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Overview of the Operational Design Domain Monitoring for Safe Intelligent Vehicle Navigation

Thibault Charmet^{1,2}, Véronique Cherfaoui¹, Javier Ibanez-Guzman², Alexandre Armand²

Abstract—The operational safety of intelligent vehicles (IV) is a central topic and a complex issue on which many research projects are focused. While there is no consensus yet on the most reliable way to validate driving automation systems, several methods exist such as scenario-based testing and real-time operational domain (OD) restriction based on the specification of the operational design domain (ODD). In our case, we focus on the role of the ODD concept as a safety guarantee for IVs and how, combined with real-time monitoring of their operational domain (OD) can act as a safeguard for complex mobile systems. We propose to analyze the related literature, standards, works and proposals made in the field of OD/ODD monitoring for operational safety and to assemble them into 3 categories : the first concerns the use of taxonomies and ontologies to represent the elements of the vehicle driving environment ; the second concerns the formal definition of the ODD through a dedicated language ; the third concerns techniques allowing the monitoring of the vehicles' OD to improve operational safety. By taking a step back from the identified methods, we highlight how they can be combined in a coherent manner, to progress towards a framework enabling ODD definition and OD/ODD monitoring.

I. INTRODUCTION

Passenger vehicles are becoming more complex through the introduction of advanced driving assistance systems (ADAS) and higher levels of autonomous driving functions (ADS), the need for assured safety becomes critical. Current vehicles could be divided into two types: Vehicles with ADAS functions, where drivers remain in the control-loop, represented by SAE levels 1 and 2, these functions only provide driver assistance. Vehicles with ADS, where drivers are temporarily or completely outside the control-loop, represented by SAE levels 3 to 5 [1]. The design and deployment of autonomous vehicles by industry and academia have shown that ensuring their safe operation in all conditions is difficult, requiring millions of kilometers of validation drives [2]. Their autonomous navigation environment remains limited to a given number of situations, depending on the capabilities of the vehicles [3]. These situations are represented by geography, roads infrastructure, traffic speed, environmental conditions, etc., may reflect technological limitations, vehicle design, risk management, business considerations, etc. They need to be defined formally for

several reasons: to control the conditions under which the vehicle equipped with an ADS/ADAS would be able to navigate autonomously, to ensure the safety of passengers and other road users, etc. [1].

In this context, within the last years the formalization of the working area of autonomous vehicles has emerged, the Operational Domain (OD), while introducing the concept of Operational Design Domain (ODD) [4]. This corresponds to the set of situations and conditions for which an autonomous system has been designed, and therefore for which its operation and safety must be demonstrated and validated [1]. For example, the ODD of an ADS may consist of autonomous navigation on a motorway, with full lane markings and during day conditions. If lane markings are poor, or it is at night or a bicycle is perceived, the ADS will be outside its ODD. The concepts are detailed in Section II.

Currently, there is much interest on the formalisation of the ODD through standards, verification processes, etc. as applied to ADS. The aim of OD monitoring, often referred as ODD monitoring is to determine in real-time whether the current OD of the vehicle is compatible with the ODD for which it has been designed and validated. It means that, for OD monitoring, the environment in which the ADAS or ADS functions must operate has been defined (i.e. ODD determination). The monitoring is done in real-time to ensure the system remains within the defined ODD. That is, the driving conditions (OD) are being monitored against some specifications (ODD). In the paper, we refer to it, as OD monitoring.

The challenge is to determine in real-time whether or not a system is capable of operating in its current environment. For this purpose, different steps are needed: (i) Based on the system's capabilities, an ODD, fitting the situations where the system is working safely, must be established. (ii) This ODD must then be defined formally (i.e., a structured human and machine readable representation). (iii) It must be used in real-time to detect potentially unsafe situations (OD monitoring). However, if the ODD determination can be well established from test-based validation (Section V-B), nevertheless, the formalization of the ODD definitions and the OD monitoring are still under progress [5]. The purpose of this paper is to seek methods that allow a verifiable formalization of the ODD and enable real-time OD monitoring. The paper shall provide a structured critical review leading to the formulation of the research problem and to outline the possible approaches to follow.

