A Systematic Methodology for Specifying the Operational Design Domain of Automated Vehicles

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***Abstract*—This paper outlines a systematic approach to specifying an Operational Design Domain (ODD) for an Automated Vehicle (AV). The approach addresses the complexities arising from diverse sensor setups, the vast range of operational domain attributes, and the wide range of driving assistant functionalities with their specific regulations that impact the ODD. Our methodology focuses on identifying and excluding non-safe areas within the operational domain. By narrowing down the operational domain to a manageable subspace, this approach saves time and effort in the testing process of AVs. As a proof of concept, the proposed methodology has been validated through a practical example, demonstrating its application and feasibility.**

***Index Terms*—Operational Domain, Operational Design Domain, ODD Specification, Automated Vehicle, Sensor Setup**

I. Introduction

The operation of Automated Vehicle (AV) systems is limited by their sensors, actuators, and also their design. As a result, AVs cannot safely operate within a wide range of environmental, scenery, and traffic conditions. These limitations can pose a problem for the reliability of such automated systems. Additionally, regulations may add further constraints and restrict the operation of AVs even more. To address this, it is crucial to clearly define the Operational Domain (OD) for vehicle systems that ”refers to the attributes of the physical surroundings in which the vehicles navigate, including the natural terrain and human-made infrastructure, environmental phenomena, and traffic conditions” [1]. Then, a subset of OD can be specified, within which the AV is designed to operate safely. This subset of OD is called the Operational Design Domain (ODD), which is specified using an ODD specification.

One of the challenges in specifying an ODD is to identify the wide range of parameters that are affecting the vehicle operation. Design decisions can alter the ODD; for instance, a manufacturer may choose to restrict the ODD for a specific vehicle beyond what is required. Also, the broad variety of sensors can be affected differently by OD attributes. For instance, two camera sensors from various vendors have different responses to sun glare. Last but not least, the wide range of functionalities that an AV offers may have distinct requirements. For instance, the minimum required detection range varies across different functionalities.

Creating an ODD specification for a specific AV system is difficult due to the vast range of OD attributes and the wide range of parameters affecting the AV’s operation. It is beneficial to start with a preliminary ODD specification that is created in a systematic manner rather than creating one from scratch through trial and error. This approach saves time and effort in the early stages of development. Also, it streamlines the development process and enhances the safety and functionality of AV systems.

This work introduces a methodology to specify the boundaries beyond which vehicles bear unacceptable risks in operation. Our strategy prioritizes the elimination of all parts of the operational domain that are considered non-safe, thereby significantly reducing the risk of operating in potentially hazardous conditions. By identifying and excluding unsafe operational areas from the start, we effectively narrow down the OD to a much smaller, manageable subspace. Therefore, the refined domain requires testing on a smaller scale than the original. This approach streamlines the testing process by making it more efficient, while also facilitating ODD updates or extensions through improved sensor setup or design.

This study starts with an overview of related work regarding the specification of an ODD in Section II. Then, in Section III, a methodology is proposed to generate an ODD specification by analyzing various parameters that are important for the operation of an AV. This paper focuses on analyzing OD, regulatory requirements, and sensor setup configuration and their impact on ODD specifications, with the potential for future extension. Next, to evaluate our methodology, we conducted measurements to demonstrate the impact of sensor setup and OD attributes on sensing characteristics. These results are presented in Section IV. Finally, Section V discusses how the applied methodology contributes to creating an ODD specification and concludes our study.

II. Related Work

The operational domain of AVs consists of a vast range of dimensions. To address this, researchers proposed various taxonomies to categorize these dimensions and describe the operational domain. Koopman and Fratrik emphasized the importance of defining the operational environment for AVs by listing critical aspects such as terrain characteristics and environmental conditions [2]. They proposed a comprehensive list of factors relevant to describing the operational domain. Later, Gyllenhammar et al. developed a framework to categorize and quantify the ”operating conditions” [3]. Standardization committees also attempted to define the operational domain for AVs by developing a taxonomy of their attributes. Initially, the National Highway Traffic Safety Administration (NHTSA) identified a preliminary set of attributes categorized into six main categories [4]. Subsequently, three other standards also offered taxonomies for operational domain attributes [5]–[7]. It is important to note that the operational domain is dynamic and can evolve, leading to the emergence of new classes, properties, and attributes over time. Weshhofen et al. have addressed this, suggesting the use of ontologies to formally describe the operational domain and critical phenomena in urban traffic scenarios [8].

