How to Derive Behavioral Requirements for Automated Driving from a Behavior-Semantic Scenery Description

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Abstract: For development and safety validation of highly automated vehicles, there is currently no systematic approach for the derivation of requirements. However, deriving requirements directly from the specified operational design domain (ODD) seems promising. Therefore, this paper presents an approach for deriving behavioral requirements based on the scenery as the main component of the ODD. With the help of Behavior-Semantic Scenery Description (BSSD), lane-specific routes within the scenery are derived and the corresponding resulting behavioral demands are identified. These behavioral demands are then used for the specification of behavioral requirements. Finally, the entire approach is applied as an example for a selected real-world scenery section.

Key words: automated driving, behavioral requirements, ODD, requirement derivation

1 Introduction

Ensuring a safe intended functionality is essential from the beginning of the development of highly automated vehicles (HAV) that shall move safely through road traffic [1]. The intended functionality defines the desired vehicle behavior within the operational design domain (ODD), which specifies operating conditions for a specified operational area [2]. The ODD primarily constrains the vehicle environment, but may also define vehicle behavior and vehicle states [3]. The major part of the vehicle environment is the scenery, which mainly describes roads with associated traffic infrastructure [4]. In order to ensure safe and traffic rule compliant intended functionality within the ODD, the driving behavior of HAV must be defined accordingly within the specified scenery. In this context, the driving behavior is understood as externally observable behavior and will be referred to simply as observable behavior in the following. It represents the interaction of a vehicle with other traffic participants and the remaining environment [5]. Consequently, the observable behavior is the benchmark for evaluating safe and traffic rule compliant intended functionality. Therefore, for the successful development and safety validation of HAV, requirements for the observable behavior must first be identified and defined. In the following, these requirements are referred to as behavioral requirements.

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2 Problem Statement

The HAV development process requires approaches and methods that first identify the constraints of the observable behavior and then define behavioral requirements. In addition to basic collision-preventive behavior, such as defined in the Responsibility-Sesitive Safety (RSS) [6], it is necessary to establish the scenery dependency of behavioral requirements. Glatzki et al. [7] present an approach to a Behavior-Semantic Scenery Description (BSSD) that represents behavioral constraints using behavioral attributes. Thereby, the behavioral demands are directly derived based on the scenery as a central component of the ODD. However, the derivation of behavioral requirements based on the behavioral demands remains unclear. The authors of this paper are not aware of any approach that presents a method for deriving those essential behavioral requirements systematically starting from the ODD or scenery. Different subdomains of the HAV development chain such as the randomized scenario generation for testing [8] or the derivation of safety goals based on different intermediate steps [9, 10] are addressed, but not systematically started and executed in a holistic context. Without this context, it is not clear, on the one hand, how exactly the intended functionality is defined on the basis of the ODD and, on the other hand, how the intended functionality is tested and validated in the development process. Based on a BSSD, we therefore present an approach for a systematic derivation of behavioral requirements for HAV to potentially overcome this root specification problem.

3 Fundamentals of the BSSD

In the following, the approach for BSSD using behavioral attributes according to Glatzki et al. [7] is described as a basis for further steps. BSSD describes the scenery with the help of behavioral demands limiting the vehicle behavior. In this process, scenery and applicable traffic rules are combined so that the corresponding behavioral demands are available for each part of the scenery. In this way, the complexity of a scenery is reduced to the behaviorally relevant information. The behavioral demands are mapped using four behavioral attributes. These four behavior dimensions span the behavior space as the delimited set of legally possible behaviors. The behavior space consists of at least one atomic behavior space, which usually represents one lane section of a scenery. It is thus the smallest possible behavior space in which the behavioral demand does not change. In the following, the atomic behavior space will be called behavior space for simplicity.

