Investigating the Role of Simulation in the Approval Process of Automated Vehicles for Defined Operational Domains

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Abstract - *This paper investigates the role of simulation in the approval process of automated vehicles for defined Operational Domains (OD), focusing on the credible simulation of the Operational Design Domain (ODD), i.e., capabilities of the automated vehicle, and the OD, i.e., the actual environment. Considering current regulations and standards, e.g., EU 2022/1426 and ISO 34503, requirements for simulations are examined considering the OD approval process. The 6-layer model from the VVM project is used to structure the requirements for mapping elements of the OD. The approach is demonstrated for the AUTOGVZ project, which aims to automate existing truck traffic in a freight village and bring it into regular operation, using the Model-in-the-Loop simulation toolchain GEMSTAR to map the OD and the automated vehicle. This includes mapping the route on the basis of existing Open Street Map data and integrating a realistic traffic model generated with the traffic simulation software SUMO. The first results highlight the suitability of the approach for initial OD assessment and approval. Since our approach focuses on perception and can incorporate different sensor and environment models, it can be scaled to larger operating areas.*

Keywords: *Automated driving, Operational Design Domain, Simulation*

Introduction

The technological advances of Automated Driving System (ADS) are improving rapidly and the levels of automation (according to SAE definition (SAE International, 2021)) emerging into the market are continuously rising. While the commercial operation of Level 4 vehicles is progressing, especially in the USA and China (e.g., Waymo, Baidu), many manufacturers in Europe are still in testing phases. Beside the technical realization, the biggest challenge is to reach a comprehensive assessment, proof of reliability and robustness of the automation under test (Winner et al, 2019). As of now, in Germany, all SAE Level 4 vehicles operate with test licences, i.e., there is a safety driver on board. The German Regulation defines two main steps for full approval (German Federal Ministry for Digital and Transport, 2022):

- First, a comprehensive operating license, i.e., type approval, for the vehicle.
- Second, an approval of the Operational Domain (OD), i.e., a distinct area and operational conditions.

To approve an ADS for operation in a defined operating area the belonging OD must be compared with the capabilities of the ADS. The Operational Design Domain (ODD) refers to the conditions, like weather and traffic, under which an ADS is designed to function (SAE International, 2021). However, OD refers to the actual conditions in the real world and, therefore, differs from the ODD. Nevertheless, the relevant state authorities have to check the compatibility of the ODD to actual or potentially occurring circumstances and statistically known weather conditions in the OD. As testing on real roads is very expensive and time consuming, the shift to simulation-based testing and validation of automation functions is inevitable (Wachenfeld and Winner, 2016), where mainly model- (MiL) or software-in-the-loop (SiL) simulations are intended to be used, as they can be parallelized and sometimes accelerated. While ADS simulation is already being used regarding the type approval (Stavesand and Engel, 2023; Wiegand and Stavesand, 2024) it is not yet clear how the ODD-OD compatibility check can be conducted through simulation to support authorities and reduce real-road testing. A recently published assessment catalog for evaluating whether the ADS can actually perform the driving task within the operating area (German Federal Ministry for Digital and Transport, 2024) can serve as a starting point, but its implementation in simulation remains unclear.

This paper focuses on examining the role of simulations in OD approval. First, the approval process in the EU and in Germany as well as existing simulation-based approaches for type approval and possible quality metrics for simulations are presented. This is followed by the concretion of the research gap and the formulation of the specific research question, which is answered in this paper. Our approach to use a MIL simulation for mapping the OD and the ODD is then introduced and the intended usage for the OD approval is explained. This is followed by a presentation of the AUTOGVZ project, which is used to exemplify the methodology. The results achieved are then demonstrated and evaluated with regard to their suitability for use in OD approval. In addition, various simulation methods and integration levels for supporting the OD approval are discussed. Finally, an outlook on future developments and next steps is given.

Related work

The following section introduces existing definitions and relevant contributions in the field of automated vehicle approval and simulation from both industry and research.

Approval process of automated vehicles

Operational Design Domain (ODD): ISO 34503:2023 defines ODD as the conditions under which an ADS or its feature is designed to operate, including environmental, geographic, and time-based factors (ISO, 2023). There are several international taxonomies and standards for the characterization of elements in the ODD, PAS 1883:2020 (The British Standards Institution, 2020), SAE AVSC00002202004:2020 (Automated Vehicle Safety Consortium™, 2020), ISO/SAE PAS 22736:2021 (SAE International, 2021) and ISO 34503:2023 (ISO, 2023), which contain different categorizations of elements of the ODD, e.g., scenery, environmental conditions and dynamic elements in traffic. These efforts have introduced taxonomies, though none offer formal representation. ASAM's OpenODD aims to fill this gap with a machine- and human-readable format (ASAM e.V., 2021).

