A CONCEPT TO SUPPORT AI MODELS BY USING ONTOLOGIES - PRESENTED ON THE BASIS OF GERMAN TECHNICAL SPECIFICATIONS FOR LANE MARKINGS

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ABSTRACT

Artificial Intelligence (AI) and Machine Learning (ML) deliver promising approaches to the development of assisted as well as automated and autonomous driving [1] technologies. However, learning all possible traffic situations and outcomes is almost not feasible. Furthermore, machine learning-based models are usually regarded as a black box and we cannot trace their decisions for a certain behavior. To counteract this, we propose an ontology-based model, which integrates normative knowledge, to support the decision making of the AI for automated and autonomous vehicles. Since traffic rules and laws are explicitly defined in the model, we can easily track any derived decisions, eliminating the necessity of learning all possible traffic situations. We formalize the German Technical Specifications on Lane Markings into an ontology for a better representation of the traffic environment and thus improve the situational awareness of automated and autonomous vehicles. Additionally, the reasoning capacity of an ontology based-model allows for deriving concepts in multiple ways, which can serve as redundant information about lane and lane markings to enhance the understanding of the traffic situation. Finally, in contrast to learning-based models, our transparent ontology-based model allows for the validation and verification of automated and autonomous systems and vehicles.

INTRODUCTION

Advanced driver-assistance systems (ADAS) are usually programmed on rule-based algorithms. With the increasing level of automation, the requirements for these systems become more complex, especially for the automated driving systems (ADS). These ADS must comply with rules and laws, consider guidelines, mathematical and physical laws, expert, and world knowledge. This increasing complexity poses a huge challenge for the automotive industry, because there are too many hand-crafted rules that need be taken into account while programming. To this end, data-driven AI and ML algorithms are a very promising tool to solve the challenge of the high complexity. With the development of various advanced sensors and communication systems, more and more data is generated in traffic and available for processing with learning-based models. In this field, driving data recorded with cameras, radar, and lidar are essential for the development of functional and safe systems. These sensors can record, depending on the type, from 1 MB/s up to 500 MB/s, which translates to about 6 TB per day for a setup of assistance Level 2 or even 100 TB per day for a setup of autonomous driving at level 4 and 5 [2]. This amount of data and the increasing computational power allows for the application of data-driven AI models. For the use of AI models, we need to consider two types of applications. There are non-safety-critical and safety-critical applications. The former ones include speech processing, virtual assistants, chatbots, and search engines, which has relatively high tolerance to errors and misclassifications. The latter include diagnostics in medicine and the automated driving in the automotive industry, where a misclassification can result in severe injuries or even death. In the case of automated and autonomous driving, the machine learning-based models can be used for the object classification of the perceived surrounding of the automated and autonomous vehicle (AV), for the recognition of driving scenarios and for the subsequent trajectory prediction and planning of the AV. All these are safety-critical tasks that must perform properly and be robust in their abilities, which highlights the importance of the validation and verification of AI models used in automated and autonomous systems. A shortcoming of learning-based models is that they cannot learn all possible rules, laws, and interactions on the street to achieve higher accuracy. Additionally, using imitation learning [3], AI systems are prone to learn non-rule conforming behavior. An example of learning wrong rules is keeping a minimal distance when a car is passing a bicyclist. According to the German traffic regulations, in urban areas the passing vehicle must keep a distance of at least 1,5 m to the bicyclist and in non-urban areas the passing vehicle must keep a distance of at least 2,0 m (Sec. 5, para. 4, StVO) [4]. This law is fairly new and not many drivers know this new distance or they just do not follow the rules. From this, we can never learn rule compliant behavior for safety concerns. A favored idea, to overcome the shortcomings of solely data-driven AI models, is the proper combination of rule-based algorithms and data-driven algorithms to enhance their advantages and eliminate disadvantages. In the field of automotive engineering, a lot of research is being performed to aggregate, consolidate, and harmonize different terms for a unified traffic scene representation with respect to the driving safety of automated and autonomous vehicles [5]. For the representation of a complex structured traffic environment, Scholtes et al. [6] proposed the 6 Layer Model. Maierhofer et al. [7] formalized partially machine-readable German traffic regulations in temporal logic. Bermejo et al. [8] demonstrated that the ontology-based representation of traffic scenes can enhance situational comprehension on the traffic roads, improve traffic safety, and support a centralized traffic management system. Bagschik et al. [9] proposed an ontology to assist experts in creating scenes based on formalized knowledge covering a wide range of scenarios. Other research focused on deriving rule compliant behavior of road users at complex road intersections, where an ontology was used to infer which agent has the right of way [10, 11].

In this work, we propose a concept to support AI models by formalizing the German Technical Specifications on Lane Markings within an ontology. The German Road and Transportation Research Association (FGSV) defines technical standards and specifications related to road and transportation. Part of these standards and specifications pertain to the definitions of lane markings [12]. The knowledge from these documents is formalized into an ontology by creating concepts and relations between concepts. It can then be used in AI algorithms to support the entire system. With the support of the lane marking ontology, the AV will be able to reason more information about lane markings and thus enhance its understanding on the traffic situation, such as inferring traffic areas of lane markings and identifying the type of lane markings when accurate sensor data is missing. This information is crucial for subsequent trajectory prediction and planning tasks to ensure that the AV derives rule compliant behavior.