The four behavioral attributes are *speed*, *boundary*, *reservation* and *overtake*. The *speed attribute* contains all behavioral demands regarding the maximum or the minimum permissible speed. The *boundary attribute* limits the behavior space not only in terms of driving behavior but also geometrically. There is one longitudinal boundary specifying the crossing demand when entering the behavior space longitudinally and two lateral boundaries specifying the crossing demand when leaving it laterally. The *reservation attribute* contains behavioral demands with respect to staying in a behavior space. Here, the demands are linked to the priority rules that apply. In this way, for example, crosswalks or intersections can be represented with the appropriate traffic participants having priority. Finally, the *overtake attribute* describes the behavioral demands regarding overtaking maneuvers.

4 Preliminary Considerations

Before the BSSD can be used to systematically derive behavioral requirements for automated driving functions, the relationship between ODD, scenery and requirements must first be shown. The simplified UML class diagram in Figure 1 is used to illustrate this relationship. The starting point for the considerations is an automated vehicle with a defined observable behavior. This behavior only exists if the vehicle also exists, so it is modeled as a composition of the vehicle. Such a vehicle is operated in a defined ODD, which demands requirements for automated driving (AD) within it. During operation, the automated vehicle moves or drives within the scenery, which constitutes the main part of the ODD, but in principle also exists without ODD definition. It therefore represents an aggregation of the ODD. The scenery can basically be described by the BSSD with respect to the behavior-relevant information. It represents the behavioral demands defined by the scenery. Even without BSSD, these behavioral demands exist, but without explicit representation. Thus, the BSSD acts as a tool to explicitly represent the scenery-based behavioral demands. These can potentially be used to derive behavioral requirements. They are a central part of the overall requirements for automated driving and explicitly define the observable behavior of the automated vehicle under consideration.

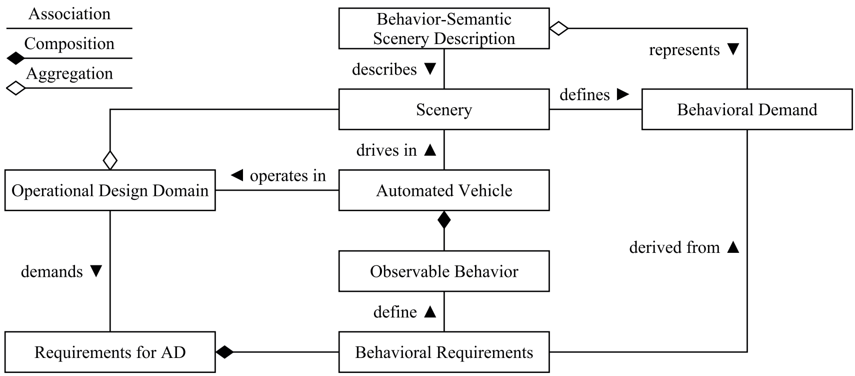


Figure 1: Relationship between ODD, scenery and requirements for AD

5 Systematic Derivation of Behavioral Requirements

Based on the identified relationship between scenery and requirements for automated driving, the behavioral requirements are derived using the BSSD. We first distinguish local from global behavioral requirements. *Global requirements* are requirements for the behavior of HAV that do not result from a specific scenery. They are scenery-independent, generally valid and have a global scope. These requirements essentially reflect the requirement of being collision-free, which is ideally satisfied always and everywhere. One approach to describing and formalizing collision avoidance requirements is RSS [6]. *Local behavioral requirements*, on the other hand, are requirements for the behavior of HAV that result from a specific scenery. They are scenery-dependent, not generally valid, and have a local scope. These requirements result from a specific combination of scenery elements and traffic rules. Within a considered scenery or ODD, the same local behavioral requirements may apply in several places, but still the local reference remains, so that no globality can be attributed to these requirements. They are derived directly on the basis of the BSSD, in which the behavioral demands resulting from combinations of scenery elements and traffic rules are already present. In parallel, the global requirements are to be defined, which always apply everywhere. In case of conflicts of the required vehicle behavior from local and global requirements, the behavior has to be prioritized based on the global requirements. In the context of this work, only the *local behavioral requirements* are considered, which are simply called *behavioral requirements* in the following.