Operational Domain (OD): Also defined in ISO 34503:2023, OD refers to real-world operating conditions tied to geographic areas (ISO, 2023). Shakeri and Rohne et al. link OD directly to physical environments over time and space (Rohne, Richter, and Schwalb, 2022; Shakeri, 2024).

Operating Area: Often used in non-technical contexts (MOIA, 2023) this term refers to the geographic component of an OD and can be viewed as a subset of it (Castellanos-Ardila, et al., 2022; Mehlhorn, et al., 2025).

Furthermore, Garcia et al. introduce the concept of the Operational Road Section (ORS), focusing on the operational environment from the infrastructure operator's perspective (Garcia, et al., 2022). An ORS represents road sections where all known ODDs are met, enabling safe operation of any ADS. In line with this, Carrera et al. (Carreras, et al., 2018) present the ISAD levels, developed in the European INFRAMIX project, to classify road networks based on their support for automated driving. Similar to SAE levels for vehicles, ISAD levels range from E (no support) to A (full infrastructure-controlled cooperative driving). Factors like HD maps or digital traffic light signals contribute to higher ISAD levels.

For the regular approval of an automated vehicle, two regulatory paths exist:

1. EU type approval for small series: Based on Article 41 of Regulation (EU) 2018/858 (European Commission, 2018), this process treats the vehicle manufacturer as the applicant, who must provide detailed information about the ADS and its associated ODD (European Commission, 2022).
2. National regulations for regular operation: Under Article 42 of the same regulation (European Commission, 2018), individual EU member states can implement national rules. In Germany, this is governed by the Autonomous Vehicle Approval and Operation Ordinance (AFGBV) (German Federal Government, 2022). The German authority Kraftfahrtbundesamt (KBA) may issue testing approvals for ADS at SAE Levels 3–5 and national type approvals for Levels 4 and 5, in accordance with the Autonomous Driving Act (in effect since 2021).

Both EU and national approvals apply only to vehicles operating in defined areas, requiring alignment with national regulations on ODs. In Germany, this leads to a two-stage approval process: First, Vehicle approval, including verification of the ODD, resulting in an "abstract OD" [§4 AFGBV]. Second, approval of a specific OD [§7 AFGBV], tied to a geographic area and operational conditions (e.g., time of day), coordinated with local authorities. To obtain such an OD permit, detailed information on the operating area and conditions must be provided.

Simulation-based approaches

Various approaches aim to enhance the use of simulation in the development, validation, and approval of automated vehicles. The various integration levels are commonly distinguished in MiL, SiL, Hardware-in-the-Loop (HiL), and, if applicable, Vehicle-in-the-Loop (ViL) (Bringmann and Krämer, 2008). Furthermore, potential users or other stakeholders can be integrated, i.e., Human-in-the-loop or Driver-in-the-loop (Rothrock and Narayanan, 2011).

One example is the German project VVM (verification and validation methods), which provides a comprehensive framework to build safety arguments based on thorough safety analyses, legal compliance, and a balanced mix of real-world and simulation testing (Nuffer, et al., 2023). The EU project HEADSTART offers a similar approach but with a stronger focus on specific use cases (Wimmer, et al., 2020). Both highlight the value of simulation in reducing development time and costs. The VVM process relies on a scenario-based approach to define and assess safety within the OD (Glasmacher, et al., 2023), using logical scenarios—specific scenarios with defined parameter distributions (Menzel, Bagschik, and Maurer, 2018) to model the system's ODD. A 6-layer model structures relevant ODD attributes, where layers 1–3 represent static elements such as road infrastructure and layers 4–6 encompass dynamic objects and states (Scholtes, et al., 2021). Resulting scenarios can be categorized as functional (abstract descriptions), logical (with defined parameter ranges), or concrete (specific values assigned to all attributes). Scenarios are derived from real-world data (e.g., field tests, accident databases, and traffic studies). The EU projects SUNRISE (SUNRISE Project, 2025) and SYNERGIES (SYNERGIES Project, 2024) aim to harmonize scenario formats and improve access to scenario databases, ultimately streamlining simulation-based validation.

