not be falsified[126]:

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

For this work, the scope is the BSSD for an automated motor vehicle. Thus, given considerations and examples address HAV 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 work 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 HAV it is necessary to know the connection of the behavioral demand to a real scenery or a real route network. In this way, for example, an ODD selection within a route network becomes possible. Thus, the goal is a traceable connection between real scenery and behavior space. This means that 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 HAV 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

---

[126] Popper, K. R.: The logic of scientific discovery (1968).

behavior space. Thus, the goal is a scenery description that enables the navigation through the individual atomic behavior spaces comparable to a map.

***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 description must provide contradiction-free and unambiguous behavioral information for each part of the scenery. This prevents parts of the scenery that should be described in the same way from a behavioral point of view from being represented differently in the description.

***Generality***: Different use cases of HAV 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 automated vehicles 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 driving.

Based on the previously mentioned goals and the resulting challenges in developing the BSSD, requirements for the description are derived in the following.

### 4.3.1 Requirements

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:

***REQ 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:

***REQ 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. 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 HAV development and operation (e.g. ODD specification or routing). Due to this endeavor, the following requirement is formulated:

***REQ 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:

***REQ 4****: If different sceneries impose the same behavioral demands, they shall always be represented by the same behavior 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:

***REQ 5****: The BSSD shall represent the behavior space to any real scenery.*

### 4.3.2 Generic Structure

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 4.3.1 are met. Figure 4-5 represents the generic structure of the BSSD resulting from the derived necessary elements and their relationship to each other.

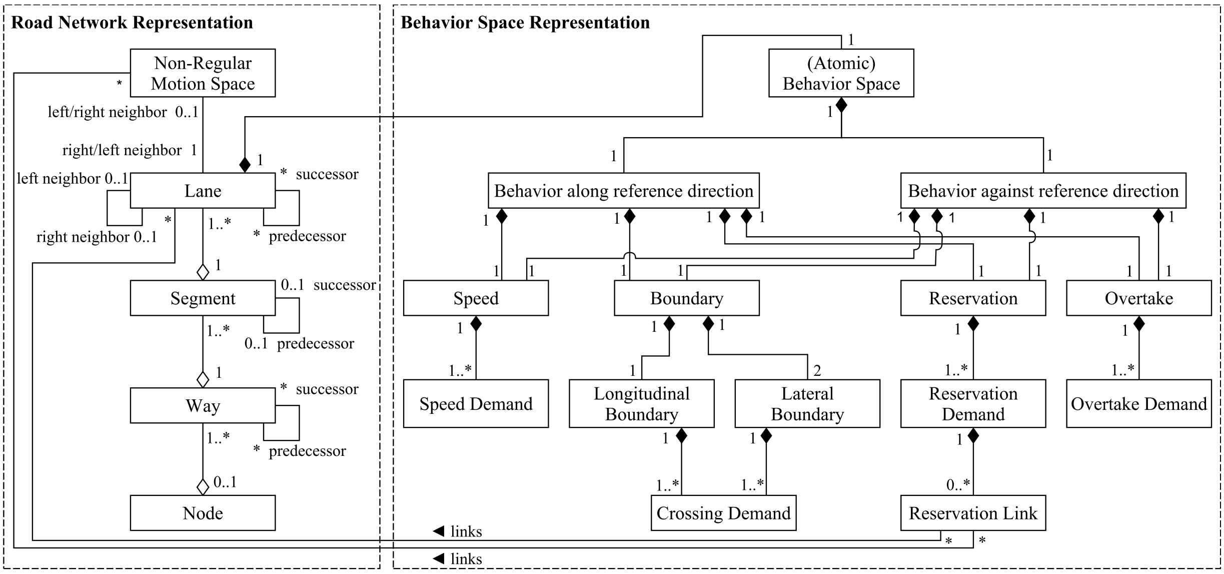


Figure 4-5: Structure of the Behavior-Semantic Scenery Description[125]

## 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. 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, 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 as they exist in reality must therefore be represented. For every point in the route network where multiple driving options follow, the available behavior spaces must be represented. 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 HD map would be evident based on geometric adjacency alone, without the need to define further dependencies. 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* 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 4-2 are necessary for mapping the BSSD to a road network. The resulting structure of the road network representation within the BSSD is shown in Fig. 4-5 on the left-hand side.

### 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 HAV. 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

Table 4-2: Necessary elements for BSSD of a road network

| **Term** | **Description** |
|---|---|
| Node | Area in which multiple ways overlap 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 way in which the mapped behavior space is constant (no change at all) |
| Non-regular motion space | Area outside of the regular motion space. |

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 road users 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 system. Here, different crossing demands apply for active or inactive traffic lights.

*Reservation Attribute*: As introduced in section 4.2, 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, none) further elements are required. For the externally- and equally-reserved cases, the type of the reservation-entitled road users must be represented. Additionally, there is the *reservation link* element, which indicates the origin and, if necessary, the destination direction of these road users 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 in Figure 4-5 on the right hand side. 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 derived in the previous chapter. The resulting overall structure (Figure 4-5) now represents not only each individual behavior space, but also their concatenations. Thus, the behavioral demands resulting from subsequent behavior spaces are represented and their sequence is directly accessible.

# 5 Functional Specification

With the format describing the behavior constraints being available, it is now of high interest to extract the behavior constraints based on a present ODD in order to outline the functional specification based on local traffic rules of a HAV. This means that all atomic behavior spaces present in the road network are identified and the respective characteristics of the behavioral attribute serve as behavior constraints for the HAV. This chapter introduces the methods to extract the BSSD from an ODD under consideration and derive the functionalities necessary on system and sub-system level to fulfill these constraints.

## 5.1 Extraction of the Behavior Constraints from the ODD

This section addresses RQ3:

*How can the abstract behavior rules be inferred on the basis of a present scenery?*

Fig. 5-1 illustrates the method to derive the behavioral attributes from a present scenery. While the method is applicable to complete route networks, for simplicity a short route section going from left to right through the scenery (indicated by the arrow) is considered here. The section consists of a change in road layout, multiple speed limit signs, a pedestrian crossing and an intersection with stop signs that advise to yield for crossing traffic. The method consists of three steps which are briefly outlined in the following. In the succeeding sections each step is covered in detail individually. Finally, the implementation of the method is described in section 8.2.1.

### Segmentation of the Road Network

The behavioral attributes are only assigned to the regular motion space. Because the HAV should not reside outside of this space anyhow, there are no explicit local traffic rules stated. Therefore, outside of this space special care and cautious driving is required. Consequently, in the first step the regular motion space is identified. This means selecting the lanes that are intended for driving with a motor vehicle. Because the behavioral attributes shall be assigned to sections of a lane (the route network shall be organised in atomic behavior spaces), the identified regular motion space needs to be subdivided based on changes in the behavioral attributes. Since these attributes are not known a priori, during this step the road network is segmented at each element that will possibly induce a change in the behavior constraints. In the example in Fig. 5-1 these are the road layout change at the beginning of the section, the various traffic signs (incl. pedestrian crossing) and the intersection.

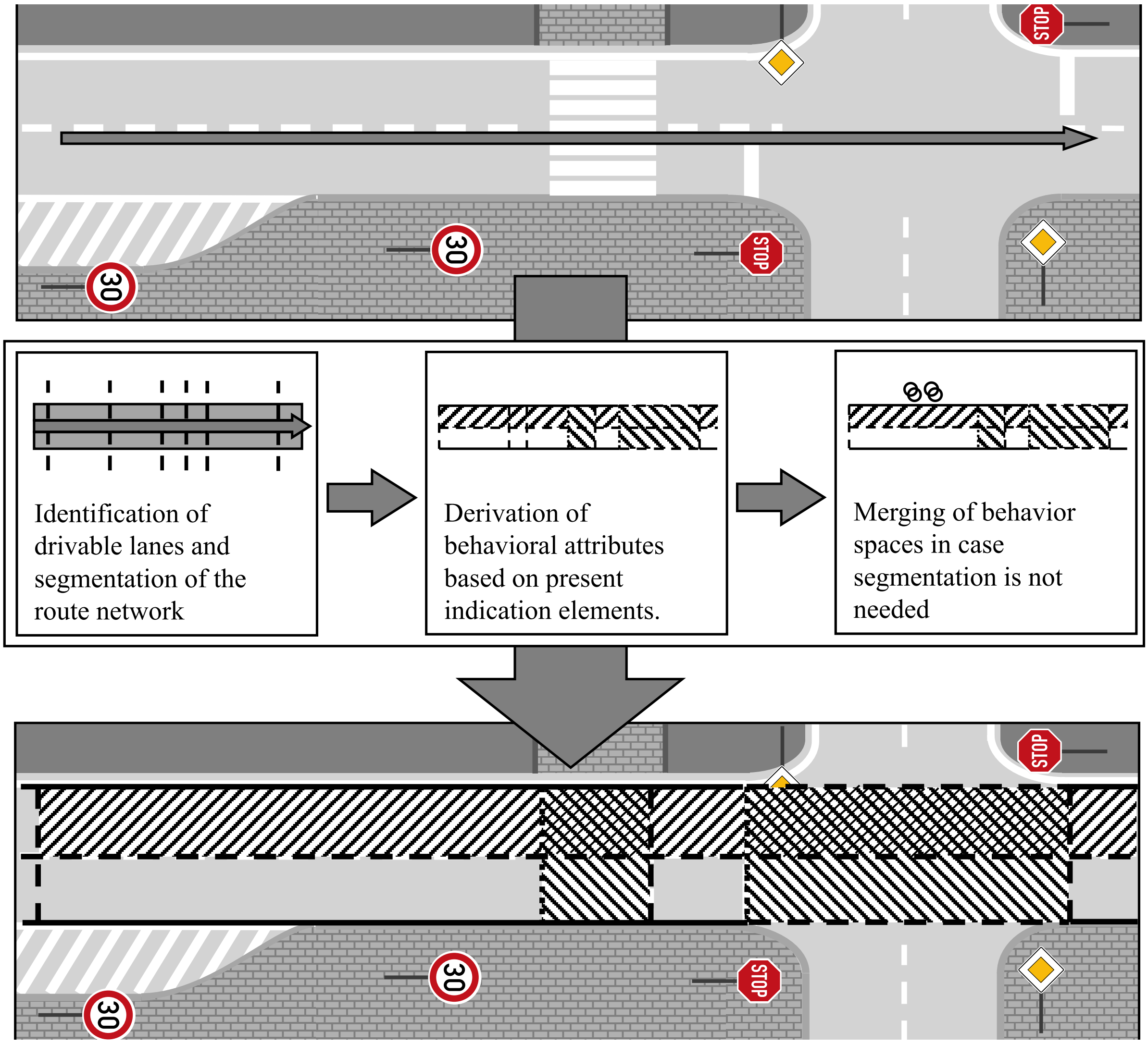


Figure 5-1: Method to extract the behavior constraints from the ODD
The different hatchings (▧, ▨, ▩) indicate different characteristics of the atomic behavior spaces, a detailed representation is omitted for reasons of clarity. The symbol ⊘ denotes a merging of two adjacent behavior spaces.

### Inference of Behavioral Attributes

Within the sections the behavioral attributes need to be derived per lane based on the present indication elements. Therefore, based on their validity the indication elements need to be assigned to the sections. It is possible that specific indication elements are valid beyond a section (e.g. speed limit sign). The basis for the assignment and the derivation of the attributes is the present traffic regulation. Each traffic sign will have one or multiple resulting constraints. This step provides the relationship between all elements to determine the behavioral attributes based on the constraints. In the present example, this results in a speed limit of 30 km/h, as well as external reservations (indicated by the hatchings in Fig. 5-1) in oncoming traffic, at the pedestrian crossing and for crossing the intersection.

### Merging of Behavior Spaces

After the behavioral attributes are determined, it is possible that the a priori segmentation was not necessary, because the different indication elements did not result in a change of behavior constraints. Therefore, in the final step, not needed segmentations are removed and these behavior spaces are merged together. In the example, the change of the solid lane boundary marking to the curbstone have the same constraints (do not drive over) and the second speed limit sign (30 km/h) just repeats the present speed limit. Thus, these two segmentations are removed.

## 5.1.1 Segmentation of the Road Network

In order to identify the regular motion space, it is necessary to understand the different elements of the road. The Road and Transportation Research Association[127a] specifies the different elements of the road cross section. Fig. 5-2 gives an overview of the most important elements with a simple road layout. In the following paragraph, the elements will be analyzed regarding their belonging to the regular motion space.

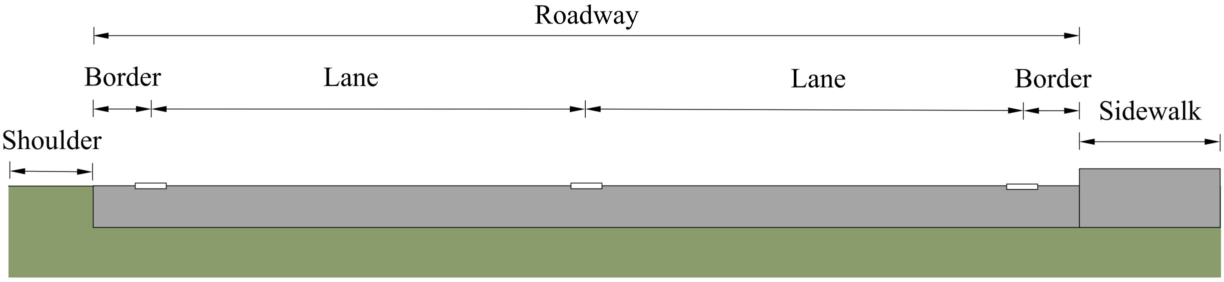


Figure 5-2: Elements of the road cross section (own illustration based on definitions for the road and transportation[127a])

### Roadway

The roadway is the continuously paved part of the road consisting of lanes and shoulder.[127b] This part of the road is intended for driving with vehicles. In order to highlight orientation and guidance, road markings are applied onto the roadway. Therefore, this part of the road is part of the regular motion space with one exception. For motor vehicles, it is not allowed to drive on restricted areas which are marked by white slashes (see also Fig. 5-1). These are part of the roadway, but not included in the regular motion space.

### Lane

A lane is a marked part of the roadway intended for the movement of one row of vehicles.[127b] Since all lanes are part of the roadway, they are part of the regular motion space as well. Even though there are multiple types of lanes designated for a special type of traffic participants only

---

[127] Road and Transportation Research Association: Begriffsbestimmungen für das Straßen- und Verkehrswesen (2020), a: pp. 76-82; b: p. 77; c: p. 80; d: p. 81; e: p. 51.

(e.g. bike lane for bicycles), these might be used by motor vehicles in special cases as well. For example, there are bike lanes delimited by dashed lane markings at intersections where motor vehicles need to cross these lanes to perform a turn maneuver. Another example is a bus lane that separates parking spots from the lanes for motor vehicles. In case of parking this bus lane might need to be crossed to get to the parking spots.

### Border

The border is a visually marked part of the roadway immediately adjacent to the traffic lanes, which delimits the side of the roadway.[127c] Since the border is part of the roadway, it is part of the regular motion space as well. Often it is delimited by a solid lane marking and therefore, not allowed to be entered by motor vehicles. Still, it is a drivable area of the road network, which might be used in special situations.

### Hard Shoulder

The hard shoulder is a lane immediately adjacent to the traffic lanes and continuously paved with the roadway, which is not, or only exceptionally, used for flowing traffic.[127d] Because it may be exceptionally used, the hard shoulder is part of the regular motion space.

### Soft Shoulder

The soft shoulder is an unpaved portion of the road immediately adjacent to the roadway or hard shoulder.[127d] Because this part of the road is not paved, it shall not be used by motor vehicles and is therefore not part of the regular motion space.

### Sidewalk / Bike Path

A sidewalk is a path intended for pedestrian traffic on which vehicular traffic is generally prohibited.[127e] Since this part of the road is generally prohibited for motor vehicles, it is not part of the regular motion space. A roadway-accompanying bike path or independently guided bike path is intended for bicycle traffic.[127c] Contrary to the bike lane which is part of the roadway, a bike path is separate from the roadway and clearly intended for bicycle traffic only. Therefore, it is not part of the regular motion space as well.

Based on this categorization, the regular motion space is identified. Now, based on the present elements in the scenery the road network is segmented into sections. In Chapter 4 all relevant elements of the road environment have been analyzed regarding possible constraints on the behavior. Every element that initiates a constraints leads to a new segment. The following list summarizes these elements:

- Start of a new roadway
- Overlapping of roadways (e.g. intersections)

- Change to the road layout: addition or removal of lanes
- Boundary changes (lane markings, curbs, etc.)
- Traffic signs that cause behavior constraints (incl. lane markings)
- Impassable static objects (crash barrier, gate)

### 5.1.2 Inference of Behavioral Attributes[128]

Highly accurate maps[129,130] provide a detailed representation of the scenery. They contain road geometry, markings, traffic signs as well as other infrastructure of a traffic area. Thus, they represent the source of the necessary information for deriving the behavioral attributes. In order to derive the behavioral attributes, a road network, which is available in the form of a high definition map, must first be divided into sections corresponding to the atomic behavior spaces. The atomic behavior spaces are spanned by the four attributes speed limit, boundaries, reservation and overtake. The atomic behavior spaces are accordingly assigned to individual scenery sections, which in turn contain indication elements that instantiate and specify the rules valid in the section. Fig. 5-3 summarizes the relations for deriving the behavioral attributes in the form of an entity-relationship model.

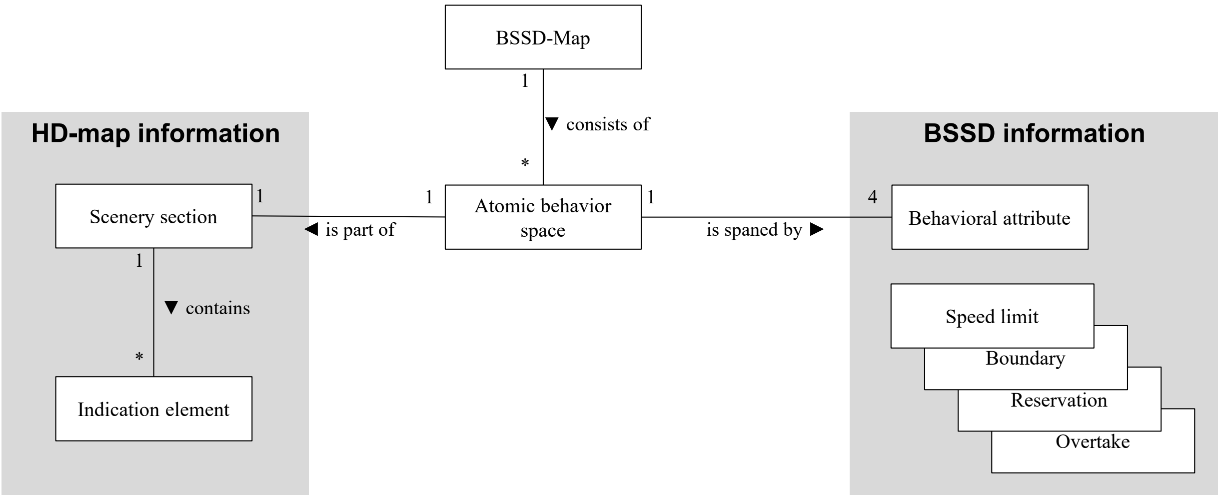


Figure 5-3: Entity-relationship model for BSSD map, HD-map information and BSSD information

Within the atomic behavior spaces, the behavioral attributes are derived from the existing indication elements. In the following paragraphs, the procedure for determining the behavioral attributes within an atomic behavior space is presented. This forms the basis for the implementation of an automated derivation of behavioral attributes based on map data. Fig. 5-4 shows the relations between the individual entities that lead to the determination of the behavioral attributes.

---

[128] This sub-section was partly taken and translated from the publication: Glatzki, F. et al.: Inferenz von Verhaltensattributen der BSSD (2022)

[129] ASAM: OpenDRIVE (2020).

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

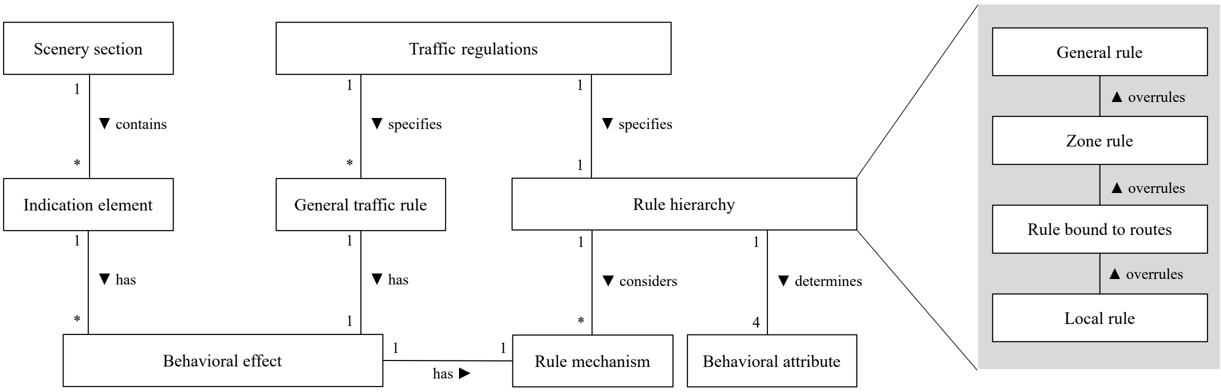


Figure 5-4: Entity-relationship model to determine the behavioral attributes

The basis for the derivation of the behavioral attributes are the indication elements that lie within the considered scenery section. Any number of indication elements can be present within a section. Behavioral effects are directly associated with them. A behavioral effect describes the behavior constraint on the HAV emanating from the indication element. Thus, a behavioral effect serves one of the behavioral attributes. A stop sign, for example, has the behavioral effect that the vehicle must stop at the corresponding stop line before entering the section and thus, serves the boundary attribute. In this context, an indication element can cause multiple behavioral effects. As part of the analysis of the road traffic regulations in section 4.1, all traffic signs were checked for corresponding behavioral effects and linked to them. In addition to the behavioral effects caused by indication elements, behavioral effects can also be caused by generally applicable traffic rules. These are traffic rules that are locally valid even without an existing indication element. For example, in Germany, the ”right before left” rule applies at intersections without any other traffic signs. These rules are also extracted from the road traffic regulations and linked to behavioral effects. Now, the behavioral effects of individual indication elements as well as the general traffic rules are available within the section of the atomic behavior space. However, these are in competition with each other, because, as described before, individual indication elements, can cause traffic rules, which are valid without traffic signs, to be overwritten. For example, a traffic sign ”Right of way” overrides the rule ”Right before left”. This makes a hierarchy necessary for the behavioral effects found. Using this hierarchy, it is determined which of the competing effects is valid and from this the corresponding behavioral attributes, which span the behavior space, are determined. For this purpose, the mechanisms by which rules are elicited in German road traffic are discussed. Poggenhans[131] identifies four different mechanisms, which are adopted in a modified form for this dissertation. *Zone rules* define zones within which certain traffic rules apply. The zones are valid until they are suspended by an associated traffic sign. *Rules bound to roads or routes* end as soon as the road or route is left or they are cancelled by a corresponding sign. The mechanisms ”traffic lights” and ”right-of-way rules” identified by Poggenhans are summarized in the mechanism *local rules*. These rules act on a locally restricted area. In contrast to Poggenhans, local rules are not limited to traffic signals, since other traffic signs can also

---

[131] Poggenhans, F.: Generierung hochdetaillierter Karten für das automatisierte Fahren (2019).

have a local behavioral effect (e.g., a stop sign forces the driver to stop at the stop line). Since right-of-way and priority rules are also valid in a localized area, they are also included in this mechanism. In case of simultaneous existence of different behavioral effects serving the same behavioral attribute, the local regulation applies first, then the regulation bound to routes, then the zone regulation and finally the general traffic regulations. Within the local regulations there is again a subordinate hierarchy. Here it is valid that the regulations apply by instructions of police officers before light signs and light signs before traffic signs. At junctions, due to the overlapping of different lanes, a further logic is necessary to infer the priority rules stored in the reservation attribute. At intersections without traffic signals there is the possibility of the "right before left" rule based on the general traffic rules or a priority road is specified by indication elements (this includes turning priority roads). As an example, a five-arm intersection is shown in Fig. 5-5 for both cases.

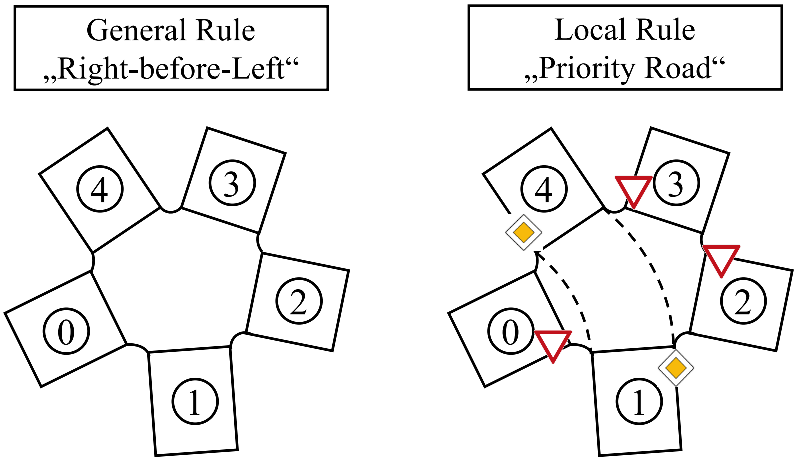


Figure 5-5: Exemplary crossings for priority derivation

To derive the priority rules, the intersection arms are numbered based on their counterclockwise orientation to represent the topological arrangement. The numbering can start at any arm. No further geometric determination is necessary. In addition, all possible connections are stored in the form of direction-dependent tuples. A connection from 1 to 4 is described by the tuple (1,4). Basically, only the connections with geometric overlap must potentially be given priority. At a "right-before-left" intersection, priority must be given to all entrances that lie within this tuple. For example, for the connection (1,4), these are entrances 2 and 3. At an intersection with a priority road, a distinction must be made between three cases.

- Along the priority road, no other entrance must be given priority ((1,4) and (4,1)).
- When entering via a priority road, but exiting into a subordinate road, priority must be given to priority entrances within the tuple. For example, connection (1,0) must give priority to entrance 4.
- When entering and exiting via a subordinate road, priority must be given to the entrances of the priority road as well as entrances within the tuple. For example, connection (2,0) must give priority to entrances 1, 3 and 4.

### 5.1.3 Merging of Segments

As seen in the example in Fig. 5-1, there might result segmentations that are not necessary. With the behavioral attributes now being available, it is possible to identify and correct these unnecessary segmentations. In this section, the conditions for merging of consecutive segments are derived. Because the behavioral attributes are determined in both directions (along and against the reference direction), segments can only be merged if *both* directions fulfill the conditions. This means that even if there is no change in the behavior constraints in one direction, there is a segmentation necessary if there is a change in the other direction. Consequently, the main condition for merging segments is that by merging the described behavior constraints do not change. By merging consecutive segments, essentially the longitudinal boundaries in between the segments are removed. Therefore, a detailed look at the characteristics of the longitudinal boundary attribute is taken. All other attributes necessarily need to be the same in all consecutive behavior spaces in both directions of the segments. This is not valid for the longitudinal boundary attribute. For example, two consecutive conditional longitudinal boundary attributes with the condition *stop* cannot be merged, since removing this boundary would remove a relevant behavioral constraint (it is necessary to stop at *both* boundaries). Opposed to that, two different longitudinal boundaries may enable a merge of segments. For example, if after a conditional boundary with the condition no red light follows an allowed boundary, it is not a problem to remove this allowed boundary, since it does not introduce a new constraint. In Table 5-1 all combinations of these boundaries are analyzed and check marks are set where a merging of segments is possible and thus, the transition is mergeable. However, as there may be multiple different longitudinal boundaries, a merging is only possible if all boundary transitions in the segment are mergeable.

Table 5-1: Long. boundary transitions

| | **to** | | Conditional | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **from** | Allowed | Stop | No stagnant traffic | No red light | Residents only | Time interval | Prohibited | Not possible |
| | Allowed | ✓ | | | | | | | |
| Conditional | Stop | ✓ | | | | | | | |
| | No stagnant traffic | | | ✓ | | | | | |
| | No red light | ✓ | | | | | | | |
| | Residents only | ✓ | | | | ✓ | | | |
| | Time interval | ✓ | | | | | ✓ | | |
| | Prohibited | ✓ | | | | | | | |
| | Not possible | ✓ | | | | | | | |

For the reservation attribute, in case of an external reservation, the links need to be checked in detail. The reservation links specify from which direction a reservation entitled traffic participant may come. While merging, it needs to be ensured that the links remain consistent and described correctly. Fig. 5-6 shows the three different configurations possible while having externally-reserved spaces. In case A, the reservation has links along the direction of the lane. This means, that the links do not refer to the same area, but each to the consecutive lane respectively. While merging such reservations, it needs to be ensured that the link refers to the lane behind the second behavior space. In case B and C, the reservations have links coming from the side of the lane. In case B, the road representation records the adjacent elements of the non-regular motion space seperately while in case C, there is only one element of the regular motion space covering both segments. For case B, there exist two possibilities. First the segments are merged. This requires the elements of the non-regular motion space also to be merged. This may not be possible, for example, because the road description format does not support this possibility or there should not be any changes to the road layout because other functions rely on this representation of the layout. In this case, the segments may remain unmerged. In case C, since the adjacent non-regular motion space is already represented as one element, the segments may be merged. The identified rules are realized in the implementation described in Section 8.2.1.

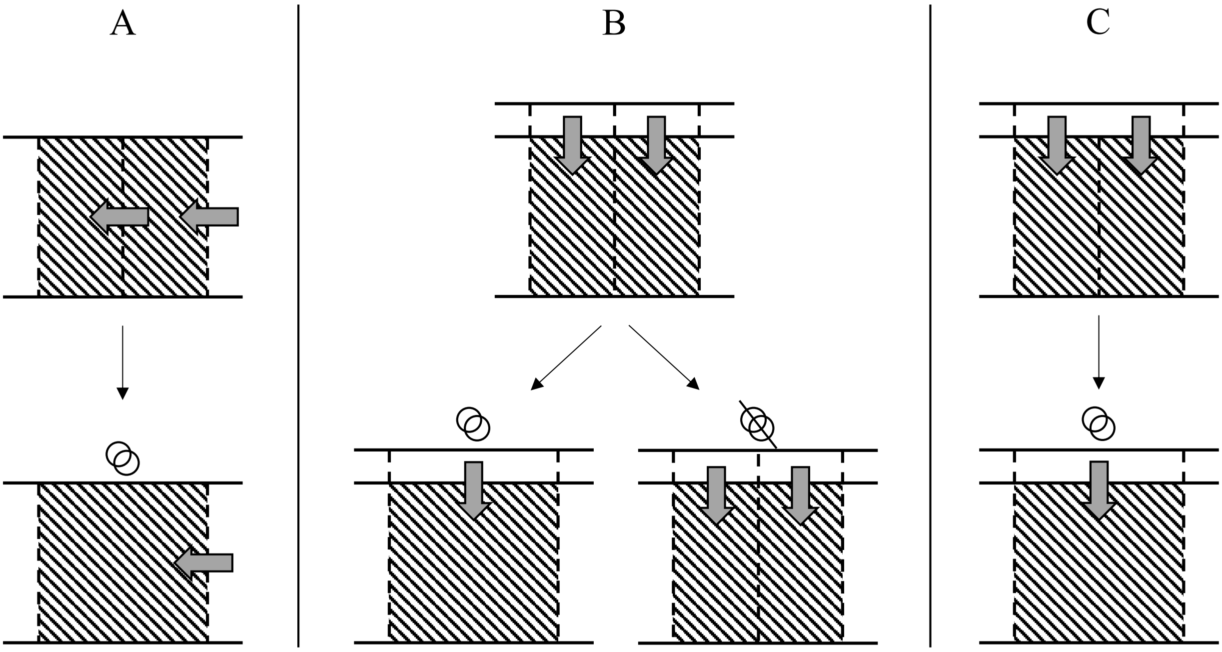


Figure 5-6: Different cases of reservation links with respect to merging of behavior spaces

## 5.2 Concatenating Behavior Spaces as Specification

After deriving the geo-located behavior constraints of the road network under consideration, the behavior space configurations of the road network are compiled in order to use the information as specification and thus, as a basis for test case derivation. A behavior space configuration is defined as follows:

A **behavior space configuration** is the composition of the behavioral attributes of one direction of an atomic behavior space. This includes the representation of linked areas within the reservation attribute.

The representation of the atomic behavior spaces is abstract and requires no geometrical information. However, for the development of functions and capabilities of the HAV, geometrical information might be relevant. For example, the angle between the direction of the lane and the linked area of a reservation link determines directly the necessary field of view to detect reservation entitled objects. In parallel work, Moritz Lippert[132] analyzes the possibility to categorize this diverse information into segments that need equal functions and capabilities. This includes not only the analysis of single behavior space configurations, but also the analysis of complete routes and thus, concatenation of multiple behavior space configurations.

During functional specification, behavior space configurations are concatenated to obtain lane specific routes. A concatenation of behavior space configurations is indispensible because there are cases in which the behavior of the vehicle needs to be adapted before the behavior space is reached. For example, if the speed limit is lowered in the next behavior space, the vehicle already needs to adapt the speed in the previous segment. Also, when approaching an externally-reserved space, e.g. at an intersection, the vehicle needs to adapt the speed before the intersection in order to yield priority to reservation entitled objects.

Fig. 5-7 shows an abstract road network. The individual behavior space configurations listed are just presented as an example and do not need to be discussed in detail, since they are not relevant for setting out the method to compiling the behavior spaces into the specification. It is important that, as given by the definition of a behavior space configuration, the linked areas of the reservation links are recorded with the behavior space representation. This is indicated by the grey arrows in the figure. The black arrows indicate the reference direction of the segment. There are various options for a vehicle to move through the route network. Different possible routes are concatenated to serve as a specification of the system (depicted by the colours blue, green and yellow). These are the routes the vehicle shall be able to accomplish. Against this specification, the system is tested at the end of the development process. A remaining question is to analyze whether these concatenated routes may repeat themselves within the ODD and how far ahead a concatenation is relevant for the behavior of the vehicle.

---

[132] Lippert, M.: Capability-Based Route Planning (2023).

