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RESEARCH ARTICLE

A Framework to Define Operational Design Domains for Automated Train Operations

LUCAS GREINER-FUCHS AND MARTIN CICHON
Institute of Vehicle System Technology—Railway Systems, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
Corresponding author: Lucas Greiner-Fuchs (lucas.greiner-fuchs@kit.edu)

ABSTRACT The rail system represents a sustainable and climate-friendly mode of transportation, with significant potential for future mobility. To enhance its efficiency and competitiveness in comparison with other mobility systems, it is essential to prioritize the research and development of automated and digitalized rail systems. An operational design domain represents the fundamental parameters of an operational area and the specific application field of a given technical system. This multi-dimensional space serves to delineate the safe area of use of the system from that which is unauthorized. The operational design domain is frequently employed in the development and evaluation of highly automated driving systems. The automotive sector offers the standard ISO 34503:2023 as an advanced method of defining operational design domains for highly automated road vehicles. In order to create an equivalent structure, this work establishes a framework for a railway-specific operational design domain taxonomy. Thus, the definition of an automated railway system is subject to a comprehensive examination and specification. Where applicable, elements of the automotive standard are directly transferred, while others are redesigned to align with the specific requirements of the railway sector. In some instances, non-transferable and adaptable sections are removed, while new attributes are added. In defining the taxonomy and its attributes, the focus is primarily on typical railway conditions and operational tasks, which clearly differentiates it from automated driving in the automotive sector. This paper contributes to the establishment of a standardized framework for defining the operating conditions of automated train operations, thereby paving the way for more efficient and sustainable railway systems.

INDEX TERMS Automated driving system, automated train control, automated train operation, operational design domain, railway systems, taxonomy.

I. INTRODUCTION

The prevailing economic, business, and social circumstances have mandated a transformation in mobility and transportation. This is driven by automation and digitalization of a wide range of means of transport. Compared to motorized individual transport and road-based freight transport, the railway system is regarded as a climate-friendly alternative. The advantages of rail operation include low greenhouse gas emissions and high energy efficiency, which result from the use of electromobility. Moreover, the system offers a high level of traffic safety and a high capacity for passenger and freight transport with low land consumption. Despite the recognition of the advantages of rail operations at both the social and global levels, the share of rail passenger transport has remained static in recent years, and in the case of rail freight transport, has even decreased in Europe. This is attributable to the suboptimal economic performance of the rail system. Nevertheless, in light of the current ecological and political situation, it is anticipated that there will be a notable increase in Europe. In order to accommodate this anticipated growth, it is imperative that the rail industry prioritizes research and development in automated systems and digital solutions [1].

The automotive industry has already established a range of research approaches, tools, and methods for the development and testing of highly automated driving systems (ADS). However, the railway system differs significantly

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from the automobile in several respects, which gives rise to different and novel challenges, requirements, and priorities in the development, testing, and regulations of automated train operations (ATO).

First of all, the driving dynamics of rail vehicles differ from that of road vehicles. The high mass of the vehicle and the coefficient of friction between the wheels and rails result in long braking distances. Furthermore, the vehicle is constrained to the track, thereby precluding evasive maneuvers or lane changes. A further distinction can be observed in the context of the actual rail network and the associated rules and guidelines. It is possible to operate trains in different conditions and with different responsibilities concerning train control [2]. This also implies that in faultless operation the tracks are not shared with other traffic participants and that it is not permitted for two trains to occupy the same track section simultaneously. However, statistics and databases show that there can still be a large number of accidents and unplanned situations to which the driver or an automated system must react correctly, especially in ''on-sight'' driving modes, e.g. shunting. For these reasons, in non-automated operation rail vehicles are only operated by personnel who have received the requisite training, and there is no individual private traffic. In addition to the primary driving task, there are a number of other operational tasks and guidelines that must be adhered to in rail transport, which is explained in more detail in chapter II-B1.b.

In conclusion, the implementation of ADS in railway vehicles is contingent upon the specific area and application or task of the railway vehicle in question. For instance, due to the long braking distances, sensor-based on-board perception systems are only applicable to trains that are operating on-sight or in specific instances (such as entering or leaving a train station, or in the event of an emergency requiring the train to operate on-sight).

In addition to the implementation of the required technical and functional specifications, it is also essential to establish the parameters of the operational framework and the field of application within which the system must operate in a safe and reliable manner, or alternatively, within which it can be used. To achieve this, the term Operational Design Domain (ODD) has been established across domains. Extensive research has already been conducted in the automotive sector on the subject, as well as the development of the first publicly available taxonomy to describe an ODD [3] and the standard based on it [4]. In the rail industry, the subject is even less prevalent and there is no equivalent taxonomy. Given the inherent differences and challenges associated with the rail system, a direct transfer of the aforementioned standard is not feasible.

In order to bridge this gap and establish an analogous framework for defining railway-specific ODDs, this study will examine the transferability and adaptability of the automated standard to the railway system, as well as conduct a comprehensive investigation of the railway-specific attributes and definitions of a corresponding taxonomy.

II. AUTOMATED DRIVING SYSTEM

ADS are being employed with growing frequency across a range of domains. The systems are increasingly being defined and regulated concerning their system requirements, limitations, and scope. This chapter offers a basic overview of the current state of the art in automated driving on roads and railways. The principal focus of this chapter is on the definitions of automated driving and the levels of automation, as well as the role of an ODD.

A. AUTOMATED DRIVING IN AUTOMOTIVE APPLICATIONS

In the context of road traffic, ADS assume the role of the driver in terms of both longitudinal and lateral dynamics, as well as monitoring the driving environment and assuming responsibility for safe operation. The continuous development and improvement of system tasks and the resulting complexity in terms of regulations and responsibility in road traffic led the Society of Automotive Engineers (SAE) to define the SAE J3016 standard [5] in 2014. The standard focuses on defining driving automation systems and the associated driving tasks. A further key element is the basic definition of an ODD, which represents the limiting application area of an ADS.

1) DEFINITION OF DRIVING AUTOMATION SYSTEMS

The SAE J3016, entitled ''Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles'', represents the most widely recognized definition of driving automation systems in terms of the degree of automation currently in use. It is regarded as the industry standard and defines driving automation systems in the context of the Dynamic Driving Task (DDT), Object and Event Detection and Response (OEDR), as well as the six levels of automation [5].

a: DYNAMIC DRIVING TASK INCLUDING OBJECT AND EVENT DETECTION AND RESPONSE

The automotive standard defines the DDT as ''all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic'' [5]. The DDT is generally comprised of six subtasks, each of which can be assigned to an operational or functional driving function. Subtasks one and two describe the operational function of vehicle control of lateral dynamics through steering and longitudinal dynamics through acceleration and braking processes. Subtasks three and four are both operational and tactical functions, which are summarized as OEDR. In the initial step, the system must observe the driving environment, detect and recognize possible objects and events, classify them, and prepare an appropriate response. In the second phase, the reaction is executed. The fifth subtask pertains to the planning of maneuvers, while the sixth subtask concerns the conspicuity of the vehicle in traffic through the use of lighting, activation of the vehicle horn, signaling, and so forth. Both subtasks are tactical functions. Moreover, strategic vehicle management functions are not included in the DDT. In addition to the planning and selection of routes, this also applies to the definition of the destination and corresponding waypoints [5].

b: SAE AUTOMATION LEVEL

The subdivision of automation levels according to the SAE standard is subject to certain criteria, which are outlined below. A distinction is made between the responsibility of the driver and that of the ADS. On the one hand, this refers to the execution of the DDT, which is divided into the transfer of longitudinal and lateral dynamics, as well as the OEDR. On the other hand, the determination is made as to which entity is responsible for ensuring the safe operation of the ADS and the fallback level of DDT. Furthermore, it is indicated whether the ADS of the corresponding level is constrained by a specific ODD [5].

In Level 0, "No Driving Automation," the driver assumes complete responsibility for all driving operations. In Level 1, "Driver Assistance," a part of the DDT is assumed by the system. However, the system assumes either longitudinal or lateral dynamics, with the functions not executed simultaneously. In Level 2, "Partial Driving Automation," the driving dynamics are entirely executed by the system, while the OEDR and the fallback level remain the responsibility of the driver. At Level 3, "Conventional Driving Automation," the term "automated driving" is employed instead of "assisted driving." In this instance, the DDT is entirely assumed by the ADS, with the driver being informed of the takeover in the event of a fallback. Consequently, the driver remains responsible for the driving task. In Level 4, "High Driving Automation," all driving tasks and responsibility for safe operation are transferred to the system. The driver is no longer required to be integrated into the driving process. Nevertheless, levels one to four of the automated system are only applicable to a limited ODD and can only function within the parameters of this ODD. When the ADS is leaving the ODD the responsible unit has to perform a fallback for the DDT to reduce the risk or get back to safe operating within the ODD. Level 5, "Full Driving Automation," pertains to the functionality of an ADS in an unlimited ODD [5].