To create actual value for the approval process, the credibility of the simulation and the simulation content is key. The EU regulations 2022/1426 (European Commission, 2022) sets principles for the credibility assessment of the use of a virtual toolchain including modeling and simulation in the type approval process of automated vehicles. It mentions five properties of modeling and simulation that need to be investigated to achieve credibility:

- capability – what can the modeling and simulation do, and what the risks are associated with it;
- accuracy – how well does modeling and simulation reproduce the target data;
- correctness – how sound and robust are modeling and simulation data and algorithms;
- usability – what training and experience is needed.
- fit for purpose – how suitable is the modeling and simulation for the ODD and ADS assessment

The Credible Simulation Process Framework (Heinkel and Steinkirchner, 2021) defines layers of credibility determined by different levels of software formalization (Ahmann, et al., 2022). One mayor contribution for trust and credibility is the quality of the simulation, which can be assured by using ASAM standards, especially the ASAM OpenX family and ASAM OSI (ASAM e.V., 2023).

Research gap

In order to efficiently carry out the OD approval for larger geographical areas and to reduce the dependency on test runs on site simulation-based support should be considered. While ADS simulation is already used in type approval processes to some extent (Stavesand and Engel, 2023; Wiegand and Stavesand, 2024) and there are already assessment standards for credibility (European Commission, 2022), simulation is not yet mentioned in the OD approval, e.g., in the recently published assessment catalog for OD approval (German Federal Ministry for Digital and Transport, 2024). Consequently, simulation does not play a role yet in the process of OD approval. Currently, it is unclear which requirements apply to simulations for OD approval and how ODD–OD compatibility checks can be effectively performed through simulation to support authorities.

In order to tackle the task of clarifying the possible role of simulation and simulation results in the OD approval, this paper focuses on the following research question:

> *What are the important factors and prerequisites for the usage of simulation tools and hence simulation results in the course of the OD approval process regarding SAE Level 4 ADS?*

As this paper cannot offer a complete solution for using simulation within the OD approval, further questions, e.g., on the orchestration of different integration levels of simulation, e.g., MiL, SiL, and HiL, are also raised and discussed.

Methodology

In order to determine relevant aspects and prerequisites for the use of simulations and simulation results, the principles for the credibility assessment of the use of a virtual toolchain in EU 2022/1426 (European Commission, 2022) serve as a basis. As we want to investigate the use of simulations for OD approval and, thus, determine the degree to which the simulation provides an accurate representation of the real world (OD) and the vehicles capabilities (ODD), we focus on validating the simulation and simulation content. The scope of validation includes all tools and the corresponding models in a toolchain. To enable the transfer of the considerations to other simulation tool chains, we focus on the content of the simulation, i.e., models and (real) data, and not on the simulation software itself. However, for demonstration purposes, the simulation tool chain GEMSTAR, which is intended to support the OD approval, is presented in the next section.

According to EU 2022/1426 (European Commission, 2022) the manufacturer shall provide documentation showing that the data used to validate the models covers the intended functionalities that the toolchain aims at virtualizing. However, the criteria by which this can be shown are not mentioned. Thus, we try to approach the documentation of the credibility of the simulation content by using the 6-layer model, which is used for depicting the operational domain. For each layer of the 6-layer model, relevant aspects for credibility are discussed in the context of OD approval, e.g., accuracy and validity of input data and uncertainty characteristics. For integrating the vehicle and its ODD, we focus on mapping the perception chain through sensor models and their placement in the virtual world.

Mapping of Operational Domain and vehicle

To check ODD-OD compatibility, both the mapping of the OD and the ADS and the resulting ODD violation check must be credible.

In order to create a credible representation of the OD that contains relevant aspects for the OD-ODD compatibility check, it is necessary to take a closer look at the contents of the individual layers of the 6-layer model considering existing standards for ODD attributes like ISO 34503 (ISO, 2023). To obtain critical aspects of the OD, identifying real-world road networks properties and the typical behavior of road users interacting with the ADS is necessary. For the simulation results to be valid, it is essential that each object in the virtual representation of the OD is significant for the automated vehicle. Objects or content that are not relevant for the compatibility check should be omitted from the analysis.