ONTOLOGY

The word "ontology" has different meanings depending on the community. In philosophy, the branch that deals with the nature and the structure of reality, ontology is the study of attributes that belong to things due to their nature [13]. In Computer Science, ontology takes a different meaning, which is however related and based on the philosophical meaning. Gruber et al. [14] defines the computational meaning of an ontology as the explicit specification of a conceptualization of a domain knowledge. This means that an ontology describes concepts and relations that can exist between concepts [14]. Advantages of an ontology are the efficient exchange of information due to sharing and reusing formalized knowledge and that they are human and machine readable, as it clearly assigns semantics to unambiguous concepts represented by a set of unique symbols [13]. Humans are able to directly identify concepts, its hierarchical structure, axioms, and rules. Machines understand the concepts and relationships due to the unique symbols, hence they can handle the symbols with logic using computer software [9]. For a better representation of knowledge in an ontology, RDF Schema, Ontology Web Language (OWL) and If-Then rules are often used [15]. Ontologies usually comprise a terminological box (T-Box) and an assertional box (A-Box) [16]. The T-Box defines concepts of the ontology, where these concepts are called classes that can have data type properties or constraints, relationships between classes, and axioms and rules [9]. The A-Box describes specific instances of classes called individuals [9], which are taken for certain situations. Modelling and verification of the ontology can be done in a software like protege [17, 18, 19].

In this work, an ontology for lane markings is created using the formalized knowledge from relevant national documents. We demonstrate that the structure of knowledge in the corresponding documents can easily be fitted into the hierarchical structure of ontologies, furthermore the relational information can be used to capture more important knowledge on lane markings. Additionally, the created ontology on lane markings is integrated into a base ontology

6.4.4. Objects and events include, but are not limited to, the following:

6.4.4.1. The system shall be able to detect the roadway

6.4.4.2. The system shall be able to identify lane location (w/, w/o markings)

6.4.4.3. The system shall be able to detect and identify lane markings

6.4.4.4. The system shall be able to detect objects in its defined field of view

Figure 1. Guidelines for requirements for automated and autonomous vehicles proposed by the Informal Working FRAV. Taken from [20]

on the traffic domain, the combined one is further expanded to include missing concepts of the autonomous driving domain for example use cases, and it is tested in a reasoning software in combination with exemplary traffic rules to show benefits of an extended ontology.

FORMALIZATION OF NORMATIVE KNOWLEDGE

In this section, we present the legal framework for the type-approval of vehicles, that includes automated and autonomous vehicles, whether they are based on AI models or not. This framework leads to relevant documents on international and national level. On an international level, we show the working document of the UNECE working group for Functional Requirements for Automated Vehicles (FRAV), which defines the requirements for automated vehicles as a guideline document. On the national level, we discuss the German Technical Specifications on Lane Markings from the German Road and Transportation Research Association (FGSV), which is the main contributor of expert knowledge for this work. After extraction, we present the structure of the knowledge and demonstrate how it can be translated into an ontology, which is specialized in the domain of lane markings. We take this ontology and integrate it into a more general one, which functions as a basis. This basis is the ASAM OpenXOntology, which offers formalized knowledge on the general domain of traffic and thus it is easily extended with knowledge on lane markings.

Knowledge Sources

On an international level, there are activities to advance the regulation of automated and autonomous vehicles. The responsibility of automated and autonomous vehicles lies within the Working Party on Automated/Autonomous and Connected Vehicles (GRVA), which prepares draft regulations and guidance documents. The GRVA set out a mandate that a subgroup must formulate and develop functional requirements for automated/autonomous vehicles, which resulted in the formation of the Informal Working Group (IWG) on Functional Requirements for Automated/Autonomous Vehicles (FRAV). Development shall be captured in a working document, which functions as a guideline document [20]. Guideline documents of this kind do not have regulatory character, however they will be the basis for upcoming UN Regulations (UN-Rs) or UN Global Technical Regulations (GTRs), which must be adhered to when type-approving new vehicles. Hence, it makes sense to to consider the guidelines created by FRAV during the design process of new automated and autonomous functions and vehicles.
There are numerous requirements formulated in the document, however these requirements have different areas of importance. Fig. 1 shows a selection of requirements for the Object and Event Detection and Response (OEDR). Here, the first requirement is the ability of the system to detect the roadway. A relevant question for this requirement is ”What is a roadway?”. There are different possibilities to identify the roadway for an automated and autonomous vehicle, however, we come to the conclusion that one major aspect for the identification of the roadway are lane markings. Additionally, the detection and identification are also requirements formulated by FRAV. Hence, if we are able to correctly detect and identify lane markings, and later handle them properly, we are one step closer to safe and transparent autonomous driving. Even if the general idea of lane markings is the same in most countries, there are many different types, shapes, and forms of lane markings with different meanings, which have an effect while following traffic regulations. Thus we are taking lane markings as a use case for this work to show how this kind of knowledge can be formalized into ontologies for the development of automated and autonomous vehicles.
Here, we concentrate on the German Technical Specifications for Lane Markings (RMS-1) [12] as it handles all relevant traffic areas (urban, non-urban, and motorway) and the general knowledge on type, dimension, and form of

	Motorway	Other Roads
Thin Line	15 cm	12 cm
Thick Line	30 cm	25 cm

Figure 2. Width of longitudinal lane markings for thin and for thick lines and for motorways and other roads (urban and non-urban). Adapted from Ref. [12]

Name of Lane Marking Form	Visualization of Lane Marking Form	Lane Marking
Thin Solid Line		Lane Boundary Road Boundary Cycle Lane Boundary Parking Space Boundary
Thin Broken Line Outside of Junctions (NonJunction)		Guiding Line
Thin Broken Line Inside of Junctions (Junction)		Guiding Line
Thick Solid Line		Road Boundary Special Lane Boundary Cycle Lane Boundary

Figure 3. Excerpt of the table that shows the name of lane marking, the visualization of the lane marking form, and the lane marking type for longitudinal lane markings. Adapted from Ref. [12]

standard lane markings. Further knowledge appears in the form of proper definitions, area of appearance, and conditions for specific lane markings. The document offers a reliable source of knowledge that can easily be extracted and then properly formalized.