To systematically derive the behavioral requirements, the relevant behavioral demands of the BSSD are identified. It is not possible to speak of a general relevance, since the behavioral demands depend on the selected route within the scenery or ODD. Specifically, the behavioral demands are dependent on the behavior spaces that are part of the considered route. Since order and transitions of the navigated behavior spaces influence the resulting behavioral demands of the route, a concatenation of the behavior spaces must be considered. Thus, a directed analysis in form of a lane-specific route within the BSSD, that specifies a concatenation of behavior spaces, is always necessary to derive behavioral requirements. A part of these requirements results directly from the individual concatenated behavior spaces and another part results from the concatenation itself. Figure 2 shows these steps for a derivation of behavioral requirements in simplified form. The BSSD of a road network represents the behavior spaces and thus offers the possibility to concatenate these behavior spaces as in a lane-specific route. Within the concatenation, the transitions between the individual behavior spaces are defined. Depending on

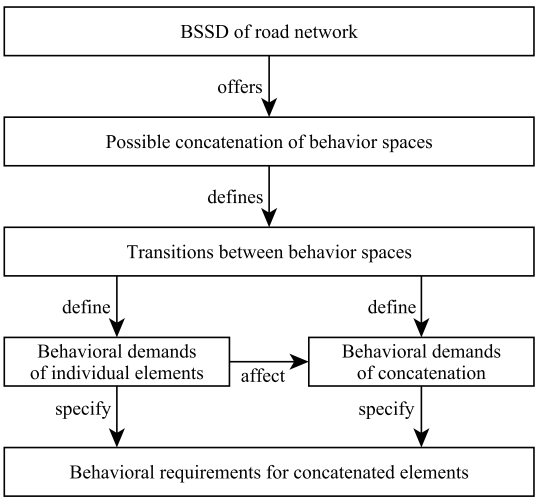


Figure 2: Derivation of behavioral requirements based on BSSD

the transitions, the relevant behavioral demands of the individual behavior spaces are defined. Additionally, the transitions between the individual behavioral demands result in behavioral demands of the concatenation. Together, the behavioral demands of the individual behavioral spaces and the concatenation specify the resulting behavioral requirements. In the following, the individual steps are explained in more detail. The BSSD and its derivation are taken as given in this work, but Glatzki and Winner [11] present an approach to derive the behavioral attributes.

5.1 Transitions within the BSSD

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

Each behavior space is represented by the four behavioral attributes *speed*, *boundary*, *reservation*, and *overtake*. Only the *boundary attribute*, in addition to limiting the possible behavior of an HAV, also limits the physical dimensions of the behavior space itself. Consequently, this attribute gives the abstract behavior space its physical geometric shape. The behavior spaces can be simplified as rectangles as shown in Figure 3. For clarity, spacings are drawn between the individual behavior spaces that do not exist in a real scenery. In reality, the behavior spaces correspond to lane sections, for example. Due to the directionality of the behavioral demands, a driving direction must be assumed for the consideration of the behavioral spaces (here from left to right). Since only the geometric shape is relevant for a consideration of the possible transitions between several behavior spaces, only the *boundary attribute* is visualized accordingly. A behavior space is always bounded by two lateral boundaries (right and left) and a longitudinal boundary. The longitudinal boundary is located at the beginning of the behavior space according to the

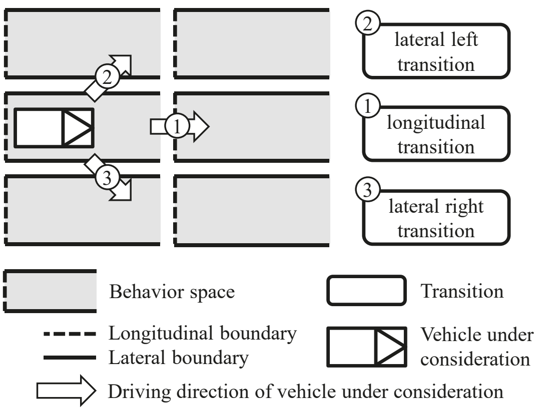


Figure 3: Transitions within BSSD

direction of travel, i.e. at the left edge of the behavior space in the figure shown.