2) OPERATIONAL DESIGN DOMAIN

There is considerable diversity in the sources that define an ODD. In addition to the fundamental definition of the informative value and scope of an ODD, it is essential to adhere to a systematic methodology when creating an ODD. The use of a taxonomy as a comprehensible structure for the ODD is becoming increasingly prevalent.

a: DEFINITION

Following the SAE standard an ODD includes the "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 roadway characteristics" [5]. The Underwriters Laboratories Inc describe an ODD in the ANSI/UL 4600 standard as a "set of environments and situations the item is intended to operate within" [6]. A Definition of the United Nations Economic Commission for Europe (UNECE) delineate that an ODD "refers to the environmental, geographic, time-of-day, traffic, infrastructure, weather and other conditions under which an automated driving system is specifically designed to function" [7].

In summary, an ODD is always mentioned in connection with an ADS or its functions and features. It defines the area in which the system can and may operate and considers geographical, infrastructural, weather-related, and digital influences and limits. An ODD can be employed to delineate the system boundaries during the development process or to define the scope and limits of system testing. When an ADS is leaving the ODD the system has to perform a fallback for the DDT to reduce the risk or get back to safe operating within the ODD.

The ISO 34503:2023 standard, entitled "Road Vehicles - Test scenarios for automated driving systems - Specification for operational design domain", makes a distinction between the ODD and a target operational domain (TOD). The TOD describes "the real-world conditions that an ADS may experience and is required to safely operate in" [4]. It can thus be seen to represent a superset of the specific ODD of an ADS. In a given TOD, situations may arise that lie outside the specified ODD of the ADS, which results in the system no longer acting in a confirmed manner in these situations. Given the general structure of the ODD, it is only capable of covering the real environment in which an ADS is located to a certain degree. The ODD thus defines the boundary conditions of a specific ADS, whereas different ADS can operate within a TOD [4].

b: ODD TAXONOMY

In the course of developing a generally applicable standard for defining ODDs of automated road vehicles, a number of solutions were devised. In 2018, the National Highway Traffic Safety Administration published an initial taxonomy for describing an ODD in the report "A Framework for Automated Driving System Testable Cases and Scenarios" [8]. An alternative structure of a taxonomy was published in the form of a publicly available specification (PAS 1883) in 2020 by the British Standards Institution [3]. The definition of the ISO 34503:2023 standard is based on this premise [4]. The structure of the ODD taxonomy comprises three top-level attributes: scenery elements, environmental conditions, and dynamic elements. Each attribute is further delineated into specific sub-attributes, which describe different areas and conditions of the ODD. The number and detail of sub-attributes may vary depending on the application. The attribute scenery elements provides an overview of the fundamental static infrastructure components and delineated zones, along with an examination of the roadway design. The attribute environmental conditions describe the general conditions regarding weather, particulates, illumination, and the manner of information transfer to the ADS. Finally, in the context of dynamic elements, the attributes of the ego-vehicle (vehicle in which the ADS is integrated and which is controlled by it) are described in addition to information regarding traffic agents. This includes any potential moving objects and their mobility [4].

B. AUTOMATED DRIVING IN RAILWAY APPLICATIONS

The primary function of train control systems is to guarantee the safety of rail operations. In the event that the locomotive or the train driver exhibits inappropriate conduct, such as disregarding a signal, the system will automatically intervene in the control of the train, employing a controlled braking mechanism. The exchange of information and data occurs via a wireless communication interface between the vehicle and the landside. A considerable variety of train control systems is in use around the world. A distinction can be made according to the technology employed, whereby there is a differentiation between intermittent train control (transmission of signal information only at certain points) and train control with continuous data transmission. The latter can be implemented as a track conductor system (transmission of signal information via a line conductor installed in the track) or as a radio transmission system (transmission of signal information via radio technology). Examples of well-known and widely used systems include the intermittent automatic train running control (ger.: Punktförmige Zugbeeinflussung, PZB), continuous train control (ger.: Linienförmige Zugbeeinflussung, LZB), Communication-Based Train Control (CBTC) and the European Train Control System (ETCS) [2], [9].

The realization of an automatic train control system, also known as Automatic Train Control (ATC), requires the integration of a variety of distinct components. The technical implementation of automated driving railway vehicles is schematically illustrated in FIGURE 1 as a CBTC system. The system comprises the Automatic Train Protection (ATP) subsystem, with the potential for the inclusion of the ATO and Automatic Train Supervision (ATS) subsystems, contingent upon the level of automation. The function of the ATP is to ensure the safe operation of trains in terms of signaling and to prevent accidents such as collisions or derailments. The fundamental functions of the subsystem are the protection of the designated route, the ranging of the vehicle's location, and the automatic interval control. The system is installed in both the infrastructure and the vehicle components. The ATO system is responsible for the automated control of vehicles. In consideration of the level of automation in question, the system is tasked with performing those operations typically undertaken by the driver and train personnel, such as controlling the vehicle's longitudinal dynamics. In order for the ATO system to receive trackside information, it is necessary for it to be connected to the ATS. The system guarantees that the entire train operation is monitored and that the timetable is adhered to in passenger transport. In the event of a malfunction, the system identifies the most appropriate solution and transmits it to the ATO component of the train [2].

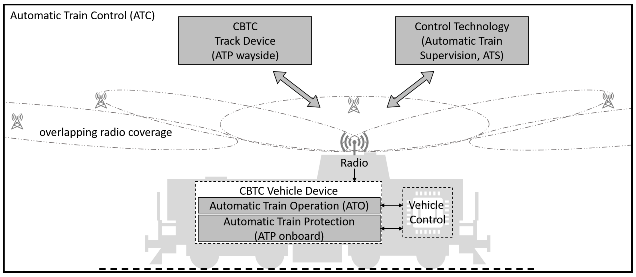

FIGURE 1. Structure of ATC system according to [2].

In the field of rail vehicle automation, the objective is to supplant the human driver with the ATO system. The automated component is thus incorporated into the ATC as an additional, novel component. In conjunction with ETCS, ATO over ETCS represents a state-of-the-art approach, as demonstrated by its application in automatic driving mode as semi-automatic train operation (GoA2, as discussed in the following chapter). In consequence of the removal of the human driver, a significant challenge in the development of ATO components is to establish a mapping of all the tasks and activities undertaken by the driver through the system, with a view to enabling driving that is at least as reliable. It is of particular consequence to consider challenging situations and scenarios with heightened risk potential. This also has implications for the requirements placed on the system and the associated grade of automation, which will be discussed in more detail in the following chapter.

1) GRADE OF AUTOMATION

A standardized definition of the grade of automation (GoA) in train operation is provided in the standard IEC 62290-1:2014 "Railway applications - Urban guided transport management and command/control systems - Part 1: System principles and fundamental concepts" [10] as well as originally in the IEC 62267:2009 standard "Railway applications - Automated urban guided transport (AUGT) - Safety requirements" [11]. In addition to the existing standard for urban rail passenger transport, research is being conducted into expand the GoA definition with regard to the mainline.

a: DEFINITION OF THE DEGREE OF AUTOMATION IN TRAIN OPERATION

As with the SAE levels in the automotive sector, the GoA levels vary according to the responsibility for specific driving and monitoring tasks. The basic functions include "ensuring safe movement of trains", "driving", "supervising track", "supervising passenger transfer", "operating a train", and "ensuring detection and management of emergency situations" [11]. In terms of implementation, this process can either be carried out by the operator or by the ATO system. GoA0, "on-sight train operation with driver", represents the manual level without automation, wherein the operator assumes all tasks and functions, as well as responsibility for safe operation. At the GoA1 level, which is defined as ''non-automated train operation'', the vehicle is operated manually on a route where vehicle movements are secured by a railway interlocking system. The system thus assumes responsibility for the safety of the train movement on a given trajectory, with the exception of speed monitoring. At GoA2, ''semi-automatic train operation'', the system assumes responsibility for the safety of the train movement and for driving the vehicle. The monitoring and responsibility for the functions remain with the driver, as well as for all other tasks. The initial stage of the highly automated operation is designated as GoA3, which is defined as ''driverless train operation''. In this context, the system is held responsible for the execution and fulfillment of all tasks and functions. The role of the driver on the locomotive is no longer required. Nevertheless, operational tasks and the fallback level in the event of a fault are still carried out by a trained train conductor. At the level of GoA4, ''unattended train operation'', the system assumes full responsibility for the vehicle and all tasks. The necessity for a driver or train conductor to be present in the vehicle is no longer a requirement. The implementation of full automation is associated with high demands on the sensors and system control [2], [10], [11].

The division of automation levels applies solely to urban guided transport and affects automated driving trains on a track network that is separate from other traffic. Nevertheless, the standard is frequently applied to other areas of rail transport.

b: DEFINITION OF THE GRADE OF AUTOMATION FOR THE MAINLINE TRACK

Within the findings of the ATO research of the German Centre for Rail Transport Research (DZSF), in the context of the ATO sensor technology project [12], a proposal was put forth to address the discrepancy in the definition of the GoA level for the mainline area. In the project, the standard and subtasks of the train driver are derived from an analysis of the driving service regulation (Guideline 408) [13] and assigned to the existing description of the GoA level [12], [14].

In addition to the urban guided transport sector, rail operations are conducted primarily on the mainline track. This encompasses passenger and freight transportation on the fundamental railway network, including shunting operations. In the event of automation of a rail vehicle, the ATO system must therefore be capable of assuming all responsibilities previously assigned to the human driver. In consideration of the driving service regulations [13] and the findings of the ATO sensor technology project [12], the standard and sub-tasks of a train driver are delineated.