Alongside operational domain characterization, efforts have been made to develop specification languages to specify an ODD for AV systems. Irvine et al. (2021) propose a structured natural language approach to defining an ODD for Automated Driving Systems (ADS), aiming to enhance clarity and accessibility for a diverse range of stakeholders, including regulators and system designers. Schwalb et al. built upon Irvine's work, transitioning from a structured natural language format designed for clarity and accessibility towards a more formal representation aimed at programmatic execution. At the time of writing this article, the ASAM OpenODD standardization committee is actively working on developing a standard for the specification of ODDs [9].

Having a specification language alone is insufficient for creating an ODD specification. Techniques are needed to deduce ODD statements by observing operational domain attributes and analyzing their impact on AVs. Studies on empirical data from a field test in the Netherlands indicate that environmental factors like weather, lane width, and street lighting can significantly impact lane-keeping system performance [10], [11]. Furthermore, defining ODDs is complex due to varying risk factors. Lee et al. proposed a systematic approach based on statistical data and risk tolerance to establish ODDs based on a preset risk threshold [12]. Their work differs from the current study, which aims to establish ODDs by analyzing the impact of the operational domain, regulations, and sensor setup on sensing characteristics.

Several studies have shown that sensing characteristics such as range, accuracy, sensitivity, and response time are directly influenced by operational domain attributes like rain, fog, temperature, and lighting. These environmental factors can reduce sensor range and accuracy, reduce sensitivity, and increase response time, impacting the operation of AVs. Table I summarizes studies that measured the effects of various environmental conditions on these key sensing parameters.

Finally, it is important to highlight a recent work, which addresses existing misconceptions and misinterpretations in the domain of ODD-related studies [1]. This work proposes defining the operational domain as a key concept and clarifies the relationship between ODD, ODD specification, and the operational domain by presenting a formal representation of these concepts. The current study adopts the terminology and relationships established in that work [1].

III. Methodology

In this section, the methodological approach to deriving an ODD specification in a structured way is presented. For a better understanding of the dependencies between the relevant elements and their interplay along the procedure, a model-based visualization using Systems Modeling Language (SysML) diagrams and syntax was selected [21]. The methodology is described using three main diagrams: Block Definition Diagram (BDD), Requirements Diagram (REQ), and Activity Diagram (ACT). All three diagrams are aligned with each other and holistically represent our approach from three different perspectives. To help with grasping the overall concept, the structural representation of our approach (BDD and REQ) will be illustrated first. After that, the actual procedure utilizing the structural elements will be explained (ACT). The shown approach is deliberately kept generic so that it is open to company-specific tailoring.

First, the high-level dependencies between the relevant elements for ODD derivation are shown via a BDD. Figure 1 illustrates the BDD.

As shown in Figure 1, a sensor setup is part of an AV. The same sensor setup could be used in different variants of an AV. The sensor setup consists of one or more sensors and possesses one or more sensing characteristics. The OD is characterized by one or more OD attributes [6]. An ODD is a subset of the OD [1] and the OD can have multiple ODDs as a subset. The relationships to requirements of the REQ shown in the BDD will be explained in the following section, where the REQ is being described in detail.

The further dependencies between corresponding requirements or specifications and their relationships to the elements of the BDD are shown in a REQ. Figure 2 illustrates the REQ.

Typically, we derive maneuver requirements from regulatory requirements for (automated) driving functions, e.g., from the UNECE R157 regulation regarding automated lane keeping systems (ALKS) [22], as well as from relevant safety requirements and traffic rules. The maneuver requirements are satisfied by the AV in its respective configuration. While also taking into account the relevant OD attributes and the respective sensor setup (trace dependency), the sensing requirements are derived from the maneuver requirements. The sensing requirements are then satisfied by the sensing characteristics possessed by the sensor setup (see Figure 1). Ultimately, the ODD specification, which is satisfied by the actual ODD, can be derived from the sensing requirements.

As already mentioned at the beginning of this section, the BDD and the REQ together serve as the structural representation of our approach. Now that the structure and elements of our approach are known, the procedure for structured derivation of an ODD specification can be defined. Ultimately, our proposed method or procedure for structured derivation of an ODD specification is shown in Figure 3 as an ACT.

As implicitly stated in the description of the REQ above, the regulatory requirements as well as the relevant safety requirements and traffic rules are considered as input information for derivation of the maneuver requirements.