The paper is structured as follows: Section II, presents the context and definitions needed to understanding what

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OD monitoring is. We then review existing works centered around concepts relevant to OD monitoring: taxonomies and ontologies of ODD attributes, ODD definition languages and OD monitoring. Section III presents the taxonomies used to structure and define attributes describing the driving environment of intelligent vehicles. They are the basis of ODD definitions and constitute most of the related literature. Section IV looks into the languages used to define/describe the ODD. These formulate in a coherent manner the attributes defined in the ODD taxonomies. Section V looks into what constitutes OD monitoring and the methods used. Finally, Section VI concludes the paper, by summarizing findings and proposing the directions that future work will seek, to implement real-time OD monitoring, to determine whether the vehicle is operating within the environment for which it was designed.

II. DEFINITIONS

A. Operational Domain (OD)

The OD is the domain of operation of the vehicle i.e. the full range of real-life driving conditions. In practice, we observe and understand it through sensors and situation understanding algorithms, but it does not guarantee a complete representation of the real situation. Thus, it could be represented in many ways, the most common is as a finite set of attributes (like environmental, geographical or object information). This OD representation is a granular representation of the world. The attributes will be explained in section II-C.

B. Operational design domain (ODD)

a) *Definition:* The ODD, is defined by SAE J3016 [1] as "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". For example, a traffic jam chauffeur should be able to drive inside slowed traffic (< 60km/h), on highways, with good illumination (no night, tunnels, etc), forgiving weather (no snow, storm, etc) and as long as it has access to network information including maps, alerts, etc. The ODD can be extended with other conditions include being able to drive under unfavorable weather (rain, etc) but at reduced max speed can be added. It is up to the system developers to define the ODD in terms of operational guarantees they want to provide.

b) *Motivation:* There are three main reasons why it is necessary to understand and use the ODD.

First, for safe operation, i.e. all safety measures taken in real-time, during the operation of a system, to ensure its safe use. Because an ODD is a subset of all the driving conditions that can be encountered while driving (i.e. the OD). By restricting those conditions and controlling the driving conditions, it makes it easier to guarantee the safe operation of a system. It makes the task of creating highly autonomous driving automation systems much easier [1]

(fig. 1, based on constructors official information¹). The OD monitoring is ensuring the safe operation of a system, by comparing the measurable OD representation of a given situation with pre-established specifications (i.e. the ODD) that must be respected.

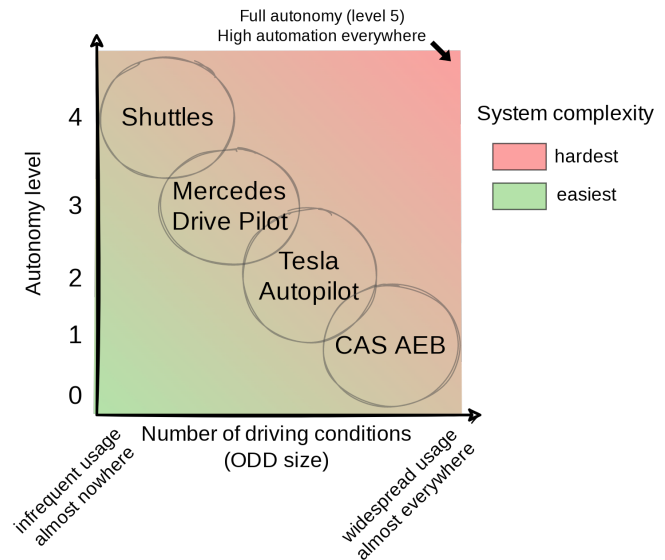


Fig. 1. SAE levels vs the number of driving conditions (ODD size). Level 4 autonomous shuttles, by limiting their ODD to predetermined paths, slow speeds, etc are able to reach high automation. Level 3 Mercedes Drive Pilot provides conditional automation by limiting the conditions to traffic jams under 60 km/h, daylight, no tunnels, etc. Level 2 Tesla Autopilot can be used in many situations but under the driver's liability. Because level 0 Automatic Emergency Braking (AEB) systems are simple, they can be used safely in almost any driving condition.