Formalization of Knowledge Sources into an Ontology

Before we look at the structure in more detail, we note, that it is stated, in the beginning of the document, that the construction authority must adhere to these technical specifications and larger changes to these specifications must be authorized by the supreme traffic authority. However, these changes cannot alter regulatory law.
The first important section of the Technical Specification is the chapter *Dimension of Lane Markings*. From this chapter, we can extract a significant part of the overall knowledge needed for the ontology. Relevant knowledge is well-structured in tables and easily readable. Generally, we can distinguish between longitudinal markings, markings for restricted areas, markings for stopping and parking prohibition, perpendicular markings, arrows, and miscellaneous markings. Focus will be put on longitudinal and perpendicular markings. For the longitudinal markings, there is a very important distinction between the width of longitudinal lane markings on motorways and on other roads (urban and non-urban regions) and a distinction between thin and thick lane markings, which can be seen in Fig. 2. Then, there are tables, that list the name, visualization of the lane marking form, and the lane marking type of possible lane markings. These can be found for all the aforementioned classes of lane markings (see Fig. 3. The name of the lane marking (left column) describes the basic form in a structured manner, where we obtain the information of the width of the line (thin or thick), structure (solid or broken), number of lines (single or double), and if the line

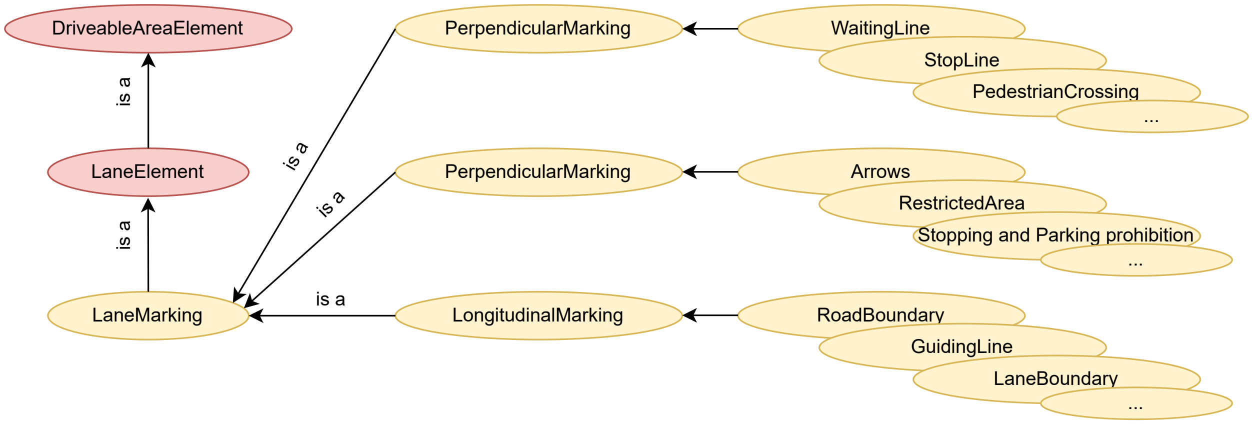

Figure 4. Hierarchical structure of the lane markings type.

is broken in what ration the dashed lines appear (2:1, 1:1, 1:2). The visualization of the form (center column) reflects the name in a visual form, which is useful knowledge for the perception task of an autonomous vehicle. In the last column, there is the lane marking type, which gives a specific name to the basic form and this name (here called type) is the same as referenced in the traffic regulation. Most assertions of basic form and name to a certain type are unique, hence we have only one basic form for one type, however, some assertions are ambiguous, where one form can have several types and some types can have several forms depending on where they appear. In a further table for longitudinal markings, the ratios for the broken lines are defined with their lengths for specific situations, but this information was not in the focus in this work.

Following sections filter lane marking types by their area of appearance regarding junctions and non-junctions and their conditions for appearance. A junction is usually a crossing, where often different types of lane markings appear compared to non-junction areas. For example, solid roadway boundaries often change to broken roadway boundaries with a certain ratio to signify that they can be crossed by traffic. Conditions of appearance are i.e. the existence of roadway boundaries which are usually depicted by solid lines at the sides of the roadway, however in urban areas these solid lines can be omitted, if the sides of a roadway are clearly defined by the architecture like a curbside. We are focusing less on the latter in this work.