TABLE I
THE TABLE REFERENCES THE STUDIES THAT INVESTIGATED THE IMPACT OF DIFFERENT OPERATIONAL DOMAIN ATTRIBUTES ON SENSING CHARACTERISTICS SUCH AS RANGE, ACCURACY, SENSITIVITY, AND RESPONSE TIME.

		Sensing Characteristics			
		Range	Accuracy	Sensitivity	Response Time
Operational Domain Attributes	Fog	[13], [14]	[15]	-	-
	Rain	[13], [14], [16]	[16]	[17], [18]	-
	Lighting	[16], [19]	[16], [19]	[20]	[20]

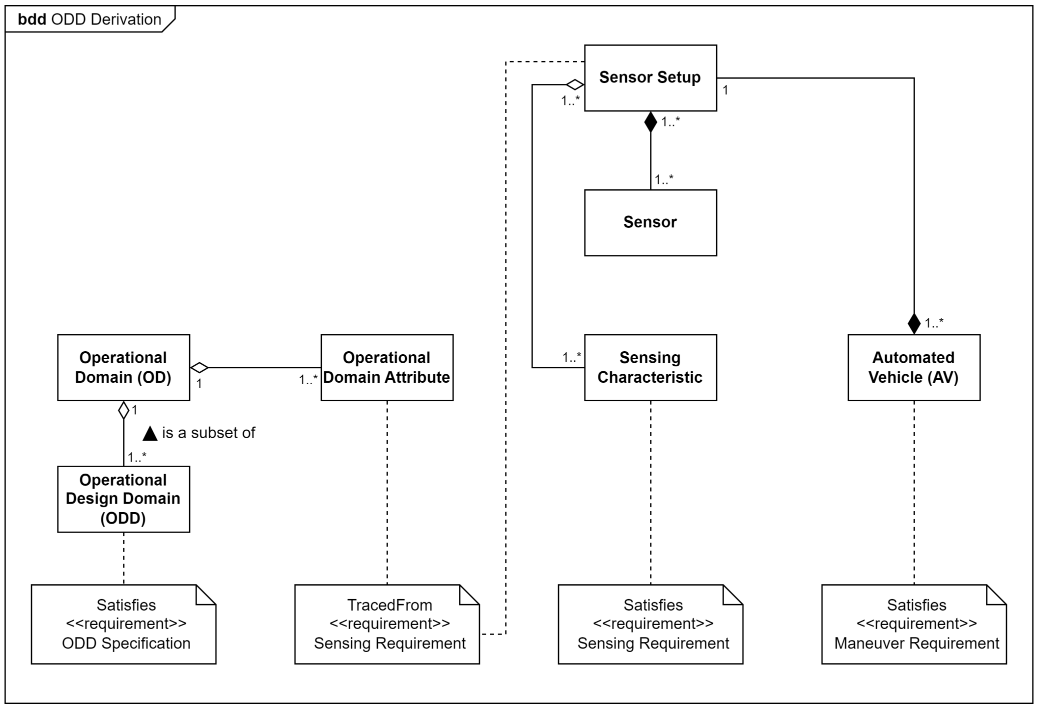

Fig. 1. Block Definition Diagram (BDD) for ODD derivation.