The layers 1 to 3 are primarily spatial 3D objects with given geometry and texture. In order to achieve a certain credibility with this information, it is necessary to use real maps, e.g., Open Street Map (OSM), and data, e.g., tree registers and 3D images. Satellite-based mapping is also possible. With regard to the absolute and relative accuracy of the spatial information, it must be determined which requirements are sufficient to adequately map the OD. Most data sources have global accuracy metrics about the placement of objects in the world. But a global shift should not influence the results in virtual testing. Only the relative accuracy between objects in the OD should be relevant. Therefore, the relative error should be significantly lower than global positioning error. Analysis of the public OSM data show high positional accuracy, but larger distortions between high and low population areas than in commercial datasets (Helbich, et al., 2012). As Gao et al. point out, obtaining accurate data on the existing transportation infrastructure remains a challenge (Gao, et al., 2021). E.g., the creation of HD maps of streets or entire operating areas is often expensive.

Layer 4 contains dynamic objects with validated movements to display realistic traffic situations. If there is no information about the type and number of road users, it is not possible to assess the potential challenges for an automated vehicle without driving on site. The extraction of relevant traffic scenarios in the OD and belonging parameterization for road user models can be based on behavior and interaction data, which is obtained, e.g., from infrastructure and vehicle sensor observations as well as from accident databases. An information basis for mapping the dynamic objects in the simulation can be achieved either through elaborate field studies in reality (see, e.g., traffic data collection within VVM project (Klitzke, 2022)) or validated traffic flow models as well as fully generated scenarios.

Layer 5 includes environmental conditions that influence the lighting due to sunlight and cloud cover as well as precipitation. In layer 6, information on mobile communication coverage is particularly relevant with regard to communication with a remote assistance. Vehicle-to-Everything (V2X) communication, e.g., transmission of the traffic light status, may also become relevant in the future. Network simulations, e.g., OMNeT++ (Varga, 2010) and VEINS (Sommer, German, and Dressler, 2011), can be suitable for integrating this into the simulation.

The elements of all layers must be examined for their effects on the vehicle's perception chain. Thus, it need to be taken into account what aspects affect the different sensors, e.g. low sun positions blinding cameras or rain hindering LiDAR reflection. These impacts should be mapped through sensor effects, which alter the sensor outputs. Since the ODD-OD compatibility check in accordance with the assessment catalog (German Federal Ministry for Digital and Transport, 2024) is intended to cover not only the conditions that actually occur but also those that may occur, both statistical information and possible characteristics should be mapped across layers.

Regarding the modeled ADS, differences between real world sensors and modeled sensors are always existing (Schlager, et al., 2020). The sensor model quality is classifiable by comparison of model metrics as well as data driven approaches with neural networks. (Ngo, Paul Bauer, and Resch, 2021) To simulate these sensors, models are categorizable in different fidelity classes (Schlager, et al., 2020). If a specific effect regarding safety validation is needed, additional data needs to be provided, e.g., material properties and roughness of object parts, etc. (Linnhoff, et al., 2021), which the environment simulation has to support.

Supporting Operational Domain approval with GEMSTAR

To approach the ODD-OD compatibility check in practice, the open source software project "Open Simulation Toolchain for Automotive and Rail Research" for MiL simulation is considered (Fischer, et al., 2023) and applied. The software GEMSTAR (GEoMetry based sensor Simulation Toolchain for Automotive and Rail Research) builds upon the OSTAR components and replaces the CARLA simulator (Dosovitskiy, et al., 2017) with a custom Unreal project to meet the requirements of the ODD-OD compatibility check. Rather than checking if a specific vehicle can operate in an OD, GEMSTAR uses a generic vehicle with a parameterizable sensor setup. The gathered sensor views are transmitted as Open Simulation Interface (OSI) (ASAM e.V., 2024) messages to Functional Mock-up Interface (FMI) (Modelica, 2024) standardized sensor models. The assumption to use optimal sensor algorithms can be made, since the ADS itself is not part of the OD approval process and should contain sufficient perception algorithms by the type approval process. GEMSTAR uses an integrated SUMO (Eclipse, 2025) simulation with generated traffic patterns by flow routing traffic in the area. An analysis can be created from the results of multiple simulation runs with differing sensor setups and traffic flow patterns. To achieve a validation against the rules of the OD approval process, assumed thresholds for the number of camera pixels, LiDAR points, and radar points are considered sufficient to detect the traffic participant. Multiple simulation runs with differing sensor setups and traffic flow patterns provide boundaries for vehicles and their sensor setups. This enables the OD not only to accept one specific sensor configuration, but also a multitude of setups.