While extracting the knowledge, we see that the structure of the information in the Technical Specification is generally hierarchical (see Fig. 4). There are *Lane Markings*, which can be considered a high-level term as this term generally comprises all lane markings. These *Lane Markings* can be grouped into *Longitudinal Markings*, *Perpendicular Markings*, and *Miscellaneous Markings*, where the last comprises markings for restricted areas, markings for stopping and parking prohibition, arrows, and miscellaneous markings. All of these types of markings can be further split into definitive markings, i.e. *Road Boundary* or *Guiding Line*. This kind of hierarchical structure can be set up for 3 different categories (see Fig. 5. The first is the aforementioned branch of *Lane Markings*, which defines the type of lane marking and has specific rules attached to it. The second is the branch of *Lane Marking Form*, which depicts the exact form which can be seen on the street. This branch combines the left and center column of Fig. 3. The last is the *Traffic Area* branch, which defines the traffic areas in which the Lane Markings can appear. In addition to the hierarchical structure, nodes and leaves from each branch have links to other branches, thus relationships can be established. These well-defined concepts, the hierarchical structure, and the relations between concepts makes this knowledge perfectly suitable to be formalized as an ontology. We use protege [18, 19] as a software to construct the ontology, as this software is compatible with the OWL2 language and it allows for an easy development of an ontology. Concepts are created and obtain a proper definition that tries to mirror the knowledge of the Technical Specification. Three branches consisting of the aforementioned high-level concepts *LaneMarking*, *laneMarkingForm*, and *TrafficArea*. A proper ontology is achieved by creating relevant relationships between different concepts. Fig. 6 showcases possible relations between the concept *StopLine* and its related concepts. It shows that *StopLine* can appear in the areas *Urban*, *Non-Urban*, and in *Junction*, i.e. neither on *Motorway* nor in *Non-Junction* areas. This relation is denoted with corresponding object properties, where the affiliation of *WaitingLine* to *Urban*, *Non-Urban*, and *Junction* is described with the newly created relation *isPartOf*. The inverse relation that these concepts can contain a possible *WaitingLine* is described with *contains*. Defining the relations in this way, creates the axiom of inversion,

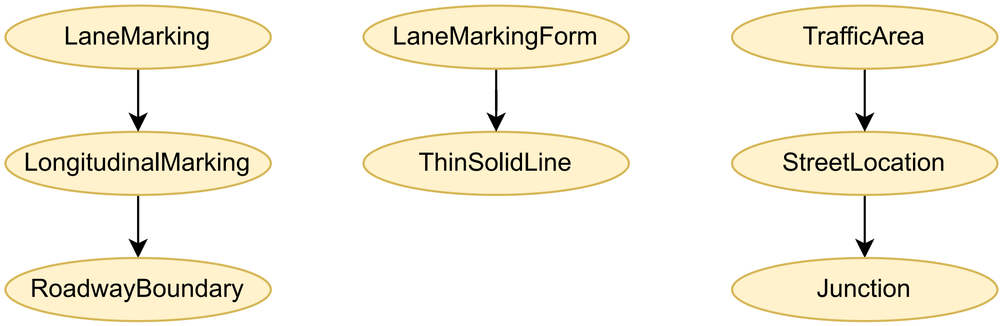

Figure 5. Three branches of identified knowledge from the German Technical Specification on Lane Markings in a hierarchical structure.

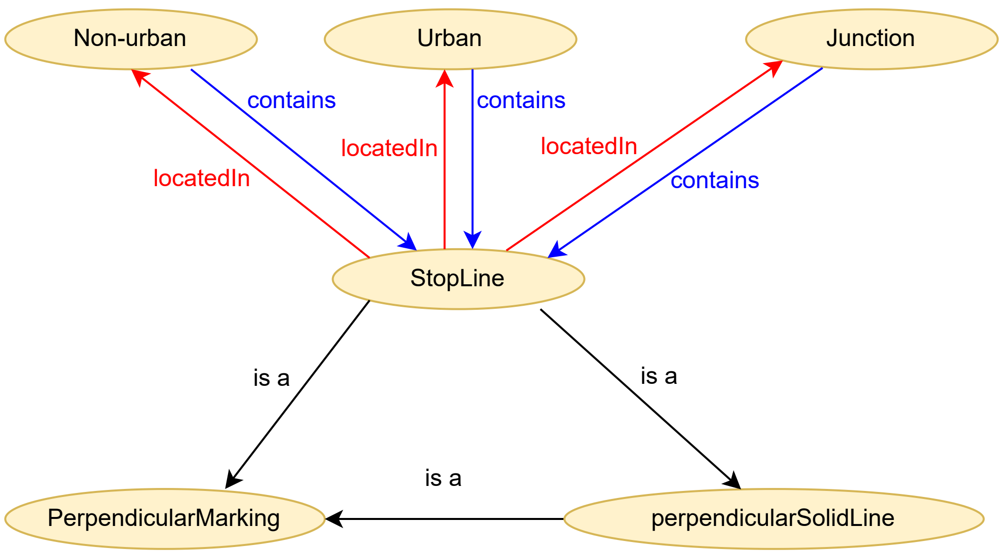

Figure 6. Relations between different concepts of the ontology with StopLine as the center concept.

which is defined by *isPartOf isTheInverseOf contains*. Furthermore, Fig. 6 denotes that it is a *PerpendicularMarking* with a basic form of *perpendicularBrokenLine2To1*, which is defined by the standard relation *is a*.