Second, for autonomous operation. The main difference between SAE level 2 and 3 is that the driving liability is transferred to the ADS when it is activated and within the ODD [1]. It implies that the driving conditions (OD) must be monitored and compared to the ODD. Note that, even though, OD monitoring is necessary for level 3, it can be applied to any system in order to improve operation safety.

Third, for safe design, i.e. all safety measures taken during the conception of the system (validation, etc). An ODD can be seen as a set of high-level specifications for which the system has been designed to operate safely. It is common to see the constructors first use it as a set of operational domain specifications that the system should reach at the end of development. Then, as the project evolves, the ODD will be refined to match the actual tested and accepted driving conditions. Thus, at the end of the process, the ODD is the set of specifications for which the system is guaranteed to function.

Its definition must be understandable by people outside the field (ADS users, regulatory authorities, decision-makers, etc) because its purpose is to be communicated with the

¹<https://easymile.com/technology/ezfleet>
<https://www.mercedes-benz.de/passengercars/technology/drive-pilot.html>
<https://www.tesla.com/support/autopilot>

public, autonomous car users, authorities and other manufacturers. It must also be precise enough to describe the majority of the attributes of the environment.

In other fields, equivalent concepts are used, such as Operational Envelope (OE) for maritime and Operational Context (OC) for railroad [6].

C. ODD attributes

As the ODD definition must be understandable by people outside the field and machine readable, ODD attributes (or OD representation attributes) are commonly used as the base elements of the OD representation and the ODD definition. They must be agreed upon before defining an ODD, so every reader can understand exactly what they mean in real life. In this document the usage of the terms OD representation attributes and ODD attributes are interchangeable as the attributes of the representation of the OD and the ones used to define an ODD are generally the same.

Let's take an example. Like the T-junction presented in the ASAM OpenODD concept paper (fig. 2) [7]. A vehicle moving in this area would have to deal with a 2 way lane, a T-junction, a traffic light, a zebra crossing, a speed bump, signs for 50km/h speed limit, a pedestrian crossing, street-lamps, and some vegetation, environmental conditions like the weather, the illumination, and road users' information like the presence or absence of car/pedestrian traffic. This is the OD of this particular area, at a specific time, expressed in natural language.

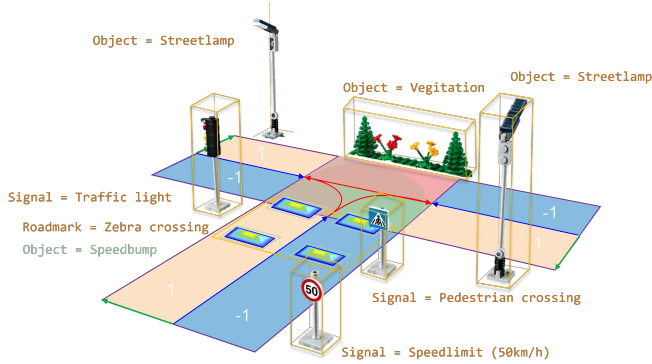


Fig. 2. Illustration of a T-junction from ASAM OpenODD concept paper [7]. With a 2 way lane, a traffic light, a zebra crossing, a speed bump, signs for 50km/h speed limit, a pedestrian crossing, streetlamps, and some vegetation.

In order to represent this OD in a numerical way, we can create a set of attributes from the perceived environment. This set of attributes is the OD representation of this particular area at a specific time, expressed in a formal way.