Project AUTOGVZ

The AutoGVZ project is being funded by the Federal Ministry for Digital and Transport (BMDV). The project consortium consists of To-be-now-logistics-research GmbH (coordinator), LUB Consulting GmbH, Roland Umschlagsgesellschaft mbH, Götting KG and the German Aerospace Center (DLR).

The aim of the project is to put an automated Hub2Hub transport system into operation within the Bremen Freight Village (German: Güterverkehrszentrum (GVZ)). Empty containers are taken from the "Roland Umschlag" depot to two packing stations, where they are loaded with car parts and then brought back to "Roland Umschlag". From there, the containers are transported to the associated seaports via a railway connection. Every day, several dozen containers are brought to the two packing stations, where they are filled and then collected again. The routes to the two packing stations are both around 3 kilometers long. The entire area is an industrial zone and is primarily used by professional drivers and experienced road users. The probability of unexpected behavior occurring is therefore considerably lower than in inner-city operating areas. The routes are depicted in Fig 1. The western route connects the packing station "C3" with the depot at "Roland Umschlag". The eastern route connects the packing station "BLG GVZ 1" with the depot respectively. Due to the low speeds and the possible deceleration (no passenger transport) for the automated vehicle, there are less safety-critical but rather operational influences to be feared.

As the project aims to implement regular operation

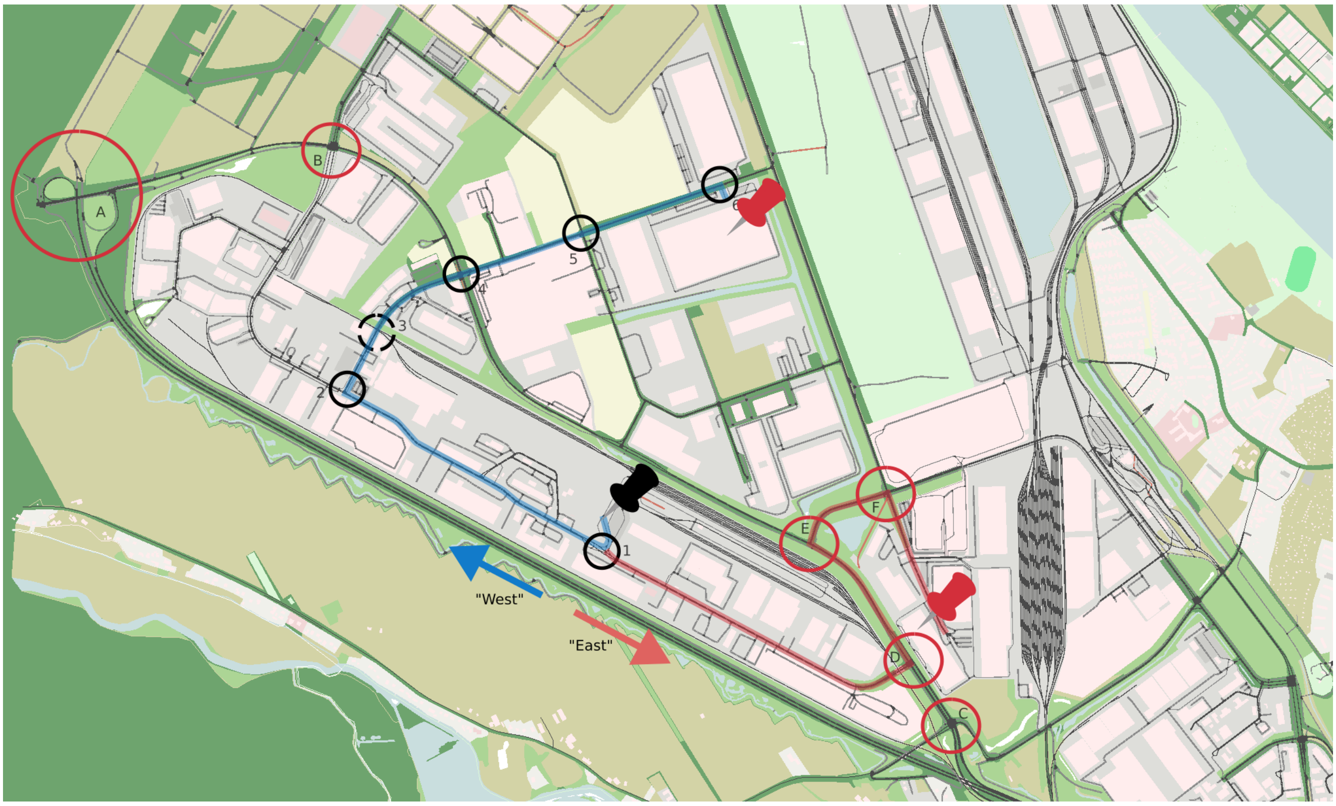

Figure 1: Two transport routes (”West” and ”East”) in the project AUTOGVZ. The pinpoints denote the ”Roland Umschlag” depot (black) and the two packing stations (red). Relevant intersections for the ”West” route are numbered. Existing traffic recording sites (A to F) are highlighted with red circles.

in accordance with the German AFGBV, a remote assistance is set up and put into operation. The remote assitant is a natural person who is located at a remote workstation and can chose and approve maneuvers proposed by the vehicle in the operating area. A potential scenario is an incorrectly parked vehicle on the road, which can be maneuvered around with the help of the remote assistant.

Results and discussion

The methodology described in the previous section using GEMSTAR and the SUMO microscopic traffic simulation was applied to the planned operating area in combination with the selected vehicle as part of the AUTOGVZ project.

Operational Domain