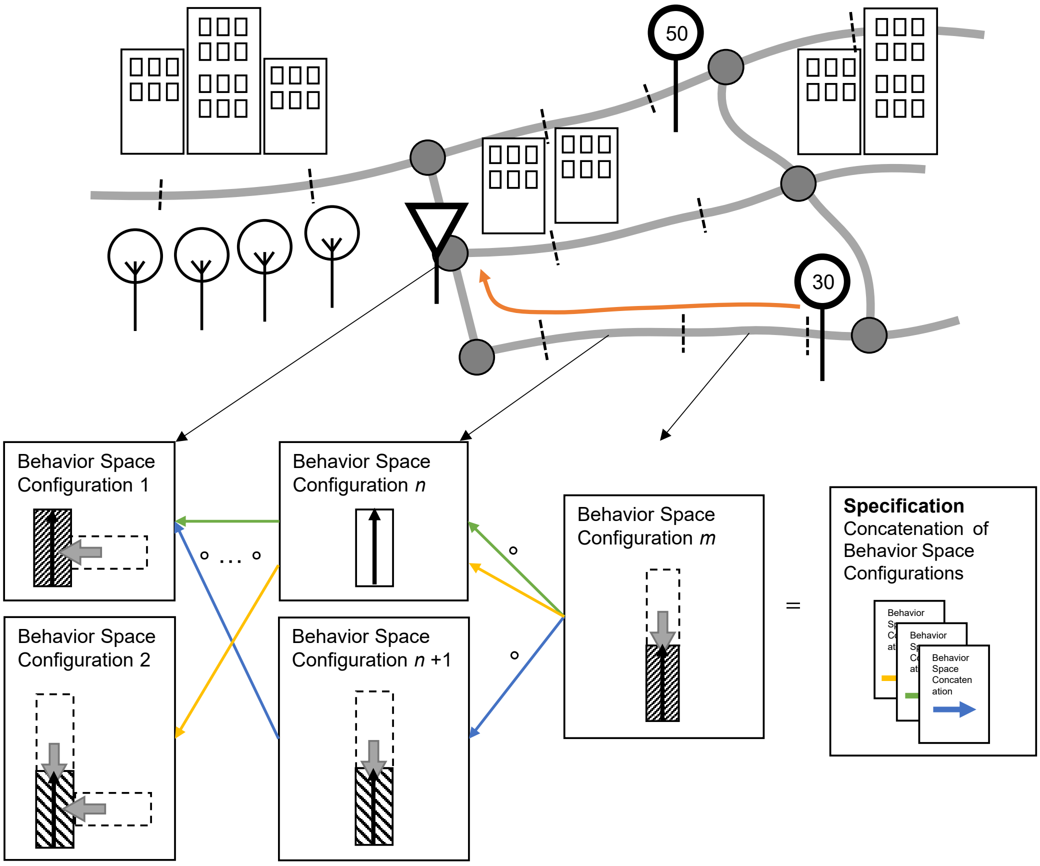


Figure 5-7: Concatenation of behavior space configurations within a road network to create behavior routes as specification.
The orange coloured arrow — indicates a sequence of road sections to be completed by the ADS.
The green —, blue — and yellow — arrows depict possible combinations of behavior space concatenations to achieve the sequence of road sections. The ∘ symbol denotes a concatenation.

## 5.3 Decomposition of Behavior Violations

From the requirement REQ6 to support the functional decomposition approach, it follows that not only tests on system level are to be defined, but also on functional decomposition level. For this, it needs to be shown that the behavioral attributes, formulated on system level, are decomposable to the functional decomposition layers. This means that for each decomposition layer pass-/fail criteria for all necessary functionalities are available. Consequently, in this section research question RQ5 is investigated:

*What conclusions can be drawn from the behavioral limits on system level for the functional specification at the sub-system level (decomposition level)?*

According to Amersbach[133] systematic methods are necessary to break down the evaluation criteria from system level to the functional layers at decomposition level. Klamann et al.[134] use proven methods such as FTA and STPA to fulfill this task. Within their method, they use an

---

[133] Amersbach, C. T.: Functional Decomposition Approach (2020), p. 62.

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

exemplary safety goal for an automated unmanned vehicle derived by a hazard and risk analysis performed by Stolte et al.[135]. While their method accomplishes the decomposition of the safety goal down to subsystem level, they do not introduce any method to find quantitative values for the decomposed test criteria. Furthermore, they do not specifically target compliance with traffic rules, but rather general safety argumentation by using safety goals on system level as a top level event. FTA is a proven method in safety engineering and handles the identification and analysis of conditions and factors that cause, may cause or contribute to the occurrence of a defined top event.[136] In the following, this method is applied in order to find possible causes for the violation of local traffic rule in each functional decomposition layer which then serve as fail-criteria. Due to the imprecise quantifiability of the probability of these causes, a theoretically feasible calculation of event probabilities using this method is not performed.

The top event to be prevented by the HAV is a *violation of traffic rules*. As Fig. 5-8 shows, both the *violation of general traffic rules* and the *violation of local traffic rules* lead to such a violation. The violation of general traffic rules is not in the scope of this work and is therefore not further analyzed (represented by the diamond shape). For complete compliance to all traffic rules, this event should also be further investigated (see e.g. Shalev-Shwartz[137] and Pek et al.[138] for investigation of collision avoidance). Any violation of one behavioral attribute (speed, boundary, reservation, overtake) leads to a violation of the local traffic rules. These attribute violations include the violations resulting from concatenation (see section 5.2) which occur before entering the respective atomic behavior space.

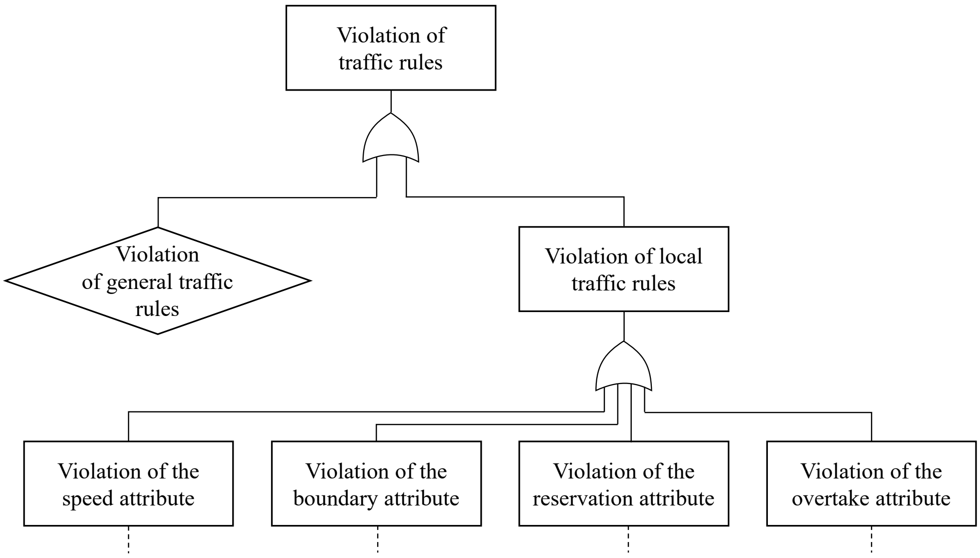


Figure 5-8: FTA for the decomposition of traffic rule violations: top event ”violation of traffic rules” with relation to general and local traffic rules as well as sub-events regarding the violation of any of the behavioral attributes

---

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

[136] IEC: IEC 61025: Fault tree anaylsis (FTA) (2006), p. 11.

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

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

A violation of a behavioral attribute may consist of different sub-violations. For example, the speed attribute is violated if the maximum allowed speed limit is exceeded, but also if the minimum prescribed speed is undercut. The individual sub-violations are caused by an error in one or more of the decomposition layers as these layers together represent the overall function of the HAV. Each layer must avoid all sub-violations in order to satisfy the behavioral attribute. This generic decomposition is shown in Fig. 5-9. The subviolations from L0 to L3 are subsumed into one event. This layer represents the basis for decision-making. The BSSD serves as specification for the static part of this situational understanding which the system can be tested against. Additionally, the dynamically changing part (e.g. conditions such as a wet road or other traffic participants) needs to be understood by the vehicle. Formulating requirements and testing against these on lower layers is complicated. A requirement that demands that certain traffic signs must be detected may not be valid if the traffic sign is present on both sides of the roadway. Here, it is sufficient to just detect one of the two traffic signs. If necessary, the error in a certain decomposition level can be decomposed into further causes when considering a concrete violation or sub-violation until they are on a suitable level to serve as fail criteria for test cases.

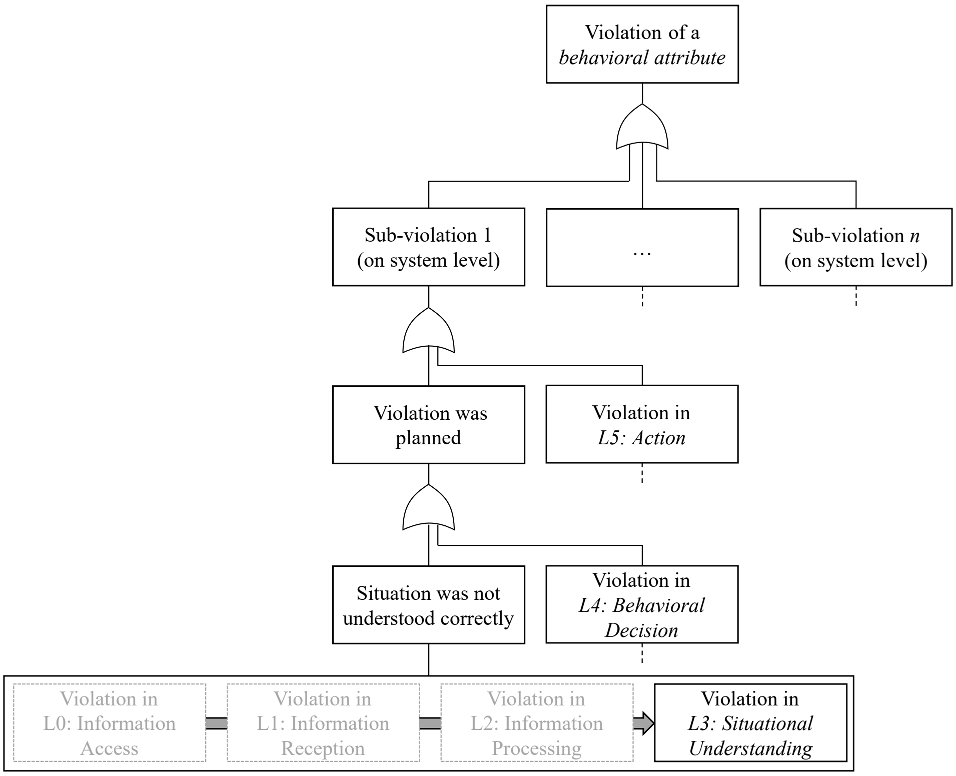


Figure 5-9: FTA for the decomposition of traffic rule violations: sub-events of violation of a behavioral attribute

To decompose these two violations to functional decomposition layers, the layers are analyzed starting from the output of L3 - situational understanding. From there, it can be determined what the subsequent layer needs as an input to fulfill the behavioral attribute. Each event (per decomposition layer) in the FTA is considered independently of other decomposition layers, meaning that only the correct or incorrect processing regarding the considered decomposition layer is of interest.

In order to show the applicability of the fault tree analysis to decompose the violation of behavioral attributes and identify criteria on decomposition level, the decomposition of the violation of the speed attribute is shown as an example. Fig. 5-10 shows this exemplary breakdown of the speed attribute. As a first step, it is necessary to identify what violating the attribute actually means. This step is as well necessary for the formalization of the attributes and therefore, is covered in more detail in chapter 6 for all attributes. As stated, for the speed attribute a violation means that either the maximum allowed speed was exceeded or the minimum prescribed speed was undercut. Therefore, the event *violation of speed attribute* is decomposed into these two sub-events, of which either one implies a violation of the speed attribute.

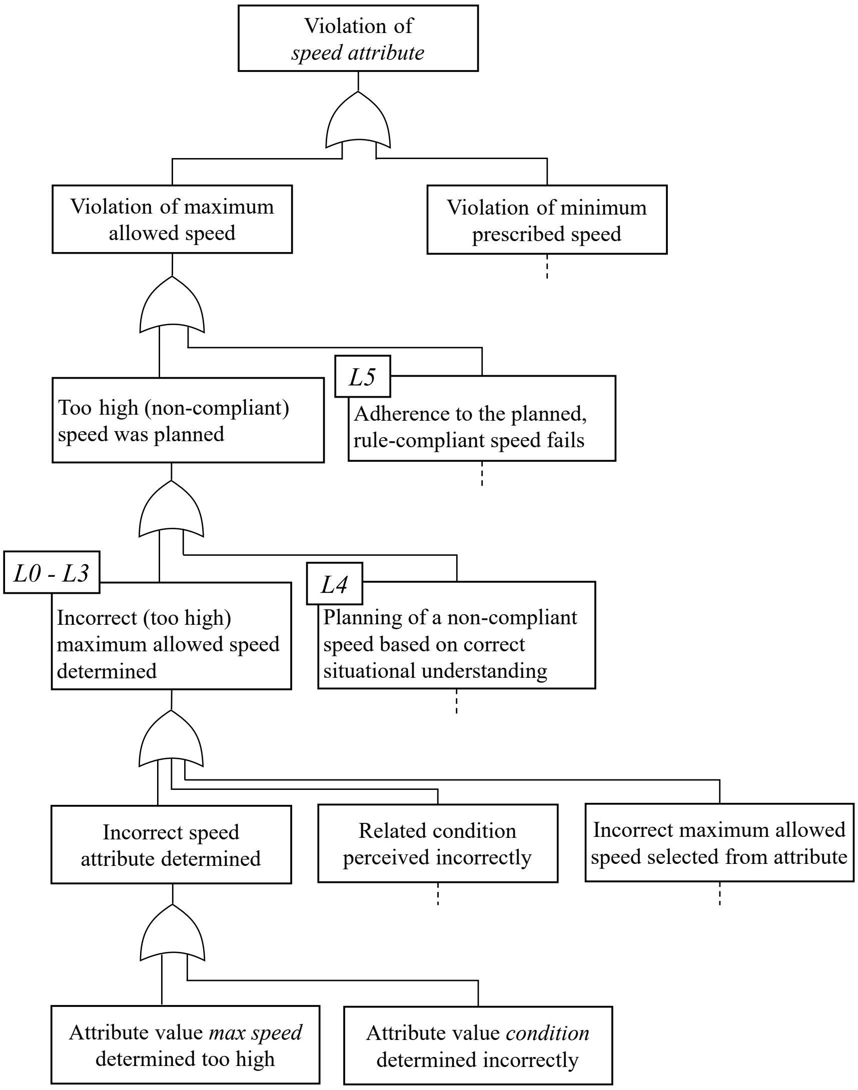


Figure 5-10: Exemplary breakdown of one violation on decomposition layer

Starting with the output of the situational understanding: the situational understanding layer needs to derive the maximum allowed speed for each location of the planned route in a certain time horizon before the vehicle arrives at this location such that the behavioral decision layer can plan the behavior accordingly. An *incorrect maximum speed determined* may lead to planned exceedance of the allowed maximum speed and is caused either by a faulty algorithm for the inference of the speed attribute or by a faulty determination of conditions that determine the maximum allowed speed or an incorrect selection of speed from these two inputs. For example, failing to understand that the road is wet, may lead to selecting the regular speed limit over the speed limit for a wet road. For the action layer to realize rule compliant speed, it needs to be planned in the layer L4 - behavioral decision. Failing to do so will cause a violation of the maximum allowed speed by *planning of a non-compliant speed based on correct situational understanding*. Although longitudinal speed planning is a basic functionality of an HAV, a reason for this could be because the behavior planning algorithm has insufficient functionality. Lastly, the decomposition layer L5 may fail to execute the (correctly) planned behavior and thus, result in an exceedance of the maximum allowed driving speed. Reasons for this could be a fault in the controller of the vehicle or the planned behavior is not physically feasible to perform for the vehicle (e.g. because of a low friction coefficient) such that *the adherence to the planned, rule-compliant speed fails*.

The events found during the FTA are converted requirements that need to be fulfilled serving as specification for the system and the underlying decomposition layers. Tab. 5-2 shows an excerpt of the derived requirements from the developed fault tree regarding an adherence to the speed limit attribute. Each requirement has an assigned fail criteria for test evaluation.

Table 5-2: Resulting requirements and respective fail criteria resulting from the performed FTA

| **Layer** | **ID** | **Requirement** | **Fail criteria** |
|---|---|---|---|
| System | SRQ1 | The HAV shall adhere to the maximum allowed driving speed | The HAV violated the maximum allowed driving speed |
| L0-3: | SRQ1.3 | The HAV shall correctly determine the maximum allowed driving speed | Incorrect maximum allowed speed determined |
| | SRQ1.3.1 | The HAV shall correctly determine the speed attribute | The speed attribute was determined incorrectly |
| | SRQ1.3.1.1 | The HAV shall correctly determine the *max speed* value of the speed attribute | The *max speed* value was determined too high |
| | SRQ1.3.1.2 | The HAV shall correctly determine the *condition* value of the speed attribute | A wrong condition (e.g. wet road, time interval) was determined |
| | SRQ1.3.2 | The HAV shall correctly perceive the related condition for the speed attribue | A wrong condition increasing the speed limit was detected |
| | SRQ1.3.3 | The HAV shall correctly determine the maximum allowed speed from speed attribute and present conditions | An incorrect maximum allowed speed was determined |
| | . . . | . . . | . . . |
| L4: | SRQ1.4 | The HAV shall plan a speed compliant to the maximum allowed driving speed | Planning of a non-compliant speed based on correct situational understanding |
| | . . . | . . . | . . . |
| L5: | SRQ1.5 | The HAV shall adhere to the planned rule-compliant speed | Adherence to the planned, rule-compliant speed fails |
| | . . . | . . . | . . .. |
| System | SRQ2 | The HAV shall adhere to the minimum prescribed driving speed | The HAV violated the minimum prescribed driving speed |
| L0 - L5 | . . . | . . . | . . . |

# 6 Derivation of Test Criteria

In this chapter the identified behavior constraints are formalized in order to be used as pass/fail criteria for tests of traffic rule compliance for HAV and thus, this chapter investigates the research question RQ6:

*How can the identified limits of traffic rule compliance be converted into concrete pass/fail criteria for system and module tests?*

First, requirements for the formalization are identified in section 6.1. As a basis for the formalization the used notation and coordinate systems are introduced in section 6.2. In section 6.3, all behavioral attributes are formalized. Finally, in section 6.4 an exemplary procedure is shown to break down the formalized criteria on decomposition level by using the fault tree from section 5.3.

## 6.1 Requirements

In order to select a suitable approach to quantify the behavioral attributes, formalization requirements (FRQ) are identified and defined. The main goal of the formalization is to be used to test the compliance to local traffic rules. For this, it is necessary that the formalization is able to quantify all attributes of the behavior space (including all underlying characteristics). In order to evaluate and use the criteria during tests, all used quantities need to be observable and measurable. Conversely, the formalization shall not use any quantities that are not observable or accessable. Since the formalization shall serve as an evaluation metric for the compliance to traffic rules, it shall make correct statements whether the performed behavior is compliant or not. This means that a behavior violating the traffic rules shall be qualified as non-compliant. Conversely, a behavior adhering to the traffic rules shall be qualified as compliant. In order for the tests to be accessable, it is necessary that the formalization gives out a clear statement whether the boundaries of the behavior space are crossed or not (meaning the local rules are violated or not). This means that the output shall be a Boolean value (binary). This value shall be *true* if the rules are violated and it shall be *false* if they are not violated. Finally, according to Schuldt et al.[139], the evaluation of test cases is only efficient if it is performed automatedly. For an automated evaluation procedure the evaluation criterion have to be formulated in a computable way. Table 6-1 lists all identified requirements.

---

[139] Schuldt, F. et al.: Effiziente systematische Testgenerierung für Fahrerassistenzsysteme (2013).

Table 6-1: Requirements for the formalization of behavioral attributes

| **No.** | **Requirement** |
|---|---|
| FRQ1 | The formalization shall quantify all attributes of the behavior space. |
| FRQ2 | The formalization shall only use observable quantities (e.g. state variables, observable information of the scenery). |
| FRQ3 | The formalization shall not qualify non-compliant behaviors as compliant and vice versa. |
| FRQ4 | The formalization shall output the boolean value *true* if the behavior space is left. |
| FRQ5 | The formalization shall output the boolean value *false* if the behavior space is kept. |
| FRQ6 | The formalization shall be formulated in a computable way. |

## 6.2 Foundations for the Formalization

In this section, the foundations for the formalization are introduced in order to reduce the risk of ambiguity or misunderstanding.

### 6.2.1 Coordinate System Notation

The following coordinate systems are used:

- $E$: earth fixed Cartesian coordinate system
- $F$: Frenet coordinate system
- $P$: vehicle fixed polar coordinate system (fixed to center of front axle)

A quantity $X$ in a certain coordinate system with exponent and index is noted as follows: ${}_{\mathrm{coordinatesystem}}X_{\mathrm{index}}^{\mathrm{exponent}}$.

### 6.2.2 Interfaces of the Functional Decomposition Layers

Section 2.2 has introduced the different functional decomposition layers according to Amersbach[140a]. As required by FRQ2 the formalization shall only use observable quantities. Therefore, it is necessary to introduce the interfaces between the functional layers as these quantities are accessible from outside of the respective layer. Amersbach[140b] defined generic interfaces for all functional decomposition layers which are presented in the following. In order to use these interfaces during the formalization, a generic notation for all used quantities is developed and introduced accordingly.

---

[140] Amersbach, C. T.: Functional Decomposition Approach (2020), a: -; b: pp. 56-58; c: p. 56.

## Input to Layer 0: Existing Information

The input to layer 0 subsumes all available information in the surrounding of the HAV. Amersbach[140c] defines *information* in this context as:

*"The term information [...] is defined as all data that is relevant for conducting the driving task. This includes - but is not limited to - states of dynamic objects, ego and traffic lights, street layout and applicable traffic rules as well as the current system capability's that might be restricted by influences from the environment or system degradation."*

This matches the defintion of the term *scene* introduced in section 2.1 complemented with additional information regarding applicable traffic rules in the ODD. The static content (scenery) of a scene can be represented in the standardized format OpenDRIVE®[141], while the temporal sequence of the dynamic content can be represented in the standardized format OpenSCENARIO®[142].[140b]

For the formalization following generic definitions are introduced to represent the secenery. The scenery is constructed out of all geo-spatially constant entities. For the formalization, the description of the road network is essential, since this represents the motion space for the HAV and enables the mapping of the introduced behavioral attributes. The road network is constructed out of a set of $n$ roads $\boldsymbol{\mathcal{N}} = \left\{ (\boldsymbol{\mathcal{R}}_i)_{i=1,\ldots,n} \right\}$. A road $\boldsymbol{\mathcal{R}}_i$ consists of $n$ consecutive sections $\boldsymbol{\mathcal{S}}_{i,1} \ldots \boldsymbol{\mathcal{S}}_{i,n}$. A section $\boldsymbol{\mathcal{S}}_{i,j}$ is constructed out of $n$ lanes $\boldsymbol{\mathcal{L}}_{i,j,1} \ldots \boldsymbol{\mathcal{L}}_{i,j,n}$. Most relevant for the derivation of the behavioral attributes are the indication elements. An indication element $\boldsymbol{\mathcal{I}}_{i,k}$ is mapped to a road $\boldsymbol{\mathcal{R}}_i$ and has the pose ${}_F\boldsymbol{\mathcal{P}} = [{}_F\boldsymbol{p}, {}_F\psi]$ where ${}_F\boldsymbol{p} = [{}_Fp_s, {}_Fp_t]$ is the position in Frenet coordinates and ${}_F\psi$ is the orientation in Frenet coordinates. The existing road network is represented by the set of roads $\boldsymbol{\mathcal{N}}_{\text{exist}} = \left\{ (\boldsymbol{\mathcal{N}}_{\text{exist},i})_{i=1,\ldots,n} \right\}$. Note: There are other formats (e.g. lanelet2) in which the relations between roads, sections and lanes is represented implicitly by geometric relations.

As for many behavioral attributes the dynamic content of the scene representation is highly relevant, following generic definitions are introduced and used throughout the formalization. An object *"is formed by grouping sets of contiguous surfaces and boundaries according to certain criteria, such as rigid body mechanics, over space and/or time"*[143]. For example, vehicles like cars or motorcycles are considered as objects. According to Czarnecki[144] dynamic objects *"are objects that have propensity to change state. Dynamic objects are endowed with deliberate or intentional behavior"*, while motion-dynamic objects *"are objects that have propensity to move. In a road environment, the main categories of motion-dynamic objects are vehicles, cyclists, pedestrians, and animal"*. A motion-dynamic object $\boldsymbol{\mathcal{O}}_i$ has the state ${}_E\boldsymbol{x}_{\boldsymbol{\mathcal{O}}_i,j} = [{}_E\boldsymbol{p}_j, {}_E\boldsymbol{v}_j, {}_E\boldsymbol{a}_j, {}_E\psi_j, {}_E\dot{\psi}_j, {}_E\ddot{\psi}_j]$ in an arbitrary cartesian coordinate system at point in time $t_j$, where ${}_E\boldsymbol{p} = [p_x, p_y]$ is the position,

---

[141] ASAM: OpenDRIVE (2020).

[142] ASAM: OpenSCENARIO (2022).

[143] SAE: J3131: Definitions for Terms Related to Automated Driving (2022), p. 4.

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

${}_{E}\boldsymbol{v} = [v_x, v_y]$ is the velocity, ${}_{E}\boldsymbol{a} = [a_x, a_y]$ is the acceleration and ${}_{E}\psi$ is the orientation of the object. The set of objects $\boldsymbol{\mathcal{D}}_{\text{exist},j} = \left\{ (\boldsymbol{\mathcal{O}}_{\text{exist},i})_{i=1,\ldots,n} \right\}$ includes all $n$ motion-dynamic objects in the existing information at the point in time $t_j$.

Since the state of the ego vehicle is of high importance for the determination and assessment of legal behavior the index "ego" is used to denote any quantities which relate to the ego vehicle, e.g. the existing state of the ego vehicle at the point in time $t_j$ is denoted as $\boldsymbol{x}_{\text{exist,ego},j}$.

### Interface between Layer 0 and 1: Accessible Information

The interface between layer 0 and layer 1 subsumes all accessible information. This includes all information that could be accessed by an ideal HAV or a human driver. This means, that accessible information is a subset of the existing information. For example, occluded elements such as traffic signs occluded by a dynamic object may not be accessible and therefore not part of this interface. Because depending on the sensor mounting positions and field of view of the sensors the accessible information changes, this information is specific to the OUT. Additionally, accessible V2X information is included in this interface.[140b]

The set of objects $\boldsymbol{\mathcal{D}}_{\text{access},j} = \left\{ (\boldsymbol{\mathcal{O}}_{\text{access},i})_{i=1,\ldots,n} \right\}$ includes all $n$ accessible motion-dynamic objects for the HAV at the point in time $t_j$. The state description of an accessible motion-dynamic follows the same notation as introduced for an existing motion-dynamic object.

### Interface between Layer 1 and 2: Sensor Raw Data

The interface between layer 1 and layer 2 subsumes the received information by the HAV. This does not include any *"advanced post-processing (e.g. object detection) other than sensor-internal processing steps"*[140b]. The interface contains external, environmental sensor data (e.g point clouds for radar or lidar reflections) and internal sensor data for the self-representation of the HAV.[140b]

### Interface between Layer 2 and 3: Subjective Scene Representation

The interface between layer 2 and 3 is a subjective scene representation from the HAV's perspective. There are multiple different types for representing this subjective scene. Per definition the subjective scene includes the representation of the scenery as well as dynamic content which may be represented in grid-based, object-based or hybrid representations.[140b]

The set of objects $\boldsymbol{\mathcal{D}}_{\text{scene},j} = \left\{ (\boldsymbol{\mathcal{O}}_{\text{scene},i})_{i=1,\ldots,n} \right\}$ includes all $n$ represented motion-dynamic objects in the subjective scene representation at the point in time $t_j$. The state description of a motion-dynamic object in the subjective scene representation follows the same notation as introduced for an existing motion-dynamic object. The road network of the subjective scene representation is represented by the set of roads $\boldsymbol{\mathcal{N}}_{\text{scene},j}$. The self representation of the HAV at the point in time $t_j$ in the scene representation is denoted by ${}_{E}\boldsymbol{x}_{\text{scene,ego},j}$.

### Interface between Layer 3 and 4: Situation Representation

The interface between layer 3 and 4 is a subjective situation representation from the HAV's perspective.[140b] The definition of the term *situation* according to Ulbrich et al.[145] is given in section 2.1. The situation entails *"all relevant parts of the scenery, all relevant dynamic elements, and all relevant aspects of the self-representation"*. Additionally, it may consist of derived information from the scene representation, e.g. predictions for the future behavior of other objects. In order for the HAV to be aware of present traffic rules in the functional layer behavioral decision, the situation must include a semantic representation of the behavior constrains based on traffic rules, e.g. in the form of BSSD.

The set of objects $\boldsymbol{\mathcal{D}}_{\text{situ},j} = \left\{ \left( \boldsymbol{\mathcal{O}}_{\text{situ},i} \right)_{i=1,\dots,n} \right\}$ includes all $n$ represented objects in the situation representation at the point in time $t_j$. The state description of a motion-dynamic in the situation representation follows the same notation as introduced for an existing motion-dynamic object. The road network of the situation representation is represented by the set of roads $\boldsymbol{\mathcal{N}}_{\text{situ},j}$. The self representation of the HAV in the situation representation at the point in time $t_j$ is denoted by $\boldsymbol{x}_{\text{situ,ego},j}$.

### Interface between Layer 4 and Layer 5: Planned Trajectory

*"The interface between layer 4 and 5 is the planned trajectory."*[140b] The trajectory describes the planned motion of the HAV by means of geometric information in form of a path and time information. While the path information can be of different types (e.g. splines, polynomials, waypoints), the time information may be included explicitly by using timestamps or implicitly by defining a velocity profile along the path.

In the scope of this dissertation, a trajectory $\boldsymbol{\mathcal{T}}_j$ starts at the point in time $t_j$ and consists of $n$ consecutive discrete trajectory points $\boldsymbol{\mathcal{T}}_{j,1}$ ... $\boldsymbol{\mathcal{T}}_{j,n}$ which are each defined by a vehicle pose $\boldsymbol{\mathcal{P}}_{j,i}$ at a point in time $t_{j,i}$. The vehicle pose $\boldsymbol{\mathcal{P}}_{j,i}$ describes the vehicle position ${}_E\boldsymbol{p}_{j,i}$ and orientation ${}_E\psi_{j,i}$ at the respective point in time. Since the velocity information is either explicitly or implicitly available, the expression $\boldsymbol{v}_{j,i}$ denotes the velocity vector of the vehicle at the respective trajectory point $\boldsymbol{\mathcal{T}}_{j,i}$. A planned trajectory as part of the interface between layer 4 and 5 is denoted as $\boldsymbol{\mathcal{T}}_{set,j}$.

### Output Layer 5: Observable behavior

The output of layer 5 subsumes the observable behavior of the vehicle. This includes the movement of the HAV as well as further actions such as operating the indicator. The vehicle state over a driven trajectory represents the vehicle movement and thus, is used for the formalization. The state of the ego vehicle at a point in time $t_j$ of a driven trajectory is denoted as ${}_E\boldsymbol{x}_{\text{ego},j}$ and the driven velocity at a respective trajectory point is denoted as ${}_E\boldsymbol{v}_{\text{ego},j}$. For the usage during tests, the driven trajectory has to be provided to evaluate the compliance to traffic rules. In real test

---

[145] Ulbrich, S. et al.: Defining the Terms Scene, Situation, and Scenario (2015).

environments, this means it is required to record the driven trajectory with adequate measurement devices. In simulation validated vehicle models are required.[140b]

### 6.2.3 Predicate Logic

Predicate logic is an extension of propositional logic. This extension enables not only to evaluate composed propositions, but also to evaluate the inner structure of the individual propositions. This is needed in order to identify and formalize the behavioral attributes.

A proposition is denoted by the capital letter $A$ and has either the boolean value *true* or *false*. In order to evaluate more complex composed propositions, propositional logic uses the connectives $\wedge$ (conjunction, ”and”), $\vee$ (disjunction, ”or”), $\rightarrow$ (implication, ”if ... then”), $\leftrightarrow$ (biconditional, ”if and only if”) and $\neg$ (negation, ”not”). For example, the proposition $A =$ ”The vehicle is stopped or the vehicle is moving” can be divided into the propositions $A_1 =$ ”The vehicle is stopped” and $A_2 =$ ”The vehicle is moving” and connected by $\vee$. These two propositions cannot further be decomposed by using propositional logic and are called atomic propositions.

Predicate logic extends the propositional logic with further symbols in order to enable the evaluation of the inner structure of the atomic propositions. The alphabet of predicate logic is composed out of the following logical and non-logical symbols:

- logical symbols:
  - logical connectives ($\wedge, \vee, \rightarrow, \leftrightarrow, \neg$)
  - quantifiers ($\forall$ (”for all”), $\exists$ (”exists”))
  - parentheses, brackets and other punctuation symbols
  - infinite set of variables ($x, y, z, ...$)
  - equality symbol ($=$)
- non-logical symbols:
  - predicate symbols ($P_0, P_1, ...$)
  - function symbols ($f_0, f_1, ...$)

This set of symbols is used in the following for the formalization of the behavioral attributes.

## 6.3 Formalization

The state of the art shows multiple approaches that successfully use logic based approaches to formalize traffic rules. These approaches fulfill the requirements after boolean values as an output of the application of the formalization and a formulation in a computable way. The attributes are therefore formalized with predicate logic using propositional statements starting from the main propositional statement $P$ given by 6-1 to outline the logic behind the violations.

$$P = \text{"The local traffic rules are violated."} \tag{6-1}$$

As introduced the atomic behavior space has attributes assigned to two directions (along and against the reference direction). Since the vehicle only drives in one direction, the following considerations always refer to only one direction of the behavioral space. This direction has to be selected according to the driving direction of the vehicle.