III. TAXONOMIES AND ONTOLOGIES FOR INTELLIGENT VEHICLES

In order to describe and structure the driving environment of vehicles, it is common to use attributes organized into taxonomies. A taxonomy is a type of hierarchical classification, often organized in tree-like structure, categorizing things into groups and subgroups (like for biological classification), such

that there is a logical semantic relation between the attributes and their parents. Taxonomies are a special type of ontology. They both share the same goal of representing information, knowledge and concepts in a formal, explicit, structured format [8]. The main difference is that ontologies are used to represent various relations between the concepts (i.e. possible interactions between multiple attributes). Ontologies are used in many domains to represent expert's knowledge, complex interactions, etc. [9] describes an ontology-based reasoning for situation awareness that can be used to model spatio-temporal relations between the road users and the infrastructure.

Most of the works around ODD definition and labelling will tend to use taxonomies for their simple and intuitive tree-like structure. While most of the works around scenario-based validation will use ontologies, as their more complex graph-like structure can represent interactions between the elements of the environment, thus making scenario generation possible.

A. Taxonomies

In the autonomous driving domain, multiple attribute taxonomies have been proposed (summarized in table I).

TABLE I
ODD TAXONOMIES PROPOSED IN THE LITERATURE.

Name	Authors	Date	# attributes
ADS 2.0 [4]	NHTSA	2017	approx. 10
DOT HS 812 623 [10]	NHTSA	2018	approx. 170
Operational world model ontology for ADS [11]	Czarnecki	2018	approx. 100
AVSC00002202004 [12]	AVSC	2020	approx. 100
PAS 1883 [13]	BSI	2020	approx. 150
ISO 34503 [14]	ISO	WIP	-
SAE J3259 [15]	SAE	WIP	-

In their 2017 report [4], the NHTSA encourages car manufacturers to define and document the ODD for their ADS. They only provide some top-level elements as example minimal information. The following year, they propose a more extensive ODD taxonomy [10], multiple levels deep. Their paper also provides an extensive literature review of ADS features, Object and Event Detection and Response capabilities (OEDR), Fail Operational (FO) and Fail Safe (FS) strategies based on around 50 sources. The same year [11], [16], [17] proposed an Operational World Model Ontology with elements like road structure, road users, animals and obstacles, road user behavior, environmental conditions, etc. It has a tree-like taxonomic structure without formal definition of the relations between attributes. Thought, is mostly aimed at driving scenarios' specifications rather than ODD specification. It can be seen as an extended ODD attributes taxonomy including behavioral information divided into two categories. Behavioral factors are information like traffic rules, informal rules, user skills, capabilities, personality, emotions, etc. behavioral models are information related to the type of model used to infer road users' behavior. This last category couldn't be used for an ODD definition, as it is not dependent on the driving environment, but from the

functional architecture of the ego driving system. In 2020, two taxonomies are proposed. One thought a report [12] aiming to establish best practices for ODD description and proposing some terminology that can be used to describe the ODD. The other, PAS 1883 [13], often mentioned, proposed a minimal taxonomy for ODD attributes. Technical standards such as ISO 34503 [14] and J3259 [15] are still under development. ISO 34503 should specify requirements for the ODD attributes taxonomy, along with a natural language definition format for use by regulators and non-coders.

All of these taxonomies attempt to list fairly exhaustively the attributes describing the driving conditions. They are often the result of extensive research in the field of transportation safety and public transport engineering, and many elements are present in all of them. The main difference between the cited taxonomies is their organization into groups and subgroups, which is more subjective. This is because one attribute can be part of multiple groups, but has to be organized under one branch. Therefore, based on our analysis of the taxonomies, we can illustrate them with a representative taxonomy containing the attributes commonly found, organized in the following distinct top-level categories:

- Road structure (road type, surface, geometry, edge, lanes, specificities, junctions, signage, etc)
- Objects and road users (road users, animals, non-static objects, etc)
- Connectivity (V2V and V2I and other communication, GNSS positioning, services availability, etc)
- Environmental conditions (weather, visibility, illumination, etc)
- Zones and areas (type of geographic area, geo-fencing, hazard zone, administrative regions, interference zone, etc)
- Operational constraints (vehicle speed, period of operation, technical constraints, etc)
- Flows and densities (car, pedestrian and other types of traffic, etc)
- Behavior (observable road users' behavior, measurable risk, etc)

B. Ontologies

Ontologies are used as knowledge representation structures for others tasks like scenario generation, situation awareness, etc. They could serve, like taxonomies, as a knowledge base for ODD attributes. In 2018, [18] used ontologies as knowledge-base for scene generation, as a basis for a scenario creation, mentioning OpenDRIVE and OpenSCENARIO as future simulation data format. In 2022, [19] proposed an ontology based on elements from ODD taxonomies, scenario-based testing, and ADS architecture, in order to help the creation of scenarios for scenario based testing. ASAM is developing OpenXOntology², an ontology combining all the attributes/objects common to their OpenX

standards (mainly OpenSCENARIO 2.0, OpenLABEL and OpenODD). The goal is to have a compatible set of objects that can be referenced by any OpenX definition.

C. Taxonomy and ontology implementation

Taxonomies and ontologies need to be implemented in order to be used by downstream tasks. Choosing a language to represent and query the taxonomy is a necessary step toward it. Through the efforts to create an ODD definition language (see section IV), multiple ways to represent the ODD attribute taxonomies or ontologies were used. JSON-like languages (YAML, etc) are best for simple taxonomies representations. They can represent simple tree-like data structures with values and hierarchy. [20] uses a DSL which is a simplification of a Ontology Web Language (OWL). ASAM's OpenXOntology needs to represent complex relations between objects that occur in scenarios, and thus is being built on an OWL base. OpenODD will probably be based on OpenXOntology. Other projects like [18] are OWL-based and use the Java-based OWL-API. The ontology built by [19] uses a UML based representation.

IV. OPERATIONAL DESIGN DOMAIN DEFINITION LANGUAGE

The ODD definition is often based on the considered use cases and written in a tabular format. Using instead an ODD definition language, may be a better way to represent the bounded driving conditions in a way:

- that is both shareable with others (because it can be written in an independent file), that can be understood both by non-developers, and by the machine.
- that is automatable, because it is understandable by the machine and can be used for OD monitoring.
- that is exhaustive because it can be based on a selected and shared set of attributes, more or less detailed as needed.

As pointed out by multiple papers, today, there is no method to completely define an ODD, whether in a formalized way or not. This means that actual ODD definitions available in papers are insufficient for other downstream tasks like scenario generation [5], [21], [22].

This part presents previous and current works on the domain. Table II summarizes the ODD definition language projects and it highlights some of the most important aspects: the ODD attributes used (taxonomies, etc), the type of representation used for those attributes (YAML, OWL, etc), the type of the definition language (DSL, etc), the possibility to define quantitative values (in addition to qualitative values), possible conditional definitions of the attributes, the presence of consistent rules toward hierarchy and the definition order, permissive and restrictive modes, if maneuvers, behaviors and probabilities are included, availability of the full language specifications, the availability of the language implementation if any.

There have been few propositions to create an ODD language. In a Five AI's presentation [20], 3 Domain Specific Language (DSL) are presented, including one for ODD

²ASAM OpenXOntology, <https://www.asam.net/standards/asam-openxontology/>

TABLE II

COMPARISON OF THE DIFFERENT PROJECTS AROUND ODD DEFINITION LANGUAGES. "?" ARE FOR NON AVAILABLE INFORMATION.