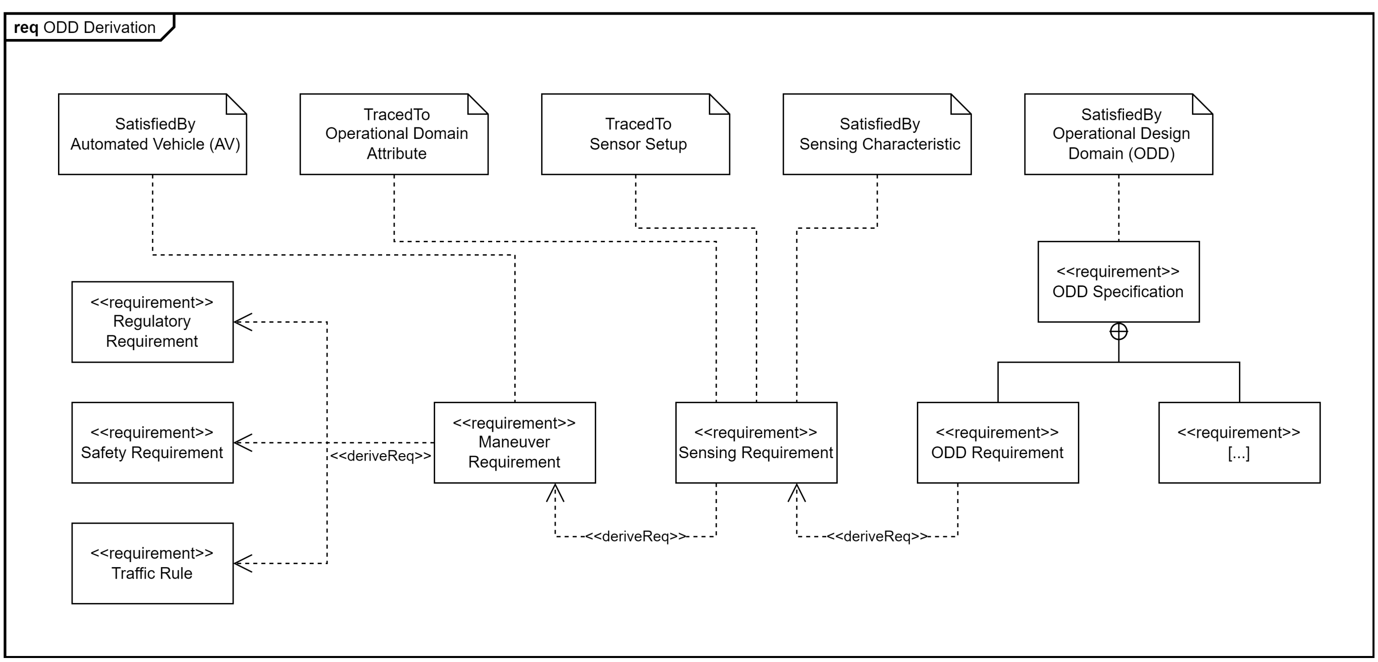

Fig. 2. Requirements Diagram (REQ) for ODD derivation.

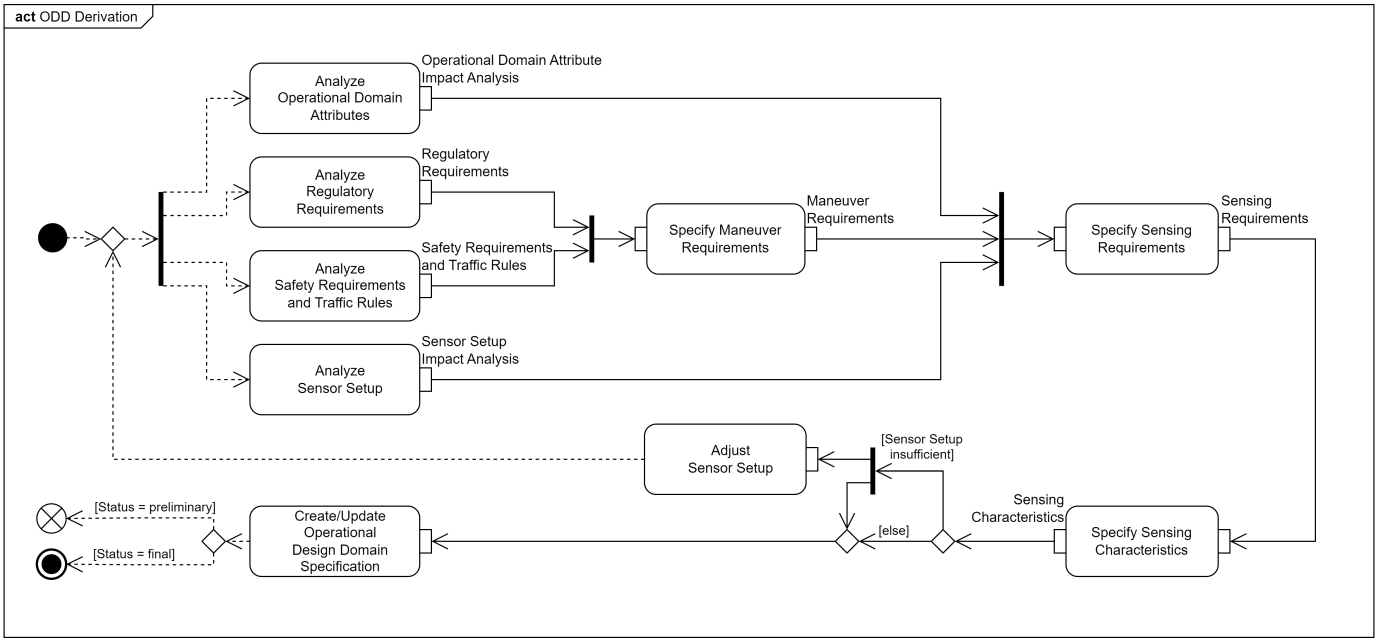

Fig. 3. Activity Diagram (ACT) for derivation of an ODD specification.