Integration into ASAM OpenXOntology

A lane markings ontology has been created on the basis of the knowledge from the German Technical Specifications, hence it comprises only knowledge from the specific domain of lane markings. However, to be able to reason in general traffic situations or for an automated or autonomous vehicle to reason in traffic situations, the domain of the ontology must encompass concepts and relations from the general traffic domain and from the automated/autonomous driving domain. A base ontology, that integrates the aforementioned concepts, is needed on which we build upon and integrate our lane markings ontology. The general consensus in the community for ontologies is that you should not create entire ontologies completely from scratch, but rather detect existing ones and identify what can be used as a basis. As a base ontology, we chose the OpenXOntology that was developed by the Association for Standardisation of Automation and Measuring Systems (ASAM). They aim to provide a foundation of common definitions, properties, and relations for central concepts of the ASAM OpenX standards in the domain of road traffic. Choosing the ASAM OpenXOntology has the advantage that it is compatible with OpenDRIVE, OpenSCENARIO, and OpenLABEL standards, that are formats to enable scenario-based testing and that are well-accepted in the automotive engineering community for scenario-based testing. Based on the generality, the ontology is mainly divided into three modules, namely core ontology, domain ontology and application ontology. The core (or upper) ontology is do-

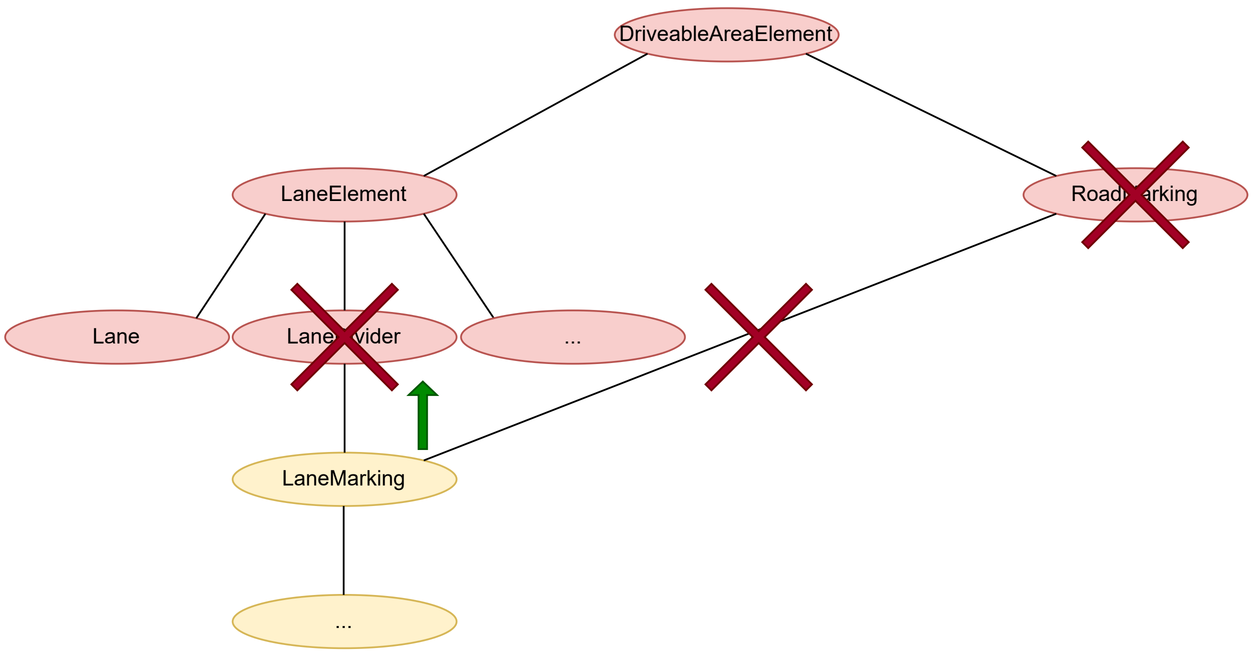

Figure 7. Structural changes of the ASAM OpenXOntology to make the new definition of LaneMarking more suitable.

main independent and describes basic concepts, such as physical objects, states, and events, that are developed based on High-Quality Data Model framework (HQDM). The domain ontology defines central concepts of the road traffic domain consisting of three layers, i.e.,*EnvironmentalCondition*, *RoadTopologyAndTrafficInfrastructure* and *TrafficParticipantAndBehavior*. The application ontology covers the concepts for a specific application, such as *EgoLane* in a simulation application. The OpenXOntology consists of 347 classes, 96 object properties and 2 data properties, and uses OWL as ontology language and Semantic Web Rule Language (SWRL) as rule language.
The methodology to integrate our ontology into the ASAM OpenXOntology is as follows. Take the highest-level concept of our ontology. Identify, if this concept exists in the OpenXOntology by searching the branches in relevant concepts and higher-level concepts. If a corresponding concept exists, compare the names of the concept and see, if it corresponds to your concept name. Should it not be the same, verify, if it needs to be changed and adapt by applying a more suitable name. Additionally, verify, if subclasses need to be adapted. If a corresponding concept does not exist, find a proper higher-level concept and add your concept as a subclass. After adding your concept, add further subclasses to the concept from your own ontology. In our case, the following steps were taken. First, the concept *LaneMarking* is integrated by searching through corresponding concepts of the OpenXOntology. We find the corresponding concept with the same name, which is a subclass of *LaneDivider* and *RoadMarking*. *LaneDivider* is a subclass of *LaneElement* and this concept with *RoadMarking* are subclasses of *DriveableAreaElement*. We adapt *LaneMarking* from our ontology and use *LaneMarking* from the OpenXOntology, however, we restructure the overall structure of the aforementioned concepts, which can be seen in Fig. 7. In the first step, we remove *LaneDivider* as lane markings can be seen as lane dividers when they are longitudinal lane markings, however, our definition of lane markings also includes perpendicular and miscellaneous lane markings, which cannot be seen as lane dividers, hence it is removed and the concept of *LaneMarking* is moved one layer upwards and is now directly a subclass of *LaneElement*. In the second step, we remove *RoadMarking* as a concept from the ontology, because *LaneMarking* is the sole subclass of *RoadMarking* and it serves no other purpose. After integrating *LaneMarking*, we change its subclasses to its created ones *LongitudinalMarking*, *PerpendicularMarking*, and *MiscellaneousMarking* also including each their respective subclasses (see Fig. 4). Second, we integrate the concept *laneMarkingForm* by identifying the concept *laneProperty* as a fitting superclass. Moreover, the new concept fits very well with the already existing sibling classes *laneDimension*, *laneMarkingColor*, and *laneMarkingWidth*. *laneMarkingForm* is further split into the classes *singleLine* and *doubleLine* with their corresponding subclasses (see Fig. 8). Lastly, we integrate the high-level concept *TrafficArea*, which is now considered a subclass of *RoadTopologyAndTrafficInfrastructure*. The sub-