The initial standard task, designated ''drive train'' encompasses the following subordinate areas: continuous speed control, adherence to speed in accordance with signalling and driving authorization, continuous location determination, monitoring of guidance variables in display-guided train control operations, determination of braking deceleration and consideration of adhesion value conditions, stopping at scheduled and other designated stopping points (operational stop, railway construction, switches) [12], [13].

The term ''shunting train'' is defined as the second standard task. This comprises the four subtasks continuous speed control, maintaining the speed in accordance with the minimum visibility, continuous location determination, as well as approaching and coupling to vehicles [12], [13].

The standard task, designated as ''monitoring the track'' encompasses the continuous observation of the currently traversed track in accordance with the granted driving authorization. This observation is conducted with regard to the following subtasks: identification of objects within and adjacent to the track, detection of collisions with objects designated as obstacles, identification of collisions with individuals within and on the neighbouring track, including those belonging to third-party vehicles [12], [13].

The next standard task, entitled ''monitoring the railway construction'' requires the continuous monitoring of the railway construction along a designated route, with particular attention paid to the specific subtasks: observe the signals in accordance with the prevailing train control operation (fixed signals, signal information in the display), observe the signalling and react to it operationally, detect disruption or absence of signals, monitor the track in accordance with the extent of damage to the superstructure and the condition of the existing adhesion value, observe the neighbouring tracks in order to ascertain any damage to oncoming trains and potential obstacles on the neighbouring track, as well as detect potential damage to an existing overhead line [12], [13].

Another standard task is to ''control and monitor entry and exit of passengers''. This encompasses the subtasks opening and closing the external passenger doors at the designated operating stop, as well as monitoring the doors for any irregularities. It is of paramount importance to guarantee the prevention of injuries to individuals, whether between vehicles within the train set or between vehicles and the platform edge. Furthermore, it is imperative to guarantee that no individuals or objects are situated at an unauthorized distance from closing doors or a departing train [12], [13].

A further standard task is ''monitor train set'', which can be described as the monitoring and interaction with the Train Control and Management System (TCMS). The monitoring of the train status comprises the following subtasks: monitoring of the status and energy supply of the braking system, monitoring the status of the traction system, door control, vehicle technology and train protection, observation of display instruments as well as recognition of open doors and displaced loads [12], [13].

In addition, two standard communicative tasks are identified. The category of ''operational communication'' is subdivided into the two subtasks communication with the dispatcher and communication with the train driver, in the event that the latter is responsible for passenger trains. The standard task of "communicating with passengers" encompasses the subtasks of ensuring communication, passenger safety and travelling comfort, as well as responding to passenger emergency calls [12], [13].

Another standard task is the "diagnosis of own vehicle and train set", whereby the underlying causes of the malfunctions must be identified and addressed. The standard task of "preparing, shutting down and stoppage the train" encompasses both the technical and operational preparation of the train, in addition to the operational procedures necessary to guarantee that the train is adequately prepared at the outset of operation and shut down at the conclusion of operation [12], [13].

The multiplicity of tasks indicates that an ATO system is responsible for a far greater range of activities than simply operating the train. In addition to its own route, the railway system must also be considered in the context of its surrounding environment, as well as the influences of various operational, infrastructural and technological conditions.

TABLE 1 provides a superior summary of the degrees of automation regarding the standard tasks of the ATO System. The responsibility of the functions is either assigned to the driver (D), the system (S), the system supervised by the driver (S+(D)), or is not yet defined (?). In addition to the division of the train's driving task between the driving of the train and shunting, further tasks have been incorporated into the GoA division. Additionally, to the previously defined supervision of guideway and passenger transfer, the railway construction and the train set have been included as standard tasks in the monitoring function. Furthermore, operational and passenger-related communication tasks have been added. The points diagnosis of the own vehicle and train set, as well as preparing, shutdown, and stoppage of the train, were already present in the original standard in a similar, but not quite as detailed definition. A definitive delineation of responsibility for the final three tasks in GoA4 operations has yet to be established [12].

TABLE 1. Description of GOA level in the mainline area [12] D = driver's responsibility, S = system's responsibility.

Standard task	GoA0	GoA1	GoA2	GoA3	GoA4
Drive train (train run)	D	D	S+(D)	S	S
Shunt train (shunting run)	D	D	S+(D)	n/a	S
Monitoring the track	D	D	D	S	S
Monitoring the railway construction	D	D	D	S	S
Control and monitor entry and exit of passengers	D	D	D	D	S
Monitor train set	D	D	D	S	S
Operational communication	D	D	D	S	S
Communicating with passengers	D	D	D	D	?
Diagnosis of own vehicle and train set	D	D	D	D+S	?
Preparing, shutdown, and stoppage the train	D	D	D	?	?

This division ensures that the responsibilities of the train driver and the duties associated with an ATO system are defined as comprehensively as possible in accordance with the automation level [12].

2) STATE OF THE ART: ODD IN RAILWAY APPLICATIONS

At present, there is no equivalent standard to the ISO 34503:2023 [4] of the automotive industry for the railway system. Nevertheless, the topic is becoming increasingly important due to the ongoing development of ATO systems and has already been addressed in several academic publications and papers.

The cross-domain utilization of an ODD to delineate the operational parameters of ADS has already been referenced in a survey by [15]. The direct application of the ODD description has already been employed in several research approaches. In [16], the ODD taxonomy of the automotive industry is utilized to generate test and training data for object recognition in the railway environment. In a multitude of studies, the ODD, as defined by the automotive standard, has been modified for a specific application in the railway sector, with the incorporation of a range of additional and extended elements. To illustrate, an ODD for a high-speed railway ATO system situated in China was established in [17]. The ODD is divided into six dimensions: railway infrastructure, related system members, information transmission, operation area, operating environment, and operational constraints. In addition to data regarding the infrastructure, operational area, and environmental conditions, the ODD encompasses information about communication and the equipment utilized. A further study considers the extension of the automotive ODD based on PAS1883 to the subject of remote-controlled railway vehicles [18]. Further considerations regarding the definition of the field of application of automated railroad systems were made, for example, in reference to the work of [19]. In the pursuit of an appropriate concept, a comparison was conducted between the ODD description in automotive applications and the operational envelope that is familiar to the maritime sector. Nevertheless, no precise structure or concept for a railway ODD or analogous approach is provided. In the field of research pertaining to automated freight trains, [20] made a distinction between an ODD for open and closed rail networks, identifying this as a significant distinguishing feature. Moreover, some sources identify essential elements and components that must be included in an ODD for specific ATO systems. For instance, [21] identifies essential components of an automated shunting vehicle, including the shunting yard type, geographic area, speed range, environmental conditions, vehicle-to-X (V2X) dependencies, and other constraints.

Nevertheless, more comprehensive ODD descriptions are already available for specific ATO systems. Reference [22] presents an ODD structure for a GoA4 system in the open rail network. In accordance with the automotive standard, it comprises supplementary attributes. The scenery is further enhanced by the inclusion of various rail network elements, including train stations, maintenance depots, tunnels, level crossings, and ordinary track sections between stations. Environmental conditions encompass weather and illumination conditions, in addition to the availability of supporting infrastructure. With regard to the domain of dynamic elements, the occurrence of obstacles in the vicinity of the ego vehicle is also considered. In the research field of run-time risk evaluation, [23] employs an ODD to delineate the ''key scenario parameters that need to be collected during the operation'' to define the conditions under which the train control system is employed. The developed ODD encompasses the inner components of the system, external risk owners, and assumptions regarding the working environment and service users. This process results in the identification of the fundamental objects as well as environmental and operational constraints that constitute the components of the ODD.

[24] is investigating the potential of utilizing an ODD for the safety argumentation of an AI-based ATO system. The ODD structure has been constructed with due consideration for ISO 34503:2023 and adapted to meet the specific requirements of the railway use case. An excerpt illustrates the adapted attributes of the taxonomy. The drivable area is divided into two distinct sections: the track and the signals. Signals comprise a signal pole, signal, signal bridge, and buffer stop. In the context of junctions, a distinction is drawn between transactions and switches. The basic structures are the platform, the overhead line, and the catenary pole. Special structures comprise the level crossing, the tunnel, and the bridge. The drag shoe is defined as a temporary structure. In addition to the environmental conditions, flames are identified as an attribute of the illumination. The category of traffic agents encompasses a diverse range of entities, including person, train (with the subcategory wagon), bicycle, motorcycle, road vehicle, animal, and wheelchair.

Within our research, we have demonstrated a comparable extension and addition of the automotive standard, here based on the PAS1883, to the railway domain in [25]. As part of our methodical approach to generate scenarios for testing highly automated on-sight train operations, we have presented a draft of an ODD using the example of an automated shunting locomotive. In our research approach to create a framework to define ODDs for ATO, this constituted our initial work step and formed the basis of this paper.