In principle, there are only two states for a considered vehicle within the BSSD. The vehicle may or may not be completely within a behavior space. If the vehicle is in more than one behavior space, we speak of overlapping. Overlapping is always initiated by a transition, which describes the moment when the vehicle crosses a boundary of the behavior space. After a transition, a vehicle can basically maintain the state of overlapping, for example by driving in two lanes at the same time, or return completely to a single behavior space. Since a behavior space always consists of one longitudinal and two lateral boundaries, this results in three basic transitions: *longitudinal*, *lateral left* and *lateral right*.

In the figure, these transitions are shown in isolation. In reality, however, the transitions are not always isolated, since the vehicle has a spatial extension and cannot be modeled as a point. Considering a lane change, the vehicle could make an additional longitudinal transition during a lateral transition, resulting in overlapping four behavior spaces. In this case, there would actually be three boundaries involved: one lateral and two longitudinal. Furthermore, a behavior space could be geometrically very short or very narrow, so that a vehicle performs several lateral or longitudinal transitions simultaneously while passing through it (e.g., in the area of a crosswalk). This problem of overlapping more than two behavior spaces will be neglected in the context of this work, since it has no influence on the derivation mechanism of the behavioral requirements. Thus, an explanation of the rule mechanism for resolving these ambiguities is omitted. As a result, a vehicle is assumed to be a point for the consideration of transitions.

5.2 Behavioral Demands of Individual Elements

In order to obtain the relevant, applicable behavioral demands for a concatenation of behavior spaces, there must be a unique assignment of behavioral demands for each possible position of a vehicle within this concatenation. If a route is considered along concatenated behavior spaces, the vehicle necessarily passes through the associated transitions. Consequently, it is necessary to identify which behavioral demands of all concatenated behavior spaces are relevant and valid for this considered route. For identification, an arbitrary concatenation of behavior spaces, in the following also referred to as elements, is traversed. A necessary prerequisite is that the concatenated elements are direct neighbors, so that a direct transition is possible.

Let M_{BS} be the set of all behavior spaces within a BSSD. We define the concatenation of $n_{\mathrm{C}} \in \mathbb{N}$ behavior spaces as the sequence $C = (E_i)_{i=1,2,\ldots,n_{\mathrm{C}}}$ while $E_i \in M_{\mathrm{BS}}$ and $(E_j, E_{j+1})_{j=1,2,\ldots,n_{\mathrm{C}}-1}$ are pairs of direct neighbors with the transition $T_{j,j+1}$ (section 5.1) between them. Let D_i be the set of relevant behavioral demands of element E_i.

Figure 4 shows an example of a concatenation C with $n_{\mathrm{C}} = 6$ elements, corresponding transitions $T_{j,j+1}$ and resulting relevant behavioral demands D_i of the individual elements to visualize the following considerations. The example section of a BSSD road network with 12 behavior spaces could represent a three-lane one way road. However, the concrete scenery or BSSD representation is not important for the considerations. Here, in particular, the relation of the different terms should become clear in order to build up an overall understanding.

Starting in the first element E_1 of concatenation C, the behavioral demands of the *speed*, *reservation*, and *overtake* attributes of this element are relevant. In general, the

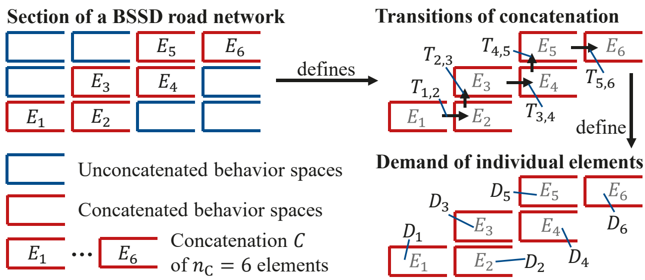


Figure 4: Visualization of an example BSSD road network section

first element is a special case because it is the only element of the concatenation that is not reached by a transition when traveling from first element E_1 to last element E_n with $n = n_C$ (E_6 in the example). For this reason, no behavioral demand results from a transition, so the behavioral demands of the *boundary attribute* are irrelevant.