After analysis of the OD attributes and the sensor setup with respect to their potential impact on sensing (requirements and characteristics), the operational domain attribute impact analysis, together with the maneuver requirements and the sensor setup impact analysis, are holistically considered for the derivation of the sensing requirements, which then serve as the basis for subsequent derivation of the sensing characteristics.

At this point of the paper, the interdependencies between the OD attributes and the sensing characteristics that are implied via the referenced studies in Table I should be more clear in terms of the respective structural relationships (BDD and REQ) and the procedure of how the OD attributes impact the derivation of sensing characteristics (ACT). In the same way, Table II in the following Section IV can now be better understood, where the interdependencies between the sensor setup and sensing characteristics are illustrated. While, according to Table I, the impact of OD attributes on sensing characteristics has already been demonstrated by multiple studies, the impact of the sensor setup on sensing characteristics, as shown in Table II, is a novel approach first presented within this paper.

As the next step in the procedure, the suitability of the sensor setup would be evaluated against the specified sensing characteristics. If the sensor setup is insufficient, e.g., if its functioning range does not meet the specified range as a subset of the sensing characteristics that are derived from the sensing requirements, adjustments need to be made. In any case, a first ODD specification would be created, taking into account the specified sensing characteristics. In case of insufficient sensor setup configuration, an iteration of the procedure would be necessary and the preliminary ODD specification would need to be updated at the end of the iteration. If there are no further iterations necessary and the ODD specification is finalized, the activity ends.

IV. Example application of methodology

The methodology for creating an ODD specification is described in Section III. In this section, the procedure that is defined in Figure 3 is applied to an example case. For instance, consider the ALKS installed on an AV as the automated system under investigation.

The first step of our methodology involves analyzing the regulatory requirements, which, for ALKS, are defined by UNECE R157. While a detailed regulatory analysis is beyond the scope of this study, we provide a simple analysis of two UNECE paragraphs. Paragraph 5.2.3.1 states that "The maximum speed up to which the system is permitted to operate is 130 km/h." and paragraph 7.1.1 dictates the minimum forward detection range (FDR) for different operational speeds. By analyzing the regulatory requirements we can specify one of the maneuver requirements as follows:

For a maximum speed of 130 km/h, the minimum forward detection range shall be at least 150 meters.

This maneuver requirement immediately implies a sensing requirement that is:

$$\text{FDR} > 150\,\text{m}. \tag{1}$$

In the next step, sensing characteristics need to be specified. In this case, FDR is a special case of "range" as one of the main sensing characteristics. By analyzing the operational domain and sensor setup we realize how a sensing characteristic such as "range" is a function of OD attributes (illumination, precipitation, etc.) and the sensor setup. After this, it is time to check whether the current sensor setup can fulfill the sensing requirement in Equation (1). If this is not the case, either the

Fig. 4. Camera image of a scene in a village during daytime.

Fig. 5. Camera image of a scene in a village during nighttime.

sensor setup configuration shall be adjusted (e.g., by adding another sensor) or the ODD specification shall be updated.

The next activities in the Activity Diagram (see Fig. 3), are analyzing OD and sensor setup to find their impact on sensing characteristics. As an example of this activity, we want to show how the sensor setup impacts the sensing characteristic ”range” through a series of measurements. Additionally, we will examine how an OD attribute, such as ”time of day,” specifically categorized as ”daytime” and ”nighttime,” influences the detection range.

To show the sensor setup and OD analysis (see Figure 3), a simulation sequence is generated using the CARLA simulator. In these simulations, different sensor setups and varying values for an OD attribute are used. Then the maximum detected range for each setup is measured.

The initial sensor setup included just one camera sensor, which was mounted on top of the ego-vehicle. This sensor setup is evaluated under two conditions: during the day (refer to Figure 4) with maximum sunlight, and at night (refer to Figure 5) without any light source.

The second sensor setup includes a camera and a LiDAR sensor. For this sensor setup, simulations consider both daytime and nighttime conditions. Figure 6 illustrates the LiDAR point cloud data converted into an RGB image. This enables detection beyond the headlight’s field of view, improving object detection in low-light conditions.