For the first and second layer of the 6-layer model, an existing OSM map is used. In addition, the maps are enriched with cadastral data from the city of Bremen. The third layer, which refers to temporary changes such as construction sites, is deliberately omitted from the initial analysis. At a later stage, for example, current or possible roadworks information should be integrated into the third layer in order to check changes to the operating area and their effects on ODD-OD compatibility. In our opinion, a highly accurate simulation of the road topology with an accuracy of less than 10 cm, for example, is not necessary. Since the creation of HD maps is expensive, a focus on a high accuracy of the maps for the simulation would reduce scaling. On the basis of existing maps (especially OSM) and 3D models a sufficiently accurate initial mapping of the operating area can be achieved. For the ODD-OD compatibility check, for example, occlusions at intersections caused by vehicles or vegetation are relevant for a specific sensor setup. Critical points, such as these occlusions, can be integrated into the simulation in specific scenarios, but do not have to be mapped statically with high accuracy.

In order to estimate the required capabilities of the vehicle in the OD with regard to logical behavior, traffic must be examined as a dynamic element in addition to the static operating area itself. A traffic model for the traffic simulation Simulation of Urban MObility (SUMO) is used for this purpose. The model was created on the basis of the network data from OSM and corrected or updated at some points in order to depict a traffic flow that is as realistic as possible. Figure 1 shows the entire network in the area of GVZ-Bremen. For the creation of the traffic model, traffic counts are available at the intersections circled in red. These can be converted into corresponding vehicle sources or sinks using the “jtcrouter” tool supplied with SUMO. For this purpose, the count data was first converted into a compatible format and then into ”routing” files for SUMO. Semi-trailers, trucks, cars, buses and vans were taken into account in the count data and converted with their own vehicle types. Motorcycles, bicycles, e-scooters and pedestrians were also recorded during the counts, but play a subordinate role in the traffic flow and are not implemented in the traffic model. There are 3 counting points for the

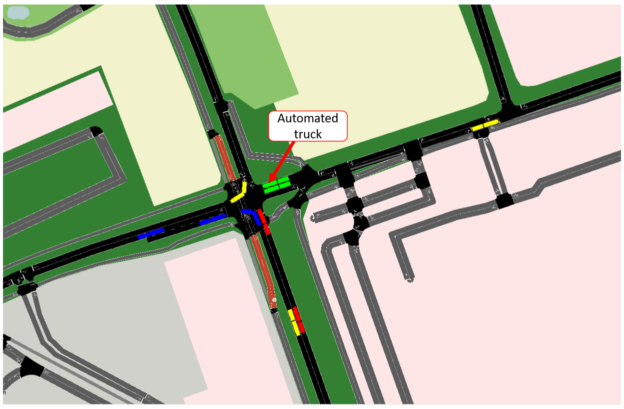

Figure 2: SUMO simulation of trucks on the intersection "4" in the project AUTOGVZ. The view of the automated truck is blocked by the other green truck next to it.