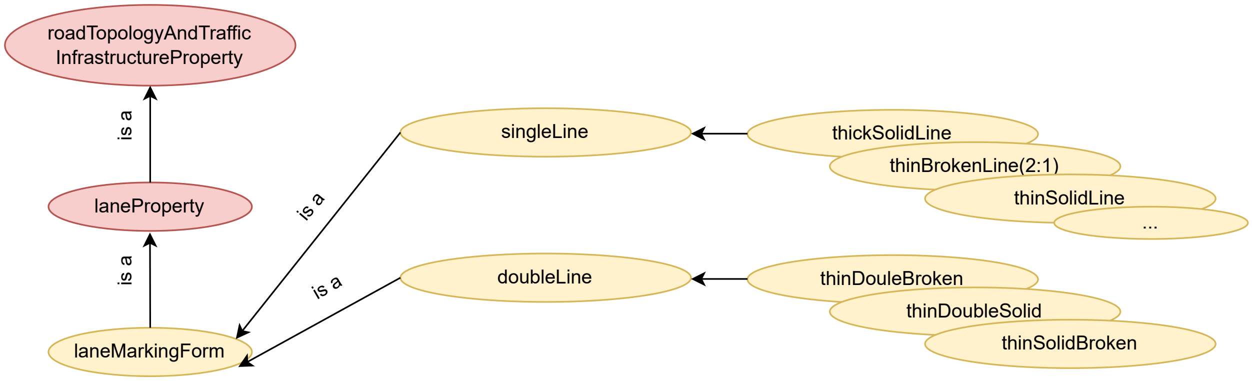

Figure 8. Modified hierarchical structure of the lane marking form.

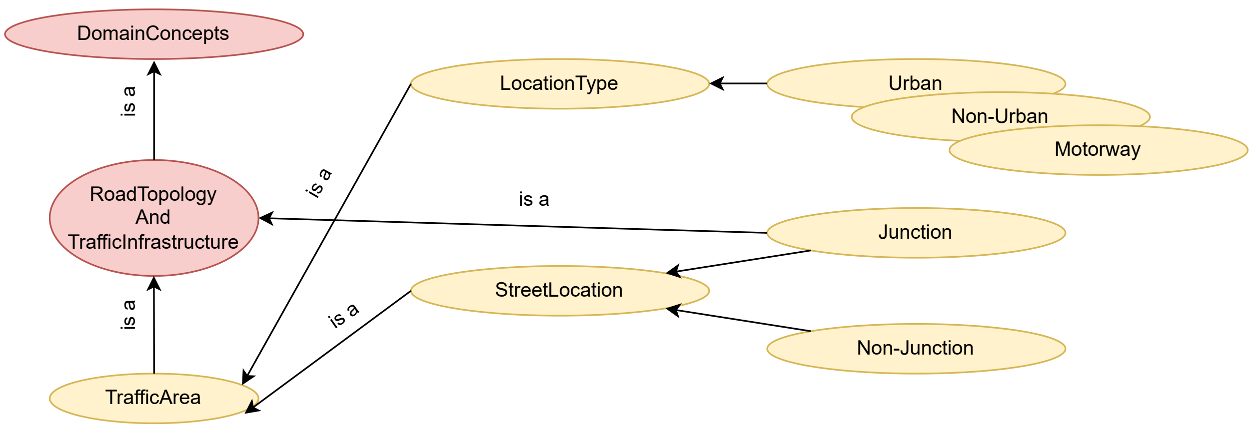

Figure 9. Modified hierarchical structure of the traffic area concept.

classes *LocationType* and *StreetLocation* are added with their respective subclasses (see Fig. 9). Important to note is, that the concept *Junction* was already present in the OpenXOntology as a direct subclass to *RoadTopologyAndTrafficInfrastructure*, *WholeLifeFunctionalSystem*, and *WholeLifeSystem*, which we did not want to remove, hence it has several superclasses in the current version.