Under the assumption that the behavior space entirely and correctly describes the local traffic rules of a scenery, violating the behavior space means violating the local traffic rules. Conversely, the behavior is traffic rule compliant if the behavior space is kept. Accordingly, a violation of the local traffic rules exists, if there is at least one violation of one of the attributes of the behavior space. Therefore, it needs to be checked for each attribute individually if it is violated. The propositions 6-2 to 6-6 formulate the violation of the individual attributes:

$$A = \text{"The speed attribute is violated"}, \tag{6-2}$$
$$B = \text{"The boundary attribute is violated"}, \tag{6-3}$$
$$C = \text{"The reservation attribute is violated"}, \tag{6-4}$$
$$D = \text{"The overtake attribute is violated"}, \tag{6-5}$$
$$E = \text{"The lighting attribute is violated"}. \tag{6-6}$$

Thus, the following connection of the propositions is derived and formulated:

$$P \leftrightarrow A \lor B \lor C \lor D \lor E \tag{6-7}$$

In the following sections, the individual statements on the violations of the behavioral attributes are derived and formalized by means of predicate logic. Thereby, the formulations from StVO[146] and the Bundeseinheitlicher Tatbestandskatalog für Straßenverkehrsordnungswidrigkeiten (transl.: Federal Catalog of Road Traffic Offences) (BT-KAT-OWI)[147] will be used. The BT-KAT-OWI is the central catalog for defining all violations of traffic regulations in Germany. Therefore, these two sources form the basis for the legal definition of the rules as well as the associated

---

[146] Bundesministerium der Justiz: Straßenverkehrsgesetz (StVG) (2021).

[147] Kraftfahrtbundesamt: Bundeseinheitlicher Tatbestandskatalog (2021).

punishments for violations. As the two documents are in German, the relevant statements are translated by the author to the best of his knowledge. The two documents do not always provide concrete statements, so they are supplemented by other sources of information as needed. At the beginning of each attribute subsection, all characteristics of the attributes are listed.

The following accents are used to distinguish between different types of predicate symbols:

- $X$: denotes a violation
- $\widehat{X}$: denotes a characteristic of an attribute
- $\widetilde{X}$: denotes a condition

### 6.3.1 Speed

Table 6-2: Characteristics of the speed attribute

| Name | Description | Optional |
|---|---|---|
| max | maximum allowed speed | |
| timeMax | maximum allowed speed for a specific time interval | x |
| timeInterval | time interval corresponding to the timeMax characteristic | x |
| wetMax | maximum allowed speed for a wet road | x |
| min | minimum allowed speed | x |

There are multiple sections in the StVO where a speed limit is defined and the violation of this speed is prohibited. This is formulated by the following two statements in the StVO:

*The maximum permissible speed is X km/h.*
*Whoever drives a vehicle must not drive faster than the indicated maximum permissible speed.*

The BT-KAT-OWI states multiple variants of violations of these rules, distinguished by the traffic area and the value of the speed exceedance. All these formulations follow the same pattern:

*You exceeded the maximum permissable speed [...] by Y km/h.*

It follows that the speed of the ego vehicle $v_{\mathrm{ego}}$ must not be greater than the maximum allowed speed $v_{\mathrm{max,allow}}$. On the other hand, there may also be a prescribed minimum speed. Accordingly, if a minimum speed $v_{\mathrm{min,allow}}$ is defined, the speed of the ego vehicle $v_{\mathrm{ego}}$ must not be less than this prescribed minimum speed. Expressed with respect to the driven trajectory, this means that at no trajectory point of the driven trajectory, the driven speed is higher than the maximum allowed speed at the location of this trajectory point. This is represented by proposition 6-8 which represents the formalized test criterion for the speed attribute:

$$\begin{aligned} A \leftrightarrow & \exists_E \boldsymbol{v}_{\text{ego},j} \in \left\{ \left( _E\boldsymbol{v}_{\text{ego},j} \right)_{j=1,\dots,n} \right\} : |_E\boldsymbol{v}_{\text{ego},j}| > v_{\text{max,allow},j} \vee \\ & \exists_E \boldsymbol{v}_{\text{ego},j} \in \left\{ \left( _E\boldsymbol{v}_{\text{ego},j} \right)_{j=1,\dots,n} \right\} : |_E\boldsymbol{v}_{\text{ego},j}| < v_{\text{min,presc},j} \end{aligned} \tag{6-8}$$

There are different characteristics of this maximum allowed speed (max, timeMax, wetMax). Some of these are optional, since they do not necessarily need to be specified within the atomic behavior space. If the timeMax or wetMax values are specified, the maximum allowed speed changes depending on the environmental conditions (time and wetness of the road). In order to select the correct values for the maximum allowed and prescribed minimum speed the following propositions describe the existence of the optional characteristics and whether the respective conditions are fulfilled:

$$\widehat{A}_1 = \text{"A maximum allowed speed for a wet road } v_{\text{wetMax}} \text{ is defined"}, \tag{6-9}$$

$$\widehat{A}_2 = \text{"A maximum allowed speed for a specific time interval } v_{\text{timeInterval}} \text{ is defined"}, \tag{6-10}$$

$$\widehat{A}_3 = \text{"A minimum allowed speed } v_{\text{min}} \text{ is defined"}, \tag{6-11}$$

$$\widetilde{A}_1 = \text{"The road is wet"}, \tag{6-12}$$

$$\widetilde{A}_2 = \text{"The current time is within the specified (periodic) time interval } T\text{"}. \tag{6-13}$$

While the statement regarding the time being within the specified time interval can be checked easily, for checking whether the road is wet a clear and agreed definition of a wet road is needed. This definition is not in the focus of this dissertation. With these propositions, the following cases define the selection of the maximum allowed speed $v_{\text{max,allow}}$ and the prescribed minimum speed $v_{\text{min,presc}}$ closing the formalization for the speed attribute[148]:

$$v_{\text{max,allow}} = \begin{cases} v_{\text{wetMax}} & \text{if } \widehat{A}_1 \wedge \widetilde{A}_1, \\ v_{\text{timeInterval}} & \text{if } (\widehat{A}_2 \wedge \widetilde{A}_2) \wedge (\neg(\widehat{A}_1 \wedge \widetilde{A}_1)), \\ v_{\text{max}} & \text{else.} \end{cases} \tag{6-14}$$

$$v_{\text{min,presc}} = \begin{cases} v_{\text{min}} & \text{if } \widehat{A}_3, \\ 0 & \text{else.} \end{cases} \tag{6-15}$$

### 6.3.2 Boundary

Within the boundary attribute of an atomic behavior space, there exist three different boundaries (longitudinal, left and right). While left and right boundary describe the rules when crossing the

---

[148] This follows the introduced notation:
$\underline{X}$: denotes a violation, $\widehat{X}$: denotes a characteristic of an attribute, $\widetilde{X}$: denotes a condition

boundary from within the atomic behavior space in lateral direction, the longitudinal boundary describes the rules while crossing the boundary from outside and thus, entering the atomic behavior space in longitudinal direction. Any violation of one of these boundaries results in a violation of the boundary attribute. Because the longitudinal boundary describes the entrance into the next segment, the violation of a boundary in the next segment $B_{\text{long}}$ needs to be considered. This is represented by the proposition 6-16:

$$B \leftrightarrow B_{\text{left}} \vee B_{\text{right}} \vee B_{\text{long}} \tag{6-16}$$

Thus, separate evaluation for each of the three boundaries is needed. Table 6-3 gives an overview of the characteristics of an individual boundary. Some of this characteristics may only apply to longitudinal boundaries.

Table 6-3: Characteristics of one boundary

| **Name** | **Description** | **Optional** |
|---|---|---|
| crossing | rule regarding the crossing of the boundary | |
| trafficLightActive | needs to be specified if the longitudinal entry is controlled by a traffic light. Defines whether the crossing of the boundary applies for an active or inactive traffic light | x |
| redLightCondition | needs to be specified if the longitudinal entry is controlled by a traffic light and turn on red is allowed | x |
| condition | defines the condition for crossing if crossing = conditional | x |

The crossing attribute may have different values (*allowed*, *prohibited*, *conditional*, *not possible*) describing the rule while crossing the respective boundary. All these rules need to be formalized. *Allowed* does not need any formalization, as per definition it is not possible to violate an allowed crossing. *Prohibited* and *not possible* have the same formalization for a violation, because in both cases the boundary shall not be overdriven in any case. Between the both values, there is just different outcome (violation for not allowed vs. crash for not possible). Finally, the formalization of the *conditional* rule will depend on the assigned condition(s). If the assigned condition(s) to cross the boundary is/are not fulfilled, it needs to be determined whether the boundary is crossed (geometrically). Therefore, in a first step, the crossing of any boundary is formalized. This does not necessarily mean that the boundary attribute is violated. For this, the formulations in the StVO regarding crossing a *not allowed* boundary are considered, since crossing an *allowed* boundary is not further specified. The most prominent example is a solid lane boundary. The StVO states:

*Anyone driving a vehicle shall not cross the solid line even not partially.*

The BT-KAT-OWI states for a general non-allowed crossing of the lane boundaries:

*You illegally drove across the lane limit.*

From the formulation of the StVO follows that driving across a boundary also includes only partially crossing the boundary. This means, that no part of the vehicle is allowed to cross the boundary.

A crossing exists when the representation of the boundary is not disjoint from that of the vehicle contour. Thus, in that case the radial length from an arbitrary point within the vehicle contour to the representation of the vehicle contour would be greater or equal than to the representation of the boundary. To evaluate this, a representation in a vehicle fixed polar coordinate system is chosen. The geometric representation of the vehicle contour is denoted by $\boldsymbol{\mathcal{C}}$ and the geometric representation of the boundary is denoted by $\boldsymbol{\mathcal{B}}$. Generally, an arbitrary reference point inside the vehicle contour for the origin of the polar coordinate system may be selected. For usage during the testing activities and respecting FRQ2, the center of the front axle is chosen. This point often serves as measured reference point or is given as an output from the simulation environment. The polar coordinate system is aligned with the orientation of the vehicle. By using this representation, depending on the angle $\varphi$, the distance $r$ from reference point to the vehicle contour and lane boundary is given respectively as stated by equations 6-17 and 6-18:

$$ {}_P\boldsymbol{\mathcal{C}}(\varphi) : \varphi_{\boldsymbol{\mathcal{C}}} \mapsto r_{\boldsymbol{\mathcal{C}}} \tag{6-17} $$

$$ {}_P\boldsymbol{\mathcal{B}}(\varphi) : \varphi_{\boldsymbol{\mathcal{B}}} \mapsto r_{\boldsymbol{\mathcal{B}}} \tag{6-18} $$

For a boundary ${}_P\boldsymbol{\mathcal{B}}_{k,j}$ represented in polar coordinates where $k$ denotes the respective boundary ($k =$ left, right, long), a driven trajectory is crossing this boundary when there exists an angle $\varphi_{\text{cross}}$ at a point in time $t_j$ in the value range of the considered boundary $[\varphi_{k,j,\text{start}}, \varphi_{k,j,\text{end}}]$ at the same point in time, for which the distance between reference point and the considered boundary $r_{\boldsymbol{\mathcal{B}}_k,j}(\varphi_{\text{cross}})$ is less than or equal to the distance between reference point and vehicle contour $r_{\boldsymbol{\mathcal{C}}}(\varphi_{\text{cross}})$. This condition is expressed by the following proposition:

$$ \widetilde{B}_{1,k} = \exists \varphi_{\text{cross}} \in [\varphi_{k,j,\text{start}}, \varphi_{k,j,\text{end}}] : r_{\boldsymbol{\mathcal{B}}_k,j}(\varphi_{\text{cross}}) \leq r_{\boldsymbol{\mathcal{C}}}(\varphi_{\text{cross}}) \tag{6-19} $$

Fig. 6-1 illustrates this by depicting an angle $\varphi_{\text{cross}}$ for which the criterion is fulfilled for $k =$ left.

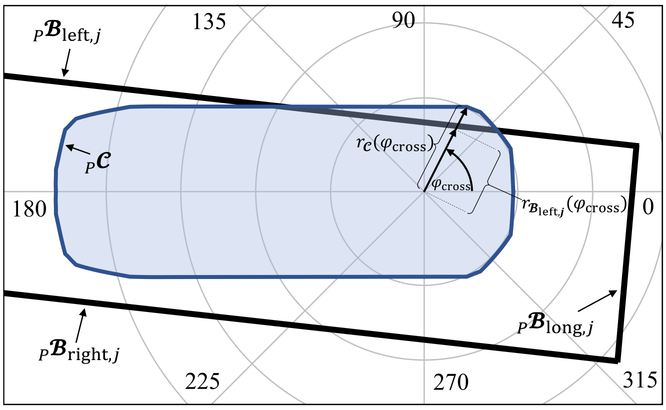


Figure 6-1: Illustration of the fulfilled criterion for boundary crossing

It is possible that there exist multiple sub-boundaries for each *left*, *right* or *longitudinal* boundary, since the different options for an active or non-active traffic light as well as for an allowed turn on red need to be covered. There may be $n \leq 3$ different sub-boundaries within one characteristic specified. The boundary crossing of a boundary $k$ is violated if at least one of these sub-boundaries $j$ is violated. This is expressed by the following proposition, where $B_{k,m}$ denotes a violation of the sub-boundary $m$:

$$B_k \leftrightarrow B_{k,1} \vee \ldots \vee B_{k,m} \vee \ldots \vee B_{k,n} \tag{6-20}$$

Fig. 6-2 gives an overview of the violation of the boundary attribute decomposition to boundaries $B_k$ and sub-boundaries $B_{k,m}$.

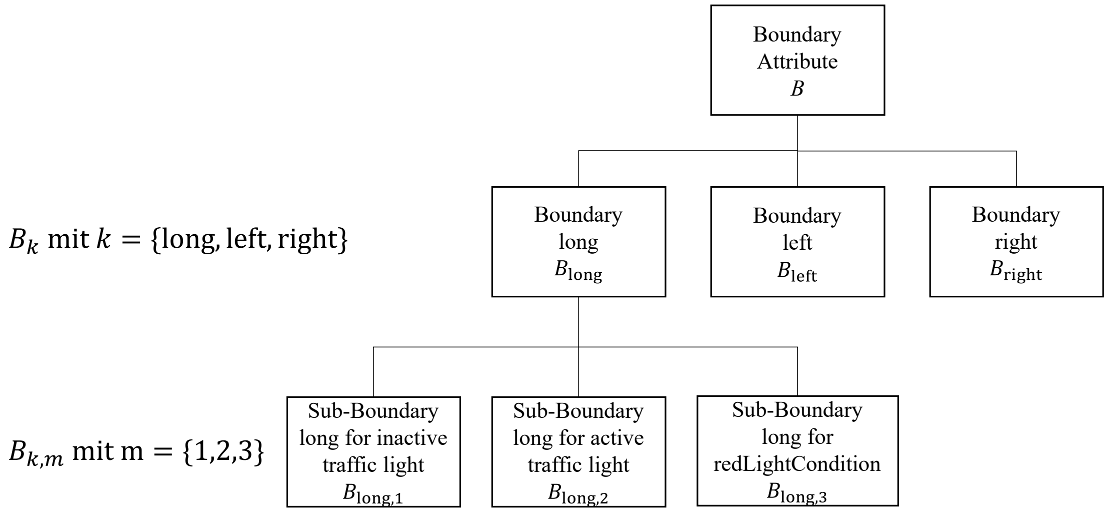


Figure 6-2: Decomposition of the boundary violation

These individual sub-boundaries may have different conditions for crossing. The following propositions formulate the existence and fulfillment of these conditions for each sub-boundary $m$:

$$\widehat{B}_{1,k,m} = \text{"The sub-boundary } k,m \text{ is valid for a traffic light in active state",} \tag{6-21}$$

$$\widehat{B}_{2,k,m} = \text{"The sub-boundary } k,m \text{ is only valid for a traffic light in red light condition",} \tag{6-22}$$

$$\widehat{B}_{3,k,m} = \text{"The sub-boundary } k,m \text{ is valid for all active traffic light conditions",} \tag{6-23}$$

$$\widehat{B}_{4,k,m} = \text{"The crossing type of sub-boundary } k,m \text{ is prohibited or not possible",} \tag{6-24}$$

$$\widehat{B}_{5,k,m} = \text{"The crossing type of sub-boundary } k,m \text{ is conditional",} \tag{6-25}$$

$$\widetilde{B}_{2,k} = \text{"The traffic light of the boundary } k \text{ is in active state",} \tag{6-26}$$

$$\widetilde{B}_{3,k} = \text{"The traffic light of the boundary } k \text{ is in red light condition",} \tag{6-27}$$

$$\widetilde{B}_{4,k,m} = \text{"The specified conditions of sub-boundary } k,m \text{ are fulfilled".} \tag{6-28}$$

Depending on the state of the traffic light and the respective conditions the correct sub-boundary needs to be selected. The correct sub-boundary is selected if both the sub-boundary is correctly chosen regarding the traffic light state as well as the red light condition.

The sub-boundary is correctly chosen regarding the traffic light state if either...

... the sub-boundary is valid for a traffic light in active state and the traffic light of the boundary is in active state

... or the sub-boundary is valid for an inactive traffic light and the traffic light of the boundary is in inactive state.

The sub-boundary is correctly chosen regarding the red light condition if ...

... the sub-boundary is valid for a traffic light in red light condition and the traffic light is in red light condition

... or the sub-boundary is only valid for a traffic light in non-red light condition and the traffic light is in non-red condition

... or the sub-boundary is valid for all traffic light conditions.

For sub-boundaries without a specified red light condition, the boundary is valid both for a traffic light in red light condition as well as in non-red light condition. The selection of the correct boundary is expressed by proposition 6-29:

$$\begin{aligned}\widetilde{B}_{5,k,m} =& ((\widehat{B}_{1,k,m} \wedge \widetilde{B}_{2,k}) \vee (\neg \widehat{B}_{1,k,m} \wedge \neg \widetilde{B}_{2,k})) \wedge \\ & ((\widehat{B}_{2,k,m} \wedge \widetilde{B}_{3,k}) \vee (\neg \widehat{B}_{2,k,m} \wedge \neg \widetilde{B}_{3,k}) \vee \widehat{B}_{3,k,m})\end{aligned} \tag{6-29}$$

The sub-boundary $B_{k,m}$ is violated if the geometric boundary is crossed, the correct sub-boundary is selected and either it is prohibited to cross the boundary or the crossing is conditional and the assigned conditions are not fulfilled. This is expressed by the following proposition:

$$B_{k,m} \leftrightarrow \widetilde{B}_{1,k} \wedge \widetilde{B}_{5,k,m} \wedge (\widehat{B}_{4,k,m} \vee (\widehat{B}_{5,k,m} \wedge \neg \widetilde{B}_{4,k,m})) \tag{6-30}$$

Proposition $\widetilde{B}_{4,k,m}$ states that all specified conditions of the sub-boundary are fulfilled. For $n$ conditions, this means that the following proposition evaluates to *true*:

$$\widetilde{B}_{4,k,m} \leftrightarrow \widetilde{B}_{4,k,m,1} \wedge \widetilde{B}_{4,k,m,2} \wedge \ldots \wedge \widetilde{B}_{4,k,m,n} \tag{6-31}$$

The different types of conditions are subdivided into the following categories based on the type of condition:

- conditions based on vehicle properties
- conditions based on scenery properties
- conditions based on dynamic traffic events

Conditions based on vehicle properties describe properties of the vehicle that need to be fulfilled (e.g. maximum width of the vehicle, maximum weight of the vehicle). These properties may change internally (e.g. lighting). Conditions based on scenery properties describe properties of the static traffic environment that need to be fulfilled (e.g. no red light, specific time intervall). These properties may change externally. For both of these types of conditions they will be either clearly fulfilled or not, depending on the properties of the vehicle or scenery. Therefore, a presentation of the formalization of all of these conditions is omitted. Finally, for the last category based on the dynamic traffic events, it is different. Since these describe dynamic events, it is not clear without a formalization whether these conditions are fulfilled. A *stop* and *no stagnant traffic* condition are defined in this category. The propositions $\widetilde{B}_{4,k,m,1}$ and $\widetilde{B}_{4,k,m,2}$ evaluate to *true* if the respective condition is fulfilled. In the following paragraphs the stop condition is formalized as an example.

$$\widetilde{B}_{4,k,m,1} = \text{"The } \textit{stop} \text{ condition of sub-boundary } k, m \text{ is fulfilled"}, \tag{6-32}$$

$$\widetilde{B}_{4,k,m,2} = \text{"The } \textit{no stagnant traffic} \text{ condition of sub-boundary } k, m \text{ is fulfilled"}. \tag{6-33}$$

The formulations of the StVO for the required behavior at a stop line and a stop sign state:

*Anyone driving a vehicle must stop here.*
*Anyone driving a vehicle must stop.*

The BT-KAT-OWI states for a violation of this rules:

*You did not stop at the stop line.*

From these formulations, it becomes evident that the vehicle needs to stop ($|\boldsymbol{v}_{\text{ego}}| = 0$) before crossing the stop line. There is no further clarification of the meaning of the terms *here* and *at*. Therefore, the regulations do not clearly state in which corridor in front of the boundary the vehicle needs to come to a stop. Such a threshold corridor needs to be discussed and defined in order to evaluate the violation of this condition. Selecting the size of the corridor is not in the focus of this dissertation. For the formalization of the *stop* condition, it is only important that the vehicle comes to a stop within this corridor before crossing the boundary. For any state of a driven trajectory ${}_F\boldsymbol{x}_{\text{ego},j}$ in Frenet coordinates violating this condition means that there exists no position ${}_F\boldsymbol{p}_{\text{ego},j}$ with an $s$-coordinate ${}_Fp_{s,\text{ego},j}$ in the corridor $[s_{\text{stop}} - \Delta s_{\text{thresh}}, s_{\text{stop}}]$ for which the vehicle speed $|{}_F\boldsymbol{v}_{\text{ego},j}| \leq \varepsilon$. $\varepsilon$ is introduced as a threshold because the velocity cannot be measured with arbitrary accuracy. There is no value determined for $\varepsilon$ because it depends on the accuracy of the implemented measurement system. This condition is represented by proposition 6-34:

$$\widetilde{B}_{4,k,m,1} \leftrightarrow \exists_F p_{s,\text{ego},j} \in [s_{\text{stop}} - \Delta s_{\text{thresh}}, s_{\text{stop}}] : |{}_E\boldsymbol{v}_{\text{ego},j}| \leq \varepsilon \tag{6-34}$$

### 6.3.3 Reservation

Table 6-4: Characteristics of the reservation attribute

| Name | Description | Optional |
|---|---|---|
| type | defines the type of the reservation | |
| object | defines the reservation entitled type of object, needs to be specified if type = externally-reserved OR equally-reserved | x |
| trafficLightActive | needs to be specified if the longitudinal entry is controlled by a traffic light. Defines whether the reservation applies for an active or inactive traffic light | x |
| redLightCondition | needs to be specified if reservation is controlled by a traffic light and turn on red is allowed | x |
| turnArrowActive | needs to be specified if reservation is controlled by a traffic light and a separate turn arrow light is present | |
| links | defines the linked areas/lanes from which the reservation entitled objects may come | x |

An atomic behavior space may have $n$ reservations. A specific reservation is denoted by the index $k$. As soon as one reservation is violated, the reservation attribute is violated as well:

$$C \leftrightarrow C_1 \vee \ldots \vee C_k \vee \ldots \vee C_n \tag{6-35}$$

There exist multiple types of reservations. In this section, *external* reservations are considered. An external reservation means that another type of traffic participant has the right of way in this space. There is no clear definition of the term *priority* in the StVO, but the BT-KAT-OWI specifies multiple types of violations of priority rules:

*You disregarded the right of way of the vehicle with priority, so that the vehicle with the right of way was obstructed.*
*You disregarded the right of way of the vehicle with priority, so that the vehicle with the right of way was endangered.*
*You disregarded the right of way of the vehicle with priority. It came to an accident.*
*You did not let another road user pass.*
*You have not enabled the road user to cross.*
*You did not approach the priority road/pedestrian crossing at a moderate speed.*

The formalization of the external reservation needs to cover all these statements, since it aims to cover all priority rules. Therefore, it needs to be analyzed what the terms *obstruct* and *endanger* mean. There exist explanations[149] to the StVO, which are handed to police officers in education.

---

[149] Deutsche Polizeiliteratur: Polizei-Fach-Handbuch (2019).

These explanations further specify obstruction and endangerment as follows:

*Obstruction is any impairment of traffic participants, whether by interfering with movement (forcing the driver to swerve, brake or stop) or by preventing or impeding further travel. The transitions to endangerment are seamless (an obstruction can cause an endangerment).*

*Endangerment is the bringing about of a condition that gives rise to a concern that harm is imminent.*

From this, it becomes evident that an endangerment is more severe that an obstruction. If an endangerment is present, there certainly is an obstruction present as well. Same goes for the case of an accident. So, all three violations are covered by specifying the obstruction only. In order to provide a grading of violations the endangerment would need to be formalized as well, but this is not in the scope of this dissertation.

By further analyzing the definition of obstruction, it can be seen that it covers multiple of the other violations stated by the BT-KAT-OWI as well. *Forcing the driver to swerve, brake or stop or preventing further travel* cover the two violations *did not let pass* and *have not enabled to cross*, because these violations mean that the other participant was either forced to brake or stop and thus, further travel was prevented. Therefore, only two violations remain which are covered by the propositions $C_{1,k}$ and $C_{2,k}$. If either of these is violated, the reservation $k$ is violated as well, which is stated by proposition $C_k$.

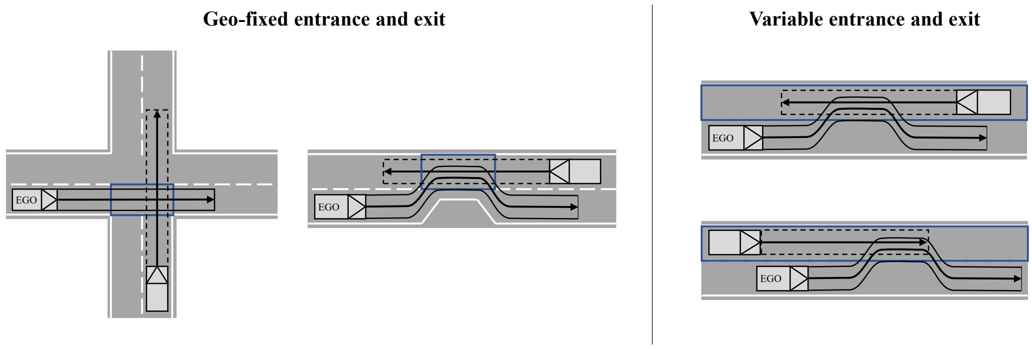
$$C_{1,k} = \text{"The externally-reserved space is approached with non-moderate speed"}, \tag{6-36}$$

$$C_{2,k} = \text{"A reservation-entitled object of the reservation } k \text{ is obstructed"}. \tag{6-37}$$

$$C_k \leftrightarrow C_{1,k} \vee C_{2,k} \tag{6-38}$$

There exist two different cases of driving through a reservation space: Entrance/exit via longitudinal boundaries and entrance/exit via lateral boundaries. In the case of entrance and exit via longitudinal boundaries, the entry and exit to this area is geometrically fixed. Examples include intersections and narrowed roads, as shown in Fig. 6-3 on the left. This is not the case for entry over lateral boundaries, the vehicle can decide itself at which point it enters and exits over the lateral boundary and thus, the entrance and exit is variable. Examples of this are lane changes as shown in Fig. 6-3 on the right. Depending on the type, there are different consequences for the formalization.

For the entrance over a lateral boundary, the vehicle drives along the externally-reserved space prior to entering. Therefore, a definition of approaching with moderate speed is not meaningful. Thus, proposition $C_{1,k}$ always is evaluated to *false* for this case. For geo-fixed entrances, a criteria for violating moderate speed has to be derived. There is neither a value stated in the StVO for a moderate speed, nor what moderate speed means. Therefore, a definition is derived within this


**Geo-fixed entrance and exit**

**Variable entrance and exit**

Figure 6-3: Examples for geo-fixed and variable entry/exit

dissertation. The decision to enter an externally-reserved space may only be made after it has been ensured that no traffic participant with priority will be obstructed or vice versa: The vehicle must always be able to stop in front of the externally-reserved space as long as it is not sure that it is crossing the space without obstruction. In the extreme case, this means stopping with maximum deceleration in front of the externally-reserved motion space. Performing such strong braking maneuvers would clearly violate the moderate speed rule, because other traffic participant would be irritated by this behavior as it seems like that the vehicle is not yielding for them. Therefore, a maximum deceleration $D_{\mathrm{max,appr}}$ with which coming to a stop before the intersection is defined. With this a non-moderate speed is prevented. Such a speed profile in dependence on the distance to the externally-reserved space $\Delta s_{\mathrm{ext}} = s_{\mathrm{ext}} - {}_F p_{s,\mathrm{ego}}$, for ${}_F p_{s,\mathrm{ego}} \leq s_{\mathrm{ext}}$ is given by equation 6-39. A monitoring of the deceleration of the ego-vehicle only would not be sufficient, since while being below the speed profile high accelerations may be allowed. Exceeding this profile is only allowed if the HAV can assure to cross the externally-reserved speed without obstruction. This means that the decision to enter the externally-reserved space is made. If no exceedance of this profile would be allowed, it would be impossible to enter an externally-reserved space.

$$v_{\mathrm{appr}}(\Delta s_{\mathrm{ext}}) = \sqrt{2 \cdot D_{\mathrm{max,appr}} \cdot \Delta s_{\mathrm{ext}}} \tag{6-39}$$

This means that exceeding the velocity profile does not necessarily result in a violation of the moderate speed. It is only a violation if the vehicle falls back below the speed profile during the approach, meaning that it was not sure (or erroneously sure) to enter the externally-reserved motion space. Meaning, if the vehicle exceeds the velocity profile in at the coordinate $p_{s,j}$ to the externally-reserved space then there exists a smaller distance to the externally-reserved motion space with the coordinate $p_{s,i}$ where the speed of the vehicle falls back below the velocity profile. This is expressed by the following proposition:

$$\begin{aligned} C_{1,k} \leftrightarrow \exists_F p_{s,\mathrm{ego},j} \in [s_{\mathrm{ext}} - \Delta s_{\mathrm{max}}, s_{\mathrm{ext}}] :& \\ |_F \boldsymbol{v}_{\mathrm{ego},j}({}_F p_{s,\mathrm{ego},j})| > v_{\mathrm{appr}}(s_{\mathrm{ext}} - {}_F p_{s,\mathrm{ego},j}) \wedge& \\ \exists_F p_{s,\mathrm{ego},i} \in ({}_F p_{s,\mathrm{ego},j}, s_{\mathrm{ext}}] : |_F \boldsymbol{v}_{\mathrm{ego},i}({}_F p_{s,\mathrm{ego},i})| \leq v_{\mathrm{appr}}(s_{\mathrm{ext}} - {}_F p_{s,\mathrm{ego},i})& \end{aligned} \tag{6-40}$$

After exceeding the velocity profile, the vehicle has a certain time to leave the externally-reserved space before it is in the path of the reservation entitled traffic participant. This time is defined by the time that a reservation entitled traffic participant will arrive at the space. It can be calculated by assuming a velocity profile for the reservation entitled traffic participant. As identified before, an obstruction means that the movement of another traffic participant is interfered more than necessary. In order to ensure continuing into an externally-reserved motion space, it is sometimes necessary to squeeze into traffic and expect the other traffic participant to perform reasonable deceleration $D_\text{r}$. This is not considered as an obstruction which is more than necessary and therefore, considered in the following future speed profile $v_\text{fut}(t)$ of an existing traffic participant $\boldsymbol{\mathcal{O}}_{\text{exist},i} \in \boldsymbol{\mathcal{D}}_{\text{exist},j}$:

$$\begin{aligned} v_{s,\text{fut},\boldsymbol{\mathcal{O}}_{\text{exist},i}}(t) = &\min\left({}_{F}v_{s,\boldsymbol{\mathcal{O}}_{\text{exist},i},j} + a_\text{r}\cdot t, \max\left(v_\text{m}, {}_{F}v_{s,\boldsymbol{\mathcal{O}}_{\text{exist},i},j} - D_\text{r}\cdot t\right)\right), \\ &\text{for } {}_{F}v_{s,\boldsymbol{\mathcal{O}}_{\text{exist},i},j} > 0 \end{aligned} \tag{6-41}$$

This velocity profile considers the initial speed component in the direction of the lane towards the externally-reserved motion space ${}_{F}v_{s,\boldsymbol{\mathcal{O}}_{\text{exist,i}},j}$ of the traffic participant. Since this velocity may be low initially (e.g. the vehicle starts to move because it waited for another traffic participant) on the one hand a profile is considered where the traffic participant accelerates reasonably with $a_\text{r}$. On the other hand, if the initial speed is high, a reasonable deceleration $D_\text{r}$ over time is considered, but only until a threshold value for a moderate speed $v_\text{m}$ is reached, because otherwise the traffic participant may be forced into standstill. The velocity profile is determined by the minimum of these two speeds.