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

Table 1: Relevant behavioral demands with respect to the transitions

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

5.3 Behavioral Demands of Concatenation

With the help of the identified relevant behavioral demands for driving through a concatenation of behavior spaces, the derivation of the associated behavioral demands becomes possible. For each element E_i of a concatenation C, the behavioral demands for driving in this element depending on the entry transition are known. The behavioral demands can be semantically transformed in order to specify the associated behavioral requirements in a further step. But are these behavioral requirements alone sufficient? So far, only the resulting behavioral demands of individual behavior spaces have been considered. A simple example shows that the behavioral demands of each individual behavior space might not be sufficient in any case. We consider a transition from E_j to E_{j+1}. In this case, the behavioral demands change from D_j to D_{j+1}. Only the change in behavioral demands of the *speed attribute* is considered in this example. Given D_j demands a higher speed limit than D_{j+1}, a vehicle is allowed to drive faster in E_j than in E_{j+1}. However, the current consideration does not provide more information. A vehicle would exceed the speed limit when entering E_{j+1} due to kinematic dependencies, since it would have had to decelerate before entering this element in order to comply with this limit. Thus, it can be concluded that an additional demand for speed adjustment before entering the element is necessary in this case.

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

To determine the behavioral demands $D_{j,j+1}$, in particular, the kinematic dependencies of a moving vehicle must be considered. These dependencies lead to the fact that behavioral demands with respect to allowed speeds or accelerations are possible from all four behavioral attributes. For example, if a behavior space is externally-reserved due to the *reservation attribute*, a vehicle must give priority when entering this space. This behavioral demand directly affects the demanded speed profile when entering this space.

In order to derive the behavioral demands $D_{j,j+1}$ holistically, all possible combinations of the concatenated behavioral demands of D_j and D_{j+1} must be explored. Although the behavioral-level abstraction within the BSSD allows for a large reduction in the necessary information compared to other approaches, the goal is to minimize the parameter space for an analysis even in this combination approach. Since the BSSD classifies the behavioral demands into four independent behavioral attributes, there is no need to combine the

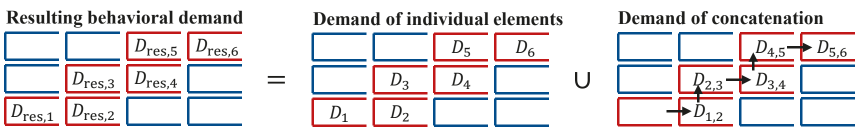


Figure 5: Visualization of relationship between behavioral demands $D_{\text{res},i}$, D_i and $D_{j,j+1}$

attributes due to the independency among them. This means that combining behavioral attributes with different characteristics does not create new behavioral demands. For example, it has no influence on the behavioral demands with respect to the *speed attribute* whether a combination additionally changes the *reservation attribute*. As a result, a demand for a maximum allowed speed profile may arise in each case, but independently from each other. In case of different arising speed demands, a minimum prioritization depending on a ordinal scale would be possible. However, the scales of the different behavioral demands are not part of this work.

Due to the independency, the combination of the behavioral demands is done separately for each behavioral attribute. The behavioral attributes not considered are neglected. For each combination D_j and D_{j+1} it is checked whether further behavioral demands $D_{j,j+1}$ result from this specific concatenation. In the following, a specific combination of behavioral demands is considered for three behavioral attributes by way of example.