After integrating the concepts into the OpenXOntology, relationships between the newly integrated concepts are setup, however no new relationships are created, thus all previous ones are just adopted. In the following chapter, we showcase how the ontology can be used to infer information from the surrounding of the autonomous vehicle. For our specific use cases, we need the concept of *EgoLane*, which is the traffic lane that the ego vehicle is driving on.

DEMONSTRATION ON USE CASES

The normative knowledge formalized with the help of an ontology can support automated and autonomous vehicles not only to make rule compliant decisions [21], but also to improve the confidence of the perceptual results. Although advanced on-board sensors and deep learning-based algorithms have achieved encouraging results in autonomous driving system, they are prone to fail in some edge cases, such as loss of GPS signal and occlusion of lane markings. In this section, we demonstrate that by using formalized normative knowledge the agent is able to correctly detect desired targets by reasoning over perceived data. As shown in Fig. 10, we formalize the German Technical Specification on Lane Markings via an ontology defined in the T-Box and map the Specification into the A-Box. The model takes the real driving data, collected from on-board sensors and computational results of machine learning-based models, as inputs and maps these onto the A-box via the ontology. On the top of the knowledge base consisting of A-Box and T-Box, we build a reasoner that executes queries to answer the questions about the traffic scenarios. We illustrate two use cases, which frequently happen in the real driving environment, to demonstrate the functionality of our model. For implementation, we edit and manage our ontology in protégé [18, 19], formalize our inference rules using SWRL [22], formulate queries using SPARQL [23], and use Stardogs [24] as the knowledge graph platform to store our database and to derive new facts.

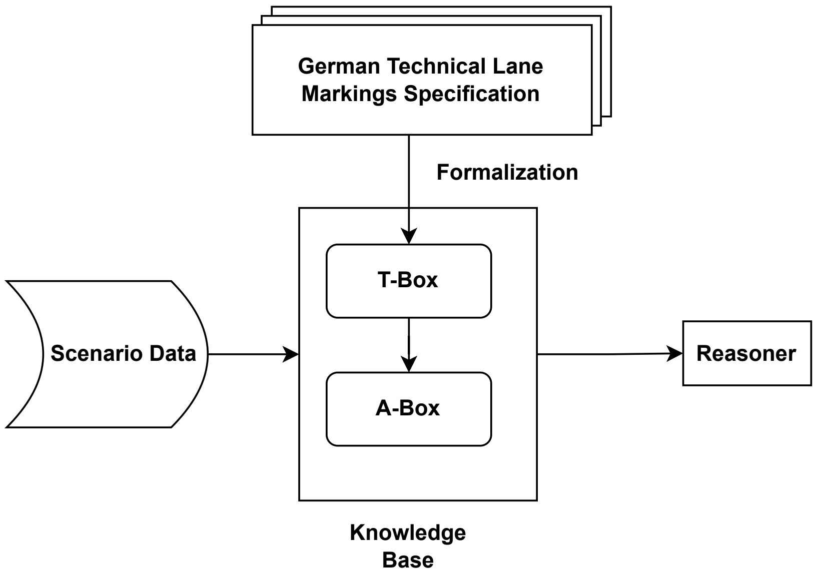

Figure 10. Model architecture consisting of T-Box, A-Box, Reasoner and German Technical Specifications on Lane Markings.

Use Case 1 - Determining the General Traffic Areas

Correct identification of the traffic area in which the current ego vehicle is located is a prerequisite for the proper application of corresponding traffic rules. When losing signals from onboard sensors, such as GNSS and IMU, the detected lane markings can be used as an indicator of the traffic area. According to the German Technical Specification on Lane Markings, we formalize the possible traffic areas for stop line and thin broken lines with the patterns of 1 m to 1 m and 1 m to 2 m in the A-Box as follows:

```
:StopLine :locatedIn :Junction, :Urban, :NonUrban
:thinBrokenLine1To1 :locatedIn :NonUrban, :Urban, :Junction
:thinBrokenLine1To2 :locatedIn :NonUrban, :Urban, :Motorway,:NonJunction
```

After uploading these facts together with the T-Box, we request our knowledge base to answer the following queries in SWRL:

- **Query 1.1:** Retrieve all possible traffic areas that contain stop line.
- **Answer 1.1:** Junction, Urban, NonUrban
- **Query 1.2:** Retrieve all possible traffic areas that contain guiding line.
- **Answer 1.2:** Junction, Urban, NonUrban, NonJunction, Motorway

Although we use *:contains* as the keyword to formulate the relation between the traffic area and the lane marking in our queries, the system can still retrieve the results in the first query by using the owl property axiom, i.e., *:contains owl:inverseOf :locatedIn*. In the second query, we ask about the guiding line, which is not explicitly defined in the A-Box. However, the thin broken lines 1 m to 1 m and 1 m to 2 m are defined as the subclasses of guiding line. Thus, the system can infer all five possible traffic areas for guiding line.

Use Case 2 - Determining the Type of Guiding Line using Environmental Context

The pattern of the lane markings varies in traffic scenes, indicating different meanings. For instance, the broken line with the pattern 1 m to 2 m is used for cycle guiding line and 3 m to 6 m is for the urban guiding line. Correctly identifying the guiding line is meaningful to the driving safety, such as keeping safe distance to the cyclist. These two types of lines are not easy to distinguish without any reference, since they have the same ratio of the lengths. However, we utilize the context information to infer the type of the target using our ontology.