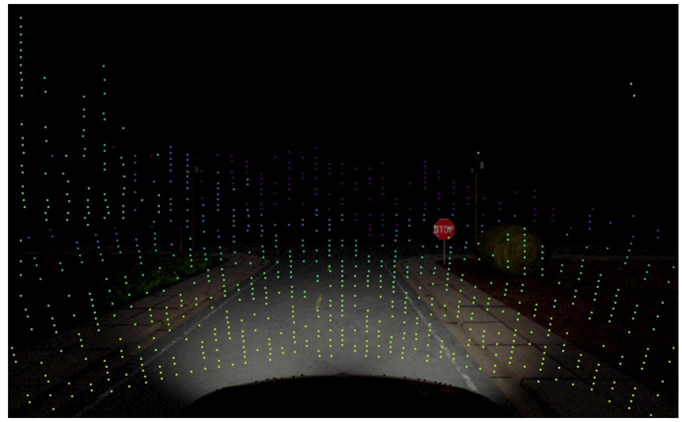

Fig. 6. Camera-LiDAR sensor setup during night detecting target vehicle beyond the FOV of the AV’s Headlight

TABLE II
FORWARD DETECTION RANGE (FDR) IN METERS FOR DIFFERENT SENSOR SETUPS DURING DAY AND NIGHT.

	Day	Night
Camera	204.8 m	135.0 m
Camera-LiDAR	204.8 m	193.4 m

To quantitatively assess the effect of different sensor setups and values of OD attribute ”time of day”, we calculated the FDR in meters. For the camera sensor, FDR is measured using the method that is described in [23]. Also, for the LiDAR sensor, FDR is measured from the point clouds in the multi-sensor setup (Figure 6). Table II shows the measured maximum detected range for different setups.

The result of analysis in Table II shows the impact of changing the sensor setup and adjusting the values of an OD attribute, in this case, ”time of day”, on the sensing characteristic ”range”. The next step is to explore how these analysis results can influence the ODD specification.

The performance of AVs’ sensors, as shown in Table II, depends on sensor setups and the specific values of operational domain attributes. More specifically, we observed that the visible range at night is lower with the camera sensor compared to during the day. Therefore, a system with a camera sensor shall put some limitations on its ODD specification such that the vehicle does not operate beyond its capabilities. Also, following the example that we introduced in Section III, we want to show how regulations can also influence an ODD specification.

Analysis of the regulatory document for ALKS, as reflected in Equation 1, establishes specific sensing requirements for ALKS. However, Table II indicates that the maximum detection range for a vehicle with a camera sensor operating at nighttime is about 134 meters. It is evident that the detection range is insufficient to meet the UNECE R157 requirements for ALKS. Therefore, it is necessary to revise the ODD specification to explicitly restrict the operation of our AV during nighttime. To address this issue, an ODD statement should be added to the ODD specification to restrict the operation of our exemplary AV at night:

The system shall not operate at nighttime up to speed of 130 km/h.

Similarly, other OD attributes such as precipitation and fog also significantly impact the detection range. Therefore, a comprehensive analysis of these attributes is essential. Such detailed studies depend on the specific sensor technologies used and the characterization of the OD in taxonomy standards like ISO 34503. While this detailed analysis is beyond the scope of the current study, manufacturers, who are aware of the limitations of their systems, should conduct these measurements to ensure safe and compliant operation.

V. Conclusion

As concluding remarks, in this paper, we proposed a systematic approach to creating or updating an ODD based on analysis of regulations, sensor setup, and impact of operational domain attributes on the operation of AVs. We addressed the complexities associated with diverse sensor configurations, a vast range of operational domain attributes, and varying driving assistant functionalities subject to specific regulations. Our methodology focused on identifying and excluding unsafe areas within the operational domain, thereby reducing risks and streamlining the testing process. By narrowing down the operational domain to a manageable subspace, we demonstrated how time and effort in the development and testing of AVs can be saved.

Through a practical example, we validated the feasibility of our approach, showing how it can help in formulating precise ODD specifications that ensure the safe and reliable operation of AVs. This study highlights the importance of detailed analysis and regulation compliance in defining an ODD, ultimately contributing to the advancement of AV reliability and its safe integration into real-world environments. As with any study, this work had a limited scope, focusing on developing a methodology rather than exploring the technical measurements specific to each system. By emphasizing the analysis of key input factors—namely regulation, sensor setup, and operational domain attributes—we hope this work serves as an initial step toward shaping future works in the direction of creation and updating of ODDs.

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