III. TOWARD THE DEFINITION OF A RAILWAY-SPECIFIC ODD TAXONOMY

The current state of the art does not include an overarching taxonomy to define automated railway vehicles. Some promising approaches have been proposed based on existing definitions of the automotive standard, but no comparable structure has been established. Our experience in the development and testing of automated driving systems in the shunting sector has highlighted the challenges and difficulties involved in defining an ATO system for driving on-sight. This resulted in the creation of a preliminary ODD design for automated shunting operations [25]. In the course of developing this ODD structure, it became evident that it could be applied to other railway contexts. Consequently, the objective was to adopt a comprehensive railway-specific approach to defining an ODD taxonomy. The definition of a railway-specific ODD taxonomy will commence with the extension of the automation level for mainline applications (see Chapter II-B1.b). This will be followed by a discussion and redefinition of the function of the DDT with respect to railway operations. Finally, this will result in the definition of an ODD that is specific to the railway sector.

A. EXTENDING THE DEFINITION OF GoA-LEVEL FOR MAINLINE

As previously stated, the automation levels for the mainline area are equivalent to the definitions set out in IEC 62267 in certain respects, with any necessary specifications or extensions being derived from the driving service regulations. In general, the definition is comprehensive and detailed. However, the driving task is defined relatively vaguely in the ''Monitoring the track'' section and is primarily to be understood as the detection of objects and persons. A comprehensive overview of the aforementioned section can be found in the left part of TABLE 2. The continuous monitoring of the current route to be traveled in accordance with the driving permit is divided into several points. The degree of automation determines the system or driver's responsibility for specific subtasks. These include ''detecting possible objects in or on the track'',' detecting collisions with objects classified as obstacles'', and ''detecting collisions with persons in or on the track for the ego-vehicle and other vehicles in the direct neighboring track''. Nevertheless, the execution of the corresponding vehicle reaction can only be partially deduced from the description ''according to driving permit.'' [12]

In contrast, IEC 62267 is more explicit in its statement, using the wording ''Preventing a collision with obstacles/persons'' [11]. Furthermore, the classification of objects, which is an indispensable prerequisite for the execution of shunting operations such as coupling and uncoupling, is conspicuously absent from the enumeration. Accordingly, an additional subdivision is proposed in the right section of TABLE 2. The initial addition is comprised of a classification of objects that permits the differentiation of the system response in accordance with different tasks performed by the ATO system. The second addition pertains to the absence of a defined vehicle reaction in response to the detection of potential collisions.

B. DYNAMIC DRIVING TASK IN RAILWAY OPERATION

A direct transfer of the DDT to the railway system is not a viable option. Firstly, there is no lateral vehicle guidance in

TABLE 2. Extension GOA definition mainline [12].

Monitoring the track: Continuous monitoring of the current route to be traveled in accordance with the driving permit with regard to ...	
Existing subdivision	*Additional subdivision*
detecting possible objects in or on the track	classifying possible objects in or on the track
detecting collisions with objects classified as obstacles	preventing collisions with objects classified as obstacles
detecting collisions with persons in or on the track for the ego-vehicle and other vehicles in the direct neighboring track	preventing collisions with persons in or on the track for the ego-vehicle and other vehicles in the direct neighboring track

place, as seen in the automotive sector, which is provided by the track guiding in the railroad system. Secondly, there are no additional tasks for monitoring the vehicle and for communication in the subdivision according to SAE J3016. In order to define a potential DDT in the railway sector, a comparison is made between the tasks of an ATO system from the ATO sensor technology project and the subdivision according to SAE J3016.

The tasks ‘‘drive train’’, ‘‘shunt train‘‘, ‘‘monitoring the track’’ and ‘‘monitoring the railway construction’’ can be compared to the DDT used in automotive applications. With the aforementioned extension in mind, these tasks describe the dynamic control of the vehicle, the OEDR, and the tactical procedures. In addition, the tasks ‘‘control and monitor entry and exit of passengers’’, ‘‘monitor train set’’, ‘‘operational communication’’, ‘‘communicating with passengers’’, ‘‘diagnosis of own vehicle and train set’’ and ‘‘preparing, shutdown and stoppage the train’’ do not describe a direct operational or tactical task and cannot be assigned to any description of the DDT according to SAE J3016. The functions designated as ‘‘monitor train set’’ and ‘‘diagnosis of own vehicle and train set’’ constitute supplementary monitoring activities to be actively executed by an ATO system throughout the train journey. The parts ‘‘operational communication’’ and ‘‘communicating with passengers’’ are communicative tasks of the ATO system. In addition, the ATO system must also be capable of performing two supplementary operational tasks: ‘‘control and monitor entry and exit of passengers’’ and ‘‘preparing, shutdown and stoppage the train’’. In conclusion, the aforementioned points are designated as Required Operating Tasks (ROT) [12].

It should be noted that the definition of the movement or shunting order, including the track vacancy of the route and the setting of the switches, as well as the planning of timetables and train sequences, are not included in the DDT or the ROT.

C. DEFINITION OF A RAILWAY ODD

The ODD serves as the limiting framework for the operating conditions suitable for the operation of an ATO system, implicitly the functions and features of the system, with regard to geographical and infrastructural areas, as well as possible interference from climatic, atmospheric, and digital conditions. In addition to the DDT, the ODD in the rail sector must also take into account the ROT of the automated system. This requires the additional limitation of the operational capability based on the operational task scopes.

In system testing, the ODD serves as an area in which the system can be operated safely, it is defined by the manufacturer of the system. The process of narrowing down the field of application allows for a systematic selection of the entities that may occur in a scenario and a targeted derivation of the test scenarios. In the context of system development, the ODD serves as a supplementary tool for determining requirements concerning basic boundary conditions. However, it should be noted that the ODD does not represent a direct and complete list of requirements. The ODD does not include functional or technical requirements. Rather, such requirements are defined in a specifications sheet.

The fundamental elements of the ODD definition, in terms of geographical and infrastructural aspects, as well as influences from weather and digital conditions, are not significantly divergent in the railway sector when compared to the automotive sector (see II-A2.a). Nevertheless, it is important to note that an ATO system differs from an ADS in road traffic with regard to its specific tasks and areas of application. This distinction must be taken into account in the ODD definition and consequently in the methodical procedure for setting up an ODD. An ODD in the railway sector thus considers the particular railway system (e.g., mainline, branch line, tramway) for which an ATO system is deployed, as well as the delineation of operational tasks in the system that extend beyond the driving task. It should also be noted that the transferability of the ATO systems should not be carried out without extensive testing. Accordingly, a railway-specific ODD definition is proposed, and the subsequent chapter presents a taxonomy for establishing an ODD in the railway sector.

In summary, an ODD in railway applications can be defined as follows: *“The ODD delineates the operational parameters within which an ATO system is designed to operate, including geographical and railway-specific infrastructural factors, influences from climatic, atmospheric and digital variables, as well as requirements from communicative and monitoring tasks within train operation. Consequently, the ODD restricts the usability of the ATO system to the specific multi-dimensional area for which it was designed, thereby preventing the transfer of the system to related application areas without prior testing.”*

IV. TAXONOMY FOR A RAILWAY-SPECIFIC ODD

The substantial dissimilarities between the railway and automotive applications necessitate the utilization of a railway-specific structure to describe an ODD. This is due to the aforementioned circumstances of a markedly differing network between road and rail, disparate driving dynamics resulting from the significant mass differences, and other elements in frictional contact, as well as specific rules, regulations, and infrastructural guidelines and conditions. For a uniform definition of ODDs in the rail sector, it is expedient to apply a generally valid structure and nomenclature. This is defined as a taxonomy and serves as a framework for the ODD definition of automated railway systems. Therefore, the PAS 1883 standard [3] and corresponding ISO 34503:2023 [4] of the automotive industry are used as a model, as they provide a comprehensive and well-organized structure whose fundamental understanding offers a solid basis for transfer to the rail applications. The taxonomy is first analyzed with regard to its structure, attributes, and links between them. The components of the structure are evaluated to determine whether they can be transferred directly to the railway applications, whether the attributes can be adapted, or whether no transfer is possible. Based on the current state of research on the topics of ODD in the railway sector and requirements for ATO systems, as well as our own experience and knowledge through the research focus on the development and testing of ATO systems, the adaptable attributes are adjusted to the railway sector and extended if necessary, and additional railway-specific attributes are determined. This process leads to a railway-specific taxonomy for the definition of ODDs inspired by the automotive industry standard shown in FIGURE 2.

At the top level, the ODD shall be structured into the attributes of Scenery, Environmental Conditions, Dynamic Objects, and Operational Conditions. The scenery is defined as the static elements of the operating environment, such as tracks or catenary. One challenge of the ODD is that the application area of the automated system changes frequently, and often large spatial areas have to be covered. Environmental conditions include different weather and atmospheric conditions, such as rain or fog. It is evident that environmental conditions exert a considerable influence on the functionality of automated systems. Such conditions can have a detrimental effect on object recognition systems, as well as on connectivity and physical properties. The dynamic elements of the ODD are defined as the dynamic elements of the system, including operational mobility and the subject vehicle. In addition to the driving dynamics of the ego vehicle, other road users and vehicles have a significant influence on automated systems. It is of great importance to consider the movement of the actors in order to implement a system that protects vulnerable users and prevents accidents. Operational conditions shall consist of necessary tasks the system has to fulfill, e.g. entry and exit of passengers at regularly scheduled stops. It is also of great importance to ensure the safe and reliable execution of operational tasks, in addition to the actual driving task. It is crucial to pay attention to the operational scope and to take the correct action in appropriate situations.