Speed: The example at the beginning of this section is considered again. Thus, D_j demands a higher speed limit than D_{j+1}, so that a vehicle must drive slower in E_{j+1} than in E_j. This results in the behavioral demand $D_{j,j+1}$, which demands a speed adjustment to the changed speed limit before entering E_{j+1}. In contrast, given D_j demands a lower speed limit than D_{j+1} would not result in a new behavioral demand $D_{j,j+1}$, since a vehicle is not legally forced to increase speed in the absence of a minimum speed constraint.

Reservation: let E_j be own-reserved and E_{j+1} be externally-reserved. Accordingly, D_{j+1} requires that certain traffic participants with certain directions of arrival who have reservation rights to the area E_{j+1} are not obstructed. Obviously, an obstruction can only occur if other traffic participants with reservation claim are actually nearby when entering this area. If this is the case, these traffic participants must therefore be guaranteed to continue their driving as unhindered as possible. For this purpose it is important to indicate to these traffic participants that the own waiting obligation is fulfilled (see also German road traffic regulations [12]). Another behavioral demand $D_{j,j+1}$ is therefore to indicate in advance that the respective traffic participants will be given priority.

Overtake: If D_j is a permission and D_{j+1} is a prohibition to overtake, then initially there is only the demand that overtaking is not allowed in E_{j+1}. But what if a vehicle starts an overtaking maneuver beforehand and does not finish it prior to entering E_{j+1}? In this case, the behavioral demand would clearly be violated, so that another demand $D_{j,j+1}$ is needed. $D_{j,j+1}$ states that a potential overtaking maneuver is to be completed before entering area E_{j+1}.

5.4 Resulting Behavioral Requirements

After deriving the resulting behavioral demands $D_{\mathrm{res},i}$ for all elements E_i of a concatenation C, the specification of the behavioral requirements is possible. The specification essentially consists of a semantic processing of the derived behavioral demands. This step is necessary in order to use the behavioral requirements in the context of automated driving. This means, on the one hand, that the behavioral requirements are used to precisely specify the observable behavior and, on the other hand, that the remaining requirements for the automated driving task are inferred based on the behavioral requirements. In particular, it must be ensured that the set of possible behaviors of a vehicle is restricted only as far as necessary. For this purpose, the requirements should be formulated as negated as possible, since in this way, as with the behavior space itself, only the limit of the permitted behavior is defined.

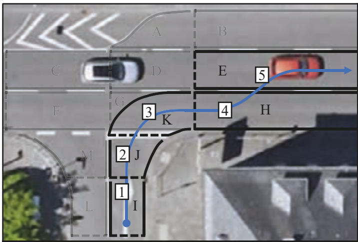
The following simple example of an imprecise formulation shows an intervention in the behavioral planning of a vehicle that clearly goes beyond the definition of the behavioral limit. If the entry into a behavior space is controlled by a traffic light, then the crossing demand of the *boundary attribute* results in "no red light". Thus, the vehicle is not allowed to cross the associated boundary when the traffic signal is red. A restrictive requirement would be: *The vehicle shall stop at the boundary when the traffic light is red.* With this requirement, the vehicle is forced to stop, although it could approach the traffic light just as foresightedly in order not to have to stop. Further example requirements are additionally shown in the following section.

6 Real-World Application Example

To demonstrate the presented method, a real scenery from Darmstadt (Germany) is considered in Figure 6. The aerial view shows a T-intersection with a multi-lane one-way road running from left to right and a two-lane side road with two-way traffic. An abstract representation of the BSSD is shown as the second layer. Here, the dark frames show part of the behavior spaces on this scenery section, which are marked with capital letters. Since there is always one behavior space per direction of travel (even against the one-way street) and these can also overlap in intersection areas, not all behavior spaces are shown for clarity (including the behavior space of the restricted area). The present segmentation of the behavioral spaces is based on changes in the behavioral demands in the longitudinal direction. If there are changed behavioral demands due to the scenery, a new segment is created. The behavior spaces are present in the BSSD unconcatenated, so that initially only information about the relative position of the behavior spaces to each other is known. Therefore, a possible concatenation of the behavior spaces is represented as the third level. The concatenation follows the path drawn in blue, which can potentially be followed by a vehicle. Non-concatenated behavior spaces are shown slightly transparent compared to the concatenated ones.