"East"-route, at each of which the traffic on the route was counted ("D", "E" and "F"). For the "West"-route, there is no counting point directly on the route. The traffic can be estimated on the basis of the surrounding counting points or generated by the model. The container transport implemented in the project is currently represented by conventional trucks and is not covered by any counting point. Approx. 50 containers are transported daily via the "West"-route. These journeys were added to the traffic model manually.

The traffic model is used to add the dynamic level of traffic to the simulation. Depending on the operating environment, typical maneuvers are determined that are performed by other road users or that must be performed by the automated vehicle itself in order not to significantly impede the flow of traffic. SUMO simulates at the level of the individual vehicle and can therefore also be used to determine possible occlusions. The traffic model can be used to determine with little effort how often certain scenarios occur in traffic and whether a special measure is required to ensure that the automated vehicle can cope with the scenario more quickly. For example, the automated vehicle on the "West"-route has to cross a priority road at junction "4". An additional lane is available for vehicles turning left and, if used by an semi-trailer at the same time, can lead to cross traffic being obscured. The automated vehicle cannot see the priority traffic, as the left-turning semi-trailer completely blocks its view. This scenario is shown in Figure 2.

Without additional infrastructure (e.g., V2X-Collective Perception Messages (CPM) from a camera system at the junction), the automated vehicle can only wait until the left-turning truck has turned and the view is clear again. A human driver usually uses the moment the truck turns, as this provides a kind of interlocking route safety for straight ahead traffic. Implementing such a function for an automated vehicle or equipping the junction could only be justified by a significant impact on traffic. Initial investigations with the traffic model show that precisely this scenario only occurs around 3 times an hour at the "4" junction. The waiting time of the turning truck is always less than 30 seconds, so a significant influence on traffic is not to be expected. The study was carried out using classic driver models. The use of automated vehicles (with different penetration rates) can further increase the probability of the scenario occurring, as the waiting times for straight ahead traffic are generally somewhat longer for automated vehicles than for conventional vehicles. This is generally due to greater safety distances that are stored in the vehicle control systems.

Statistical weather data is used to map the environmental conditions in order to record average conditions as well as minima and maxima. The values for Bremen based on the German Weather Service are shown in Table 1. Depending on the ODD of the vehicle, statements can now be made in advance. If, for example, the ODD does not include snow or ice on the road, it can be assumed on the basis of the average ice days that no operation is possible on approx. 15 days per year due to this restriction. Furthermore, the various weather conditions are included in the simulation with the help of GEMSTAR.

	Min.	Mean	Max.
Annual mean temperature (℃)	7.2	9.4	11.4
Absolute temperature (℃)	-23.6	–	37.6
Annual mean precipitation (mm)	404.4	696.4	1061.7
Daily precipitation (mm)	0	-	78.5
Annual sunshine duration (h)	1273.9	1545.0	2062.6
Monthly sunshine duration (h)	7.3	-	341.4
Frost days (Tmin <0 ℃)	24	70.8	105
Ice days (Tmax <0 ℃)	0	14.9	54

Table 1: Climate and weather in Bremen (01.01.1890 - 13.04.2025). Mean values: 1981-2010, extremes: 1890-2025. (German Meteorological Service (DWD), 2025)

Vehicle and Operational Design Domain

Since the driving function is already tested in the type approval for its decision making based on environmental perception and, thus, the automated vehicle is confirmed to be suitable for driving in a so-called "abstract OD" (German Federal Government, 2022), it makes sense to focus on the differences between the abstract OD and the aimed OD including a geographically specific operating area and their effect on the perception. To model the vehicle, a 3D model of the truck used is procured and integrated into the simulation. A specific sensor setup can be mapped and analyzed by integrating and placing generic or specific sensor models in the simulation. Generic sensor models abstract the essential characteristics of actual sensors — such as field of view, range, resolution, detection uncertainty, occlusions, latency, and noise patterns — without being tied to specific hardware implementations. This abstraction allows for simulating various sensor configurations and assess their impact on the perception chain. While generic sensor models provide an abstract representation of sensor behavior, specific sensor models are more detailed and closely mimic the behavior of a particular real-world sensor, often based on manufacturer data and empirical measurements. However, as Schlager et al. pointed out differences between real world sensors and modeled sensors are always existing (Schlager, et al., 2020).