	year	attributes	representation	language type
[20]	2020	PAS 1883	OWL based	simple DSL
[23]	2021	PAS/AVSC/ISO	OWL	SQL-like queries
[22]	2022	ISO 34503	?	YAML
[7]	2024	PAS/AVSC	OWL based	OSC2.0 and SQL

project	values	conditions	consistent	modes	maneuvers	behaviors	probabilities	specifications	availability
[20]	✗	✓	✓	✓	✓	✗	✗	✗	✗
[23]	✓	✓	✓	✓	✗	✗	✓	✓	✗
[22]	✓	✓	?	?	✗	✗	✓	✗	✗
[7]	✓	✓	✓	✓	✗	✗	later	✓	✗

definition and one for "high-level scene annotation" (i.e. OD representation for scenarios). Quantitative values can be used to define qualitative attributes in the ontology, then only qualitative attributes are used in the ODD definition. Maneuvers are part of the ODD attributes. Conditional definitions are implemented using a global/local fashion. And it is partially compatible with OpenX.

In this pair of papers [21], [23], the authors introduce a specific language that allows to define the ODD, at 2 levels of representation: semantic, and formal. For the semantic language, they propose a SQL-like query language composed of statements like: CLASS, ACCEPT, etc. Conditional definitions of attributes can be made with "WHEN" and "EXCEPT" keywords. Operators can be used for value comparison as long as units are specified. There is consistency between the statements when they are imported. Once an attribute has been accepted or rejected in some conditions, it cannot be changed by subsequent statements by mistake. Attribute accepted uncertainty can be represented using probabilities and the "QUALIFIER" and "@" keywords. e.g. "pedestrian@P8.E6" would mean a pedestrian occurrence less than once per 10^8 hours, or a pedestrian detection error less than 2^{-6} ($> 98.5\%$ accuracy). This initiative, although interesting, remains to this day only theoretical. Indeed, no publication presents whether this language has been implemented and used in real conditions.

Recent works such as [22] are starting to build ODD frameworks. Their ODD definition language is based on [23] and the paper generally inspired by it. They made their own ODD attributes taxonomy composed of around 760 terminal nodes (i.e. attributes) inspired by [14], though the definition format used is unknown. They propose a method for validating defined ODD against situations datasets. They use situations datasets to estimate the OD in different areas, which can be then compared to an ODD. The ODD, YAML-based, is monitored against a small subset of ODD attributes. Conditional statements can be made and combined logically with "WHEN" and "EXCEPT" keywords. There is little in-

formation about the consistency of the definition when doing multiple statements and imports and restrictive/permissive modes are not mentioned. Even if the paper is proposing a prototype implementation, there is little reproducibility as neither the code nor the taxonomy are given.

The most recent work is the OpenODD [7]. If the V1.0.0 is still under progress, they already proposed two syntax for an ODD language. There is a quite exhaustive list of 15 requirements for the language including human/machine readability, composability, conditional statement, extensibility of ontology, binary boundary, units, and a general compatibility with OpenX standards. It should support quantitative values and even variables storing values. Uncertainties and probabilities should be added in later versions. They clearly define that behavior information are reserved for scenarios and not ODD. The project is backed by members from many companies and universities such as the University of Warwick, Five AI, etc. There is a quite extensive research done about what functionalities must be included in the ODD definition language (user stories, requirements, etc). The release date is due for January 2024, however, no official implementation of OpenODD is expected by ASAM as they are a standardization group.

The ISO 34503 standard [14] can also be mentioned here. This standard, still under development, will provide an ODD natural language definition format for use by regulators and non-coders. As no computer readable format is planned, this wasn't added to the list with others.

V. OPERATIONAL DOMAIN MONITORING

OD monitoring is not a new concept, as any autonomous system would have to limit their functionalities to some conditions. Commercial level 3 ADS like Honda's traffic jam pilot for their Legend Hybrid EX and Mercedes's traffic jam pilot, restricted to 60km/h speed limits, in traffic jams, good lightning conditions, are good examples. If the best practice publications mention the ODD of their system, it is very rare to find the methods that have been used for the OD monitoring. In this part, we present some of the methods used.