In order for the reservation attribute to be violated, the object under consideration $\mathcal{O}_{\text{exist},i}$ needs to have the specified type of the external-reservation of the attribute and needs to enter the intersection from within one of the specified links. This is expressed by following conditions:

$$\widetilde{C}_{1,\boldsymbol{\mathcal{O}}_i} = \text{"The type of the object } \boldsymbol{\mathcal{O}}_i \text{ is within the types specified in the external reservation",} \tag{6-42}$$

$$\widetilde{C}_{2,\boldsymbol{\mathcal{O}}_i} = \text{"The object } \boldsymbol{\mathcal{O}}_i \text{ is geometrically within one of the reservation links specified in the external reservation".} \tag{6-43}$$

From equation 6-41 as well as the initial distance of the objects to the externally-reserved space the duration $\tau_{\boldsymbol{\mathcal{O}}_{\text{exist,relevant},i}}$ for all relevant objects $\boldsymbol{\mathcal{O}}_{\text{exist,relevant},i}$ to arrive at the externally-reserved space is determined. Relevancy in this context is given if both $\widetilde{C}_1$ and $\widetilde{C}_2$ evaluate to *true*:

$$(\widetilde{C}_{1,\boldsymbol{\mathcal{O}}_i} \wedge \widetilde{C}_{2,\boldsymbol{\mathcal{O}}_i}) \rightarrow \boldsymbol{\mathcal{O}}_{\text{exist,relevant},i} \in \boldsymbol{\mathcal{D}}_{\text{exist,relevant},i} \tag{6-44}$$

Brian et al. introduce the Post Encroachment Time (PET) as *"the time from the end of encroachment to the time that the through vehicle actually arrives at the potential point of collision"*. Empirical study show that human drivers will naturally keep a PET while entering a conflict area.[150] Therefore, a PET is respected in the time for leaving an externally-reserved motion space and may be selected based on the type of reservation entitled traffic participant. The fixation of a representative value for the PET is not in the scope of this dissertation. The allowed duration $\tau_{\text{allow,leave}}$ for leaving the external motion space is defined as:

$$\tau_{\text{allow,leave}} = \min\left(\left(\tau_{\mathcal{O}_{\text{exist,relevant},i}}\right)_{i=1,\ldots,n}\right) - \tau_{\text{PET}} \tag{6-45}$$

A driven trajectory obstructs a reservation-entitled object of the reservation $k$ for geo-fixed entrances and exits if this time for leaving the space is exceeded. This is expressed by the following proposition:

$$C_{2,k,\text{fix}} \leftrightarrow \tau_{\text{ego,leave}} > \tau_{\text{allow,leave}} \tag{6-46}$$

For variable entrances and exits (see Fig. 6-3) there will be no fixed initial distance. The distance to the exit will depend on where the vehicle leaves the externally-reserved space. Therefore, for each possible distance to leave the space $d_{\text{leave}}$ a separate arrival time $t(d_{\text{leave}})$ is determined. If for the actual leaving distance this time is exceeded, the reservation-entitled object is obstructed. This is expressed by the following proposition:

$$C_{2,k,\text{var}} \leftrightarrow \tau_{\text{ego,leave}}(d_{\text{leave}}) > \tau_{\text{allow,leave}}(d_{\text{leave}}) \tag{6-47}$$

### 6.3.4 Overtake

Table 6-5: Characteristics of the overtake attribute

| Name | Description | Optional |
|---|---|---|
| permission | defines the permission to overtake | |

The StVO differentiates between overtake (§5) and passing (§6). But in both sections there is no clear definition of the two maneuvers. The administrative regulation to the StVO states to §5 and §6:

*Participants of the roadway traffic who want to move on in the same direction, but have to wait, are not driven by, they are overtaken. Those who are delayed by the traffic situation or by an order wait.*

This means that overtaking does not require a lane change or adjustment of speed. It only states

---

[150] Arun, A. et al.: Review of traffic conflict-based safety measures (2021).

the fact, that one vehicle moves past another vehicle that is also participating in roadway traffic. This means that a first vehicle overtaking a second vehicle moves faster than the second one. This matches the definition of overtaking from section 4.2. For the formalization it is only relevant that the ego vehicle is behind another traffic participant and at a later point in time is in front of this traffic participant. Behind means that the full ego vehicle length is behind the other vehicle's rear and in front means that any part of the ego vehicle is in front of the other vehicle's front. A relevant object for overtaking is therefore an object that is within the segment of the ego vehicle. This is given by the following condition:

$$\widetilde{D}_{1,\boldsymbol{\mathcal{O}}_i} = \text{"The object } \boldsymbol{\mathcal{O}}_i \text{ is geometrically within the segment of the ego vehicle."} \tag{6-48}$$

$$\widetilde{D}_{1,\boldsymbol{\mathcal{O}}_i} \rightarrow \boldsymbol{\mathcal{O}}_{\text{exist,relevant},i} \in \boldsymbol{\mathcal{D}}_{\text{exist,relevant},i} \tag{6-49}$$

To take into account that the ego vehicle is behind the other vehicle before entering the behavior space with an overtaking prohibition, it is checked as well whether it was behind the object at a point in time $t_j$ before entering the behavior space at $t_{\text{entry}}$. It then needs to be ensured that there was no point in time between $t_j$ and $t_{\text{entry}}$ where the object was in front of the other vehicle. This is expressed by the following proposition:

$$\begin{aligned} D \leftrightarrow & \exists \boldsymbol{\mathcal{O}}_{\text{exist,relevant},i} \in \boldsymbol{\mathcal{D}}_{\text{exist,relevant},i} : \\ & (\exists t_j \in [t_0, t_{\text{exit}}] : {}_F p_{s,\text{ego,front},j} < {}_F p_{s,\boldsymbol{\mathcal{O}}_{\text{exist,relevant,rear},i},j} \wedge \\ & \nexists t_m \in (t_j, t_{\text{entry}}] : {}_F p_{s,\text{ego,front},m} > {}_F p_{s,\boldsymbol{\mathcal{O}}_{\text{exist,relevant,front},i},m} \wedge \\ & \exists t_k \in [t_{\text{j}}, t_{\text{exit}}] : {}_F p_{s,\text{ego,front},k} > {}_F p_{s,\boldsymbol{\mathcal{O}}_{\text{exist,relevant,front},i},k}) \end{aligned} \tag{6-50}$$

## 6.4 Decomposition of Formalized Attributes

Section 5.3 showed how the semantic behavioral attributes can be decomposed to layers of the functional decomposition in order to use them as functional specification. The results of this decomposition are particular fail-criteria without a quantified and thus, testable value. This section introduces a method to break down the formalization of a behavioral attribute to the decomposition layers of the functional decomposition in order to give formal particular fail-criteria which enable the evaluation of test cases, especially in virtual testing.

The input to this method is the fault tree of a violation of a behavioral attribute resulting from the decomposition process in section 5.3 as well as the formalized violation of this attribute. Figure 6-4 depicts the introduced method for the decomposition of formalized attributes which assigns the criteria to the fault tree.

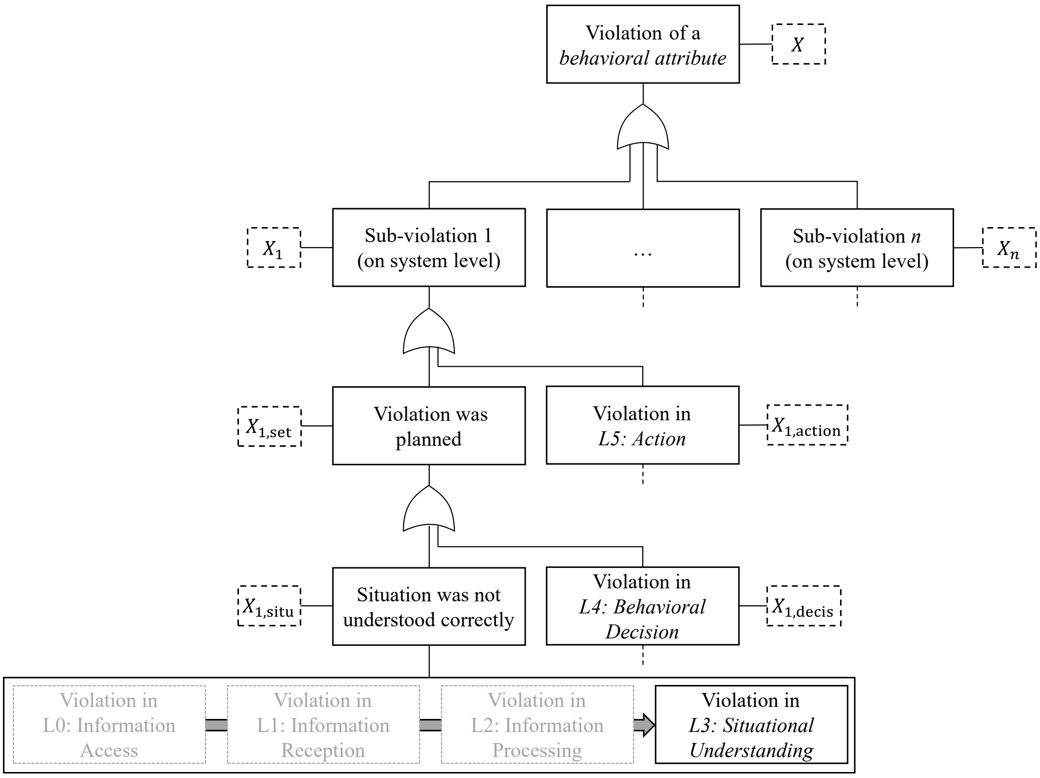


Figure 6-4: Method to decompose formalized attributes

The first step is to assign the derived formalization to the events on system level. The formalization $X$ denotes a violation of a behavioral attribute and may be decomposed into different sub-violations (still on system level, see equation 6-51). These sub-violations are assigned to the respective events in the fault tree. In this process a logical OR ($\vee$) in the formalization matches an OR-gate in the fault tree.

$$X \leftrightarrow X_1 \vee \ldots \vee X_n \tag{6-51}$$

For each sub-violation the formalization of this event is then decomposed according to the functional decomposition. The formalization on system level serves as a starting point. While a violation in a later layer may result from an erroneous input from an earlier layer, the goal of the formalization is to delimit these violations from each other. This means that a violation in a certain layer is not resulting from a violation from another layer. For example, a violation in the action layer $X_{1,\text{action}}$ means that the observable behavior violates $X_1$ while no previous layer violated the respective criteria:

$$X_{1,\text{action}} \leftrightarrow X_1 \wedge \neg(X_{1,\text{situ}} \vee X_{1,\text{decis}}) \tag{6-52}$$

where $X_{1,\text{situ}}$ denotes a violation in either the information access, information reception information processing layer or situational understanding layer and $X_{1,\text{decis}}$ denotes a violation in the behavioral decision layer. Starting from that point, all functional decomposition layers are formalized, always asking the question *what does the next layer need as an input to provide such that it may fulfill the formalization?* Information access (L0), information reception (L1), information processing layer (L2) and situational understanding (L3) are subsumed in one criteria (see also section 5.3). The output of L3 can be described in a generic way by using BSSD and the notation introduced in section 6.2, although there may be other representations (e.g. grid based) that do not fit this representation. In this case, the representation either needs to be converted or new criteria from the criteria presented in this work need to be derived. In the following the speed attribute is decomposed as an example.

In the first step, the derived violation $A$ of the speed attribute from section 6.3 and the decomposed violations $A_{\max}$ and $A_{\min}$ are assigned to the fault tree.

$$A_{\max} \leftrightarrow \exists_E \boldsymbol{v}_{\text{ego},j} \in \left\{ \left( _E\boldsymbol{v}_{\text{ego},j} \right)_{j=1,\dots,n} \right\} : \left| _E\boldsymbol{v}_{\text{ego},j} \right| > v_{\text{max,allow},j} \tag{6-53}$$

$$A_{\min} \leftrightarrow \exists_E \boldsymbol{v}_{\text{ego},j} \in \left\{ \left( _E\boldsymbol{v}_{\text{ego},j} \right)_{j=1,\dots,n} \right\} : \left| _E\boldsymbol{v}_{\text{ego},j} \right| < v_{\text{min,presc},j} \tag{6-54}$$

The decomposition of sub-violations is performed exemplarily for $A_{\max}$. The derived fault tree with assigned violations is depicted in Fig. 6-5.

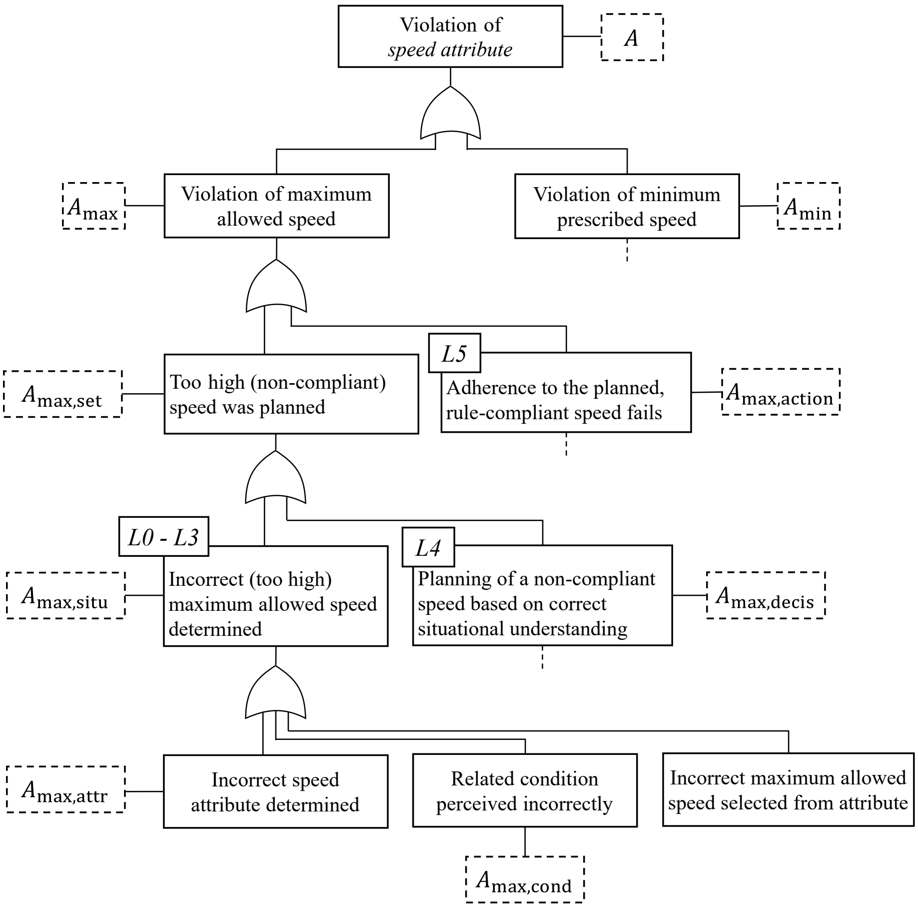


Figure 6-5: Decomposition of the formalized speed attribute

A violation in the action layer means that a trajectory compliant to the maximum allowed speed limit was planned, but the actual behavior deviates from this trajectory in such form that the maximum allowed speed is violated:

$$A_{\text{max,action}} \leftrightarrow A_{\text{max}} \wedge \neg A_{\text{max,set}} \tag{6-55}$$

More likely is an error in an upstream functional layer, since with the current state of the art longitudinal control for speed limit compliance already works well [151,152] and for control in the range of maximum allowed speeds, no large accelerations shall be used.

Going one layer back, the behavioral decision layer needs to provide a trajectory compliant to the maximum allowed speed. Therefore, a violation in the behavioral decision layer $A_{\text{max,decis}}$ means that a non-compliant driving speed was planned although a correct maximum allowed speed as well as the fulfillment of the linked conditions was known in time, meaning there was a correct output within the situation description. In this case, the planner did not provide the intended functionality:

$$A_{\text{max,decis}} \leftrightarrow A_{\text{max,set}} \wedge \neg A_{\text{max,situ}} \tag{6-56}$$

$$A_{\text{max,set}} \leftrightarrow \exists {}_{E}\boldsymbol{v}_{\text{set},j,1} \in \left\{ \left( {}_{E}\boldsymbol{v}_{\text{set},j,1} \right)_{j=1,\ldots,n} \right\} : |{}_{E}\boldsymbol{v}_{\text{set},j,1}| > v_{\text{max,allow},j,1} \tag{6-57}$$

Analyzing what leads to an incorrect situation description regarding speed limit attribute, this is either an incorrect derivation of the present speed attribute $A_{\text{max,attr}}$ or an incorrect determination whether the specified conditions within the attribute are fulfilled $A_{\text{max,cond}}$.

$$A_{\text{max,situ}} \leftrightarrow A_{\text{max,attr}} \vee A_{\text{max,cond}} \tag{6-58}$$

A derivation of an incorrect speed attribute means that the identified maximum allowed speed is incorrect. This only leads to a violation of the speed limit if the situation representation identified a maximum allowed speed $v_{\text{max,allow,sit}}$ higher than the actual maximum allowed speed $v_{\text{max,allow,act}}$:

---

[151] Mercedes-Benz Group AG: Aktiver Geschwindigkeitslimit-Assistent (2022).

[152] Volkswagen AG: Automatische Distanzregelung (Active Cruise Control - ACC) (2022).

$$A_{\mathrm{max,attr}} \leftrightarrow v_{\mathrm{max,allow,situ}} > v_{\mathrm{max,allow,act}} \tag{6-59}$$

A determination of an incorrect related condition means that the wrong maximum allowed driving speed from the attribute will be selected. This is the case if the condition of the situation representation is different from the actual condition. As an example the criterion for an incorrect determination of a wet road is given:

$$A_{\mathrm{max,cond,wetroad}} \leftrightarrow \widetilde{A}_{1,\mathrm{situ}} \neq \widetilde{A}_{1,\mathrm{act}} \tag{6-60}$$

In Annex B the decomposition for the reservation attribute is shown as a further example as this presents the most challenging example for the methodology.

# 7 Test Plan for Traffic Rule Compliance

This chapter adresses research question RQ7:

*How can a test plan for the validation of local traffic rule conformity be defined?*

In order to answer this question, an overview of the (software) testing process is given based on current literature. This will provide the context necessary to introduce a systematic approach to derive a test plan for traffic rule compliance in the second section of the chapter based on current approaches in the state of the art. Within this systematic approach the benefits of the findings from previous chapters are highlighted and presented.

## 7.1 Test Process

Steimle et al.[153] propose a framework for a taxonomy containing basic vocabulary relevant for scenario-based development and test approaches based on different standards (e.g. ISO 26262[154], ISO 29119[155], IEEE 829[156a]) and publications (e.g. ISTQB Glossary[157], Spillner et al.[158], Witte[159]). The introduced test process within the framework and related terms are outlined in the following and used as a basis for the test plan derivation in the following. Fig. 7-1 gives an overview of the test process according to Steimle et al.[153].

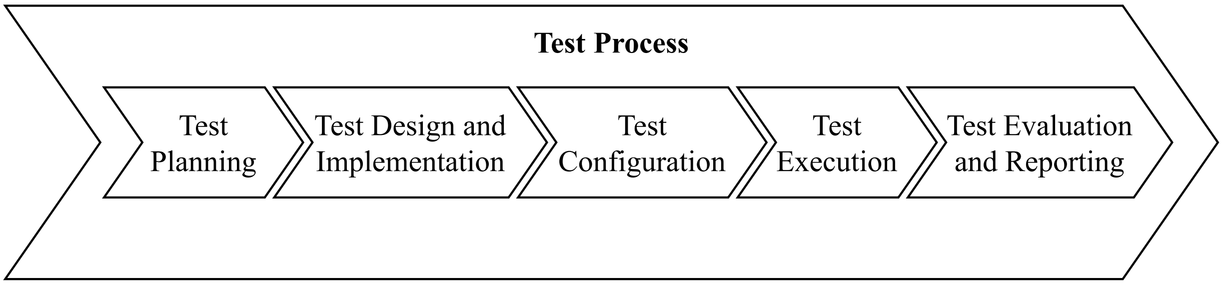


Figure 7-1: Overview of the test process (own illustration based on Steimle et al.[153])

The first phase of the test process is the test planning. Within this phase one or more test plans are created that list the scope, the procedure, the resources as well as the time schedule of the

---

[153] Steimle, M. et al.: Toward a Consistent Taxonomy for Test Approaches (2021).

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

[155] ISO: ISO 29119: Software and systems engineering (2022). a: -; b: Part 1, p.15; c: Part 1, p.14.

[156] IEEE: IEEE 829: Standard for Software and System Test Documentation (2008). a: -; b: p.11.

[157] ISTQB: Standard Glossary of Terms Used in Software Testing (2021).

[158] Spillner, A. et al.: Software testing foundations (2014).

[159] Witte, F.: Testmanagement und Softwaretest: Theoretische Grundlagen und praktische Umsetzung (2019).

intended tests with all involved activities.[153,155] This includes the identification of the items and related features to be tested, the testing tasks as well as who will perform the testing tasks.[156b] Consequently, the test planning lays the foundation for all subsequent testing activities. Within the next phase (test design and implementation) the test specification is created.[153] The test specification is the *"complete documentation of the test design, test cases and test procedure for a specific test item"*[155b]. During the test configuration phase all elements necessary to execute the specified test cases are defined.[153] This results in one or more test bench configurations necessary for the specified test cases. A test bench consists of the test object and models (e.g. simulation models) and their specific parameter values to stimulate the test object in order to execute one or more test cases.[153,160] Within the test execution phase, the defined test cases are executed. The test evaluation and reporting is a separate phase from the execution phase since the evaluation may be performed independently based on recorded data.[153] According to Steimle et al.[153] the process steps should not be performed strictly sequential, but rather serve as a rough framework for orientation.

The entirety of test plans resulting from the test planning phase (also called master test plan[155c]) encompass all testing activities on a project. However, this dissertation focuses on testing traffic rule compliance. As a consequence, in the following section a systematic method for the derivation of a test plan for the evaluation of traffic rule compliance is investigated. The method is not restricted to this application and may be transferable to other types of test plans (e.g. for safety validation). Since the resources available as well as the time schedule of the intended tests is highly dependent on the individual project, these topics will not be considered within the method.

## 7.2 Derivation of a Test Plan

In this section a method for the systematic derivation of a test plan for the evaluation of local traffic rule compliance is presented. For this, within this section the test objective, test object and scope of the test plan are outlined to delineate the context of the method. Within section 7.2.1, current methods for systematic derivation of a test strategy are presented and in section 7.2.2 extended to fit the outlined context.

The test objective is the *"reason or purpose for deriving and executing test cases"*[161] and may be subdivided into further test objectives. The following test objective is defined for the test plan:

*Validate whether the complete system (vehicle) behaves compliant to the local traffic rules within the specified ODD.*

---

[160] Klamann, B. et al.: Comparing Different Levels of Technical Systems (2021).

[161] Steimle, M. et al.: Toward a Consistent Taxonomy for Test Approaches (2021)

The test object is the *"hardware and/or software to be tested and is specific to the considered test level"*[161]. Therefore, for this test plan the test object is the complete system (vehicle including ADS). The test scope *"summarizes the features of the test object(s) to be tested"*[161]. The features to be tested are subsumed by applying the method to derive the functional description (dependent on the ODD) from chapter 5. Because the functionalities derived during the application of this method are directly assigned to the functional decomposition layers, they may also be tested within particulate tests specifically on this respective functional decomposition layer to reduce the test effort. According to Amersbach[162] this makes the respective functional layers test objects. Therefore, the test objective is subdivided into the following objectives per functional decomposition layer (test object). Based on the structure of the specification resulting from section 5.3 the first four layers are tested together. For each layer, the derived criteria for violation are tested. The test goals are as follows.

*Validate whether . . .*

- . . . *the information access, reception, processing layer and the situational understanding layer are aware of and provide the present local behavior constraints and related information to fulfill these rules.*
- . . . *the behavioral decision layer plans rule compliant behavior.*
- . . . *the action layer realizes the planned behavior with sufficient accuracy.*

A fulfillment of these test goals is not necessary but sufficient to prevent a violation of the local traffic rules on system level. This means that a violation of one test goal not necessarily leads to a violation of the local traffic rules. For example, a missing awareness of a certain speed limit may not lead to a violation if the vehicle in front is adhering to this limit and the ego vehicle is not overtaking. Similarly, for each individual test goal, a sufficient test set may be derived. This is dependent on the test strategy of the individual project. For example, proving that the vehicle generally is not able to drive faster than 30 km/h would sufficiently prove that the vehicle is not violating a speed limit of 50 km/h. Similarly, specifying and testing that a virtual object in a occluded space is always considered would be possible instead of finding a worst case test where an actual object is within the occlusion. When defining criteria that are sufficient, it needs to be carefully proven that this is definitely the case.

### 7.2.1 Test Strategy for Systematic Testing

The test strategy *"describes the approach to testing for a specific project, test level or test type"*[163]. It usually includes some or all of the following *"the test levels and test types to be implemented; the retesting and regression testing to be employed; the test design techniques and corresponding*

---

[162] Amersbach, C. T.: Functional Decomposition Approach (2020), p. 78.

[163] ISO: ISO 29119: Software and systems engineering (2022), Part 1, p. 15.

*test completion criteria to be used; test data; test environment and testing tool requirements; and expectations for test deliverables."*[163]

Schuldt[164] presents a modular, virtual testing kit for the safety validation of automated driving. This testing kit presents an organized procedure containing methods and techniques for the systematic execution of the test process and thus, addresses the listed contents of a test strategy. An overview of the model is shown in Fig. 7-2.

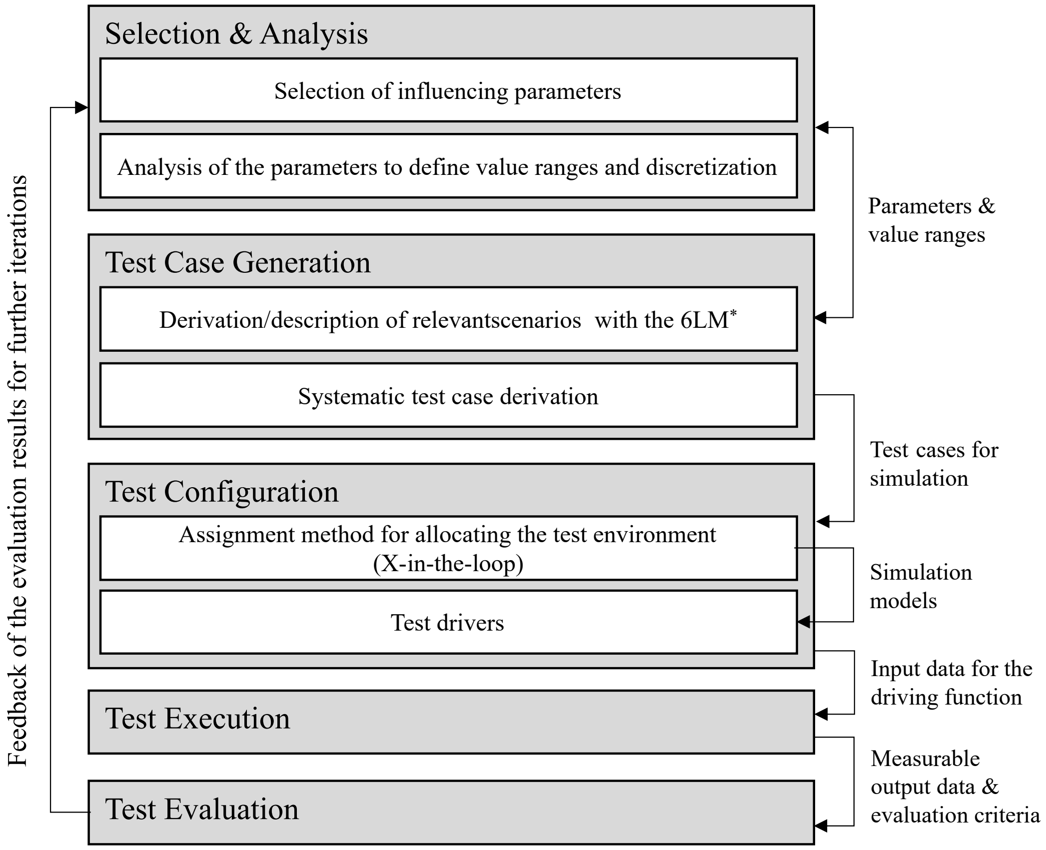


Figure 7-2: Overview of the testing kit developed by Schuldt[164] (own illustration)

Within the selection and analysis step, influence parameters for the test object are selected based on various sources (e.g. functional specification, system requirements, existing scenario catalogs, guidelines and standards). The parameters are then analyzed based on statistics, expert knowledge as well as standards and guidelines in order to determine valid value ranges as well as discretization of the parameters. During the test case generation the identified parameters are passed to the 6-Layer-Model[166] in order to generate logical scenarios. A systematic test case derivation is used to derive concrete test cases with specified parameters and evaluation criteria. This systematic derivation makes use of dynamic analysis methods from software testing (e.g. equivalence partitioning[167a], boundary value analysis[167b], combinatorial algorithms[167c], see section 2.2.4)

---

[164] Schuldt, F.: Methodischer Test von automatisierten Fahrfunktionen (2017), pp. 81-84.

[165] Scholtes, M. et al.: 6-Layer Model for a Structured Description of Urban Traffic and Environment (2021)

[166] The 4-Layer-Model used by Schuldt has been updated with the 6-Layer-Model by Scholtes et al.[165]

[167] ISO: ISO 29119: Software and systems engineering (2022), a: Part 4, p. 10; b: Part 4, p.12; c: Part 4, p.15

to determine input parameters as well as test coverage. The step test configuration[168] assigns a suitable test environment (X-in-the-Loop) by using an assignment method. Matching simulation models based on the test environment serve as test drivers to provide the input data for the test object (driving function). The remaining two steps represent the test execution and evaluation.[164]

As outlined before, when using functional decomposition each functional layer is an individual test object. Therefore, influence parameters have to be analyzed and allocated for each layer individually.[169a] Amersbach and Winner[170] propose a method for intuitive allocation of influence parameters by using an overview matrix. This matrix compares the parameters to the functional levels and the influence of the parameter on the functional level is then determined intuitively. An example of an overview matrix is given in Tab. 7-1. Amersbach states that the intuitive allocation is not reproducible and also not feasible for large-scale applications and thus, a rule-based allocation is necessary.[169b] Other than this, Amersbach finds the existing methods introduced by Schuldt are suitable for the generation, execution and evaluation of particulate test cases.[169c] The issue of intuitive influence allocation is tackled in the following subsection in the context of traffic rule compliance. An open question that remains is the determination of the required test coverage for a scenario-based validation.

Table 7-1: Exemplary overview matrix for intuitive allocation of the influence

| | | **Influence on funct. layer** | | | | | |
|---|---|---|---|---|---|---|---|
| **Layer of the 6LM** | **Parameter** | L0: Inf. Access | L1: Inf. Reception | L2: Inf. Processing | L3: Sit. Understanding | L4: Behavior. Decision | L5: Action |
| L1: Road network | Lane width | x | x | | | x | x |
| | Lane marking type | x | x | x | | | |
| | Type of traffic sign | x | x | x | | | |
| | ... | | | | | | |
| L2: Roadside structures | Tree height | x | | | | | |
| | Tunnel material | | x | x | | | |
| | ... | | | | | | |
| L3: Temporary modifications | ... | | | | | | |
| ... | ... | | | | | | |

---

[168] This step has been renamed by the author to better fit the definition of the introduced test process step from section 7.1

[169] Amersbach, C. T.: Functional Decomposition Approach (2020), a: p. 78; b: p. 72; c: p.80.

[170] Amersbach, C. et al.: Funktionale Dekomposition (2018).

### 7.2.2 Test Strategy for the Test of Traffic Rule Compliance

The procedures introduced by Schuldt[171] and Amersbach[172] are suitable to derive a test strategy for automated driving functions. However, within this dissertation the test strategy has a different scope of validating traffic rule compliance. Within this scope, the methods developed in the previous chapter can be embedded in the development of the test strategy to tackle the open issue regarding influence allocation. As can be seen from the example in Table 7-1, there is no level in the 6-Layer model to represent the behavior space. During intuitive allocation this is implicitly considered. For example, the traffic sign type itself has no influence on the behavioral decision layer. The influence on the behavioral decision layer resulting from the type of traffic sign is not represented though. In the scope of local traffic rules, BSSD (or rather the functional specification resulting from the method in chapter 5) exactly describes this influence. Therefore, the method to develop the test strategy is adapted. An overview of the adapted test strategy is given in Fig. 7-3.

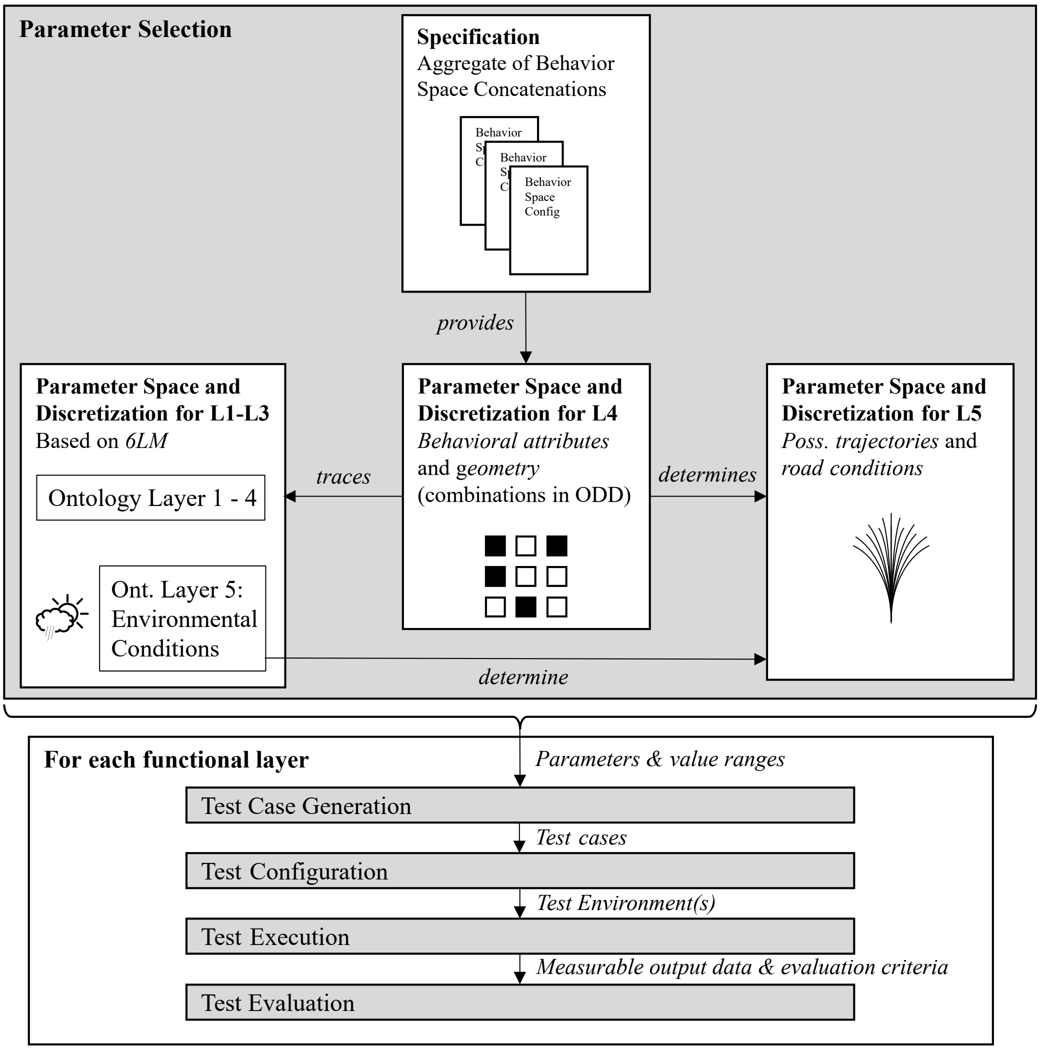


Figure 7-3: Overview of the test strategy for local traffic rule compliance

---

[171] Schuldt, F.: Methodischer Test von automatisierten Fahrfunktionen (2017).

[172] Amersbach, C. T.: Functional Decomposition Approach (2020).