Although the ODD is intended to be applied as comprehensively as possible to railway applications, it should be noted that certain areas of the railway system are explicitly excluded from its scope. The ODD taxonomy is generated for track-bound vehicles with classic wheel-rail contacts of steel. A significant commonality between the various railway systems is the separation of the transport network, including specific rules and areas. Furthermore, the ODD taxonomy does not consider any road elements that may affect an ATO system for tramways. The taxonomy includes only those attributes that are crucial for trams but not relevant in road traffic. For the purposes of tramways, it would be beneficial to combine the automotive and railway ODD taxonomies to consider the application area in both domains. Mountain railways, such as funicular railways and rack and pinion railways, are not included in the ODD taxonomy due to their specific application area and construction. Additionally, track-bounded tire track systems, monorail systems, and magnetic levitation systems are not included in the ODD taxonomy due to their low prevalence and limited application. However, they could be incorporated into the taxonomy if necessary. Finally, it should be noted that the ODD has been initially designed for use in the German railway system. The transferability with regard to the interoperability of EU railways can be readily achieved through the addition of corresponding extensions or specifications to the ODD attributes. In particular, specific circumstances arising from environmental conditions and geographical peculiarities, as well as regular and technical peculiarities, must be taken into account. Nevertheless, as the attributes of the taxonomy are primarily universally applicable, a deviation mainly affects the description of a specific ODD, such as the shape and design of signals, track gauges and clearance gauges, as well as train control systems and the design of typical railway infrastructure. In summary, it is possible to adapt or supplement the characteristics of certain attributes as required.

The following chapters provide a more detailed description of the attributes of the ODD and present arguments for or against the transfer and adaptation of attributes from the automotive standard or the introduction of new attributes.

A. SCENERY

For the scenery, the basic structure of the automotive standard was used with minor adjustments. In addition, specific infrastructure areas that do not occur in road traffic, such as stations have been added. Similarly, significant accidents have been included due to their high-risk potential and economic damage. Thus, the scenery is subdivided into the general attributes' zones, drivable area, junctions, railway stations, basic track structures, special structures, temporary track structures, and accidents.

In defining the attributes of the scenery, it is important to recognize that the potential use of high-performance sensor systems and processing algorithms gives rise to a highly complex system in which it is not feasible to take full account of the environmental influences affecting the hardware and software components and in what manner. Accordingly, the attributes of the scenario extend beyond the vehicle's own

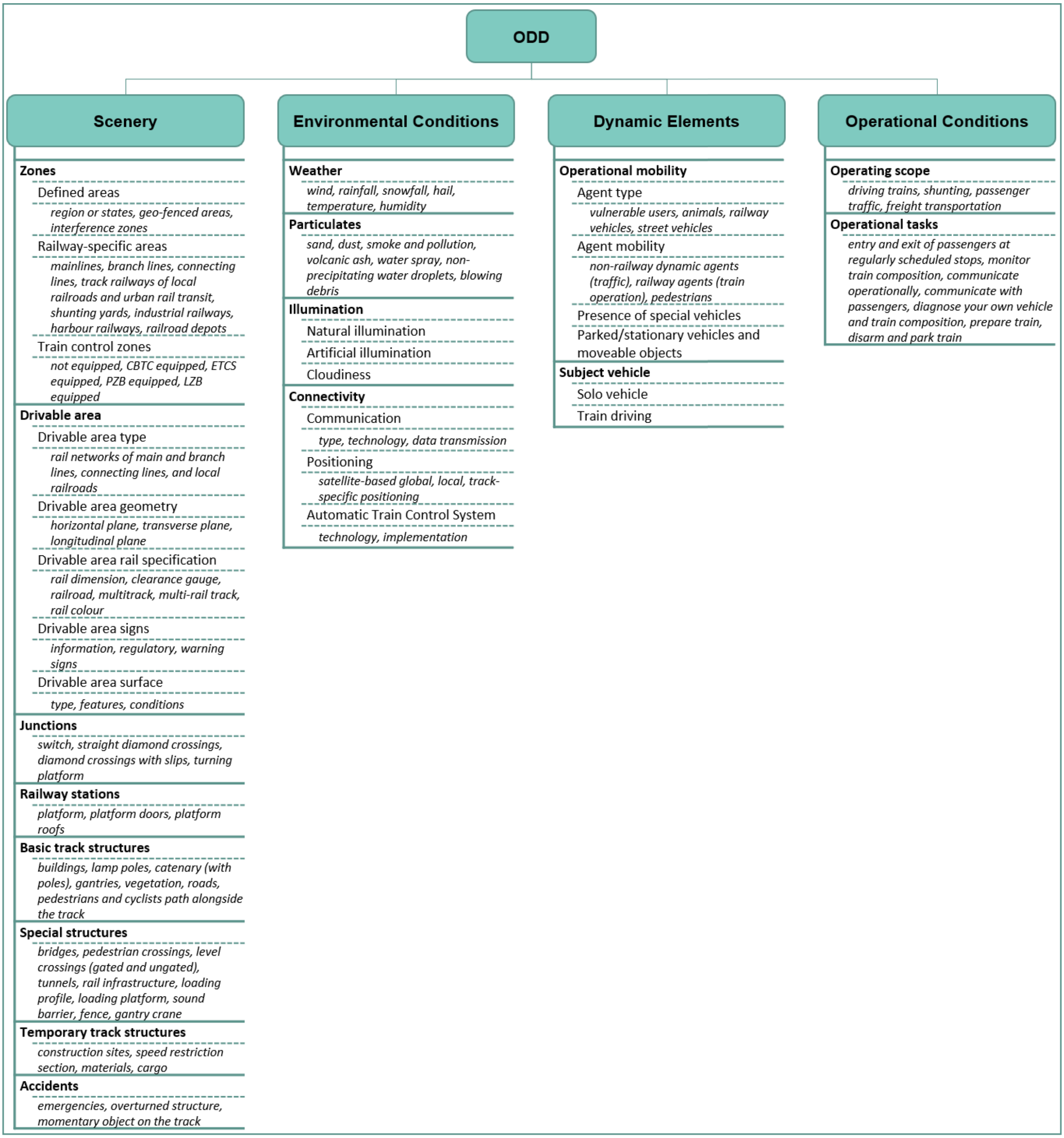

FIGURE 2. Structure ODD taxonomy for railway systems.

secured route and the task areas of the system that lie outside its own route.

1) ZONES

Zones represent the specific area of the railway where the ATO system is applied. In addition to predefined areas that can influence the system, such as geo-fenced areas and interference zones, as well as the specification of the region or country (due to different guidelines), other attributes are unable to adapt to the railway applications. The structured organization of the railway ODD is further subdivided into special railway lines and areas that may differ from the railway system and typical train control, or areas with specific regulations or conditions. For example, some ATO systems may be restricted to specific zones where the system can operate safely, such as the automated subway in Nuremberg [26].

The determination of the attributes can be explained by the designation of open and closed networks, which integrate different track infrastructures and track areas. A closed network is defined by the absence of intersections and the occurrence of rail traffic within a closed system [20]. In contrast, an open network is not intersection-free and must contend with a multitude of unpredictable variables.

The Attributes of open rail networks include railway areas such as mainlines, branch lines, connecting lines, track railways of local railroads, and urban rail transit, like tramway systems and light rail systems, as well as shunting yards. A more detailed classification, such as the various areas of a shunting yard, including arrival tracks, humps, distribution zones, classification tracks, and exit tracks, can be included in the ODD. The closed rail network included the railway areas of industrial railways, harbor railways, railroad depots, and also track railways of local railroads and urban rail transit, such as light rail systems and subway systems. Tramway systems are typically constructed as non-intersection-free and open rail networks, with routes that are largely dependent on the course of the road. Subway systems operate in an intersection-free manner and utilize a closed rail network. Light rail systems are typically operated within a closed system that is not completely crossing-free, with a minimal number of tracks within the available road space. Consequently, the categorization of light railway systems is in part dependent upon the specific construction of the operational area of the ATO system. A more detailed classification of light-rail systems can be achieved through the categorization of railroads (outlined in §16 of the German Ordinance on the Construction and Operation of Rail Systems for Light-Rail Transit (ger.: Verordnung über den Bau und Betrieb der Straßenbahnen (BoStrab)) [27]) into three distinct categories. Road-level railroads have embedded tracks within the carriageway. These are distinguished from special railroads, which run within the traffic area of public roads but are separated from other traffic by fixed obstacles. Finally, independent railroads are located outside the traffic area of public roads. The potential for disparate rail networks and regions within the ODD definition permits a tangible interpretation of the fundamental scope of applicability. Consequently, a transfer of an ATO system for a tramway, for instance, cannot be made directly to the mainline domain.

As an additional attribute category railway lines are equipped with a variety of train control systems, whereas an ATO system requires a specific system to function reliably. Typical zones include CBTC-equipped zones, ETCS-equipped zones at Levels 1 or 2, zones with intermittent train control, and zones equipped with continuous train control systems [2]. In certain instances, it is also possible that no train control system is installed [28].