A. Geofencing

The simplest way to define the ODD and to then monitor the OD in real time is to use geofencing as an approximation of the driving conditions. Geofences are virtual perimeters describing real geographic areas. They can be used by ADS to bound the areas inside which the system can be used, or inside maps, to describe areas or interest (e.g. school zones, low emission zones, etc) [24]. As simple restrictions on vehicle location are easier to implement and understand than high-dimensional ODD descriptions, this is the most common approach. In their guidelines [25], the Global Mining Guidelines Group (GMG) restricts conditional automation to "designated autonomous area". Ohmio level 4 shuttles, and robotaxis in general, evolve in very specific geofenced areas, at restricted speed limits.

B. Measuring the ODD

Some works focus on identifying and defining the ODD through data collection or depending on system capabilities (maneuvers or object and event detection and response). [3] define a Restricted OD (ROD) when some system capabilities are lost (Degraded Operation Mode, DOM). They consider using OWL as a structured language to represent the ODD attributes ontology in future works. They mention the ontology of [16] as a base to build an ODD. [26] are identifying a geographical and environmental ODD by evaluating the conditions in which the ADS is underperforming. For each combination of ODD attributes, the estimated risk is computed based on expected severity, contextual exposure to the attribute, and system-measured performance in those conditions. Attribute combinations associated with high risk are removed from the initial permissive ODD. In a NIST publication [27], the idea of measurable OD representation is developed through what they call an Operating Envelope Specification (OES). It focuses on the operational safety side of the ODD, with OD reasoning against an ODD (OD monitoring), but do not detail about how it should be done and formalized. [28] proposes a way to determine the ODD of a system based on collected data, and proposes a real-time assessment for perception algorithms. They also do robust training for perception using data augmentation. [29] have a data-driven, out-of-ODD research via counter example trained machine learning (ML). They focus on few temporal attributes that can be predicted over time for the environment, and use specific rules corresponding to faulty behaviors to find out-of-ODD situations.

C. ODD for safety validation

Most of the works around ODD and using taxonomies and ontologies are for design safety (i.e. ADS safety validation). The main focuses being scenario generation [18] and scenario database advanced labelling. Deepen AI and the Warwick Manufacturing Group (WMG) worked in collaboration on SafetyPool™, a public scenario database repository with multiple features³⁴. They allow the creation and filtering of scenarios based on multiple labels including ODD attributes from BSI PAS 1883. They have their own scenario definition language that can be converted to an OpenSCENARIO format. They generally try to be compatible with OpenX standards. They can also generate CARLA⁵ simulations from those scenarios. They plan to add testing and other new safety related features in order to provide a platform with a full safety validation workflow. In their case the ODD attributes are used as labels for scenarios. This is one use case that allows them, for example, to display on a map all the roads corresponding to a given set of ODD attributes. Those attributes can be compared to the information available on the map to determine which one corresponds and which one

don't. This is the same method that would be used by level 4 path planning systems to avoid roads outside a given ODD.

D. Interactions with the ODD

Other works may focus on the interactions between the ODD definitions, users and the infrastructure. [30] mention, for future works, the use of ODD for managing Transition Areas in a Cooperative Automated Driving context to mitigate handovers and minimal risk maneuvers. There is the Traffic Management for Connected and Automated Driving (TM4CAD) project⁶, expected to finish in March 2023. The project is targeted toward regulatory bodies, in particular the National Road Authority (NRA), responsible for the national road network in Ireland. They mainly provide insights and recommendations about the ODD management (via perceived and exchanged ODD-relevant information by the infrastructure and CAVs) from the point of view of the infrastructure providers. Basically, they are trying to answer the question "how traffic management systems and CAV vehicles can best interact to improve traffic operations" ? They give insights about the detectability or availability of the ODD attributes (e.g. today's CAV may not be able to measure the road surface friction and will never be able to detect roadside obstructions in advance without the information from the infrastructure), the change frequency of ODD attribute information (e.g. weather changes faster than the road geometry).