The main adaption is within the parameter selection process. As the functional specification directly provides all present behavior space configurations (including geometry), the parameter space including discretization for the behavioral decision layer is directly available. By definition, it is clear that all attributes have an influence on the behavioral decision, since they have to be respected. Thus, the parameter space is already reduced to the relevant minimum without any intuitive selection process. The classification of the configurations considering the geometry into equivalence classes is investigated in a parallel work as part of the dissertation of Lippert[173]. Additionally, from the FTA in section 6.4 the functionalities that need to be provided by preceding layers is derived. Within these functionalities, it is specified what types of elements of the scenery as well as objects must be detected in functional layers L0-3, so the parameter space for these levels is directly traced from the functional description of the respective layer. Additionally, relevant parameters of the environmental conditions are given by the definition of the ODD. The influence allocation of these conditions is dependent on the employed sensor types. A starting point for the systematic analysis of the first three layers could be the Perception Sensor Collaborative Effect and Cause Tree (PerCollECT) by Linnhoff et al.[174] Within their methodological approach to specify sensor models, they capture cause-effect chains for various sensor types. These cause-effect chains show the influence of various effects resulting in errors in sensor data. The influence on the action layer must result from a separate analysis. The parameter space for the behavioral decision layer determines the set off possible behaviors for the HAV. Based on this set, a set of parameters for the trajectories (which is the interface) to the action layer can be determined. Blödel[175] investigates a method to derive and generate such trajectories for the test of the action layer. In addition to the trajectory as input, the road condition will have an influence on this layer. A low friction coefficient for example, may complicate the adherence to a planned trajectory. The remaining steps of the test strategy remain as identified by Schuldt[176]. Although they are applied to each functional layer individually as identified by Amersbach[177].

Despite the method is only investigated in the context of traffic rule compliance, it may be adapted to general validation activities in the field of automated driving. The important step that needs to be performed is finding a semantic representation for the behavioral decision layer that finds and explicitly states all information for the behavioral decision of the vehicle. As a benefit of the proposed method the intuitive allocation of influence parameters is highly reduced. Additionally, the test criteria can directly be derived and formalized as shown in chapter 6.

---

[173] Lippert, M.: Capability-Based Route Planning (2023).

[174] Linnhoff, C. et al.: A Collaborative Method to Specify Sensor Models (2021).

[175] Blödel, A. P.: Generierung von Trajektorien für das modulare Testen (2021).

[176] Schuldt, F.: Methodischer Test von automatisierten Fahrfunktionen (2017), pp. 81-84.

[177] Amersbach, C. T.: Functional Decomposition Approach (2020), p. 78.

# 8 Application

After chapters 4 - 7 introduced a methodology for the test of traffic rule compliance for HAV, the applicability of this methodology is investigated in this chapter. This analyzes the research question RQ6:

*Is the developed methodology practically applicable?*

To analyze the applicability, a real world use case is selected. The selected use case is presented in section 8.1. Within this use case a high-definition map is used, based on which the method to derive the functional specification is applied in section 8.2. Based on the derived functional specification exemplary test cases are derived in section 8.3. Finally, in section 8.4 a subset of these test cases is conducted with the prototype vehicle of the use case and the developed test criteria from chapter 6 are applied to evaluate the traffic rule compliance. Finally, the applicability of the method is evaluated in section 8.5 by comparing the results to the stated requirements from chapter 3.

## 8.1 Overview of the Use Case

In the research project PRORETA 5[178], methods for automated driving are investigated and implemented in a prototype vehicle. The project focusses on urban scenarios in narrow roads developing an *urban pilot for narrow roads*. The driverless system shall be able to cope with situations where pedestrians move with changing directions as well as handle priority situations where the road is narrowed by parked vehicles on the side of the road. Fig. 8-1 gives an overview of the targeted functional scenarios in the project. During test drives a safety driver will always be present to observe the system and intervene in case of hazardous behavior.

While the target is to deploy the system in a traffic area in the city of Griesheim in Germany, the test of the system is performed virtually (in simulation) as well as on the test track and demonstrated on the test track only. In order to understand the scope of the system, the operational design domain of the system is described in section 8.1.2, the prototype vehicle is presented in the following section and the functional architecture is given in section 8.1.3

---

[178] www.proreta.de

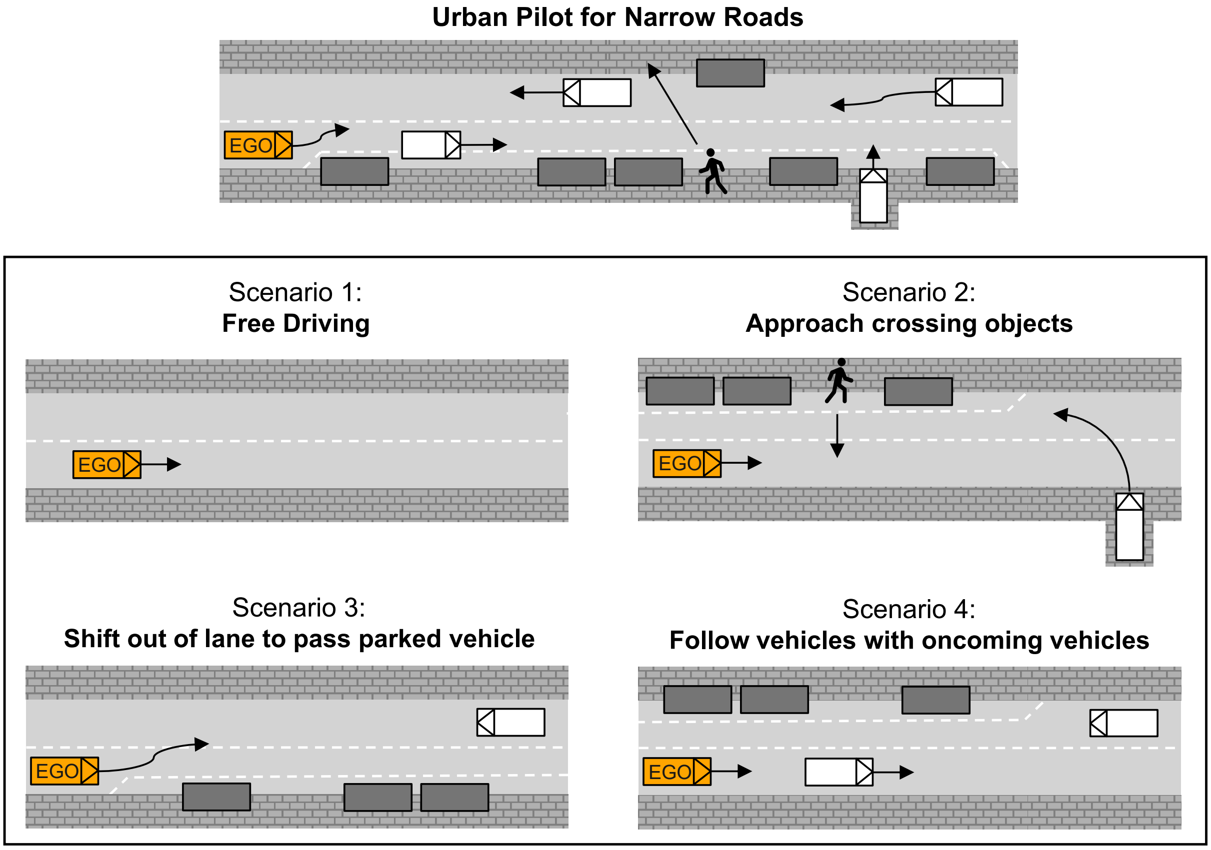


Figure 8-1: Functional scenario set within the urban pilot for narrow roads use case of PRORETA 5

### 8.1.1 Prototype Vehicle

As vehicle prototype within PRORETA 5 a Volkswagen Passat B8 is used. This vehicle is equipped with a sensor setup for environmental perception, self-perception as well as multiple computers for data processing of the received sensor data and planning of the vehicle behavior. These computers have access to the interfaces of the vehicle actuators in order to control the vehicle motion. Fig. 8-2 gives a schematic overview of the mounted sensors (left) and their respective field of view (FOV) (right). For localization an Inertial Navigation System with Real-time Kinematics (OxTS RT4000) is used.

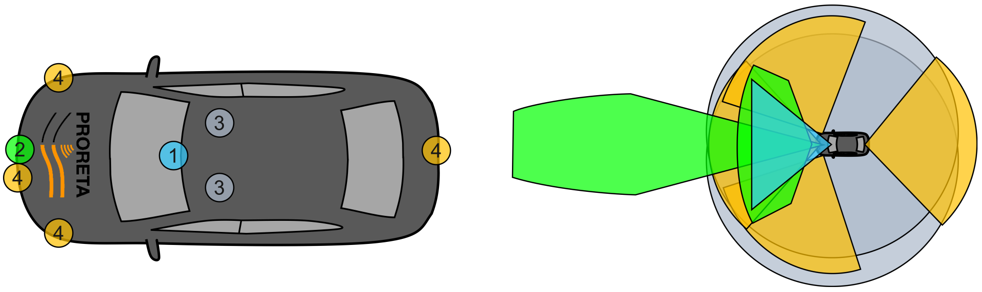


Figure 8-2: Sensor setup of the PRORETA 5 prototype vehicle,
left: mounting positions of the sensors, right: horizontal FOV of the sensors,
①: Mono-frontcamera Continental MFC431, ②: Radar Continental ARS430,
③: Lidar Velodyne Puck (VLP-16), ④: Lidar Ibeo LUX-8

## 8.1.2 Operational Design Domain

The target system developed in the PRORETA 5 should be able to move driverless in urban scenarios. This means that the driving function needs to cope with every possible challenge within the system boundaries of urban environments. The target system is a passenger vehicle for individual transportation and therefore privately owned. The system provides mobility to family members across generations in urban environments. The automated transport of children, persons with reduced mobility and persons authorized to drive is performed by the system. The persons within the car have agreed destinations. As PRORETA 5 is a research project and the development of functionalities and methods is in the foreground rather than developing a series ready product, the focus lies on the following challenges that an urban environment poses on an HAV:

- Highly dynamic traffic environment: Pedestrians and bicyclists moving and/or quickly changing directions
- Interaction and cooperation: priority situations with oncoming traffic in narrow roads
- Occlusions and obstructions: parked and preceeding vehicles obstruct other traffic participants

Based on these challenges, a route area in the City of Griesheim was selected as deployment area for the system. The area is highlighted in Fig. 8-3. Based on the best practices for ODD description[179], an ODD description was derived using the bottom-up approach. The ODD-description is summarized in Table 8-1.

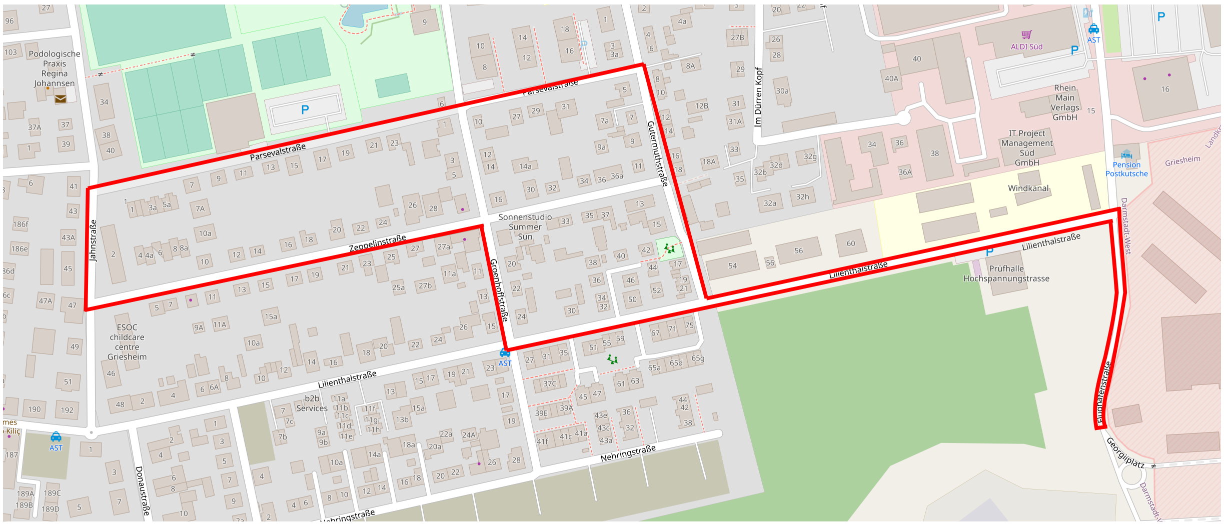


Figure 8-3: Geographic boundaries (—) of the Operational Design Domain

---

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

Table 8-1: Operational Design Domain of the PRORETA 5 system

| **ODD Category** | | **Explicitly within ODD** | **Explicitly outside ODD** |
|---|---|---|---|
| Roadway Infrastructure | Route Network | City of Griesheim, Germany (see map boundaries in Fig. 8-3) | any other |
| | Road types | Bidirectional roads, two lane roads | any other |
| | Speed limit | 30 km/h on all roads | any other |
| | Lane width | 2.25 m - 3.5 m | any other |
| | Intersections | Uncontrolled intersections | any other |
| | Traffic control devices | Signs (205, 206, 207, 274, ...)[180], pollard (narrowed road) | any other |
| | Grade | $\leq 2$ % | any other |
| | Superelevation | $\leq 2$ % | any other |
| | Vertical curvature | No significant vertical curvature | any other |
| | Horizontal curvature | $\leq 0.1$ 1/m | any other |
| | Ramps | none | all types of ramps |
| | Road surface conditions[181] | - | Cracking, rutting, raveling, potholes |
| | Quality of road marking[181] | Good, fair | Poor |
| | Road surface obscurants[181] | Dry, damp | Wet, snow-covered, icy, sand and gravel, leaves |
| | On-street parking | Parallel parking on one or both sides | any other |
| Env. Conditions | Temperature | > 0 °C and < 40 °C | any other |
| | Precipitation[182] | Light rain | drizzle, mist, snow, fog, freezing rain and any other |
| | Sky condition[182] | Sunny, mostly sunny, partly sunny, mostly cloudy, cloudy | - |
| | Illuminance[183] | Sunlight, full daylight, overcast day | Very dark day, twilight, moonlight and any other |
| | Sun angle | altitude: 20° - 60°, azimuth: -110° - 110° | any other |
| | Wind[184] | 0 - 5 on Beaufort wind scale | any stronger winds |
| Road users | | Automobile, bicyclist, pedestrian, motorcycle, scooter, micromobility vehicles, wheelchairs | Emergency vehicles, trucks, transit |
| Non-static roadside objects | | Overhanging vegetation, guard rails, trees | - |

---

[180] Not all included traffic signs are listed here for the means of clarity

[181] scale according to SAE: Best Practice for Describing an Operational Design Domain (2020), pp.14-16.

[182] scale according to American Meteorological Society: Glossary of Meteorology (2020)

[183] scale according to U.S. Naval Observatory: Rise, Set, and Twilight Definitions (2022)

[184] scale according to National Oceanic and Atmospheric Administration: Beaufort Wind Scale (2022)

### 8.1.3 Functional Architecture

Fig. 8-4 gives an overview of the architecture of the developed system within PRORETA 5. This architecture has been derived based on the reference architecture for automated vehicle guidance by Lotz[185]. Note: The interface descriptions in the figure do not name all actually transferred information.

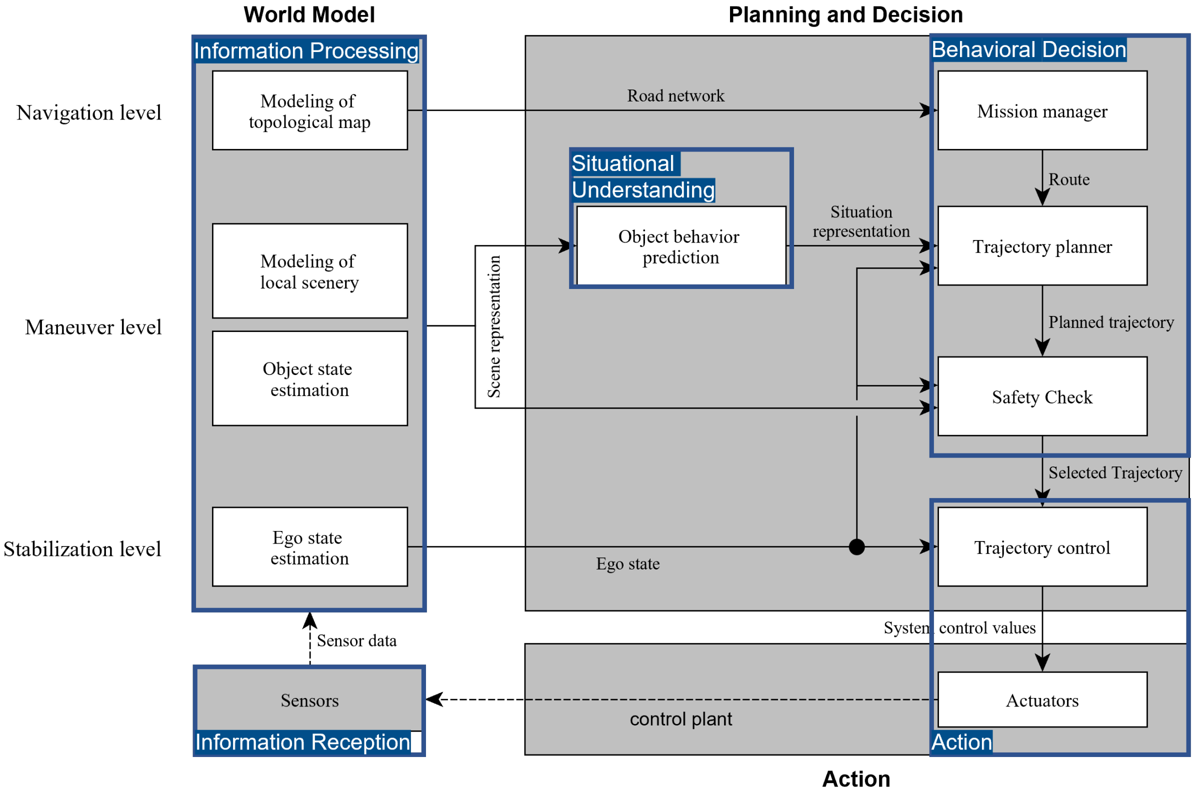


Figure 8-4: Architecture of the developed system in PRORETA 5

In Fig. 8-4 the consolidated modules forming a functional decomposition layer according to Amersbach[186] are highlighted in blue. The layer *information access* is not included. The following subsections briefly introduce the functional modules of the PRORETA 5 system.

## Sensors

The automation driving system receives information about the surrounding traffic environment from the presented suite of sensors. The environmental sensors are responsible for providing data in order to detect static (e.g. static obstacles) and dynamic (e.g. passenger vehicles, pedestrians, bicycles, animals) objects in the surrounding environment. The sensor suite is extended with information from a high-definition map on the basis of which the local scenery is modeled. In addition to the aforementioned data about the surrounding traffic environment, the system relies

---

[185] Lotz, F. G. O.: Eine Referenzarchitektur für die automatisierte Fahrzeugführung (2017), pp. 127-134.

[186] Amersbach, C. T.: Functional Decomposition Approach (2020).

on data from internal sensors, which provides information about the vehicle's current state. This data helps to compute a state estimation of the vehicle.

### World Model

The modeling of a topological map provides the available route network to the system. This includes drivable lanes as well as assigned indication elements. The ego state estimation provides the estimate of the vehicle state. The state consists of position, velocity, acceleration and orientation. The modeling of the local scenery provides a model of the local scenery around the vehicle on the basis of the high-definition map data combined with the position data from the ego state estimation. The module object state estimation detects static and dynamic objects within the surveillance area of the sensors, estimates their state and tracks traffic participants based on the detection outputs. Because multiple detection sensors are used, sensor fusion algorithms are employed to combine data from individual sensors.

### Planning and Decision

The mission manager provides a preselected route to the trajectory planner based on the received route network. The task of the behavior prediction module is to predict the future motion of surrounding traffic participants based on past observations. Based on the received information of the situation, the trajectory planner provides a target trajectory within the observed environment of the system. The planner considers interaction with other traffic participants. The safety check module checks the planned trajectory in terms of physical feasibility and criticality of detected objects' positions. Additionally, the available internal vehicle sensor data as well as dynamic objects are checked for plausibility. This check provides a rating whether the planned trajectory is „safe" or "not safe" to perform. In parallel to the „regular" trajectory planner, a second „alternate" trajectory planner is calculating a target path for the system. This alternate trajectory planner relies on other calculation principles as well as reduced environmental data than the regular planner and always brings the system to a stand-still in a risk-minimal condition.

### Action

The vehicle dynamics and trajectory control influences the vehicle movements under control of the actuators on the basis of the ego state estimation. Depending on the operating state, the trajectories of „automated operation" or „alternate trajectory" are taken into account. The actuators provide the functions of acceleration, deceleration and yaw at vehicle level. The vehicle dynamics and trajectory control component directly influences the actuators in the course of vehicle motion control.

## 8.2 Functional Specification

In this section, the developed methods to derive a functional specification for traffic rule compliance of HAV is applied to the introduced use case of the PRORETA 5 project. For the defined route network of the ODD, a high-definition map is available.

### 8.2.1 Implementation with OpenDRIVE

The introduced method has been implemented in Python to derive the BSSD of HD-maps in the OpenDRIVE format. The implementation has the following restrictions: Only road layouts with one lane per driving direction are covered and no dynamic signals (e.g. traffic lights) are considered. The result of the implemented method is an OpenDRIVE file integrated with the BSSD. Fig. 8-5 gives an overview of the implemented steps. In the following, the implemented algorithms in the individual steps are presented and the special aspects of the implementation with OpenDRIVE are discussed.

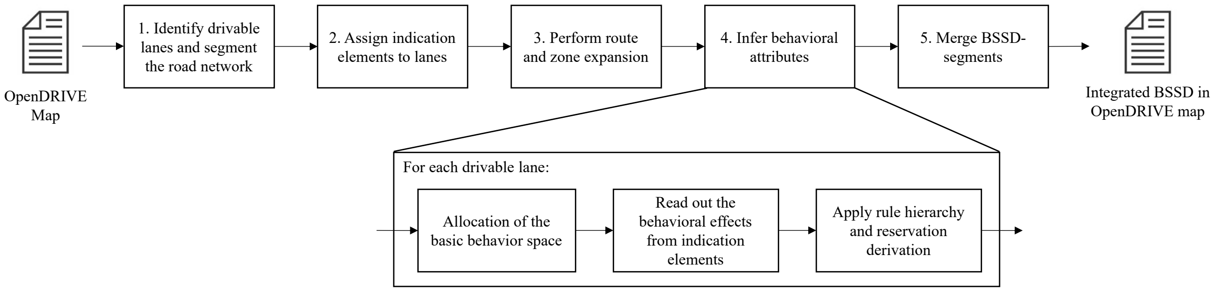


Figure 8-5: Overview of the implementation to infer the BSSD

#### 1. Identify Drivable Lanes and Segment the Road Network

The implementation of this step has been performed in the course of the master thesis by Berghöfer[187]. It is subdivided into four steps:

1. automatic search for drivable lanes
2. automatic extraction of segments
3. creation of BSSD-lanes
4. linkage of OpenDRIVE & BSSD-lanes

The drivable lanes are identified based on the lane type attribute of OpenDRIVE. During the extraction of segments, the criteria introduced in section 5.1.1 are used and the BSSD-segments are created in the <userData>-Element of OpenDRIVE. In order to create BSSD-lanes within the BSSD-segments, the overlaps between OpenDrive lane sections and segments are detected. Based

---

[187] Berghöfer, M.: Integration der BSSD in hochgenaue Karten (2022)

on this, the corresponding BSSD-lanes in the respective segments are created. Finally, the linkage between OpenDRIVE- and BSSD-lanes is created. For a more detailed description of these steps, please refer to Berghöfer[187]. The resulting format to include the BSSD into OpenDRIVE is depicted in Fig. 8-6.

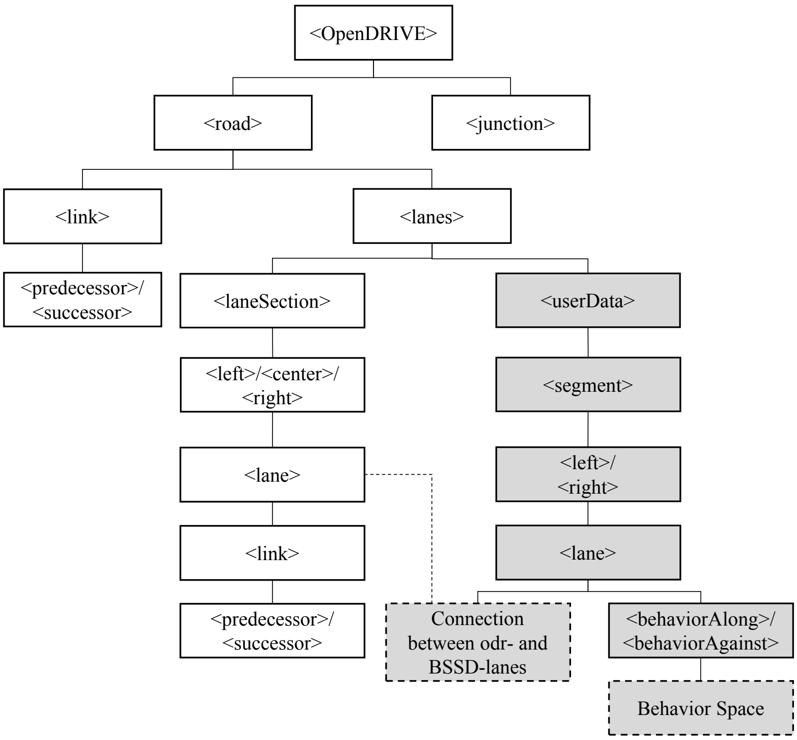


Figure 8-6: Integration of BSSD into the OpenDRIVE format (own illustration according to Berghöfer[187])

## 2. Assign Indication Elements

With the BSSD-segments and BSSD-lanes being available, in order to derive the behavioral attributes the indication elements need to be assigned to the BSSD-lanes. For this, it is looped over all OpenDRIVE roads and OpenDRIVE signs and objects. The OpenDRIVE sign specifies location, type and orientation of the traffic sign as well as to which OpenDRIVE lanes it applies. The corresponding BSSD-segment is identified based on the location of the sign and is matched via the s-coordinate. Because the segmentation was performed based, among other criteria, on the location of the traffic signs, traffic signs will either be at the start or end of a segment. The orientation of the sign is given with respect to the reference direction of the OpenDRIVE road which is specified by the predecessor and successor of the road. Based on the orientation of the sign, it is matched with the start or end coordinate of a segment. It is then added to the corresponding BSSD-lanes for which the sign is valid. At the same time the behavioral effect and rule mechanism is read from a database and linked with the sign. This database includes all German traffic signs specified by StVO[188] according to section 5.1.2. For the route and zone expansion in the next step, it is recorded which BSSD-segments start such a route or zone. The

---

[188] Bundesministerium der Justiz: Straßenverkehrsgesetz (StVG) (2021).

result of this step is the assigned indication elements per BSSD-lane and a list of segments that start a route or zone respectively. The implemented procedure for assigning the indication elements is illustrated by Algorithm 1.

**Algorithm 1** Add indication elements to BSSD-lanes

```
for all BSSD-Segments in all OpenDRIVE-roads do
    if OpenDRIVE-road part of OpenDRIVE-junction then
        add junction indication to all BSSD-lanes of BSSD-segment
    end if
    for all objects in OpenDRIVE-Road do
        if heading of object is ”+” then
            if object is at start of segment then
                add indication element to valid BSSD-lanes in ”along” direction
                add to list of starting segments in case the element starts a route or zone
            end if
        else if heading of object is ”-” then
            if object is at end of segment then
                add indication element to valid BSSD-lanes in ”against” direction
                add to list of starting segments in case the element starts a route or zone
            end if
        end if
    end for
    for all BSSD-lanes in BSSD-segment do
        find corresponding OpenDRIVE-lane
        get and add boundary indication to BSSD-lane
    end for
end for
```

### 3. Perform Route and Zone Expansion

The algorithm needs to be run through for all segments that start a route or zone. The main difference between route and zone expansion is, that routes are always expanded straight or along the priority road over intersections, while zones always expand along all possible directions at intersections. While the ending signs (see section 5.1.2) are individual to each route or zone sign, everything else is identical during the execution of the algorithm. The result of this step is that all indication elements are mapped to the segments/lanes that they are valid for.

The main challenge with the implementation of this step in OpenDRIVE is the identification of the successor segment of the current segment under investigation. There are three options for this. The next segment is . . .

. . . in the same OpenDRIVE-road.

. . . in the next/previous OpenDRIVE-road.

. . . in a junction (resulting in potentially multiple next segments).

In addition to the three options, the direction of the expansion as well as the direction of the next segment have to be considered. The implemented procedure for zone expansion is illustrated by Algorithm 2. Only the zone expansion is presented for simplicity.

**Algorithm 2** Perform zone expansion

```
for all BSSD-Segments that start a zone do
    find successor BSSD-segments
    for all successor BSSD-segments do
        if BSSD-segment already visited then
            go to next successor BSSD-segment in list
        end if
        if corresponding zone end sign in successor BSSD-segment then
            go to next successor BSSD-segment in list
        end if
        map indication element to successor element
        recursion: find successor BSSD-segments
    end for
end for
```

### 4. Infer BSSD-attributes

This step realizes the determination of the behavioral attributes in both driving direction based on the relations shown in section 5.1.2. To represent the general local traffic rules, a standard behavior space is assigned to each BSSD-lane. Based on the rule hierarchy the behavioral attributes are determined. In a final step, additional reservations at intersections are derived according to the introduced concept from section 5.1.2. The implemented procedure for inference of the behavioral attributes is illustrated by Algorithm 3.

**Algorithm 3** Infer BSSD-attributes

```
for all OpenDRIVE-roads, all BSSD-segments and all BSSD-lanes do
    assign standard behavior space (along and against)
    infer attributes based on indication elements and corresponding behavioral effects
    infer reservation at junctions
end for
```

### 5. Merge BSSD-segments

A change in the road layout (meaning here: change in the amount or connection of lanes) in OpenDRIVE is only possible by introducing a new lane section. Therefore, only if the segment change location corresponds to the start of a new lane section a change in road layout needs to be checked. An ending lane would have no successor and a newly added lane would have no predecessor. Thus, there is no change in the layout if all lanes in the first segment have a successor in the second segment and all lanes in the second segment have a predecessor in the first segment.

If this condition is fulfilled all corresponding behavior spaces are checked for similarity. This means checking that all attributes except for the longitudinal boundary are equal. If all behavior spaces are mergeable, the segmentation is removed while correcting the reservation links as explained in section 5.1.3. For this implementation in OpenDRIVE, segments of the non-regular motion space are not merged, because there should be no modification to the base HD-map to ensure that it is usable for all other intended functions. After this step, the map, including the BSSD, is exported and saved. The algorithm to merge BSSD-segments is illustrated by Algorithm 4.

**Algorithm 4** Merge BSSD-segments

```
for all OpenDRIVE-roads, all BSSD-segments and all BSSD-lanes do
    if BSSD-lane does not end at start of lane section OR (BSSD-lane ends at start of lane section
      AND all BSSD-lanes of current BSSD-segment have a successor AND all BSSD-lanes of
      succeeding BSSD-segment have a predecessor) then
        if all connected behavior spaces are similar then
            if all boundary transitions are mergeable then
                merge segments (i.e. delete second segment and correct links)
            end if
        end if
    end if
end for
```

### 8.2.2 Results

In order to test the method, it has been applied to an artificially created route network containing of multiple intersections, various traffic signs and road markings. It covers route as well as zone regulations and different types of priority regulations at intersections. Finally, there are narrowed road sections covered in the route network. An overview of the route network is given in Annex A. For this test network, the method segmented the network and determined the behavioral attributes for each behavior space correctly. Limits of the implementation are that temporal changes cannot be covered with an HD-map. This means that adapted speed limits, because of a temporary construction zone and the span of these speed limits, cannot be inferred. Finally, only roads with one driving lane per direction and without traffic lights are covered.

The implemented method to infer the BSSD from the high-definition map has been applied to the ODD of PRORETA and results in the compiled behavior spaces depicted in Fig. 8-7. In the scope of this dissertation, it is only differentiated between geometrically straight, left-turning and right-turning atomic behavior space configuration. Each behavior space configuration has a parameter space assigned that covers all geometric shapes present in the ODD.

There is a total of eight behavior space configurations present within the ODD. In the following list an overview is given what kind of roads are covered by the respective configurations. This

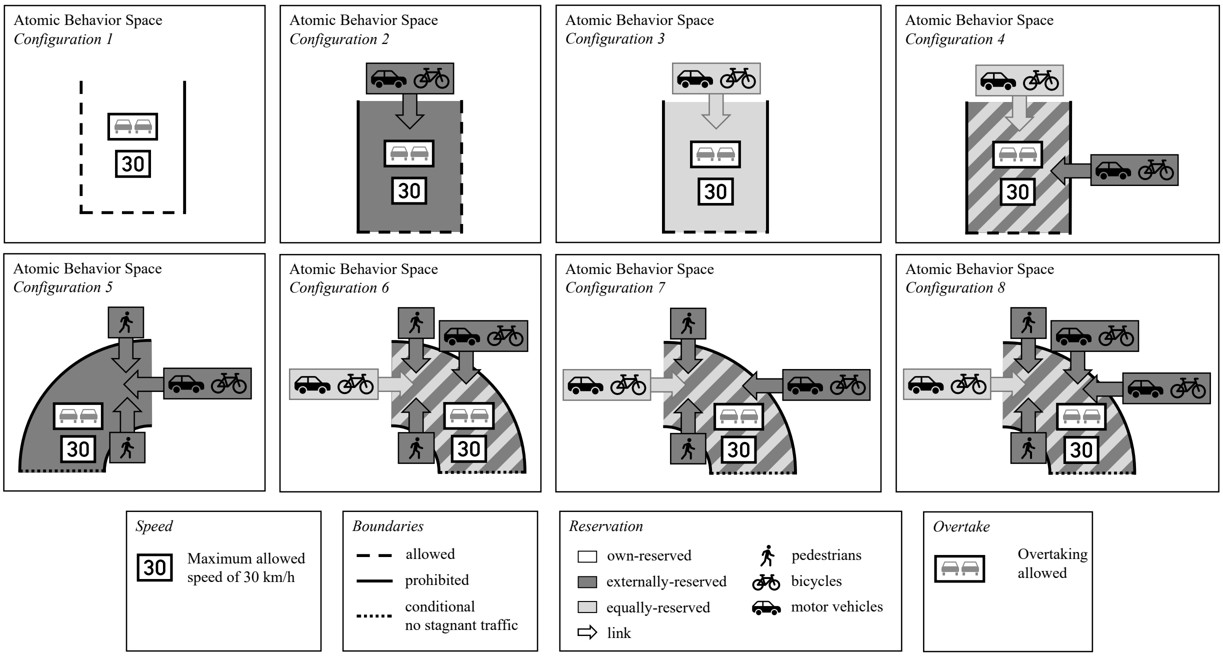


Figure 8-7: Compiled behavior spaces of the PRORETA 5 ODD
A hatched filling indicates that both reservations are present.

highlights how BSSD is able to abstract the scenery present in the ODD in order to derive the parameter set for the test of the behavioral decision layer. A concatenation of behavior spaces is not depicted in this overview.