In accordance with the ATO system, it may be advantageous to subdivide the zones on a smaller scale. A more detailed final ODD allows for a more limited number of additional options to be considered in the system development process. For instance, railway-specific areas may be delineated through the definition of railway constructions, as outlined in §4 of the Ordinance on the Construction and Operation of Railways (ger.: Eisenbahn Bau- und Betriebsordnung, EBO) [28]). These are divided into categories including lines, stations, and other railway constructions, which are used for specific purposes such as shunting. However, this ODD taxonomy provides the most comprehensive framework for defining ODDs, although it can be further concertized in the specific ODD description as required.

In the event that a zone is designated as an ODD attribute, all components, and thus also ODD attributes pertaining to them, are automatically incorporated into the ODD unless they are explicitly excluded.

2) DRIVABLE AREA

The term drivable area refers to the area on which the train is moving and an ATO system must function in a safe manner. This encompasses various track areas to which defined construction regulations and guidelines, as well as speed limits, are assigned. Furthermore, the track topology in all spatial directions, the rail system (including superstructure, clearance gauge, rail type, number of side tracks, etc.), signaling, and the characteristics of the surface, rail, and track are considered in defining this term.

Similarities to the automotive standard can be observed in the general attributes, including the drivable area type, geometry, rail specification, signs, and surface. However, there are exceptions to this, such as the drivable area edge. This is because the rail vehicle does not allow any deviations from the track due to its rail-bound nature. Therefore, no track edge is defined. There are notable similarities in the track geometry, surface conditions, and categorization of signs. Nevertheless, other attributes are not amenable to adaptation due to the substantial divergences in the track systems between railways and automobiles, as well as in infrastructural constructions.

a: DRIVABLE AREA TYPE

The attributes of the drivable area type are primarily related to the different rail networks of the main and branch lines, connecting lines, and local railroads and differ on the one hand in terms of construction regulations and, on the other hand, have different speed specifications.

In the context of railroad terminology, the term mainline track is used to describe the standard track of an open line. In contrast, branch lines are tracks that are not regularly utilized by trains. A specific category of mainline track is that of high-speed lines, which are designed exclusively for high-speed trains and thus have particular requirements. The term operating points is used to describe the attribute of sections of open lines where special rules and possibilities for changing tracks, entering sections of line, or stopping apply. The tracks within railway stations are considered to be part of the railroad facilities, which typically include at least one switch. These tracks allow for the starting, ending, stopping, overtaking, crossing, and turning of trains. They represent the termination of an open line. Furthermore, tracks at shunting yards are part of a distinct category of stations designated for the formation of trains, which are subject to a separate set of regulations [29].

The rail network of connecting lines comprises tracks that are connected to the railway network but are subject to their own rules and are private track systems of non-public transport [9].

In the last category, tracks of tramways, subways, and light rails of local railroads are typically not connected to the mainline track and are subject to specific rules [27].

b: DRIVABLE AREA GEOMETRY

The attributes of the drivable area geometry are in correspondence with the structure of the automotive standard. The horizontal plane area is divided into two distinct categories: straight track and curves. The transverse plane is comprised of a single track, as rail vehicles are essentially constrained to a single track due to their track-bound nature as well as banking. A third alignment is provided by the longitudinal plane, which is subdivided into up-slope, down-slope, and level planes. This attribute can be pivotal for image-driven lane detection systems, as an unknown and untested track guidance could potentially lead to misinterpretations.

c: DRIVABLE AREA RAIL SPECIFICATION

The specification of the rail differs fundamentally from that of the lane in the automotive sector. This is due to the rail guide of the vehicle and the resulting lack of lateral movement. Nevertheless, in the rail sector, specific parameters and criteria are also of paramount importance for defining the driving area. Such parameters can have a direct impact on the performance of ADS.

The first attribute to be determined is the track gauge, which can be divided into three categories: standard, narrow, and broad gauge. In addition, the clearance gauge must be determined as a further attribute. This distinction is evident between the boundary line, which must be completely kept clear, and the outer area of the clearance gauge, within which specific objects may occur (e.g., signals, platform edges). It is of paramount importance that an ATO system is able to identify and react to obstacles within the clearance gauge of a rail vehicle at an early stage, as it is not possible for the vehicle itself to avoid such obstacles. This attribute is of greater consequence in on-sight train operation, as the driver bears responsibility for collision avoidance and is traversing a speed range that allows for timely braking. Nevertheless, scenarios necessitating the observation of the clearance gauge (such as the act of entering or exiting a platform edge) also arise in the context of mainline tracks [28], [29], [30].

Another attribute pertains to the fundamental structure of the rail system, which is comprised of rail, sleeper, and track bed. The rail type may be defined as standard rail, flat-bottom rail, or grooved rail, for instance. Typical sleeper types include wood, concrete, steel, plastic, and none in the case of a slab track. The track bed is typically composed of ballast, a slab track such as concrete, asphalt, or cobblestone, as well as turf, or, in rare instances, none at all. While the superstructure may not exert a significant influence on driving behavior, a specification in the ODD can serve as a safeguard for certain ATO systems. In particular, when employing sensor-based systems for environmental detection, alterations to the surface can result in aberrant sensor images, which, in the worst case, may precipitate incorrect decisions [29].

Even if a rail vehicle is incapable of traversing a different set of rails in the absence of a switch, it is nevertheless of critical importance to determine whether a given track configuration includes multiple tracks. For instance, an ATO system must not be adversely affected by the regular oncoming or overtaking of trains. The attribute multitrack can be defined as regular track and counter track, for example. Alternatively, lines with more than two tracks can be referred to as parallel sections of regular track and counter track. Moreover, an essential element of the multitrack attribute pertains to the distance between the tracks. In addition to the possibility of parallel tracks, in some areas there is the situation of multi-rail tracks. This occurs when different gauges are combined in the same rail network and can be challenging for ATO systems with rail detection [28], [30].

The final attribute of the rail specification is the color of the rail. In most cases, rails are not painted and have the color of steel or rusty steel. However, there are exceptions to this rule. For instance, due to heating reasons, some rails are white in color [31].

d: DRIVABLE AREA SIGNS

The ability to identify and follow signs is a significant challenge for ADS. The fundamental structure of the information, regulatory, and warning signs attributes is derived from the automotive standard. Nevertheless, it is necessary to consider certain railway-specific circumstances in the context of regulatory signs. In the railway sector, a distinction is made between onboard signs, which are displayed to the driver directly in the driver's cab by a train control system, and trackside signals, which are placed at the edge of the track. These may take the form of electrical light signals, mechanical signals, or building site signs. Furthermore, hand signals are also prevalent in the railway industry, as are signals attached to the vehicle, such as the headlights. In addition to the signposting of hazardous substances, warning signals also include the tail light, which symbolizes the end of a train [32].

Following the existing ODD taxonomy, the signals in rail transport may be categorized as variable or uniform, and their operation duration as full-time or temporary.

e: DRIVABLE AREA SURFACE

The basic structure of the automotive standard is also adopted in the drivable area surface subgroup. The surface type is defined as rail, as there is no alternative surface available for railway vehicles (track-bounded tire track systems are excluded from this taxonomy). The attribute surface features are susceptible to damage caused by traffic and environmental conditions. In the railway sector, this encompasses two primary categories: rail position errors and plant covering. Surface conditions can have a significant impact on ADS. In addition to changes in driving behavior (e.g. braking distances), perception systems can also be affected. Track conditions can also lead to changes in regulations such as speed limits, masking of signals, and track closures. The attribute is subdivided into icy, flooded tracks, mirage, snow on the drivable surface, standing water, wet track, and surface contamination, equivalent to the automotive standard. In addition, ice hanging on the catenary or on the masts is added, which does not have a direct effect on the surface, but can have a similar effect on the ATO systems.

3) JUNCTIONS

Junctions are the only way for a railway vehicle to switch or cross between tracks (except tunnels and bridges). An automated system operating there must be capable of handling this situation in a reliable manner and must consider regulations while driving over junctions. On the main line, there are usually switches or crossings. While switches allow you to change from one track to another, straight diamond crossings allow you to cross another track without changing tracks. A combination of both is diamond crossings with slips. There are also special crossings such as turnouts beyond the main lines. These are only for single vehicles and not for whole trains [30].

Similar switch designs depend on the track. Lines can separate into two (or more) lines, merge two (or more) lines into one, or allow two lines to switch to each other. Common constructions are standard, one-sided double, double-sided double, similar flexure, and contrary flexure switches. A straight diamond crossing usually exists in only one constellation, while diamond crossings with slips can be found in several variations. A sub-categorization can be made into single-slip, double-slip, similar flexure single-slip, contrary flexure single-slip, and curved diamond crossings [30].

4) RAILWAY STATIONS

Railway stations represent a specific area within the wider context of railway construction, and as such, are subject to a distinct set of guidelines. They are a common component of railway operations. In order for a potential ATO system to function effectively, it is essential to consider the attributes of railway stations. As a specific section of railway lines, stations are characterized by a number of attributes. These include platforms, which are separated in terms of classification, height, and side. In addition, there are platform doors as well as a platform roof, and the corresponding clearance gauge [30].

5) BASIC TRACK STRUCTURES

Basic track structures are stationary infrastructure elements that can occur regularly in railway operations. The elements may be found on, adjacent to, or in the vicinity of the track. The automated system should not be adversely affected by the structures and is required to respond in an appropriate manner. Furthermore, it is the driver's responsibility to monitor the railway property with belonging facilities and surroundings and report any irregularities or anomalies. This is also the role of the ATO system in driverless operation. The attributes of basic track structures include typical railway infrastructure like buildings, lamp poles, catenary (with poles), gantries, vegetation as well as roads and paths for pedestrians and cyclists alongside the track [30].