With regard to the OD-ODD compatibility test, it has been shown that the use of generic sensor models is already highly informative for initial assessments, e.g., with regard to the rough placement of sensors on a vehicle. However, specific models should be used in the further course in order to be able to make more precise statements and, if necessary, to make decisions between several sensors. However, the challenge here is that sensor manufacturers might not provide the data for modeling or even their own sensor models.

Discussion

In this section, the considerations on the prerequisites of simulations for use in the OD approval as well as the steps implemented and results achieved in the AUTOGVZ project will be discussed.

While driving simulations are indispensable in the type approval process in order to test the automated driving function under parameterizable scenarios, the orchestration of different integration levels, e.g., HiL, MiL, SiL or Driver-in-the-loop, is still open in the OD approval. With regard to remote assistance, human-in-the-loop simulations can play a central role, for example to examine possible perspectives and information for a remote assistance to classify a traffic situation or to train personnel. By integrating a human operator into the simulation environment, realistic interaction scenarios between the remote assistance and the automated vehicle can be studied. Especially in geographical areas that are newly used as operating areas for automated vehicles, a simulation can be helpful to identify critical, unclear points from a sensor perspective and, for example, to supplement them with infrastructure-side detection technology. Additionally, human-in-the-loop simulation allow, e.g., for evaluating response times, decision-making processes, and workload under different operational conditions.

Since the OD approval only focuses on the matching between ODD and OD, it is possible that classic driving simulations, in which an automated driving function of a manufacturer is integrated into the simulation environment, do not play a role. On the other hand, the informative value of simulations increases if not only the perception chain, i.e., the sensors and sensor placement on the vehicle, but also the interaction with an automation function is considered. Therefore, we are also planning to integrate an open-source automated driving function into GEMSTAR.

In addition to the question of the type of simulation, our thoughts on simulation content and its credibility need to be discussed. Regarding the five properties of modeling and simulation that support credibility (European Commission, 2022), we proposed a digital representation for the individual layers of the 6-layer model, which is based on real data and is sufficiently meaningful for an initial consideration of the OD-ODD compatibility check. On the ODD side, we propose the use of generic sensor models attached to a vehicle in the simulation.

However, some questions remain that require future research:

- How can the trade-off between map accuracy and scalability be systematically assessed across different operational areas? Do satellite-based methods for creating 2D/3D models provide sufficiently accurate results?
- How can temporary changes in the OD, such as construction sites or temporary road signs, be effectively and reliably integrated into the simulation workflow and what data sources can be used?
- How can rare but safety-critical scenarios be represented? Can additional data (e.g., historical traffic incident reports) be integrated to capture edge cases?
- What criteria determine the transition from using generic sensor models to rather specific ones during the simulation process? How could a standardized library of validated sensor models (open or proprietary) support simulation-based approval across different projects?
- How can a standardized format and an associated interface for the provision of static or statistical OD information look like who maintains it?

Conclusion

This paper has explored the role of simulations in the approval process of automated vehicles, focusing on the Operational Domain (OD) approval. We have presented the existing approval processes in the EU and Germany, along with current simulation-based approaches for type approval and potential quality metrics for simulations. The research gap was identified as the need for a systematic approach to use simulations for OD approval, which is currently not existent.

Our approach, based on a Model-in-the-Loop (MiL) simulation, was introduced as a means to map the Operational Design Domain (ODD) and the OD in a credible manner. By leveraging the 6-layer model for scenario description we investigated different criteria for enhancing credibility of the virtual representation of the OD. On the vehicle side, generic and parameterized sensor models are integrated into the simulation together with a vehicle model in order to investigate the perception capabilities in the planned OD. The approach was demonstrated using the AUTOGVZ project as an example. A 3D digital image was created for the operating area in the freight village Bremen. Based on real-world data, a realistic traffic model was generated using SUMO and integrated in the simulation toolchain GEMSTAR. The results show that with our approach, valuable insights can be gained regarding occlusions, sensor coverage, and the impact of infrastructure layout on the vehicle's perception. Especially in the early phases of development, such simulations allow for rapid iteration and assessment of sensor placement in comparison to the planned OD.

With this work, we expect to increase the visibility of simulation-based methods for OD approval and to initiate a discussion with industry and authorities on the requirements for simulation frameworks and content for use in the approval process. In addition, we plan to further investigate the questions raised and also analyze the use of human-in-the-loop simulation in particular for remote assistance to support vehicles in operational areas.

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