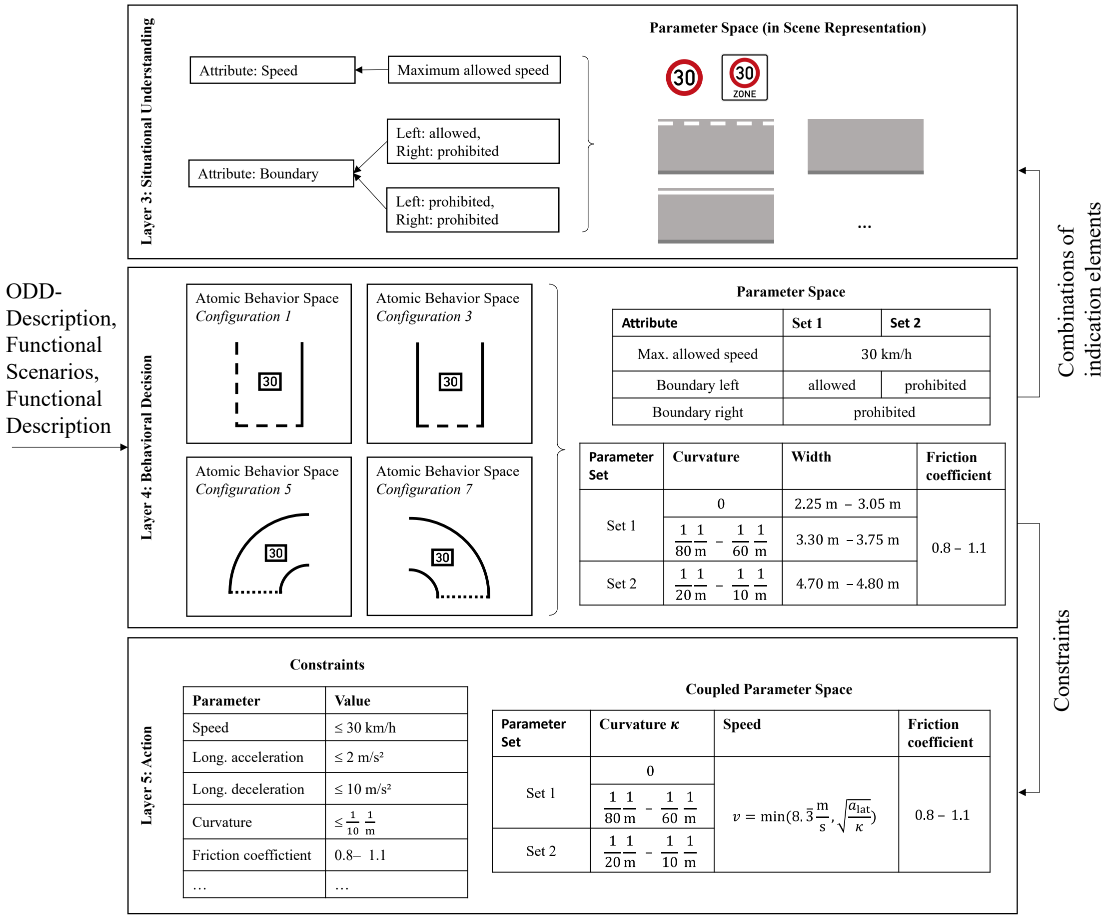
- Config. 1: right lane of a two-lane road
- Config. 2: left lane of a two-lane road, narrowed road with priority for oncoming traffic
- Config. 3: bidirectional road with equal priority for both directions
- Config. 4: straight lane over X-intersection, straight lane over T-intersection (third road coming from the right)
- Config. 5: right turning lane at X-intersection, right turning lane at T-intersection (both possible layouts)
- Config. 6: left turning lane at T-intersection (third road coming from the front)
- Config. 7: left turning lane at X-intersection
- Config. 8: left turning at T-intersection (third road coming from the right)

## 8.3 Derivation of Test Strategy

To demonstrate the derivation of a test strategy, two exemplary scenarios are selected. At the point in time where this dissertation is created, the functionality of the system is not sufficient to analyze more complex scenarios. For these configurations a test strategy is derived using the introduced method from chapter 7. The developed strategy is then applied within exemplary test cases in the test execution and evaluation within section 8.4. The process is executed for two exemplary functional scenarios of the PRORETA 5 project. First, the simple scenario *free driving* is presented for the purpose of exposition. Secondly, the scenario *shift out of lane to pass parked vehicle* is presented to apply the method to a more complex behavior space configuration.

### 8.3.1 Selection and Analysis

Fig. 8-8 gives an overview of the applied selection and analysis process. The parameter spaces given are not extensive and are listed for exemplary purposes. The input to the selection and analysis are the ODD-description as well as the functional scenarios. Because the functional scenarios have been selected based on expert knowledge, there exists the possibility that the scenario catalog is not complete. Since BSSD specifies all rule-based constraints, a systematic scenario generation approach based on BSSD (e.g. such as Bagschik et al.[189] or in combination with the approach from Sauerbier et al.[190]) could discover missing functional scenarios and result in a more comprehensive catalog.



**Parameter Space**

| Attribute | Set 1 | Set 2 |
|---|---|---|
| Max. allowed speed | 30 km/h | |
| Boundary left | allowed | prohibited |
| Boundary right | prohibited | |

| Parameter Set | Curvature | Width | Friction coefficient |
|---|---|---|---|
| Set 1 | 0 | 2.25 m – 3.05 m | 0.8 – 1.1 |
| | $\frac{1}{80}\frac{1}{\text{m}} - \frac{1}{60}\frac{1}{\text{m}}$ | 3.30 m – 3.75 m | |
| Set 2 | $\frac{1}{20}\frac{1}{\text{m}} - \frac{1}{10}\frac{1}{\text{m}}$ | 4.70 m – 4.80 m | |

**Constraints**

| Parameter | Value |
|---|---|
| Speed | ≤ 30 km/h |
| Long. acceleration | $\leq 2$ m/s² |
| Long. deceleration | $\leq 10$ m/s² |
| Curvature | $\leq \frac{1}{10}\frac{1}{\text{m}}$ |
| Friction coeffictient | 0.8– 1.1 |
| … | … |

**Coupled Parameter Space**

| Parameter Set | Curvature $\kappa$ | Speed | Friction coefficient |
|---|---|---|---|
| Set 1 | 0 | $v = \min(8.\bar{3}\frac{\text{m}}{\text{s}}, \sqrt{\frac{a_{\text{lat}}}{\kappa}})$ | 0.8 – 1.1 |
| | $\frac{1}{80}\frac{1}{\text{m}} - \frac{1}{60}\frac{1}{\text{m}}$ | | |
| Set 2 | $\frac{1}{20}\frac{1}{\text{m}} - \frac{1}{10}\frac{1}{\text{m}}$ | | |

Figure 8-8: Exemplary application of the selection and analysis method

For the *free driving* scenario a reduction of relevant behavior space configurations is possible. Since no objects or obstacles are present in the scenario by definition, the attributes reservation and

---

[189] Bagschik, G. et al.: Wissensbasierte Szenariengenerierung (2018).

[190] Sauerbier, J. et al.: Definition von Szenarien zur Absicherung automatisierter Fahrfunktionen (2019).

overtake are obsolete. There is only a distinction by the speed and boundary attribute as well as the geometry of the configuration. Within the present configurations, the longitudinal boundary is either allowed or conditional with the condition no stagnant traffic. There will be no stagnant traffic, with no objects present, therefore there is also no distinction made regarding the longitudinal boundary attribute. This results in the consideration of the behavior space configurations 1,3,5 and 7 with the disregard of aforementioned attributes. With such a geo-located well-understood ODD, the geometry is extracted from the available high-definition map. If the method had to be applied to whole traffic regions (e.g. whole Germany) or a representation of the geometry is not available, then as Schuldt[191] suggests guidelines on the design of road, laws and regulations as well as expert knowledge may be used to derive possible geometries. Lippert[192] investigates a method to categorizes the behavior space configurations based on their geometry. Resulting from the geometry extracted from the high-definition map, there are two different parameter sets: one for (nearly) straight roads and one for curves. The geometry is characterized by present parameter ranges of curvature and width of the road. Grade, superelevation and vertical curvature are disregarded because their values are close to zero for the whole ODD. While for straight roads, the left boundary might be allowed or prohibited, for curves it is prohibited in any case. The friction coefficient was estimated from road surface and surface conditions specified in the ODD-description based on Bachmann[193]. Consequently, the parameter space for behavioral decision layer is set.

During the inference process from section 5.1.2, every combination of indication elements that leads to a present characteristic of each attribute is stored. These combinations of indication elements represent the parameter space for the situational understanding layer regarding rule-awareness. As example, the sign 274-30 and sign 274.1 are listed. These signs both lead to a maximum allowed speed of 30 km/h. For the boundary attribute, the combinations with dashed lane marking or no lane marking on the left side of the lane and curbstone on the right side of the lane lead to the characteristics: left boundary allowed and right boundary prohibited. The combination solid lane marking on the left and curbstone on the right leads to the characteristics: left boundary prohibited and right boundary prohibited. It would also be possible to directly store this information within a map and remove situational understanding task regarding rule-awareness from the vehicle (e.g. by inference from a high-definition map). An open question for research in this case is, how the vehicle would ensure the up-to-dateness of the map and what happens if there is a discrepancy between the information in the map and the information derived by situational understanding.

In the case that no high definition map is available for the ODD and the vehicle is accessing the mentioned information in form of sensor data, the parameter spaces cannot be derived from this map. Thus, it would be necessary to rely on other information sources such as guidelines,

---

[191] Schuldt, F.: Methodischer Test von automatisierten Fahrfunktionen (2017).

[192] Lippert, M.: Capability-Based Route Planning (2023).

[193] Bachmann, T.: Reibung zwischen Reifen und Fahrbahn (1998).

laws and regulations (cf. Schuldt[194]). Within the PRORETA project a high-definition map of the ODD is available and the up-to-dateness is ensured manually since the traffic area is limited. For operation (as also outlined in section 8.1.3) the vehicle localizes itself in the high-definition map (by using the integrated GNSS inertial system) and extracts the indication elements in the vicinity of the vehicle. However, the situational understanding regarding rule-awareness is performed on the vehicle and therefore, is considered in the test strategy.

Lastly, the parameter spaces for the action layer are derived from the behavior space configurations. This layer receives the planned behavior in form of a trajectory and needs to realize an sufficiently accurate actual behavior with respect to this trajectory. Possible trajectories are constrained by the parameter set of the behavioral decision as well as the actual implementation of the behavior planner itself. The behavior planner may have execution limits such as limited speeds or accelerations for the planned trajectory. In PRORETA 5, for example, the lateral acceleration in planned trajectories is limited to $a_{\mathrm{lat}} = 1\frac{\mathrm{m}}{\mathrm{s}}$ and thus, the speed in curves is limited as well. Testing outside of these boundaries may still be meaningful to analyze the robustness of the action layer.

The method has been applied to the scenario *shift to pass parked vehicles* as well. In this case, since other objects are present in the scenario (parked as well as moving in oncoming direction), possible and relevant positions are intuitively derived. Again, a systematic scenario derivation based on BSSD could improve coverage and reproducability of the method. For parked vehicles, it is relevant with which lateral offset they are positioned with respect to the road, how long the parked vehicles span and in what initial distance to the test object they are. For oncoming objects it is relevant how fast they move and in what initial distance they are from the test object. An overview of the scenario is given in Fig. 8-9. The resulting parameters are listed in Tab. 8-2 with the selected discretization levels based on the following section.

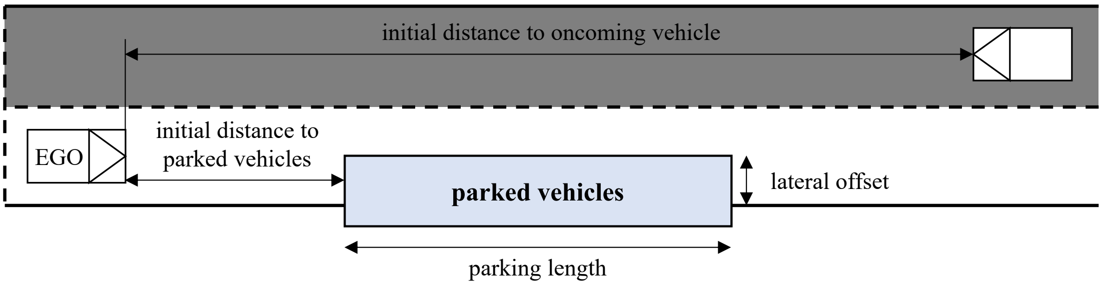


Figure 8-9: Relevant parameters for the initial position of objects within the *shift to pass parked vehicles* scenario

## 8.3.2 Test Case Generation

The test cases are derived using systematic methods. A brief overview of these methods is presented in section 2.2.4. First, equivalence classes that group together representatives of certain

---

[194] Schuldt, F.: Methodischer Test von automatisierten Fahrfunktionen (2017).

parameter ranges are formed. Based on this, representative values of these equivalence classes are identified using boundary value analysis. Finally, the test effort is reduced by means of combinatorial test case derivation. The test case generation is outlined for tests of the behavioral decision layer in the two scenarios as an example.

### Equivalence Partitioning and Boundary Value Analysis

The idea behind equivalence partitioning is that with the test of a representative of each class the complete class of parameter values is to be considered as tested. Liggesmeyer[195] speaks thereby of functional equivalence classes, since the classes are derived from the specification of the system. This functional equivalency is given by the different characteristics of the behavioral attributes and thus, their values are taken over for discretization of these parameters. For state variables (e.g. speeds) and geometry variables (e.g. vehicle width) the functional influence has to be evaluated separately. This is difficult, because even small changes in parameter values lead to a different behavior of the test object and these are not necessarily represented by the boundaries of the equivalence classes[196,197]. For geometric sizes of the road layout a non-functional grouping of discretization levels, based on the values found in the ODD is therefore performed. These values are discretized using two to four values with equal distance. For quantities that influence the interaction between objects, a functional reference is established. Examples for this are object positions and velocities in the *shift to pass parked vehicles* scenario. For example, for the offset of the parked vehicles two equivalence classes are formed: Offsets that enable the vehicle to shift within the lane to pass the parked vehicles, offsets that force the vehicle to shift out of the lane to pass parked vehicles. For the initial distance in dependence of the initial speeds, there are four equivalence classes. In the first class, the distance is chosen such that the oncoming vehicle is driven passed the parked cars before the ego arrives. In the second class, the distance is chosen such that the oncoming vehicle is along the parked cars as the ego vehicle arrives. In the third class, the distance is chosen such that the oncoming vehicle is arriving when the ego vehicle would be within the parked area when keeping the initial speed. In the fourth class, the distance is chosen such that the ego vehicle has left the parked area before the oncoming vehicle arrives. Again for these equivalence classes, the values are discretized using three values. For an applicability for larger scenario cataloges, this intuitive derivation of equivalence classes is infeasible and therefore, research has to be conducted on how to automatedly and systematically derive these equivalence classes. This results in the listed discretization levels for the identified parameters listed in Tab. 8-2.

---

[195] Liggesmeyer, P.: Software-Qualität: Testen, Analysieren und Verifizieren von Software (2009), pp. 51-53.

[196] Schuldt, F.: Methodischer Test von automatisierten Fahrfunktionen (2017), p. 120.

[197] Block, D. et al.: Simulations on Consumer Tests (2014).

Table 8-2: Overview of the influence parameters and assigned discretization levels for each scenario configuration

| Scenario | Config. | Influence parameter | Discretization levels | | | |
|---|---|---|---|---|---|---|
| Free driving | 1 | Max. allowed speed | 30 km/h | | | |
| | | Boundary left | allowed | prohibited | | |
| | | Boundary right | prohibited | | | |
| | | Initial ego speed | 10 km/h | 30 km/h | 50 km/h | |
| | 1.1 | Lane curvature | 0 | | | |
| | | Lane width | 2.25 m | 2.65 m | 3.05 m | |
| | 1.2 | Lane curvature | $0.0125\frac{1}{\mathrm{m}}$ | $0.029\frac{1}{\mathrm{m}}$ | $0.01\overline{6}\frac{1}{\mathrm{m}}$ | |
| | | Lane width | 3.30 m | 3.525 m | 3.75 m | |
| | 2 | Max. allowed speed | 30 km/h | | | |
| | | Boundary left | prohibited | | | |
| | | Boundary right | prohibited | | | |
| | | Initial ego speed | 10 km/h | 30 km/h | 50 km/h | |
| | 2.1 | Lane curvature | $0.05\frac{1}{\mathrm{m}}$ | $0.075\frac{1}{\mathrm{m}}$ | $0.1\frac{1}{\mathrm{m}}$ | |
| | | Lane width | 4.70 m | 4.80 m | | |
| Shift to pass parked vehicle(s) | 1 | Max. allowed speed | 30 km/h | | | |
| | | Boundary left | allowed | | | |
| | | Boundary right | prohibited | | | |
| | | Parking length | 2.5 m | 11.25 m | 20 m | |
| | | Lateral offset of parked vehicles | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lat},2}$ | | |
| | | Ego speed | 10 km/h | 30 km/h | 50 km/h | |
| | | Oncoming speed | 10 km/h | 20 km/h | 30 km/h | 40 km/h |
| | | Initial distance | $d_{\mathrm{lon},1}$ | $d_{\mathrm{lon},2}$ | $d_{\mathrm{lon},3}$ | $d_{\mathrm{lon},4}$ |
| | | Lane curvature | 0 | | | |
| | | Lane width | 2.25 m | 2.65 m | 3.05 m | |

## Combinatorial Test Case Derivation

With this discretization 1152 test cases would result with complete test coverage. Therefore, within the project 2-way coverage in order to reduce the number of test cases to 51 is chosen. Thereby, it is feasible to perform the test cases within the project. The resulting test cases are listed in Tab. 8-3.

Table 8-3: Test cases for *2-wise* coverage of the scenarios *free driving* and *shift to pass parked vehicles*

| **Test Case** | | | **Max. allowed speed in km/h** | **Boundary left** | **Boundary right** | **Initial ego speed in km/h** | **Lane curvature in 1/m** | **Lane width in m** | **Oncoming speed in km/h** | **Parking length in m** | **Lateral offset of parked vehicles** | **Initial distance** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Free Driving | Config. 1.1 | 1 | 30 | allowed | prohibited | 10 | 0 | 2.25 | | | | |
| | | 2 | 30 | prohibited | prohibited | 10 | 0 | 2.65 | | | | |
| | | 3 | 30 | allowed | prohibited | 10 | 0 | 3.05 | | | | |
| | | 4 | 30 | prohibited | prohibited | 30 | 0 | 2.25 | | | | |
| | | 5 | 30 | allowed | prohibited | 30 | 0 | 2.65 | | | | |
| | | 6 | 30 | prohibited | prohibited | 30 | 0 | 3.05 | | | | |
| | | 7 | 30 | allowed | prohibited | 50 | 0 | 2.25 | | | | |
| | | 8 | 30 | prohibited | prohibited | 50 | 0 | 2.65 | | | | |
| | | 9 | 30 | allowed | prohibited | 50 | 0 | 3.05 | | | | |
| | Config. 1.2 | 10 | 30 | allowed | prohibited | 10 | 0.0125 | 3.75 | | | | |
| | | 11 | 30 | prohibited | prohibited | 10 | 0.015 | 3.525 | | | | |
| | | 12 | 30 | allowed | prohibited | 10 | 0.0167 | 3.3 | | | | |
| | | 13 | 30 | prohibited | prohibited | 30 | 0.0125 | 3.525 | | | | |
| | | 14 | 30 | allowed | prohibited | 30 | 0.015 | 3.3 | | | | |
| | | 15 | 30 | prohibited | prohibited | 30 | 0.0167 | 3.75 | | | | |
| | | 16 | 30 | allowed | prohibited | 50 | 0.0125 | 3.3 | | | | |
| | | 17 | 30 | prohibited | prohibited | 50 | 0.015 | 3.75 | | | | |
| | | 18 | 30 | allowed | prohibited | 50 | 0.0167 | 3.525 | | | | |
| | | 19 | 30 | prohibited | prohibited | 30 | 0.0167 | 3.3 | | | | |
| | Config. 2.1 | 20 | 30 | prohibited | prohibited | 10 | 0.05 | 4.7 | | | | |
| | | 21 | 30 | prohibited | prohibited | 10 | 0.075 | 4.8 | | | | |
| | | 22 | 30 | prohibited | prohibited | 10 | 0.1 | 4.7 | | | | |
| | | 23 | 30 | prohibited | prohibited | 30 | 0.05 | 4.8 | | | | |
| | | 24 | 30 | prohibited | prohibited | 30 | 0.075 | 4.7 | | | | |
| | | 25 | 30 | prohibited | prohibited | 30 | 0.1 | 4.8 | | | | |
| | | 26 | 30 | prohibited | prohibited | 50 | 0.05 | 4.7 | | | | |
| | | 27 | 30 | prohibited | prohibited | 50 | 0.075 | 4.8 | | | | |
| | | 28 | 30 | prohibited | prohibited | 50 | 0.1 | 4.7 | | | | |
| Shift to pass parked vehicles | Config. 1 | 1 | 30 | allowed | prohibited | 10 | 0 | 2.65 | 20 | 8 | $d_{\mathrm{lat},2}$ | $d_{\mathrm{lon},2}$ |
| | | 2 | 30 | allowed | prohibited | 10 | 0 | 3.05 | 30 | 13 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},3}$ |
| | | 3 | 30 | allowed | prohibited | 10 | 0 | 2.25 | 40 | 18 | $d_{\mathrm{lat},2}$ | $d_{\mathrm{lon},4}$ |
| | | 4 | 30 | allowed | prohibited | 20 | 0 | 2.65 | 30 | 18 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},1}$ |
| | | 5 | 30 | allowed | prohibited | 20 | 0 | 3.05 | 40 | 3 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},2}$ |
| | | 6 | 30 | allowed | prohibited | 20 | 0 | 2.25 | 10 | 3 | $d_{\mathrm{lat},2}$ | $d_{\mathrm{lon},3}$ |
| | | 7 | 30 | allowed | prohibited | 20 | 0 | 2.65 | 10 | 8 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},4}$ |
| | | 8 | 30 | allowed | prohibited | 20 | 0 | 2.25 | 20 | 13 | $d_{\mathrm{lat},2}$ | $d_{\mathrm{lon},1}$ |
| | | 9 | 30 | allowed | prohibited | 30 | 0 | 3.05 | 10 | 8 | $d_{\mathrm{lat},2}$ | $d_{\mathrm{lon},1}$ |
| | | 10 | 30 | allowed | prohibited | 30 | 0 | 2.25 | 10 | 13 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},2}$ |
| | | 11 | 30 | allowed | prohibited | 30 | 0 | 2.65 | 20 | 18 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},3}$ |
| | | 12 | 30 | allowed | prohibited | 30 | 0 | 2.25 | 30 | 3 | $d_{\mathrm{lat},2}$ | $d_{\mathrm{lon},4}$ |
| | | 13 | 30 | allowed | prohibited | 30 | 0 | 2.65 | 40 | 3 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},1}$ |
| | | 14 | 30 | allowed | prohibited | 40 | 0 | 2.25 | 20 | 3 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},1}$ |
| | | 15 | 30 | allowed | prohibited | 40 | 0 | 2.65 | 30 | 3 | $d_{\mathrm{lat},2}$ | $d_{\mathrm{lon},2}$ |
| | | 16 | 30 | allowed | prohibited | 40 | 0 | 2.25 | 40 | 8 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},3}$ |
| | | 17 | 30 | allowed | prohibited | 40 | 0 | 2.65 | 10 | 13 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},4}$ |
| | | 18 | 30 | allowed | prohibited | 40 | 0 | 3.05 | 10 | 18 | $d_{\mathrm{lat},2}$ | $d_{\mathrm{lon},1}$ |
| | | 19 | 30 | allowed | prohibited | 10 | 0 | 2.65 | 40 | 13 | $d_{\mathrm{lat},2}$ | $d_{\mathrm{lon},1}$ |
| | | 20 | 30 | allowed | prohibited | 10 | 0 | 2.25 | 10 | 18 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},2}$ |
| | | 21 | 30 | allowed | prohibited | 10 | 0 | 2.65 | 10 | 3 | $d_{\mathrm{lat},2}$ | $d_{\mathrm{lon},3}$ |
| | | 22 | 30 | allowed | prohibited | 10 | 0 | 3.05 | 20 | 3 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},4}$ |
| | | 23 | 30 | allowed | prohibited | 10 | 0 | 2.25 | 30 | 8 | $d_{\mathrm{lat},1}$ | $d_{\mathrm{lon},1}$ |

### 8.3.3 Test Configuration

During the test configuration, the conduct of the test is prepared. The focus of this dissertation is not on developing a methodology to select the ideal test environment (see Schuldt[198] and Steimle[199]). Therefore, an exemplary environment is selected in order to enable the test conduct in the next section to demonstrate the applicability of the developed methods. Usually, in simulation various measured values are available. In real world measurements for all these values sensors are necessary in order to access them. In section 6.1 the observability of the quantities was required. Therefore, the tests are conducted in a real-world prototype with a common sensor setup to ensure that this requirement is fulfilled by the methods. The prototype vehicle was introduced in section 8.1.1. The tests are conducted on the August-Euler-Airfield in Griesheim, near Darmstadt, Germany, which serves as an closed test track to safely conduct the tests with the prototype vehicle. The introduced modules of the functional architecture in section 8.1.3 have been implemented by the project team of PRORETA 5. Since the tests are performed as closed-loop real-world tests, no additional test drivers (in the meaning of artificial input into the modules) are necessary. To conduct the test scenarios other vehicles are driven by humans.

## 8.4 Test Execution and Evaluation

### 8.4.1 Overview of the Test Cases

The *lane following* scenario is performed on a curve between the runway and taxiway of the airfield. The scenery of the test case is depicted in Fig. 8-10.

Figure 8-10: Environment for *lane following* scenario

---

[198] Schuldt, F.: Methodischer Test von automatisierten Fahrfunktionen (2017).

[199] Steimle, M. et al.: Toward a Consistent Taxonomy for Test Approaches (2021).

The *shift to pass parked vehicles* scenario is performed on the runway of the airfield where the road is straight. A vehicle is parked halfway into the lane such that the ego vehicle needs to evade into the opposing lane to continue its drive. There will be one oncoming vehicle for which the ego vehicle potentially has to yield depending on the initial distances. The scenery of this scenario is shown in Fig. 8-11. During the test drives all relevant state values are recorded by using the output of the OxTS RT4000 or the vehicle own dynamic sensors (see section 8.1.1). For the demonstration of the presented methodology, this limited validity is acceptable. However, when performing tests for a release concerning traffic rule compliance independent instrumentation with sufficient accuracy is indispensable.

Figure 8-11: Environment for *shift to pass parked vehicle* scenario

### 8.4.2 Overview of the Evaluation Process

This subsection explains test evaluation in connection with BSSD. Since an automated evaluation is essential, especially for a large amount of test data, not only the test criteria must be applicable automatically, but also the data required for this must be prepared automatically. Figure 8-12 gives an overview of the steps to achieve this goal.

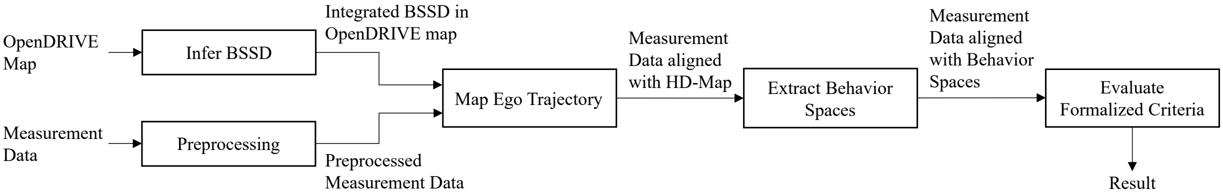


Figure 8-12: Overview of the evaluation process

The automated derivation of the BSSD and integration into the OpenDRIVE map have already been presented in the functional description (section 8.2). In the context of the automated test evaluation, this is necessary in order to read out the currently valid behavior attributes with the help of the position of the vehicle. This is accomplished in the Map Ego Trajectory step. Here, the lane boundaries are converted into polygons and then checked to see if the recorded vehicle reference position lies within one of these polygons. Before this, however, the measurement data is preprocessed (coordinate transformations and time synchronization by means of interpolation). From the determined lane, the behavior attributes can then be read out from the OpenDRIVE map and finally be evaluated with the formalized criteria.

The logic of the presented criteria was thereby implemented in Python. It should be noted that not only the mapped lane can be relevant, but also if the vehicle contour extends into another lane. This was implemented using the presented boundary criterion from Section 6.3. As soon as the vehicle contour only partially protrudes into a neighboring lane, this is relevant, for example, for the reservation attribute, since oncoming vehicles can also be hindered by a partial intrusion. In the following paragraphs the implementation of the developed test criteria is briefly explained.

### Speed

The maximum allowed speed is read from the attribute for each trajectory point and compared with the speed measured by the vehicle sensors. If the measured value is higher than the maximum allowed, the attribute is violated. Here, the vehicle reference point is evaluated as the relevant reference point. In the future, it is necessary to investigate what has to be considered with respect to the speed attribute in case of overlap with several behavioral spaces.

### Boundary

Starting from the mapped lane, corresponding to section 6.3.2, it is checked whether the lane boundaries are exceeded to the left or to the right. From the attributes is read out accordingly whether a crossing is forbidden. In the presented cases there are no conditional boundaries. The formalization for this has to be implemented in future cases.

### Reservation

Reservation also uses the logic to determine when a boundary is crossed to determine when it enters a new lane. It then checks (read from the map) whether that lane is externally reserved. If this is the case, the object type and link are read out and the state of corresponding objects is read from the measurement data. From this, the time for leaving the externally reserved space is calculated according to section 6.3.3. Leaving the space is again determined by the criterion of crossing a boundary (only this time the first time of non-fulfillment is relevant). If the time needed between the two boundary criteria is above the allowed time, the attribute is violated.

### Overtake

Since no overtaking maneuvers are possible in the tested scenarios, this criterion was not implemented. In the future, to test such scenarios, the implementation of the criterion from section 6.3.4 would be necessary.

### 8.4.3 Test Results

In this section, individual test results are presented to show the applicability and the ability to find errors. For the corresponding attributes insufficiencies found are presented.

#### Speed

The formalized logic for evaluating the speed attribute has been implemented, but there are no conditional speed limits within the ODD that need to be evaluated (such as *wet road*). In ODDs, which have such conditional speed limits, a determination of the ground truth of a wet road would be required in the future. In almost all tests, the speed attribute is violated because the speed is above the speed limit which results in test fails. The maximum exceedance is about 1.75 km/h. Applying the decomposed formalization criteria, discovered that this exceedance is planned behavior and not resulting from control deviation. Because the prototype vehicle will not be used in real traffic, it was decided to plan slightly above the speed limit to avoid gear shifts between second and third gear during slight speed deviations to increase the ride comfort. These shifts happen at around 27-29 km/h.

#### Boundary

In an early development stadium of the trajectory planner, test results show that the vehicle violates lane boundaries with the attribute ”prohibited”. Fig. 8-13 shows a driven trajectory of the *lane following* scenario through a right curve.

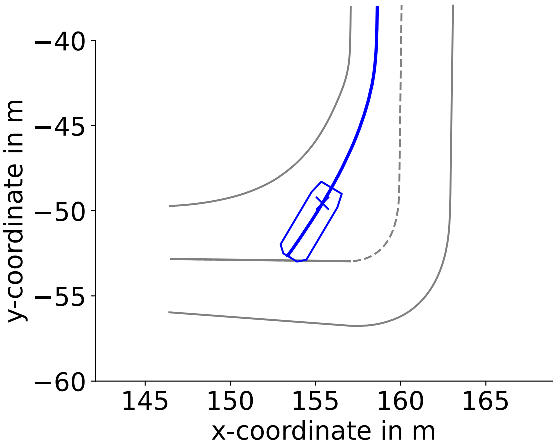


Figure 8-13: Violation of boundary attribute during the *lane following* scenario.
The driven trajectory of the center of the rear axle is given by the blue line (—). The vehicle contour at the first point in time where the boundary attribute is violated is plotted in blue as well.

The vehicle does not manage to follow the lane and violates the left boundary, which is a solid lane marking. The evaluation of the boundary attribute correctly determines this violation. Further investigations have shown that this violation was due to high steering torques because of quickly changing planned trajectories. In order to ensure that the safety drive is always able to overrule the system, the steering torque of the system is limited. If this limit is exceeded no control values are provided to the system and the safety driver needs to take over the system. Thus, the system is not active anymore and this is not regarded as a failed test. Still, in further development, the smoothness of the planned trajectory was improved and all curve radii within the test set were driven without exceedance of the steering torque limit and all prohibited boundaries were kept.

### Reservation

During the *shift to pass parked vehicles* scenario, the ego vehicle necessarily needs to drive through an externally-reserved motion space. Thus, the evaluation of the reservation attribute is of high importance. The formalization of the criterion for variable entrances and exits has been implemented. During development, insufficiencies of the vehicle behavior were found by applying this criterion. The parameters of the criterion have been set intuitively as follows:

- $a_{\mathrm{r}} = 1\,\frac{\mathrm{m}}{\mathrm{s}^2}$
- $D_{\mathrm{r}} = 1\,\frac{\mathrm{m}}{\mathrm{s}^2}$
- $v_{\mathrm{m}} = \frac{25}{3.6}\,\frac{\mathrm{m}}{\mathrm{s}}$
- $t_{\mathrm{PET}} = 2\,\mathrm{s}$

During analysis of the experiments, a finding was that the selection of these parameters influences the pass or fail of the tests. In future, when employing such a method, these parameters need to be determined and agreed on. This may be done by standard committee or e.g. by the UNECE and then employed by legislation.