E. Monitoring strategies

There are very few publications proposing actual frameworks for OD monitoring. In their paper, [31] divide OD monitoring into 4 strategies corresponding to 4 groups of ODD attributes. Direct internal conditions (like speed) on which the vehicle should have total control; conditions that can be guaranteed beforehand (like a priori information about the path, available in advance); conditions that can be guaranteed beforehand depending on geographical or temporal values (similar by more geospatial-based like weather forecast in some areas); and dynamic conditions (like road friction, real time rain). This approach helps to monitor each attribute with different adapted monitoring strategies. They also propose to combine those strategies for a same attribute. For example, coupling a weather forecast with a sensor in order to detect strong rain. A first constraint is placed on rain probability. The weather forecast gives a predicted probability distribution of rain, and the ODD decides if the probability is low enough. A second constraint is placed on rain strength. A rain sensor measure in real time the intensity and the ODD decides if it is accepted. Though this approach is interesting, this might be equally simple to have 2 attributes "rain forecast" and "rain intensity" that are both restricted by the ODD.

VI. DISCUSSION

We can state, that multiple elements are needed to ensure ODD representation and OD monitoring. They can be

³<https://www.safetypool.ai/>

⁴Demo of SafetyPool Usecase for ODD Scenario Tagging, Siddhartha Khastgir (ASAM Webinar), <https://youtu.be/1Sycwx44Glg>

⁵<https://carla.org/>

⁶<https://tm4cad.project.cedr.eu/>

referred as the *ODD framework* and can be described as follows:

- ODD attributes. Preferably organized into a taxonomy or an ontology.
- ODD attributes representation. Machine readable attributes implemented with a structured language (e.g., a tree like structure language; JSON, YAML, etc.) or with more complete ontology representations (e.g., based on a web ontology language - OWL, OpenXOntology, etc.).
- ODD definition language, machine and human readable.
- Intermediate OD representation.
- Algorithm for OD monitoring. As found in [31], it might be useful to take the divide and conquer approach and apply multiple monitoring algorithms for different types of information sources (e.g., dynamic, a priori, etc). The core of the algorithm will be the ODD and OD comparison, however, the difficult task resides on having a valid OD representation in the first place.

Finally, most studies and publications are best practices for human-defined ODD, conceptual taxonomies. Few address techniques to implement an ODD framework either for development or the system validation phase, or on-board use in real-time ; to determine if the driving conditions in which the vehicle evolves (the OD) is compatible with the ODD. There are also few propositions to represent the knowledge uncertainty inside the ODD framework.

Whilst the ODD is referred as part of several projects, there is no method for general and automatic OD monitoring. To date, the OpenODD project can be considered as the most advanced ODD definition language. For human, natural-language ODD definition, the ISO 34503 should become the norm. With regards to ODD attributes, any taxonomy or combination of taxonomies can be relevant. The simplest and one of the earliest would be PAS 1883 and the most complete SAE J3259 (in preparation). The simplest taxonomy representation would be YAML and the more advanced an OWL-based representation ideally compatible with OpenXOntology.

VII. CONCLUSION

In this paper, we identified three methods needed to effect real-time monitoring of the operational domain: taxonomies and ontologies to represent the driving environment, formal operational design domain definition languages, and methods for operational domain monitoring. So far, only specifications, and high-level ODD taxonomies have been published, little information is available on the manner how they should be formalised so they can be integrated into ADS. Formats from other domains, like ontologies used for scenario generation, could be applied. Currently there is work to provide a structure capable of representing machine-readable ODD definitions as part of the OpenODD, ASAM standard. Different approaches are being proposed towards OD monitoring, these define the ODD automatically including strategies to monitor ODD attributes. By using insights from all of these works, it would be possible to formulate a

full ODD definition and develop an OD monitoring framework beyond conventional geofencing based boundaries, and towards attribute-rich operational domain monitoring. While taking into account deployment constraints such as perception uncertainty and the non-observability of some attributes. This operational domain monitoring, will be a needed piece to ensure safe navigation of intelligent vehicles in the future.

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