6) SPECIAL STRUCTURES

Special structures are stationary infrastructure elements that can be found in the railway sector. Such structures typically manifest at specific points rather than at regular intervals. These elements can occur on, next to, and around the track. Equivalent to basic structures, they should not affect the reliability of an ATO system and occur in the vicinity of the railway construction. The presence of unknown objects or route characteristics has the potential to result in unanticipated interference and erroneous behavior in automated systems. Special structures are classified into the rail-specific attributes bridges, pedestrian crossings, level crossings (gated and ungated), tunnels, rail infrastructure (e.g. bumper, sensors, retarder chain), loading profile, loading platform, sound barrier, fence, and gantry crane. It is also possible to extend the attributes for specific areas of application [30].

7) TEMPORARY TRACK STRUCTURES

The third category of track structures is that of temporary structures. These may be placed on or adjacent to the track due to local requirements, accidents, or regulatory and operational conditions. Such conditions may include the placement of temporary emergency signage which may obstruct or impact the ADS. Temporary track structures have the attributes of construction sites, equipped speed restriction sections, materials, and cargo [30].

8) ACCIDENTS

Accidents present a significant risk to railway operations, given the high potential for adverse outcomes and the associated costs. It is therefore of the utmost importance that an automated system is capable of reacting to accidents and the corresponding unknown situations. The attributes of accidents include emergencies such as fire, smoke, derailed vehicles, catenary hanging down, and foreign objects at the catenary. Other attributes are overturned structures (e.g. tree, fence) and momentary objects on the track that should not occur there in regular operation (e.g. bike, e-scooter) [33].

B. ENVIRONMENTAL CONDITIONS

It is evident that environmental conditions exert a significant influence on ADS. In particular, perception systems are susceptible to disruption by the influence of weather, particulates, and illumination. However, the communication and connectivity of ATO systems can also be affected by external conditions. A significant challenge in this context is the high variability and changeability of environmental conditions over space and time. Consequently, the ODD is designed to demonstrate a comprehensive and generally valid structure of influences, while also representing conditions with a high impact.

The environmental conditions exhibit only slight differences between railways and automobiles. Influences such as weather, particulates, and illumination occur independently of the transportation system, which is why many components of the automotive standard are adopted and only partially supplemented. The connectivity attribute also exhibits numerous parallels, although it differs more clearly from the automotive sector due to the influence and transfer of train control systems to ADS and the task of operational communication. Automated railway vehicles (and also train drivers) receive pertinent information regarding the route, speed regulations, and signals via the train radio or specific ATC. The absence of this information precludes the possibility of safe and reliable train operation. Even when trains are operated on-sight, drivers are still provided with information pertinent to their driving task.

1) WEATHER

The weather attributes include typical meteorological conditions, such as wind, rainfall, snowfall, hail, temperature, and humidity. It should be noted that no combinations of weather conditions are listed here. Nevertheless, in consideration of the ATO system, it is imperative to incorporate the impact of particular combinations of meteorological variables into the developmental and testing phases.

a: WIND, RAINFALL, AND SNOWFALL

The definition of wind, rainfall, and snowfall are taken from the automotive standard [4]. In this context, wind is specified in meters per second and represents an average value over a specified time interval. The Beaufort scale is employed for categorizing wind speeds at an elevation of 10 m above the ground, as defined by the World Meteorological Organization (WMO) [34].

In addition to the intensity of precipitation in millimeters per hour, it is also important to provide information on the precipitation interval and spatial distribution. For a more detailed specification of precipitation in terms of droplet size, spreading, and onset rate, the automotive standard differentiates between three types of rainfall: dynamic, convective, and orographic. The intensity of rainfall is classified into five categories, beginning with light rain (less than 2.5 mm per hour) and progressing through moderate rain (2.5 mm to 7.6 mm per hour), heavy rain (7.6 mm to 50 mm per hour), violent rain (50 mm to 100 mm per hour), and culminating in a cloudburst (more than 100 mm per hour) [4].

The determination of the impact of snowfall is a challenging endeavor, as the phenomenon is defined more by the accumulation of snow depth over time. Nevertheless, the intensity of snowfall can be quantified in terms of the visibility affected solely by the snow. The standard delineates three categories of snowfall intensity: light (visibility $>$ 1 km), moderate (visibility between 0.5 km and 1 km), and heavy (visibility $<$ 0.5 km) [4].

It is likewise possible to categorize wind, rainfall, and snowfall in a variety of ways.

b: HAIL

In addition to rain and snow, hail is another type of precipitation and is included as a supplementary weather attribute in the railway-specific ODD taxonomy. The impact of hail on an ATO system can have a comparable effect to that of snow on visibility. However, due to the distinct nature and form of precipitation, it is not possible to assume an identical influence. Moreover, above a certain grain size, hail exerts a corresponding impact force that can damage or displace system components. The ANELFA scale is employed for the categorization of hail into classes A0 to A5, based on the diameter of the hailstones [35].

c: TEMPERATURE

An additional extension of the weather attributes in our ODD is the temperature. In addition to its impact on the permissible operating ranges of the hardware utilized within the system, the infrastructure can also be influenced. For instance, the deformation of rails is more pronounced at elevated temperatures, which can negatively impact driving dynamics and safety [31]. A suggested classification scheme divides temperature into the five following categories: freezing cold (less than -10°C), cold (-10 to 5°C), moderate (5 to 20°C), warm (20 to 35°C), and hot (over 35°C). Alternative scales may also be employed.

d: HUMIDITY

As a final additional weather attribute, humidity can exert a significant influence on braking behavior of railway applications. This influence can be subdivided into three categories: low, middle, and high. The definition of meaningful humidity rates presents a challenge, as the pathway to impact might be more directly related to the driving conditions. For this taxonomy, therefore, it is recommended that qualitative guidance be provided.

2) PARTICULATES

The attribute particulates are defined following the specifications outlined in the automotive standard, which include "sand, dust, smoke and pollution, volcanic ash, water spray, non-precipitating water droplets, blowing debris" [4]. The impact of particles and water droplets on the visibility of an automated system or sensor setup, as opposed to precipitation, is a key consideration in this context. As with precipitation, the density and size of the particles are the determining factors in determining visibility. Furthermore, the meteorological optical range is put forth as a potential measurement variable for assessing the impact on optical systems [36].

3) ILLUMINATION

The lighting conditions prevailing in a given situation are an important factor affecting the reliability of automated systems. In addition to the direct illumination of a scene and the associated perceptibility of individual objects, light changes and the resulting shadows, as well as glare from optical sensor systems, are factors that must not be overlooked.

In relation to the automotive standard, illumination is divided into three attributes: natural illumination, artificial illumination, and cloudiness. Natural lighting conditions are defined by the distinction between day, night, and twilight. The ambient illuminance, which is greater than 2000 lx during the day and less than 1 lx at night, is specified as the measured variable. The position and angle of the sunlight are also considered. In addition to the street lights and vehicle lights from parallel roads adopted from the standard, artificial light sources in the railway sector include the peak lights of railway vehicles, track lighting of railway lines, and the illumination of railway stations and other railway facilities. The classification of the aviation weather service, based on the unit okta, is employed to ascertain cloud cover. The cloud condition is classified as clear, partly cloudy, or overcast within the range of 0–8 oktas. The presence of cloud cover is regarded as an additional attribute, irrespective of the time of day [4].

4) CONNECTIVITY

Connectivity represents a fundamental aspect of automated driving. Information indispensable for the completion of the driving task, in addition to data associated with external ODD attributes, can be conveyed to the vehicle in this manner. Consequently, specific ATO systems are frequently reliant on specific technologies or types of data transmission. In the automotive standard, connectivity is classified into two attributes: communication and positioning. Communication is divided into three categories: type (e.g. V2X communication), technology (e.g. cellular, satellite, etc.), and data transmission (downlink or uplink). The positioning attributes are divided into two categories: satellite-based global and local. These encompass a multitude of global and local positioning systems, along with the utilization of assorted correction factors [4].

In contrast to automotive systems, railway systems are significantly more reliant on external connectivity and communication with the vehicle. The train control system is an additional essential attribute for the safe operation of trains. A distinction is made between the technology and the implementation of the system. The technologies in question are as follows: no train control, intermittent train control, and train control with continuous data transmission, such as track conductor systems or radio transmission. The implementation of the system encompasses the utilization of various technologies, including no train control (On-sight Train Operation), PZB, LZB, ETCS (levels 1 or 2), and CBTC. A further amendment to the taxonomy concerns the communication type. Typical communication in the railway sector that may be relevant for an ATO system includes speech communication for the coordination of operational tasks, data communication with an ATC, and internal communication with passengers or conductors. Additional technologies in the railway sector include the global system for mobile communications - rail (GSM-R), the future railway mobile communication system (FRMCS), and infrastructure-side systems such as Eurobalise and Euroloop. A third supplement is provided in the form of track-specific positioning systems. In addition to digital maps, this includes the utilization of balise and landmarks [2], [9].