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

As shown in the figure, the concatenation $C = (\mathrm{I}, \mathrm{J}, \mathrm{K}, \mathrm{H}, \mathrm{E})$ is considered, which consists of $n_\mathrm{C} = 5$ elements E_i with $i = 1, 2, \ldots, n_\mathrm{C}$ (number in white boxes corresponds to i). When this concatenation is followed, first a right turn is made coming from the minor road, and then a lane change to the left into the middle lane. According to these transitions, the behavioral demands D_i of the individual elements result. Along the concatenation, the demand of the *speed attribute* (S) does not change, so that a maximum allowed speed of 30 km/h applies to all elements E_i. In the first element $E_1 = \mathrm{I}$ there is no behavioral demand based on the *boundary attribute* (B) because there is no transition. In the third element $E_3 = \mathrm{K}$, there is a requirement that the vehicle stops before entering. The cause of this demand is a stop sign with associated stop line in the scenery. The



E_i	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$
$T_{i-1,i}$		longitud.	longitud.	longitud.	lateral
D_i	S: 30 km/h R: own O: yes	S: 30 km/h B: allowed R: own O: yes	S: 30 km/h B: stop R: ext. O: yes	S: 30 km/h B: allowed R: own O: yes	S: 30 km/h B: allowed R: own O: yes
$D_{i-1,i}$		-	R: indication of giving priority	-	R: yield to TP with same reservation
Requirements of E_i					
S: The vehicle shall not exceed a speed of 30 km/h.	x	x	x	x	x
B: The vehicle shall stop at the longitudinal boundary before proceeding.			x		
R: The vehicle shall not obstruct traffic participants with reservation entitlement for element E_i.			x		x
R: The vehicle shall indicate in advance that it yields to traffic participants with reservation entitlement for element E_i.			x		x
O: The vehicle shall not overtake.					

Figure 6: Behavioral Requirements of concatenated elements E_i based on behavioral demands of individual elements (D_i) and concatenation (D_{i-1}) depending on transitions $T_{i-1,i}$ (Aerial image © Orthophoto Vermessungsamt Darmstadt 2021)

other elements E_i have no demands concerning the entry (Crossing condition: allowed). Regarding the *reservation attribute* (R), there are no restrictive behavioral demands for the elements that are own-reserved (own), in these areas from an individual point of view no priority is to be given. Only element E_3 as representation of the intersection area has an external reservation (ext.), so that certain other traffic participants shall not be obstructed. For reasons of clarity, we do not specify the type of traffic participant and the direction of arrival in this example. Overtaking is allowed in every element E_i, so there is no restriction on behavior based on the *overtake attribute* (O).

From the transitions between the individual behavioral demands D_i, the behavioral demands $D_{i-1,i}$ from concatenation are derived. In element $E_3 = \text{K}$, an additional behavioral demand of the *reservation attribute* results. Accordingly, it must be indicated that priority is given to potentially occurring traffic participants who are entitled to reservation. In element $E_5 = \text{E}$, the *reservation attribute* additionally requires that traffic participants with the same reservation entitlement must not be obstructed. This means that a lane change from $E_4 = \text{H}$ to $E_5 = \text{E}$ shall only take place if traffic in the same direction of travel is not obstructed in the process. Due to this demand, the same requirement as in $D_{2,3}$ additionally applies, since it must also be indicated here that priority is given (not shown in table). For the purpose of clarity, we again omit a representation of the traffic participant type and direction of arrival of the traffic participants entitled to reservation.