Fig. 8-14 shows a test where the reservation attribute was violated. By the boundary criterion, it is detected when the ego vehicle first crosses the boundary into the externally-reserved space at $t_1$ and conversely, when the externally-reserved space is left at $t_2$. Using this, the distance of position of the oncoming vehicle at $t_1$ to the leave point of the ego vehicle is determined to $88.2\,\mathrm{m}$. With this information, and using 6-41 and 6-45 from section 6.3.3, as well as the speed of the oncoming vehicle at $t_1$ the time to leave is calculated to $9.32\,\mathrm{s}$. The actual time to leave was $12.48\,\mathrm{s}$. Therefore, the attribute was violated. This confirms the intuitive feeling of the driver and co-driver in the vehicle. Further investigations showed that the ego vehicle was leaving the ego lane already in distance to the parked object. The planner could then not robustly determine if driving in the oncoming lane results in a violation because the oncoming object was not yet detected by the environmental perception. However, it also failed to move back to the ego lane when the oncoming object was finally detected.

An adaption of the planner module (mainly in the cost function of the planner) resulted in moving in the externally-reserved motion space closer to the parked vehicle. Such a test is depicted in Fig. 8-15. In this case, the ego vehicle is able to determine and drive around the parked vehicle without violating the reservation attribute. It had $5.53\,\mathrm{s}$ to leave the lane and left the lane after $5.34\,\mathrm{s}$. Therefore, the reservation attribute was not violated. Again, this corresponds to the intuitive feeling of the driver and co-driver in the vehicle.

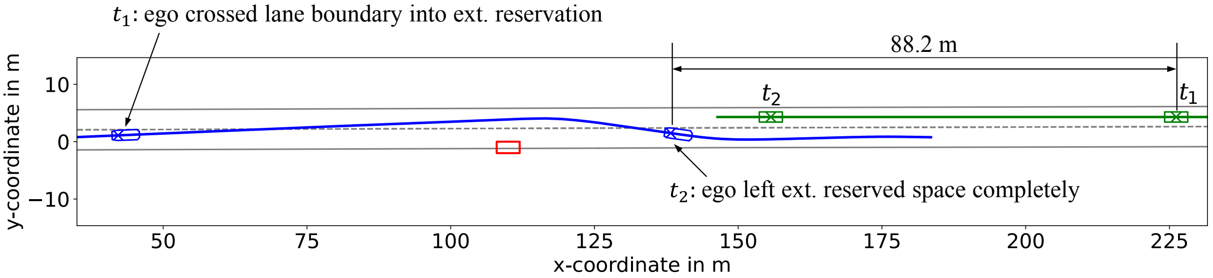


Figure 8-14: Violation of reservation attribute during the *shift to pass parked vehicles* scenario.
The driven trajectory of the center of the rear axle is given by the blue line (—).
The driven trajectory of the oncoming reservation entitled object is given by the green line (—).
The parked vehicle is given by the red contour (—).

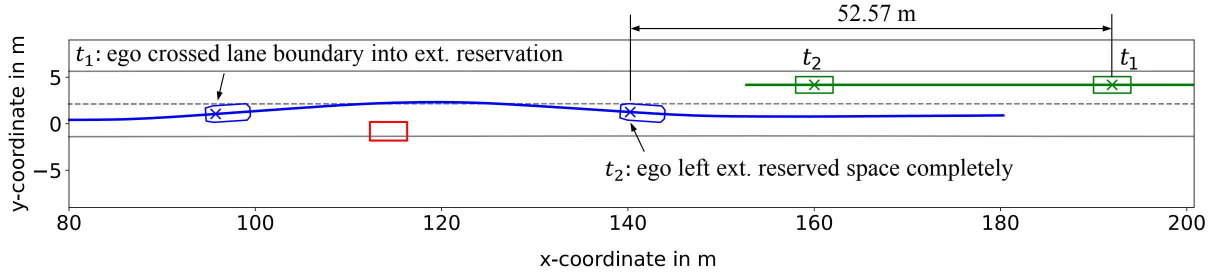


Figure 8-15: Compliance to the reservation attribute during the *shift to pass parked vehicles* scenario.

*Note*: Although the distance between the vehicles at $t_2$ is similar, the test result is different, because in the first test case the oncoming vehicle was braking nearly into standstill to give priority to the ego vehicle while in the second scenario it was driving with constant speed.

Although the formalized criterion was successfully implemented and helped detecting insufficiencies in the planner module, there are some drawbacks using this method. Especially in the first presented test case the time to leave is high. Although this a priori calculation of the time to leave is intended such that a defensive braking maneuver of the oncoming vehicle because of the ego vehicle is taken into account, the oncoming vehicle might brake out of other reasons (e.g. parking). Such behavior is currently not detected by the method and a violation might be detected where there is no violation. For the presented test cases, the criterion is valid because no other action than reacting to the ego vehicle have been performed by the oncoming vehicle.

## 8.5 Evaluation of the Application

In this subsection the application is evaluated by comparing whether the requirements derived in chapter 6.1 are met. The developed methods were applicable in general to the use case of the PRORETA 5 project resulting in a test plan for local traffic rule compliance. In order for the methods to be generally applicable for any use case (even those without a high-definition map available), it must be investigated which behavior space configurations are possible in general and how equivalence classes for these configurations are formed. The scope of this work was laid on the definition of a format (BSSD) to structure the constraints coming from the local scenery regarding traffic rules and formalize and use these constraints as test criteria. Then, an exemplary test plan has been derived, which discovered defects during the test execution in the PRORETA 5 system regarding traffic rule compliance. For a more efficient and profound selection of simulation environments valid simulation models for environment perception sensors and vehicle models are required in the future. Furthermore, the discretization of the parameter space and required test coverage have to be researched. In the following, the requirements are discussed regarding their fulfillment.

**REQ 1.** *The methodology shall not be restricted to a specific operational design domain.*

This requirement could only be validated if the methodology would be applied to every traffic region in the world. As this is not possible within the scope of this dissertation, it was ensured that the BSSD is easily extensible by adding further characteristics. By applying the description format to various sceneries in the German traffic area, it has been shown that the behavior constraints are described correctly. Since all following steps of the methodology were build on the BSSD they will be applicable as well. In the ODD analyzed within the use case, no behavior constraints not possible to describe with BSSD have been discovered and there was no restriction for the application identified based on the ODD.

**REQ 2.** *The methodology shall be able to describe the behavior constraints of a local scenery in a map.*

The systematic analysis of the StVO[200] and related violations[201] have discovered all behavior constraints defined by traffic regulations in Germany. The systematic breakdown of the traffic environment by using four key questions encoded these constraints within five behavioral attributes. Additionally, on the basis of requirements a generic format to represent these attributes within a map has been developed. Therefore, this requirement is fulfilled for the German traffic areas. As further traffic areas are structured in the same way (a traffic network consists of junctions and roads, roads consist of lanes), this description format will be applicable to other traffic areas as well, if the current set of behavioral requirements covers all behavior constraints of the area. Within the PRORETA 5 use case, all present scenery could be described using BSSD and thus, the methodology was able to describe the behavior constraints of the local scenery in a map.

**REQ 3.** *The methodology shall extract the behavior constraints of a specific ODD to serve as part of the specification of the system.*

By analyzing the relations between indication elements and behavior constraints based on rule mechanisms of the traffic regulations a method to infer the behavior constraints from a high-definition map was developed. This method is limited to roads with only one lane per driving direction, no temporary modifications and no dynamic signals such as traffic lights. As none of

---

[200] Bundesministerium der Justiz: Straßenverkehrsgesetz (StVG) (2021).

[201] Kraftfahrtbundesamt: Bundeseinheitlicher Tatbestandskatalog (2021).

these limitations were present within the considered ODD of the PRORETA 5 use case the method was able to correctly extract a total of eight different behavior space configurations. Thus, this requirement was fulfilled for this limited scope. In further research, the extension of the method to multi-lane roads with temporary modifications and dynamic signals need to be investigated. Additionally, not in every project a high-definition map will be available or a reliable source of information within the vehicle architecture. Therefore, the derivation of the BSSD on the basis of standard-definition maps and/or environmental sensor data input needs to be investigated.

**REQ 4.** *The methodology shall support the functional decomposition approach by Amersbach in order to reduce the test effort.*

As the BSSD directly delivers the constraints for the vehicle behavior regarding local traffic rules, it was possible to use it as an input to derive the parameter space for the behavioral decision layer of the functional decomposition approach. Using that, it was possible to systematically derive the parameter space for the other functional layers and thus, the approach was supported. During the application, it was discovered that a scenario derivation based on the BSSD could benefit the completeness of the scenario catalog. Since the BSSD provides the drivable spaces and assigned rules, it serves as the basis to determine possible actions of actors within a scenario. By applying combinatoric test approaches to derived parameter spaces a reduction in the testing effort could be achieved, although the test coverage was defined arbitrarily and it needs to be investigated in the future what coverage is necessary in the field of automated vehicles. A main innovation to support the functional decomposition is that a ground truth for the regulatory situational awareness layer is now available and can automatically be evaluated by using the formalized attributes.

**REQ 5.** *The methodology shall quantify the identified behavior constraints.*

The derived test criteria could be implemented as evaluation criteria within the test case execution and evaluation. Although it was not the case in the presented test set, the reservation test criteria may evaluate certain behavior as non-compliant although it is compliant. This is due to possible behavior of reservation entitled objects that is not resulting from the ego vehicle but other circumstances (e.g. parking). Additionally, in future all parameters relating to the attributes need to be analyzed systematically and determined by regulating bodies such that developers have a clear guideline on quantifying the behavioral attributes.

**REQ 6.** *The methodology shall derive a suite for the test of local traffic rule compliance of an HAV.*

By extending Schuldts[202] method to derive a test strategy for systematic testing, it was possible to derive a test suite for the test of local traffic rule compliance. The test suite could be conducted and evaluated according to the introduced methodology and was able to detect multiple defects in the ADS. These defects could be resolved during the development process based on the test results. Thus, the method posed a benefit during development of the system in the project PRORETA 5.

---

[202] Schuldt, F.: Methodischer Test von automatisierten Fahrfunktionen (2017).

It is not ensured that all defects, including severe ones, were uncovered by the test suite. Thus, for a release of the ADS the procedure is not sufficient. Open points, such as validation that the derivation process covers all possibilities and sufficient test coverage, are not yet clarified. Additionally, the methodology needs to be integrated in a rule hierarchy. At some times a rule violation might be the better option (e.g. in order to prevent a crash), but still vehicle should be aware of this violation. The introduced method lays the foundation for this awareness regarding traffic rules.

# 9 Conclusion and Outlook

In this chapter, the performed research is concluded. In section 9.1 the results are presented as answers to the stated research questions from section 3.3. In section 9.2 an outlook is given on further open research questions to fulfill the validation of traffic rule compliance for HAV.

## 9.1 Conclusion

This work aims to integrate the test of traffic control compliance into the development process of automated vehicles, formulated by the following hypothesis:

*It is possible to describe the behavioral limits based on traffic rules - independent of the application area - and to use them for specification as well as testing of the system behavior within the development process of an AV.*

For this purpose, a concept was developed in chapter 3 based on the state of the art. This concept consists of individual steps, which include the description of behavior constraints based on local traffic rules. The behavioral restrictions are extracted from an existing traffic environment and converted into quantifiable test criteria. Finally, the behavior constraints were used as an input for deriving a test strategy. For the realization of the concept, research questions were derived, which will be answered in the following and thus summarize and evaluate the results of the work.

**RQ1.** *What are the elements of the static traffic environment and what constraints on the behavior of an HAV do they have?*

The elements of the static traffic environment can be found and extracted based on traffic regulations and guidelines for the construction of roads. The resulting constraints on the behavior of the vehicle are given either from traffic regulations or expert knowledge. To record the constraints a systematic approach using a matrix which assigns the respective constraint to each design element of the road is proposed.

In this work, the application and thus, the extraction of traffic elements has only been conducted for German traffic regions. Although traffic areas in general have similar rules and constraints, there might be constraints that have not been found within the German regulations, but are present in another traffic area. However, the developed method to identify constraints is applicable to any traffic area with a valid traffic regulation and therefore, provides these additional constraints.

**RQ2.** *How can the behavior constraints imposed by the local traffic rules be described in such a way that the description is universally applicable (unlimited area of application)?*

The behavior constraints can be structured based on a generic subdivision of traffic environments. This subdivision analyzes where a vehicle is allowed to drive, under which conditions it is allowed to drive in these spaces, what needs to be respected while driving within these spaces and what behavior rules need to be observed while changing in between spaces. Five behavioral attributes with underlying characteristics are used to describe the behavior space (set of legally allowed behaviors) within the subdivided sections of the road. The five attributes are:

- *Speed*: Describing what constraints exist regarding driving speed
- *Boundary*: Describing what constraints exist when changing the space
- *Reservation*: Describing the priority rules that need to be respected while driving in a space
- *Overtake*: Describing the constraints on overtaking while driving in a space
- *Lighting*: Describing the constraints on lighting while driving in a space

Because these attributes are based on the systematic analysis of the road traffic regulations, it covers all constraints present in Germany. Since the four key questions cover generic traffic environments, applying the developed method from RQ1, the resulting constraints could be integrated into the developed structure of behavioral attributes and thus, most likely be applicable to any traffic area.

**RQ3.** *How can the behavior constraints imposed by the local traffic rules be recorded in a map representation?*

A generic structure for a map representation respecting the goals of connectivity, consistency and generality gives all necessary information to describe the relations of behavior constraints in form of behavioral attributes. The structure is subdivided into a road network representation that covers the drivable areas and their relations (neighbour, predecessor, successor) and a behavior space representation that represents the behavior constraints. Links between the two representations ensure that the relation between all elements is available. The generic structure has been implemented into the OpenDRIVE standard for high-definition maps.

Since it is not possible to verify the applicability of this format to all traffic environments in Germany, the format has been released as open source. With the widespread of the format, possible defects or incompatibilities may arise and are usable as a basis for improvement. During the application within various traffic areas no incompatibilities have been found, yet.

**RQ4.** *How can the abstract behavior rules be inferred on the basis of a present scenery?*

Based on high-definition maps, the behavioral attributes are derived using three steps. First, the drivable space is identified based on the lane type and the route network is segmented based on found indication elements and changes in the road layout. Within the segmented section of the road network the behavioral attributes are derived from the indication elements based on rule mechanisms given by the present traffic regulation. Finally, consecutive segments having the same behavior constraints are merged. Compiling all present configurations of behavior spaces gives a specification for the development of HAV in the scope of local traffic rule compliance.

The method has been implemented based on OpenDRIVE maps, in a limited scope of roads with only one lane per driving direction, no temporary adaptions (e.g. construction sites) of the road network and no dynamic signals (e.g. traffic lights). It was shown that the behavior constraints are derived correctly based on the introduced method.

**RQ5.** *What conclusions can be drawn from the behavioral limits on system level for the functional specification at the sub-system level (decomposition level)?*

The fault-tree analysis method provides a way to decompose violations against the behavioral attributes to violations per functional decomposition layer according to Amersbach[203]. These violations describe faults on sub-system level that lead to a violation of the local traffic rules and provide a semantic formulation of fail-criteria of a functionality as a basis for the analysis of RQ6. From the fail-criteria, requirements for an ADS in order to accomplish traffic rule compliance are derived, which serve as a functional specification at sub-system level.

**RQ6.** *How can identified limits of local traffic rules be converted into concrete pass/fail criteria for system and sub-system tests?*

Predicate logic provides the possibility to formalize the semantically described violations into a machine readable format. All attributes are converted into a logic-representation, which serves as a fail criteria for system tests. Since traffic regulations often contain ambiguous formulations, the logic-representation is subject to the interpretation of the author and the value of parameters remains open (e.g. accepted deceleration during the approach of externally-reserved spaces). For fail criteria of sub-systems the fault-tree from the previous research question is used to break down the formalized representations according to the semantic formulations.

**RQ7.** *How can a test plan for the validation of local traffic rule conformity be defined?*

The systematic appraoches of Schuldt[204] and Amersbach[205] are suitable for the derivation of a test plan for the validation of traffic rule compliance. The integration of the developed Behavior-Semantic Scenery description in this process results in an assignment of influence parameters for the test object. For test case generation, configuration and execution, existing strategies can be used if a required test coverage has been defined. For projects with a geographically limited operational design domain, the proposed steps can be performed manually. For a broader introduction of automated driving functions, it is necessary to further automate the process to define a test plan. This includes automated selection of relevant parameters of all functional layers, automated derivation of requirements for the test environment and suitable, validated models as test drivers.

---

[203] Amersbach, C. T.: Functional Decomposition Approach (2020).

[204] Schuldt, F.: Methodischer Test von automatisierten Fahrfunktionen (2017).

[205] Amersbach, C. T.: Functional Decomposition Approach (2020).

**RQ8.** *Is the developed methodology practically applicable?*

The extraction of behavioral constraints from the ODD with the presented method is applicable within the use case of PRORETA 5. An extension of the implemented functionality (not of the method) for more complex use cases is necessary to be applicable to a wider range of projects. A derivation of individual test cases is possible with the presented method. In the future, the test coverage must be defined in a resilient way in order to be able to achieve an actual validation of the traffic compliance of ADS. The method supports the functional decomposition by deriving test cases on decomposition level and a quantified test criterion. It has been shown that, these test criteria are applicable within test cases. The execution and evaluation of the test cases uncovered deficiencies in the present system regarding traffic rule conformance and led to improvements in the developed system.

Therefore, the stated hypothesis that it is possible to specify and test the system behavior on the basis of traffic rules cannot be falsified on the basis of the results. The method developed in the thesis has shown within the application that it is able to test the system behavior with respect to traffic rule conformity and to detect defects within the system. However, due to the limited use case and identified open questions (see also next section), the unlimited applicability independent of the application area is not sufficiently proven.

## 9.2 Outlook

To complete this dissertation, the following section provides an outlook on open research questions that were discovered during the execution of this work.

The dissertation provides methods to specify and validate local traffic rule compliance. In order to ensure safe driving and compliance to general traffic rules, similar investigations on how to specify and validate general traffic rules need to be performed. While these investigations are already advanced (e.g. Shalev-Shwartz et al.[206], Althoff et al.[207], Rizaldi et al.[208], Maierhofer et al.[209]), a clear and agreed hierarchy of all behavior specifications needs to be determined. A violation of the local traffic rules might be reasonable if a collision is avoided as part of the general rules. Censi et al.[210] provide an approach to formalize such a hierarchy in rulebooks. Consequently, as a next step it needs to be investigated how the different approaches to specify behaviors are integrated in such a framework. Within this future investigation it may be consulted how serious

---

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

[207] Althoff, M. et al.: Online Verification of Automated Road Vehicles (2014).

[208] Rizaldi, A. et al.: Formalising and Monitoring Traffic Rules for Autonomous Vehicles in Isabelle/HOL (2017).

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

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

violations are or whether one is still far from a violation. The method presented in this work only checks whether a violation is present or not.

The inference of BSSD from a present ODD developed within this dissertation relies on high-definition maps. A high-definition map will not always be available for an ODD of interest for automated driving functions. Therefore, an inference based on standard definition maps which show better coverage, could enhance the application area of the shown approach. While the general relations developed between the scenery and BSSD for inference are still valid while using standard-definition maps, it needs to be investigated if the quantity and quality of data is sufficient. Additionally, approaches to ensure the up-to-dateness of maps are necessary. For this, a check based on sensor data within the vehicle could be integrated.

As traffic regulations do not state quantified limits for the behavior regarding traffic rules, the formalization of the behavioral attributes in this dissertation serves as a first proposal of quantified semantic behavior rules. In order for an integration into real traffic and release of automated vehicles an international agreement of the regulating legislative bodies about these quantified limits is indispensible. A first step has been made with the UN regulation R79[211] which states first quantified limits for behavior during lane changes. These limits need to be extended for all parts of behavior specification.

Within the application of the dissertation a simple scenario catalog has been used to show the applicability of the methodology. Even with larger, more sophisticated scenario catalogs, a completeness of the scenarios will most likely not be given. Thus, although a scenario generation approach supported by BSSD could enhance the comprehensiveness, there need to be approaches investigated to ensure that the vehicle behaves according to the traffic rules in unknown scenarios. This could include a detection mechanism on the base of a situation description relying on BSSD. As soon as the ADS detects an unknown situation, it performs a safe stop maneuver guaranteed to be traffic rule compliant.

While BSSD serves as a tool to describe and determine the parameter space for the test scenarios regarding the behavioral decision layer of the functional decomposition approach by Amersbach[212], it only serves as a basis to determine the parameter space of other functional layers. For these layers a systematic approach to determine parameter spaces has to be investigated. A starting point could be PerCollECT by Linnhoff et al.[213] which aims at collecting cause-effect chains as a basis for specification of sensor models. Additionally, the required test coverage is still an open research question.

Finally, the semantic description of the behavior space opens various other application fields other than testing. The semantic description of the behavior space could be integrated as an

---

[211] UNECE: Regulation R 79 (2021).

[212] Amersbach, C. T.: Functional Decomposition Approach (2020).

[213] Linnhoff, C. et al.: A Collaborative Method to Specify Sensor Models (2021).

interface within an ADS and serve as an input for different modules. Intuitively, it could directly be used as an input for behavior planning algorithms, supplying them with the limits of allowed vehicle behavior. Therefore, it would need to be investigated how the behavior limits have to be considered during planning. The semantic description could also be used as an input for the prediction of the behavior of other traffic participants. Since not only the HAV needs to respect the behavior constraints of the scenery but also other traffic participants, the BSSD could be used as context information for such algorithms.

# A Test Route Network for Method to Infer BSSD

Fig. A-1 gives an overview of the route network for verification of the implementation to infer the BSSD from an HD-map.

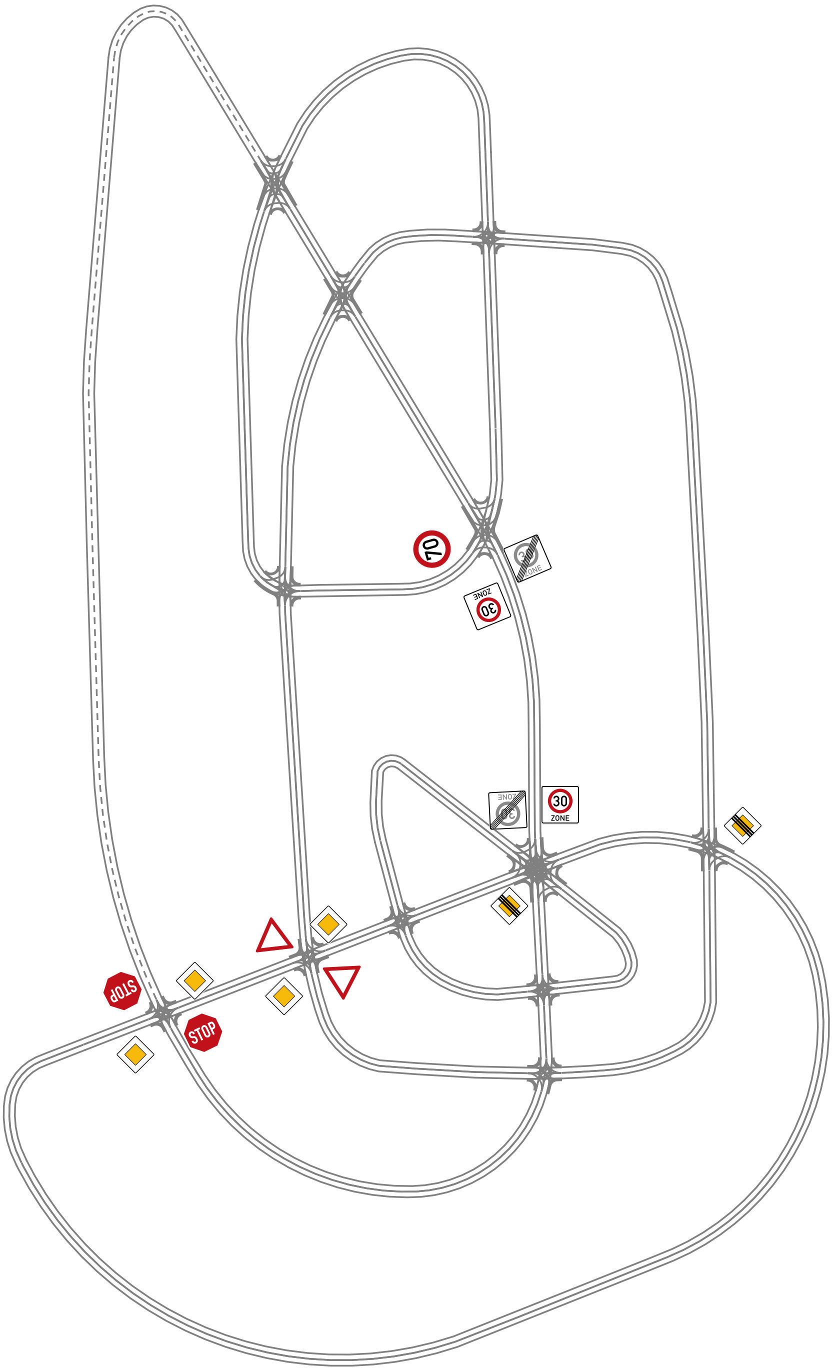


Figure A-1: Test route network for inferring the BSSD

# B Formalized Decomposition of the Reservation Attribute

In the first step, the derived violation $C$ of the reservation attribute and the decomposed violations $C_{1,k}$ and $C_{2,k}$ are assigned to the fault tree. A detailed representation of an approach to an externally-reserved speed with non-moderate speed is omitted, because it is similar to the decomposition of a maximum speed violation (see section 6.4). A violation in the action layer, means that a trajectory compliant to the reservation attribute was planned, but the actual behavior deviates from this trajectory in such form that the attribute is violated:

$$C_{2,k,\text{action}} \leftrightarrow C_{2,k} \land \neg C_{2,k,\text{set}} \tag{B-1}$$

Going one layer back, the behavioral decision layer needs to provide a trajectory compliant to the reservation attribute. Therefore, a violation in the behavioral decision layer $C_{2,k,\text{set}}$ means that a trajectory violating the reservation attribute was planned although a correct reservation attribute as well as the relevant objects including their state were known in time, meaning there was a correct output within the situation description. In this case, the planner did not provide the intended functionality:

$$C_{2,k,\text{decis}} \leftrightarrow C_{2,k,\text{set}} \land \neg C_{2,k,\text{sit}} \tag{B-2}$$

A planned violation is present as soon as the planned behavior is violating the reservation and cannot be corrected in time such that the actual behavior produces a violation. This is the case when entering the external reserved space is unavoidable and leaving it in time is not possible. Entering is unavoidable if the vehicle at a point in tim $t_j$ is closer to the external reserved space than the braking distance $d_{\text{B},j}$ necessary to come to a stop with the respective speed profile with the deceleration $D_{\text{max,appr}}$ from section 6.3.3. The distance to the external reserved space is given by $s_{\text{ext}} - {}_F\boldsymbol{\mathcal{T}}_{j,0}$. At the last time step where coming to a stop in front of the external reserved space the vehicle either has to do so by planning the deceleration of $-{}_F a_{s,j,i}$ at every trajectory point ${}_F\boldsymbol{\mathcal{T}}_{j,i}$ or it has to leave the intersection in time. This is not possible if the minimum time to leave $\tau_{\text{leave,min},j}$ the intersection exceeds the allowed time to leave the intersection $\tau_{\text{leave,allowed},j}$ at the point in time $t_j$. When entering is not avoidable anymore, the vehicle needs to plan a trajectory that keeps it possible to leave the space in time. This means, when the min time to leave the space and the allowed time to leave are equal (with an error margin $\varepsilon_\tau$) that the average speed of the planned trajectory points $\overline{v}_{j,i}$ needs to be bigger than the required average speed to leave the space in time $\overline{v}_{\text{req}}$. This is represented by the following proposition:

$$\begin{aligned} C_{2,k,\text{set}} \leftrightarrow \Big(\exists t_j \in [t_0, t_n] : |s_{\text{ext}} - {}_F\boldsymbol{\mathcal{T}}_{\text{set},j,0} - d_{\text{B},j}| \leq \varepsilon_d \land \\ \exists_F a_{s,\text{set},j,i} \in \Big\{\big({}_F a_{s,\text{set},j,i}\big)_{i=0,\dots,m}\Big\} : -{}_F a_{s,j,i} < D_{\text{max,appr}} \land \tau_{\text{leave,min},j} > \tau_{\text{leave,allowed},j}\Big) \lor \\ \Big(\exists t_k \in (t_j, t_{\text{exit,ext}}] : |\tau_{\text{leave,min},k} - \tau_{\text{leave,allowed},k}| < \varepsilon_\tau \land \overline{v}_{\text{set},j,i} < \overline{v}_{\text{req}}\Big) \end{aligned} \tag{B-3}$$

$$\text{where } \overline{v}_{\text{set},j,i} = \sum_{i=0}^{n} v_{j,i} \tag{B-4}$$

In order to plan compliant behavior, the ADS needs to be aware of all relevant aspects of the situation. On the one hand, a violation could result form an incorrect representation of the reservation attribute. This could be a wrong reservation type $C_{2,k,\text{res}}$, a wrong object type $C_{2,k,\text{type}}$ or a missing reservation link $C_{2,k,\text{link}}$. On the other hand it could result from an incorrect representation of present reservation entitled objects. This includes a missing detection of the object $C_{2,k,\text{obj}}$, a wrong representation of the object state $C_{2,k,\text{state}}$ or the object class $C_{2,k,\text{class}}$. This is represented by the following proposition.

$$C_{2,k,\text{situ}} = C_{2,k,\text{res}} \lor C_{2,k,\text{type}} \lor C_{2,k,\text{link}} \lor C_{2,k,\text{obj}} \lor C_{2,k,\text{class}} \lor C_{2,k,\text{state}} \tag{B-5}$$

The individual violations are represented by the following propositions, where $\boldsymbol{\mathcal{A}}_{\text{res}}$ denotes the reservation attribute:

$$C_{2,k,\text{res}} \leftrightarrow \boldsymbol{\mathcal{A}}_{\text{res,type,situ}} \neq \boldsymbol{\mathcal{A}}_{\text{res,type,act}} \tag{B-6}$$

$$C_{2,k,\text{type}} \leftrightarrow \boldsymbol{\mathcal{A}}_{\text{res,object,situ}} \neq \boldsymbol{\mathcal{A}}_{\text{type,object,act}} \tag{B-7}$$

$$C_{2,k,\text{link}} \leftrightarrow \boldsymbol{\mathcal{A}}_{\text{res,link,situ}} \neq \boldsymbol{\mathcal{A}}_{\text{res,link,act}} \tag{B-8}$$

$$C_{2,k,\text{obj}} \leftrightarrow \exists \boldsymbol{\mathcal{O}}_{\text{exist,relevant},i} \in \boldsymbol{\mathcal{D}}_{\text{exist,relevant},j} : \boldsymbol{\mathcal{O}}_{\text{exist,relevant},i} \notin \boldsymbol{\mathcal{D}}_{\text{situ,relevant},j} \tag{B-9}$$

$$C_{2,k,\text{class}} \leftrightarrow \exists \boldsymbol{\mathcal{O}}_{\text{situ,relevant},i} \in \boldsymbol{\mathcal{D}}_{\text{situ,relevant},j} : \text{class}(\boldsymbol{\mathcal{O}}_{\text{situ,relevant},i}) \neq \text{class}(\boldsymbol{\mathcal{O}}_{\text{exist,relevant},i}) \tag{B-10}$$

$$C_{2,k,\text{state}} \leftrightarrow \exists \boldsymbol{\mathcal{O}}_{\text{situ,relevant},i} \in \boldsymbol{\mathcal{D}}_{\text{situ,relevant},j} : \Delta \boldsymbol{x}_{\boldsymbol{\mathcal{O}}_{\text{situ,relevant},i}} > \varepsilon \tag{B-11}$$

The value of $\varepsilon$ as a threshold for the allowed state deviation is highly specific to the present situation as well as the implementation within the vehicle and therefore not further specified within this work. Fig. B-1 represents the assignment of the criteria to the decomposed tree of the reservation attribute.