C. DYNAMIC ELEMENTS

It is beyond dispute that the influence of dynamic objects on ADS, in particular perception systems, is significant. On the one hand, ATO systems must be capable of reacting to obstacles that may arise on the track. However, on the other hand, their functionality must not be constrained by dynamic elements that may be present outside the clearance gauge. Typically, railway vehicles operate on their track without encountering other moving railway vehicles on their track or dynamic elements crossing. Nevertheless, in specific locations (such as stations, industrial areas, harbors, etc.) or exceptional situations, unplanned and inadmissible crossings between railway vehicles and dynamic objects may occur. An ATO system must be designed to operate safely and be capable of reacting to unpredictable object movements. The ability of the ATO system to respond to a potential obstacle on the track is dependent upon the train control system employed, given that in situations where trains are not operating on-sight, the braking distances frequently exceed the sensor sight distance or obstacles may suddenly appear on the track. Consequently, it is not feasible to halt in advance of the obstacle. Nevertheless, depending on the implementation of the ATO system, it is still possible to react in this case and, for example, emit a whistle as a warning signal or report a collision. As an illustration, animals may traverse the main line at any point, potentially resulting in a collision. In the event of a collision, there is always a high-risk potential for the colliding object due to the high mass of the train. Furthermore, a collision is invariably accompanied by significant financial implications, stemming from the costs of repairs to the affected vehicles and infrastructure, as well as the disruption to train services during the subsequent clean-up operations. It is therefore essential to consider the potential obstacles that may arise in the track as part of the ODD.

The attribute dynamic elements are used to describe all moving elements. A differentiation is drawn between the ego vehicle, on the one hand, as well as operational and active movements, on the other. The structure of the attributes is based on the automotive standard but differs due to the railway-specific use. The operational mobility attribute pertains to the agents that occur. The agent types are differentiated as follows: vulnerable users, animals, railway vehicles, and street vehicles. The non-railway dynamic agents' mobility (traffic) is subdivided according to the automotive ODD into the density of agents, the volume of traffic, and the flow rate [4]. The mobility of railway agents (train operation) is subdivided into occurrences on sidings, movement (speed, direction), length of agents, and occurrences on the ego track. Moreover, the agent mobility attribute is employed to classify pedestrians according to their density, as well as their respective flow rates. Other components of operational mobility include the presence of special vehicles such as emergency vehicles or special railway vehicles, as well as parked, stationary vehicles and objects such as wagons or skids.

With regard to rail operations, vehicles are typically observed to travel in one of two configurations: either as a single vehicle or in a train formation. This has a significant effect on the driving dynamics of the automated vehicle and can be taken into account as an additional attribute in the ODD. Concerning the subject vehicle attribute, a differentiation must be made in the rail sector between vehicles traveling alone and train sets. In the case of a train set, a distinction is made as to whether the wagons are braked or unbraked. In accordance with the ATO system, a further subdivision can be made with regard to the braking characteristics of the attached wagons (brake weight, brake position, brake percentage). Another attribute that may be considered is the ego vehicle speed.

D. OPERATIONAL CONDITIONS

The operational tasks inherent to rail transport exert a profound influence on the implementation of an ATO system. The division of tasks into attributes within the ODD facilitates the targeted deployment of systems for specific tasks. The operational conditions attribute encompasses all tasks and actions that extend beyond the direct control of the vehicle's longitudinal dynamics, including the monitoring of the surrounding environment and the execution of operational regulations. This section addresses the constraints imposed on the system's operational capabilities concerning the ROT.

The operational conditions are divided into two distinct categories: the operating scope and the operational tasks. The driving service regulation (Guideline 408) [13] provides the necessary input for this classification. Subsequently, the scope is divided into four further categories: driving trains, shunting, passenger traffic, and freight transportation. The operational tasks are separated into entry and exit of passengers at regularly scheduled stops, monitor train composition, communicate operationally, communicate with passengers, diagnose your own vehicle and train composition as well as prepare train, disarm, and park train [13].

V. CONCLUSION AND DISCUSSION

The current mobility sector is undergoing a significant transformation as a consequence of the increasing role of digitalization and automation. It is evident that the rail industry is engaged in a process of research and development that is leading to the introduction of digital and automated solutions, which are being offered alongside those developed by the automotive sector. Given the pivotal role of the automobile in the economy and society, the research and development of ADS in the automotive sector has a significant head start. Several methods, procedures, and solutions have already been validated in recent years, and ADS have been developed to a greater extent. The railway system is particularly well-suited to automated solutions due to its distinct network and the potential for simplified vehicle guidance resulting from the absence of a degree of freedom. For instance, the first GoA4 system was presented at the Port Island line in Kobe, Japan, in 1981 [37]. Nevertheless, automated solutions in the railway sector have primarily been focused on specific systems and largely confined to closed networks. The expansion and extension of these solutions to the entire railway sector now represent a significant challenge, particularly given the necessity of this automation for the achievement of climatic, economic, and political social goals. Consequently, it is of paramount importance that the mobility industries do not compete with each other, but rather collaborate to research a sustainable mobility sector. In order to create suitable standards and methods for the development and testing of highly automated rail vehicles, it is expedient to utilize existing processes and tools from the automotive industry as inspiration. Nevertheless, due to the differences and challenges identified in this work, new approaches must be developed and revised.

One of the most crucial fundamental principles underlying the operation of ADS is the identification of the geographical area and the specific operational context within which the system is designed to function, which is referred to as ODD. This assertion contributes to the creation of a framework for defining ODDs for automated rail vehicles. To achieve this, it is essential to begin by outlining the fundamental principles and tasks associated with automated rail vehicles. The existing definitions and research approaches are utilized as a foundation, and proven standards from the automotive industry are employed as a template. In light of the aforementioned considerations, the definition of the GoA level for the mainline sector by the ATO sensor technology project [12] is expanded and transferred to a proposal for the description of the DDT and, in addition, the ROT in the railway sector. In consideration of the prevailing automotive standard for an ODD taxonomy, a rail-specific solution is being developed. The taxonomy for defining an ODD for automated rail vehicles is based in part on the automotive industry's equivalent. However, the rail system, which differs from the road, necessitates the introduction of revisions and new definitions of various attributes, particularly in the areas of infrastructural description, connectivity, and movement information for dynamic actors. Furthermore, a fourth top-level category is introduced to account for the additional operational tasks of an ATO system.

The developed framework should serve as a basis for defining the ODD of as many ATO systems as possible under different operating conditions. It is possible to extend and adapt the taxonomy in relation to specific cases and systems, but it is essential to ensure that no contradictions arise with existing ODD attributes. The structure and organization of the attributes constitute the most comprehensive possible division of significant criteria pertaining to the application field of ATO systems. The objective was to incorporate all significant elements while maintaining a transparent and coherent structure and scope for the taxonomy. In dividing up the attributes, the objective was to reuse existing and known definitions and wording from the rail environment, as well as to list essential elements that can influence the use of ATO systems. In addition to consider existing research on the subject of ATO and ODD, we also drew on our own experience of scenario-based testing of highly automated rail vehicles [25], [38], [39], [40], [41]. It should be noted that the framework is not intended to represent a final, complete status at this point. Rather, it is intended to pave the way for the creation of a standardized ODD definition in the rail sector. Future research and findings may result in the adaptation or expansion of individual attributes. Furthermore, we have classified the individual sub-attributes into a division that we believe to be logical and coherent. Nevertheless, for certain ATO systems or areas of application, an adapted scaling may be beneficial and should not be precluded by this proposed taxonomy.

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LUCAS GREINER-FUCHS received the bachelor's degree in mechanical engineering from Baden-Württemberg Cooperative State University in cooperation with Schaeffler AG and the master's degree in automotive engineering from TU Braunschweig. He worked in research on the development and testing of driver assistance systems with TU Braunschweig. Since April 2021, he has been working on the VAL project with Nuremberg Institute of Technology, where he is involved in the development of a scenario-based test methodology for a highly automated shunting locomotive. His focus here is on real field testing on the one hand and scenario definition on the other. Since January 2024, he has also been employed with Karlsruhe Institute of Technology (Institute of Vehicle Systems Technology, FAST) as part of the Ph.D. degree, where he is continuing his research in the field of scenario generation and operational design domains in the rail sector.

MARTIN CICHON received the Doctorate degree in mechanical engineering from the University of Karlsruhe. He studied rail vehicle technology with RWTH Aachen University. He was a Development and Calculation Engineer in the rail vehicle industry and in research and advanced development in the automotive industry. He was a Professor in rail vehicle technology with Nuremberg Institute of Technology, from 2014 to 2022, and since 2023, he has been chairing the Institute of Vehicle Systems Technology, FAST, Karlsruhe Institute of Technology (KIT) as an University Professor, working in depth on the automated "On-sight driving" of rail vehicles. In 2017, he and his team presented the sensor technology and the driver decision module for the demonstrator of a fully automated locomotive for the operational design domain "Locomotive driving in a train formation facility." Since 2020, he and his team have been conducting research in the field of test development for fully automated rail vehicles and for the first time presented a method for an integrated test system for this area, from scenario generation to test case generation, test execution, and evaluation in the aforementioned ODD for both virtual testing and field tests. The associated work of his team was presented with great interest at conferences in Germany and abroad.

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