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

7 Conclusion and Outlook

This work first identified the lack of a systematic and holistic derivation of requirements for HAV. An analysis demonstrated that the scenery as the main component of the ODD is a promising basis for such an approach. Here, the scenery is described using behavioral demands based on four behavioral attributes (BSSD) [7]. We identified possible transitions of HAV within the BSSD. They served as the basis for identifying the behavioral demands of the individual behavior spaces and of the concatenation itself, which were used to derive behavioral requirements. The entire approach was applied as an example for a selected real-world scenery section. We demonstrated that it is possible to derive behavioral requirements directly from the scenery considering a concatenation of behavior spaces representing a lane-specific route.

In further work, we will show the decomposition of the behavioral requirements to other functional levels of the automated driving task. Using these requirements based on concatenated behavior spaces, we will conceptualize and implement capability-based routing in order to archive a dynamic ODD. In this approach, driving capabilities will be matched with route section requirements. In order to achieve that, we also work on a holistic representation of the BSSD so that arbitrary road networks can be described and modeled in maps. The overall approach potentially enables a route-wise development and validation of HAV for a specific ODD and thus reduced validation effort.

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References

[1] "ISO/PAS-Norm 21448:2019 - Road vehicles - Safety of the intended functionality", International Organization for Standardization (ISO), 2019.

[2] "Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems", J3016, SAE International (SAE), 2014.

[3] K. Czarnecki, "Operational Design Domain for Automated Driving Systems - Taxonomy of Basic Terms", 2018.

[4] S. Ulbrich, T. Menzel, A. Reschka, F. Schuldt and M. Maurer, "Defining and Substantiating the Terms Scene, Situation, and Scenario for Automated Driving", 2015 IEEE 18th International Conference on Intelligent Transportation Systems, 2015, pp. 982-988, doi: 10.1109/ITSC.2015.164.

[5] M. Nolte et al., "Towards a skill- and ability-based development process for self-aware automated road vehicles", in IEEE ITSC 2017: 20th International Conference on Intelligent Transportation Systems: Mielparque Yokohama in Yokohama, Kanagawa, Japan, October 16-19, 2017, Piscataway, NJ: IEEE, 2017, pp. 1–6.

[6] S. Shalev-Shwartz, S. Shammah and A. Shashua, "On a Formal Model of Safe and Scalable Self-driving Cars", arXiv preprint arXiv:1708.06374, 2017.

[7] F. Glatzki, M. Lippert and H. Winner, "Behavioral Attributes for a Behavior-Semantic Scenery Description (BSSD) for the Development of Automated Driving Functions", 2021 IEEE International Intelligent Transportation Systems Conference (ITSC), 2021, pp. 667-672, doi: 10.1109/ITSC48978.2021.9564892.

[8] G. Bagschik, T. Menzel, C. Körner, and M. Maurer, "Wissensbasierte Szenariengenerierung für Betriebsszenarien auf deutschen Autobahnen", in *Workshop Fahrerassistenzsysteme und automatisiertes Fahren*, Vol. 12. Walting im Altmühltal: Uni-DAS e.V., 2018.

[9] T. Stolte, G. Bagschik, A. Reschka and M. Maurer, "Hazard analysis and risk assessment for an automated unmanned protective vehicle", 2017 IEEE Intelligent Vehicles Symposium (IV), 2017, pp. 1848-1855, doi: 10.1109/IVS.2017.7995974.

[10] T. Stolte, G. Bagschik and M. Maurer, "Safety goals and functional safety requirements for actuation systems of automated vehicles", 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), 2016, pp. 2191-2198, doi: 10.1109/ITSC.2016.7795910.

[11] F. Glatzki and H. Winner, "Inferenz von Verhaltensattributen der verhaltenssemantischen Szeneriebeschreibung für die Entwicklung automatisierter Fahrfunktionen", in *Workshop Fahrerassistenzsysteme und automatisiertes Fahren*. Vol. 14. Berkheim: Uni-DAS e.V., 2022.

[12] "Straßenverkehrs-Ordnung: StVO", Bundesministerium der Justiz und für den Verbraucherschutz, 2013.