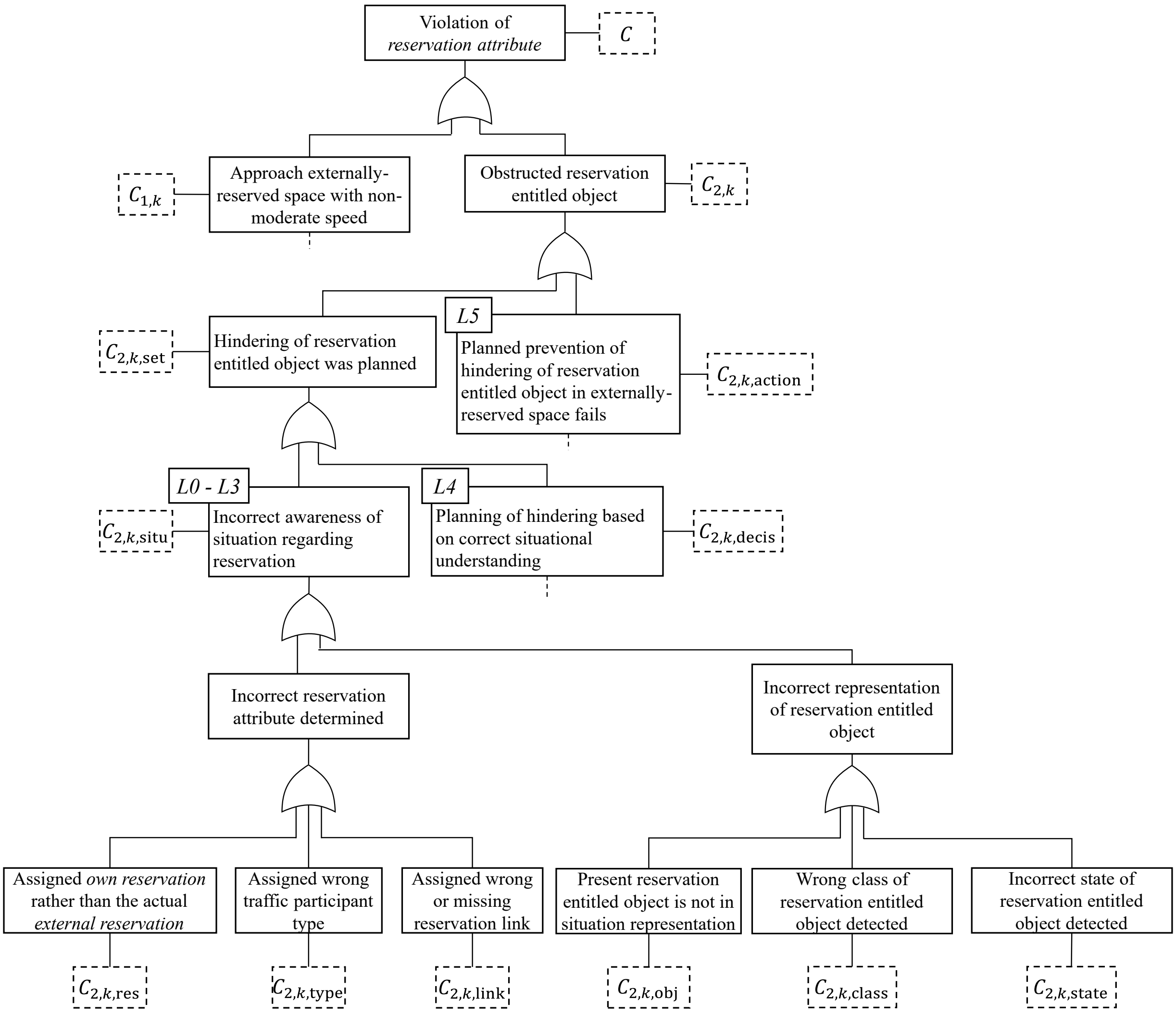


Figure B-1: Decomposition of the reservation attribute

# Bibliography

**Åberg, L.: Traffic rules and traffic safety (1998)**
Åberg, L.: Traffic rules and traffic safety, in: Safety Science, Vol. 29, pp. 205–215, 1998

**ADAC: Lichtassistenten: Diese Systeme sorgen für mehr Sicherheit (2021)**
ADAC: Lichtassistenten: Diese Systeme sorgen für mehr Sicherheit, URL: https://www.adac.de/rund-ums-fahrzeug/ausstattung-technik-zubehoer/licht-und-beleuchtung/lichtassistenten/, 2021, visited on 07/27/2022

**Althoff, M. et al.: Online Verification of Automated Road Vehicles (2014)**
Althoff, Matthias; Dolan, John M.: Online Verification of Automated Road Vehicles Using Reachability Analysis, in: IEEE Transactions on Robotics, Vol. 30, pp. 903–918, 2014

**American Meteorological Society: Glossary of Meteorology (2020)**
American Meteorological Society: Glossary of Meteorology, URL: http://glossary.ametsoc.org/, 2020

**Amersbach, C. et al.: Funktionale Dekomposition (2018)**
Amersbach, Christian; Winner, Hermann: Funktionale Dekomposition - Ein Beitrag zur Überwindung der Parameterraumexplosion bei der Validation von höher automatisiertem Fahren, in: 12. Workshop Fahrerassistenzsysteme und automatisiertes Fahren, pp. 27–33, 2018

**Amersbach, C. T.: Functional Decomposition Approach (2020)**
Amersbach, Christian Thomas: Functional Decomposition Approach - Reducing the Safety Validation Effort for Highly Automated Driving, Dissertation, Technische Universität Darmstadt, 2020

**Aptiv Services US LLC et al.: Safety First for Automated Driving (2019)**
Aptiv Services US LLC; AUDI AG; Bayrische Motoren Werke AG; Beijing Baidu Netcom Science Technology Co., Ltd; Continental Teves AG & Co oHG; Daimler AG; FCA US LLC; HERE Global B.V.; Infineon Technologies AG; Intel; Volkswagen AG: Safety First for Automated Driving, 2019

**Arun, A. et al.: Review of traffic conflict-based safety measures (2021)**
Arun, Ashutosh; Haque, Md. Mazharul; Washington, Simon; Sayed, Tarek; Mannering, Fred: A systematic review of traffic conflict-based safety measures with a focus on application context, in: Analytic Methods in Accident Research, Vol. 32, pp. 100185, 2021

**ASAM Test Specification Study Group: Collaborative Testing for ADAS & AD (2022)**
ASAM Test Specification Study Group: Evolving Landscapes of Collaborative Testing for ADAS & AD, URL: https://report.asam.net/wp-content/uploads/2022/02/ASAM-Test-Specification-Study-Group-Report-2022_V1-0-0.pdf, 2022

**Asljung, D. et al.: Using Extreme Value Theory for Vehicle Level Safety Validation (2017)**
Asljung, Daniel; Nilsson, Jonas; Fredriksson, Jonas: Using Extreme Value Theory for Vehicle Level Safety Validation and Implications for Autonomous Vehicles, in: IEEE Transactions on Intelligent Vehicles, Vol. 2, pp. 288–297, 2017

**ASAM: OpenDRIVE (2020)**
Association for Standardization of Automation and Measuring Systems: OpenDRIVE, URL: https://www.asam.net/standards/detail/opendrive/, 2020, visited on 06/11/2020

**ASAM: OpenODD: Concept Paper (2021)**
Association for Standardization of Automation and Measuring Systems: OpenODD: Concept Paper, URL: https://www.asam.net/index.php?eID=dumpFile&t=f&f=4544&token=1260ce1c4f0afdbe18261f7137c689b1d9c27576, 2021, visited on 06/22/2022

**ASAM: OpenSCENARIO (2022)**
Association for Standardization of Automation and Measuring Systems: OpenSCENARIO, URL: https://www.asam.net/standards/detail/openscenario/, 2022, visited on 07/22/2022

**Bachmann, T.: Reibung zwischen Reifen und Fahrbahn (1998)**
Bachmann, Thomas: Wechselwirkungen im Prozeß der Reibung zwischen Reifen und Fahrbahn: Zugl.: Darmstadt, Techn. Hochsch., Diss., 1998, Berichte aus dem Fachgebiet Fahrzeugtechik der TU Darmstadt, Als Ms. gedr. Edition, Vol. Nr. 360, VDI-Verl., 1998

**Bagschik, G. et al.: Wissensbasierte Szenariengenerierung (2018)**
Bagschik, G.; Menzel, T.; Körner, C.; Maurer, M.: Wissensbasierte Szenariengenerierung für Betriebsszenarien auf deutschen Autobahnen, in: (PUB): 12. Workshop Fahrerassistenzsysteme und automatisiertes Fahren, 2018

**Bagschik, G. et al.: Ontology based Scene Creation (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

**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

**Berghöfer, M.: Integration der BSSD in hochgenaue Karten (2022)**
Berghöfer, Moritz: Entwicklung eines Konzepts zur Integration der verhaltenssemantischen Szeneriebeschreibung in hochgenaue Karten, Masterthesis, Technische Universität Darmstadt, 2022

**Bertsche, B.: Reliability in automotive and mechanical engineering (2008)**
Bertsche, B.: Reliability in automotive and mechanical engineering: Determination of component and system reliability, Springer, 2008

**Block, D. et al.: Simulations on Consumer Tests (2014)**
Block, Delf; Heeren, Sönke; Kühnel, Stefan; Leschke, André; Rumpe, Bernhard; Serebro, Vladislavs: Simulations on Consumer Tests, in: ES4CPS, pp. 38–43, 2014

**Blödel, A. P.: Generierung von Trajektorien für das modulare Testen (2021)**
Blödel, Alexander Paul: Entwicklung und Implementierung eines Verfahrens zur Generierung von Trajektorien für das modulare Testen automatisierter Fahrfunktionen, Masterthesis, Technische Universität Darmstadt, 2021

**British Standards Institution: PAS 1883: (2020)**
British Standards Institution: PAS 1883:2020: Operational Design Domain (ODD) taxonomy for an automated driving system (ADS) – Specification, 2020

**Broadhurst, A. et al.: Monte Carlo road safety reasoning (2005)**
Broadhurst, A.; Baker, S.; Kanade, T.: Monte Carlo road safety reasoning, in: IEEE Intelligent Vehicles Symposium, 2005. Proceedings, pp. 319–324, 2005

**Buechel, M. et al.: Ontology-based traffic scene modeling (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

**Buerkle, C. et al.: Towards Online Environment Model Verification (2020)**
Buerkle, Cornelius; Oboril, Fabian; Scholl, Kay-Ulrich: Towards Online Environment Model Verification, in: 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC), pp. 1–7, 2020

**Bundesministerium der Justiz: Straßenverkehrs-Ordnung (StVO) (2021)**
Bundesministerium der Justiz: Straßenverkehrs-Ordnung (StVO), 2021

**Bundesministerium der Justiz: Straßenverkehrs-Zulassungs-Ordnung (StVZO) (2021)**
Bundesministerium der Justiz: Straßenverkehrs-Zulassungs-Ordnung (StVZO), 2021

**Bundesministerium der Justiz: Straßenverkehrsgesetz (StVG) (2021)**
Bundesministerium der Justiz: Straßenverkehrsgesetz (StVG), 2021

**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

**Casner, S. M. et al.: The Challenges of Partially Automated Driving (2016)**
Casner, Stephen M.; Hutchins, Edwin L.; Norman, Don: The Challenges of Partially Automated Driving, in: Communications of the ACM, Vol. 59, pp. 70–77, 2016

**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, in: 2019 International Conference on Robotics and Automation (ICRA), pp. 8536–8542, 2019

**Czarnecki, K.: Operational Design Domain for Automated Driving Systems (2018)**
Czarnecki, Krzysztof: Operational Design Domain for Automated Driving Systems - Taxonomy of Basic Terms, 2018

**Czarnecki, K.: Operational World Model Ontology - Part 1 (2018)**
Czarnecki, Krzysztof: Operational World Model Ontology for Automated Driving Systems - Part 1: Road Structure, 2018

**Czarnecki, K.: Operational World Model Ontology - Part 2 (2018)**
Czarnecki, Krzysztof: Operational World Model Ontology for Automated Driving Systems - Part 2: Road Users, Animals, Other Obstacles, and Environmental Conditions, 2018

**Department of Motor Vehicles: California Driver’s Handbook (2022)**
Department of Motor Vehicles: California Driver’s Handbook, URL: https://www.dmv.ca.gov/portal/file/california-driver-handbook-pdf/, 2022

**Deutsche Polizeiliteratur: Polizei-Fach-Handbuch (2019)**
Deutsche Polizeiliteratur: Polizei-Fach-Handbuch (PolFHa) - Ausgabe Bundesrecht, 3. Aktualisierung. Edition, Deutsche Polizeiliteratur, 2019

**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

**Glatzki, F. et al.: Behavioral Attributes for a Behavior-Semantic Scenery Description (BSSD) (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

**Glatzki, F. et al.: Inferenz von Verhaltensattributen der BSSD (2022)**
Glatzki, Felix; Winner, Hermann: Inferenz von Verhaltensattributen der Verhaltenssemantischen Szeneriebeschreibung für die Entwicklung automatisierter Fahrfunktionen, in: 14. Workshop Fahrerassistenz und automatisiertes Fahren, pp. 151–163, 2022

**Grindal, M. et al.: Combination testing strategies: a survey (2005)**
Grindal, Mats; Offutt, Jeff; Andler, Sten F.: Combination testing strategies: a survey, in: Software Testing, Verification and Reliability, Vol. 15, pp. 167–199, 2005

**Honda Motor Co., Ltd.: Honda Receives Type Designation for Level 3 Automated Driving in Japan (2020)**
Honda Motor Co., Ltd.: Honda Receives Type Designation for Level 3 Automated Driving in Japan, URL: https://global.honda/newsroom/news/2020/4201111eng.html, 2020, visited on 06/08/2022

**Huber, B. et al.: Evaluation of Traffic Situations based on Multidimensional Criticality Analysis (2020)**
Huber, Bernd; Herzog, Steffen; Sippl, Christoph; German, Reinhard; Djanatliev, Anatoli: Evaluation of Virtual Traffic Situations for Testing Automated Driving Functions based on Multidimensional Criticality Analysis, in: 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC), pp. 1–7, 2020

**IEEE: IEEE 829: Standard for Software and System Test Documentation (2008)**
Institute of Electrical and Electronics Engineers: IEEE 829: Standard for Software and System Test Documentation, 2008

**IEC: IEC 61025: Fault tree anaylsis (FTA) (2006)**
International Electrotechnical Commission: IEC 61025: Fault tree anaylsis (FTA), 2006

**ISO: ISO 21434: Road vehicles - Cybersecurity engineering (2021)**
International Organization for Standardization: ISO 21434: Road vehicles - Cybersecurity engineering, 2021

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

**ISO: ISO 29119: Software and systems engineering (2022)**
International Organization for Standardization: ISO 29119: Software and systems engineering - Software testing, 2022

**ISO: ISO 6709: Standard representation of geographic point location by coordinates (2008)**
International Organization for Standardization: ISO 6709: Standard representation of geographic point location by coordinates, 2008

**ISO: ISO/DIS 34503: Road Vehicles - Taxonomy for operational design domain (2022)**
International Organization for Standardization: ISO/DIS 34503: Road Vehicles - Test scenarios for automated driving systems - Taxonomy for operational design domain, 2022

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

**ISO: ISO/TR 4804: Road vehicles - Safety and cybersecurity for automated driving systems (2020)**
International Organization for Standardization: ISO/TR 4804: Road vehicles - Safety and cybersecurity for automated driving systems - Design, verification and validation, 2020

**ISTQB: Standard Glossary of Terms Used in Software Testing (2021)**
International Software Testing Qualification Board: Standard Glossary of Terms Used in Software Testing, URL: https://glossary.istqb.org/en/search/, 2021, visited on 07/26/2022

**Irvine, P. et al.: A Two-Level Abstraction ODD Definition Language: Part I (2021)**
Irvine, Patrick; Zhang, Xizhe; Khastgir, Siddartha; Schwalb, Edward; Jennings, Paul: A Two-Level Abstraction ODD Definition Language: Part I, in: 2021 IEEE International Conference on Systems, Man, and Cybernetics (SMC), pp. 2614–2621, 2021

**Jesenski, S. et al.: Generation of Scenes for the Validation of Highly Automated Driving Functions (2019)**
Jesenski, Stefan; Stellet, Jan Erik; Schiegg, Florian; Zollner, J. Marius: Generation of Scenes in Intersections for the Validation of Highly Automated Driving Functions, in: 2019 IEEE Intelligent Vehicles Symposium (IV 2019), pp. 502–509, 2019

**Junietz, P. et al.: Macroscopic Safety Requirements for HAD (2019)**
Junietz, Philipp; Steininger, Udo; Winner, Hermann: Macroscopic Safety Requirements for Highly Automated Driving, in: Transportation Research Record: Journal of the Transportation Research Board, Vol. 2673, pp. 1–10, 2019

**Junietz, P. et al.: Evaluation of Different Approaches to Address Safety Validation (2018)**
Junietz, Philipp; Wachenfeld, Walther; Klonecki, Kamil; Winner, Hermann: Evaluation of Different Approaches to Address Safety Validation of Automated Driving, in: 2018 IEEE Intelligent Transportation Systems Conference, 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.: Approaches for a Modular Safety Approval of Highly Automated Vehicles (2023)**
Klamann, Björn: Approaches for a Modular Safety Approval of Highly Automated Vehicles, Dissertation, Technische Universität Darmstadt, 2023

**Klamann, B. et al.: Defining Pass-/Fail-Criteria for Particular Tests of Automated Driving Functions (2019)**
Klamann, Bjorn; 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

**Klamann, B. et al.: Comparing Different Levels of Technical Systems (2021)**
Klamann, Björn; Winner, Hermann: Comparing Different Levels of Technical Systems for a Modular Safety Approval—Why the State of the Art Does Not Dispense with System Tests Yet, in: Energies, Vol. 14, pp. 7516, 2021

**Klueck, F. et al.: Using Ontologies for Test Suites Generation (2018)**
Klueck, Florian; Li, Yihao; Nica, Mihai; Tao, Jianbo; Wotawa, Franz: Using Ontologies for Test Suites Generation for Automated and Autonomous Driving Functions, in: 2018 IEEE International Symposium on Software Reliability Engineering Workshops (ISSREW), pp. 118–123, 2018

**Koenig, A. et al.: Passive HAD as a concept for validating highly automated cars (2018)**
Koenig, Alexander; Witzlsperger, Kathrin; Leutwiler, Florin; Hohmann, Sören: Overview of HAD validation and passive HAD as a concept for validating highly automated cars, in: at - Automatisierungstechnik, Vol. 66, pp. 132–145, 2018

**Kraftfahrtbundesamt: Bundeseinheitlicher Tatbestandskatalog (2021)**
Kraftfahrtbundesamt: Bundeseinheitlicher Tatbestandskatalog für Straßenverkehrsordnungswidrigkeiten: BT-KAT-OWI, 2021

**Krajewski, R. et al.: Data-Driven Maneuver Modeling for Safety Validation of Highly Automated Vehicles (2018)**
Krajewski, Robert; Moers, Tobias; Nerger, Dominik; Eckstein, Lutz: Data-Driven Maneuver Modeling using Generative Adversarial Networks and Variational Autoencoders for Safety Validation of Highly Automated Vehicles, in: 2018 IEEE Intelligent Transportation Systems Conference, pp. 2383–2390, 2018

**Kuhn, D. R. et al.: Software fault interactions and implications for software testing (2004)**
Kuhn, D. R.; Wallace, D. R.; Gallo, A. M.: Software fault interactions and implications for software testing, in: IEEE Transactions on Software Engineering, Vol. 30, pp. 418–421, 2004

**Liggesmeyer, P.: Software-Qualität: Testen, Analysieren und Verifizieren von Software (2009)**
Liggesmeyer, Peter: Software-Qualität: Testen, Analysieren und Verifizieren von Software, 2. Aufl.. Edition, Spektrum, Akad. Verl., 2009

**Linnhoff, C. et al.: A Collaborative Method to Specify Sensor Models (2021)**
Linnhoff, Clemens; Rosenberger, Philipp; Schmidt, Simon; Elster, Lukas; Stark, Rainer; Winner, Hermann: Towards Serious Perception Sensor Simulation for Safety Validation of Automated Driving - A Collaborative Method to Specify Sensor Models, in: 2021 IEEE International Intelligent Transportation Systems Conference (ITSC), pp. 2688–2695, 2021

**Lippert, M.: Capability-Based Route Planning (2023)**
Lippert, Moritz: Capability-Based Route Planning using Scenery-Derived Requirements for Automated Driving, Dissertation, Technische Universität Darmstadt, 2023

**Lippert, M. et al.: Behavior-Semantic Scenery Description (BSSD) (2022)**
Lippert, Moritz; Glatzki, Felix; Winner, Hermann: Behavior-Semantic Scenery Description (BSSD) of Road Networks for Automated Driving, URL: https://arxiv.org/pdf/2202.05211, 2022

**Lippert, M. et al.: Definition von Bestehens-/Versagenskriterien (2019)**
Lippert, Moritz; Klamann, Björn; Amersbach, Christian; Winner, Hermann: Definition von Bestehens-/Versagenskriterien für das partikuläre Testen von automatisierten Fahrfunktionen, in: (PUB): 9. Tagung Automatisiertes Fahren, 2019

**Lotz, F. G. O.: Eine Referenzarchitektur für die automatisierte Fahrzeugführung (2017)**
Lotz, Felix Gerhard Otto: Eine Referenzarchitektur für die assistierte und automatisierte Fahrzeugführung mit Fahrereinbindung, Dissertation, Technische Universität Darmstadt, 2017

**Lyft, Inc.: Lyft and Motional to Deploy Fully Self-Driving (2020)**
Lyft, Inc.: Lyft and Motional to Deploy Fully Self-Driving Vehicles in Multiple US Cities on the Lyft Network Beginning in 2023, URL: https://www.lyft.com/blog/posts/lyft-and-motional-to-deploy-fully-self-driving-vehicles-in-multiple-us, 2020

**Mahmud, S. S. et al.: Application of proximal surrogate indicators (2017)**
Mahmud, S. SohelM.; Ferreira, Luis; Hoque, Md. Shamsul; Tavassoli, Ahmad: Application of proximal surrogate indicators for safety evaluation: A review of recent developments and research needs, in: IATSS Research, Vol. 41, pp. 153–163, 2017

**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: (PUB): 2020 IEEE Intelligent Vehicles Symposium, 2020

**Menzel, T. et al.: Scenarios for Development, Test and Validation of Automated Vehicles (2018)**
Menzel, Till; Bagschik, Gerrit; Maurer, Markus: Scenarios for Development, Test and Validation of Automated Vehicles, in: 2018 IEEE Intelligent Vehicles Symposium (IV), pp. 1821–1827, 2018

**Mercedes-Benz Group AG: Aktiver Geschwindigkeitslimit-Assistent (2022)**
Mercedes-Benz Group AG: Aktiver Geschwindigkeitslimit-Assistent, URL: https://www.mercedes-benz.de/passengercars/mercedes-benz-cars/models/eqc/safety.pi.html/mercedes-benz-cars/models/eqc/safety/driving-assistance-gallery/speed-limit, 2022, visited on 08/03/2022

**Mercedes-Benz Group AG: First internationally valid system approval for conditionally automated driving (2021)**

Mercedes-Benz Group AG: First internationally valid system approval for conditionally automated driving, URL: https://group.mercedes-benz.com/innovation/product-innovation/autonomous-driving/system-approval-for-conditionally-automated-driving.html, 2021, visited on 06/08/2022

**Merriam-Webster: ”map” in merriam-webster.com (2022)**

Merriam-Webster: ”map” in merriam-webster.com, URL: https://www.merriam-webster.com/dictionary/map, 2022, visited on 07/21/2022

**Milakis, D. et al.: Policy and society related implications of automated driving (2017)**

Milakis, Dimitris; van Arem, Bart; van Wee, Bert: Policy and society related implications of automated driving: A review of literature and directions for future research, in: Journal of Intelligent Transportation Systems, Vol. 21, pp. 324–348, 2017

**National Oceanic and Atmospheric Administration: Beaufort Wind Scale (2022)**

National Oceanic and Atmospheric Administration: Beaufort Wind Scale, URL: https://www.spc.noaa.gov/faq/tornado/beaufort.html, 2022, visited on 07/28/2022

**Nolte, M. et al.: Towards a skill- and ability-based development process (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: IEEE ITSC 2017, pp. 1–6, 2017

**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 (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.: Generierung hochdetaillierter Karten für das automatisierte Fahren (2019)**

Poggenhans, Fabian: Generierung hochdetaillierter Karten für das automatisierte Fahren, 2019

**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

**Ponn, T. et al.: Identify Relevant Scenarios for Type Approval of AV (2019)**
Ponn, Thomas; Christian Gnandt; Frank Diermeyer: An Optimization-based Method to Identify Relevant Scenarios for Type Approval of Automated Vehicles, in: International Technical Conference on The Enhanced Safety of Vehicles (ESV), 2019

**Popper, K. R.: The logic of scientific discovery (1968)**
Popper, Karl R.: The logic of scientific discovery, [3. ed. revised]. Edition, Hutchinson, 1968

**Regele, R.: Using Ontology-Based Traffic Models for More Efficient Decision Making (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

**Riedmaier, S. et al.: Survey on Scenario-Based Safety Assessment of Automated Vehicles (2020)**
Riedmaier, Stefan; Ponn, Thomas; Ludwig, Dieter; Schick, Bernhard; Diermeyer, Frank: Survey on Scenario-Based Safety Assessment of Automated Vehicles, in: IEEE Access, Vol. 8, pp. 87456–87477, 2020

**Rizaldi, A. et al.: Formalising Traffic Rules for Accountability of Autonomous Vehicles (2015)**
Rizaldi, Albert; Althoff, Matthias: Formalising Traffic Rules for Accountability of Autonomous Vehicles, in: 2015 IEEE 18th International Conference on Intelligent Transportation Systems (ITSC 2015), pp. 1658–1665, 2015

**Rizaldi, A. et al.: Formalising and Monitoring Traffic Rules for Autonomous Vehicles in Isabelle/HOL (2017)**
Rizaldi, Albert; Keinholz, Jonas; Huber, Monika; Feldle, Jochen; Immler, Fabian; Althoff, Matthias; Hilgendorf, Eric; Nipkow, Tobias: Formalising and Monitoring Traffic Rules for Autonomous Vehicles in Isabelle/HOL, in: Polikarpova, Nadia; Schneider, Steve (PUB): Integrated Formal Methods, Springer International Publishing, 2017

**Road and Transportation Research Association: Begriffsbestimmungen für das Straßen- und Verkehrswesen (2020)**
Road and Transportation Research Association: Begriffsbestimmungen für das Straßen- und Verkehrswesen, 2020

**Road and Transportation Research Association: Directives for the Design of Urban Roads (2012)**
Road and Transportation Research Association: Directives for the Design of Urban Roads, 2012

**SAE International: J3016: Taxonomy and Definitions for Terms (2018)**
SAE International: Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems, 2018

**Sauerbier, J. et al.: Definition von Szenarien zur Absicherung automatisierter Fahrfunktionen (2019)**
Sauerbier, Jan; Bock, Julian; Weber, Hendrik; Eckstein, Lutz: Definition von Szenarien zur Absicherung automatisierter Fahrfunktionen, in: ATZ - Automobiltechnische Zeitschrift, Vol. 121, pp. 42–45, 2019

**Scholtes, M. et al.: 6-Layer Model for a Structured Description 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; Kortke, 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

**Schuldt, F.: Methodischer Test von automatisierten Fahrfunktionen (2017)**
Schuldt, Fabian: Ein Beitrag für den methodischen Test von automatisierten Fahrfunktionen mit Hilfe von virtuellen Umgebungen, Dissertation, Technische Universität Braunschweig, 2017

**Schuldt, F. et al.: Effiziente systematische Testgenerierung für Fahrerassistenzsysteme (2013)**
Schuldt, Fabian; Saust, Falko; Lichte, Bernd; Maurer, Markus; Scholz, Stephan: Effiziente systematische Testgenerierung für Fahrerassistenzsysteme in virtuellen Umgebungen, 2013

**Schwalb, E. et al.: A Two-Level Abstraction ODD Definition Language: Part II (2021)**
Schwalb, Edward; Irvine, Patrick; Zhang, Xizhe; Khastgir, Siddartha; Jennings, Paul: A Two-Level Abstraction ODD Definition Language: Part II, in: 2021 IEEE International Conference on Systems, Man, and Cybernetics (SMC), pp. 1669–1676, 2021

**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

**SAE: Best Practice for Describing an Operational Design Domain (2020)**
Society of Automotive Engineers: Best Practice for Describing an Operational Design Domain: Conceptual Framework and Lexicon, 2020

**SAE: J3131: Definitions for Terms Related to Automated Driving (2022)**
Society of Automotive Engineers: J3131: Definitions for Terms Related to Automated Driving Systems Reference Architecture, 2022

**Spillner, A.; Linz, T.; Schaefer, H.: Software testing foundations (2014)**
Spillner, Andreas; Linz, Tilo; Schaefer, H.: Software testing foundations, Fourth edition. Edition, Rocky Nook, 2014

**Stahl, T. N.: Safeguarding complex and learning-based automated driving functions via online verification (2022)**
Stahl, Tim Nikolaus: Safeguarding complex and learning-based automated driving functions via online verification, Dissertation, Technische Universität München, 2022

**Steimle, M. et al.: Toward a Consistent Taxonomy for Test Approaches (2021)**
Steimle, Markus; Menzel, Till; Maurer, Markus: Toward a Consistent Taxonomy for Scenario-Based Development and Test Approaches for Automated Vehicles: A Proposal for a Structuring Framework, a Basic Vocabulary, and Its Application, in: IEEE Access, Vol. 9, pp. 147828–147854, 2021

**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

**Szimba, E. et al.: Assessing user benefits of automated driving (2020)**
Szimba, Eckhard; Hartmann, Martin: Assessing travel time savings and user benefits of automated driving – A case study for a commuting relation, in: Transport Policy, Vol. 98, pp. 229–237, 2020

**Templeton, B.: Tesla's "Shadow" Testing (2019)**
Templeton, Brad: Tesla's "Shadow" Testing Offers A Useful Advantage On The Biggest Problem In Robocars, in: Forbes, 2019

**Virginia Tech Transportation Institue: Framework for Testable Cases and Scenarios (2018)**
Thorn, Eric; Kimmel, Shawn; Chaka, Michelle: A Framework for Automated Driving System Testable Cases and Scenarios, 2018

**U.S. Department of Transportation: Manual on Uniform Traffic Control Devices (2009)**
U.S. Department of Transportation: Manual on Uniform Traffic Control Devices, URL: https://mutcd.fhwa.dot.gov/pdfs/2009r1r2r3/mutcd2009r1r2r3edition.pdf, 2009

**U.S. Naval Observatory: Rise, Set, and Twilight Definitions (2022)**
U.S. Naval Observatory: Rise, Set, and Twilight Definitions, URL: https://aa.usno.navy.mil/faq/RST_defs, 2022, visited on 07/28/2022

**Ulbrich, S. et al.: Defining the Terms Scene, Situation, and Scenario (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.: Graph-based context representation (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

**Underwriters Laboratories: UL4600: Safety for the Evaluation of Autonomous Products (2022)**
Underwriters Laboratories: ANSI/UL4600: Standard for Safety for the Evaluation of Autonomous Products, 2022

**UNECE: European Agreement supplementing the Convention on road traffic (1971)**
United Nations Economic Commission for Europe: European Agreement supplementing the Convention on road traffic, 1971

**UNECE: Geneva Convention on Road Traffic (1949)**
United Nations Economic Commission for Europe: Geneva Convention on Road Traffic, 1949

**UNECE: Regulation R 79 (2021)**
United Nations Economic Commission for Europe: Regulation No. 79 - Uniform provisions concerning the approval of vehicles with regard to steering equipment, 2021

**UNECE: Vienna Convention on Road Signs and Signals (1968)**
United Nations Economic Commission for Europe: Vienna Convention on Road Signs and Signals, 1968

**UNECE: Vienna Convention on Road Traffic (1968)**
United Nations Economic Commission for Europe: Vienna Convention on Road Traffic, 1968

**Volkswagen AG: Automatische Distanzregelung (Active Cruise Control - ACC) (2022)**
Volkswagen AG: Automatische Distanzregelung (Active Cruise Control - ACC), URL: https://www.volkswagen-newsroom.com/de/automatische-distanzregelung-active-cruise-control-acc-3664, 2022, visited on 08/03/2022

**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

**Wachenfeld, W. et al.: VAAFO - A New Runtime Validation Method (2018)**
Wachenfeld, Walther; Winner, Hermann: Virtual Assessment of Automation in Field Operation - A New Runtime Validation Method, in: 10. Workshop Fahrerassistenzsysteme und automatisiertes Fahren, 2018

**Wang, C.: Silent Testing for Safety Validation (2021)**
Wang, Cheng: Silent Testing for Safety Validation of Automated Driving in Field Operation, Dissertation, Technische Universität Darmstadt, 2021

**Waymo LLC: Waymo is opening its fully driverless service (2020)**
Waymo LLC: Waymo is opening its fully driverless service to the general public in Phoenix, URL: https://blog.waymo.com/2020/10/waymo-is-opening-its-fully-driverless.html, 2020, visited on 06/09/2022

**Waymo LLC: Waymo Safety Report (2021)**
Waymo LLC: Waymo Safety Report, URL: https://storage.googleapis.com/waymo-uploads/files/documents/safety/2021-12-waymo-safety-report.pdf, 2021, visited on 11/21/2022

**Witte, F.: Testmanagement und Softwaretest: Theoretische Grundlagen und praktische Umsetzung (2019)**
Witte, Frank: Testmanagement und Softwaretest: Theoretische Grundlagen und praktische Umsetzung, 2., erweiterte Auflage. Edition, Springer Vieweg, 2019

**Zhao, C. et al.: A Negotiation-based Right-of-way Assignment Strategy (2019)**
Zhao, Can; Li, Zhiheng; Li, Li; Wang, Xiao; Wang, Fei-Yue; Wu, Xiangbin: A Negotiation-based Right-of-way Assignment Strategy to Ensure Traffic Safety and Efficiency in Lane Change, URL: https://arxiv.org/pdf/1904.06500, 2019

# Own Publications

**Glatzki, Felix**; Lippert, Moritz; Winner, Hermann: Behavioral Attributes for a Behavior-Semantic Scenery Description (BSSD) for the Development of Automated Driving Functions, 2021 IEEE International Intelligent Transportation Systems Conference (ITSC), 19.-22.09.2021, Indianapolis, IN, USA, pp. 667-672, 2021.

**Glatzki, Felix**; Winner, Hermann: Inferenz von Verhaltensattributen der Verhaltenssemantischen Szeneriebeschreibung für die Entwicklung automatisierter Fahrfunktionen, 14. Uni-DAS e.V. Workshop Fahrerassistenz und automatisiertes Fahren, 9-11.05.22, Berkheim, pp. 151-163, 2022.

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/pdf/2202.05211, 2022.

# Supervised Theses

**Berghöfer, Moritz :** Entwicklung eines Konzepts zur Integration der verhaltenssemantischen Szeneriebeschreibung in hochgenaue Karten.
Master-Thesis Nr. 839/21

**Bonneschky, Marco:** Analyse der Nutzbarkeit von IPGMovie in einer CarMaker-Simulation für die Entwicklung von Perzeptionsalgorithmen für das automatisierte Fahren.
Bachelor-Thesis Nr. 1358/20

**Hildebrand, Jannik:** Entwicklung eines Frameworks zur automatisierten Generierung der BSSD-Erweiterung für lanelet2-Karten.
Master-Thesis Nr. 837/21

**Hülsmann, Robert:** Formale Falsifikationskriterien als Grundlage für die Verhaltensplanung basierend auf Reinforcement Learning Algorithmen.
Master-Thesis Nr. 792/20

**Navaratnam, Thanush:** Entwicklung eines Tools zur Visualisierung einer verhaltenssemantischen Szeneriebeschreibung von Streckenabschnitten.
Bachelor-Thesis Nr. 1373/20

**Nguyen, Phuong Lilien:** Entwicklung eines Testkonzeptes für die Objekterkennung eines automatisierten Fahrzeuges.
Master-Thesis Nr. 793/20

**Schmidt, Marvin:** Entwicklung einer Verhaltensbeschreibung für automatisierte Fahrzeuge in semantischer und formalisierter Form.
Master-Thesis Nr. 778/20