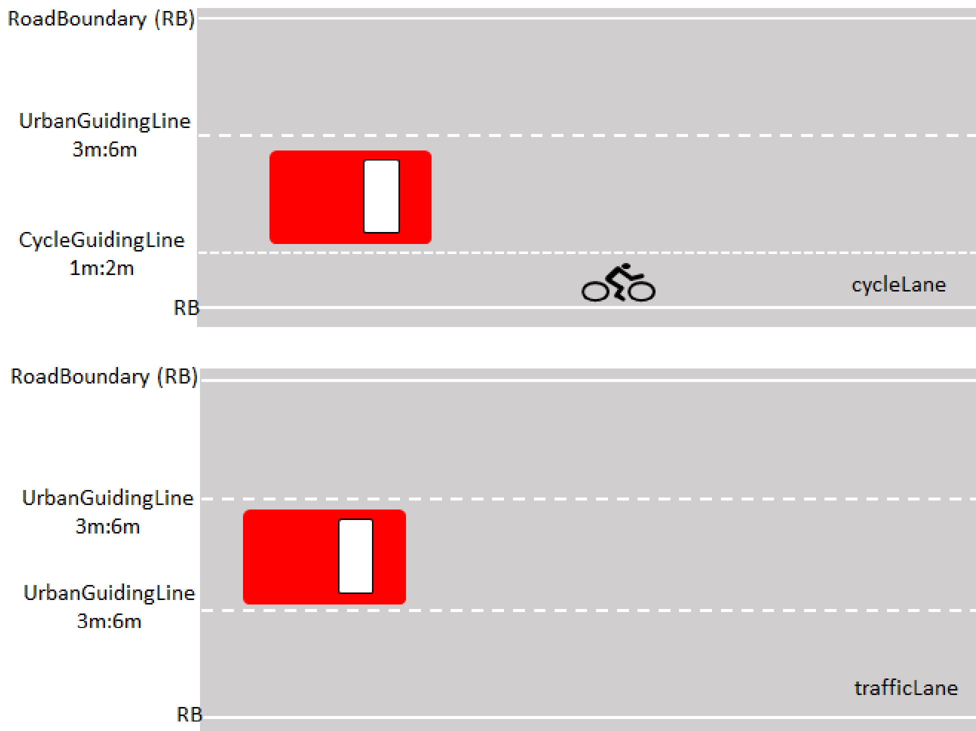

Figure 11. Ego Lanes left connected to the Urban Guiding Lines and right connected to the Cycle Guiding Line (top), and right connected to the Urban Guiding Line (bottom).

We illustrate two traffic scenes as depicted in Fig. 11, in which the top one consists of an ego lane, left connected to the urban guiding line and right connected to the cycle guiding line, and the bottom one is similar except that the ego lane is right connected to the urban guiding line. We formalize our common sense knowledge according to the German Technical Specification on Lane Markings as rules using SWRL as follows:

$$\begin{aligned} &EgoLane(?l1) \wedge LaneMarking(?m1) \wedge LaneMarking(?m2) \wedge CycleLane(?l2) \\ &\wedge leftConnectedTo(?l1, ?m1) \wedge rightConnectedTo(l1, ?m2) \wedge leftConnectedTo(?l2, ?m2) \\ &\Rightarrow CycleGuidingLine(?m2) \end{aligned} \tag{1}$$

The rule (1) states that, if a cycle lane on the right is detected, then the guiding line left connected to this lane must be a cycle guiding line.

$$\begin{aligned} &EgoLane(?l1) \wedge LaneMarking(?m1) \wedge LaneMarking(?m2) \wedge CylceGuidingLine(?m2) \\ &\wedge leftConnectedTo(l1, ?m1) \wedge rightConnectedTo(l1, ?m2) \wedge leftConnectedTo(?l2, ?m2) \\ &\Rightarrow CycleLane(?l2) \end{aligned} \tag{2}$$

The rule (2) states that, if a cycle guiding line on the right is detected, then the lane right connected to this line must be a cycle lane.

$$EgoLane(?l1) \wedge LaneMarking(?m1) \wedge LaneMarking(?m2) \wedge UrbanGuidingLine(?m2)$$
$$\wedge leftConnectedTo(l1,?m1) \wedge rightConnectedTo(l1,?m2) \wedge leftConnectedTo(?l2,?m2) \quad (3)$$
$$\Rightarrow TrafficLane(?l2)$$

The rule (3) states that, if an urban guiding line on the right is detected, then the lane left connected to this line must be a traffic lane. When the onboard sensors detect the lane marking on the right with very low confidence and a cycle lane is detected with very high confidence (Figure 11, top), we can query the type of the lane markings as follows:

- **Query 2.1:** Ask if the lane marking right connected to ego lane is cycle guiding line.
- **Answer 2.1:** True

Conversely, if the onboard sensors detect a lane marking with the pattern 1 m to 2 m (Figure 11, top), we can infer the type of this lane marking and the type of lane to the right, since the lane marking with the pattern 1 m to 2 m is assigned to the type of cycle guiding line in the T-Box.

- **Query 2.2:** Ask if the lane marking right connected to the ego lane is the cylce guiding line and the lane right connected to the lane marking is a cycle lane.
- **Answer 2.2:** True

If the the onboard sensors detect a lane marking with the pattern 3 m to 6 m (Figure 11, bottom), we can infer that this line is an urban guiding line and only that the lane on the right is a traffic lane.

- **Query 2.3:** Ask if the lane marking right connected to the ego lane is an urban guiding line and the lane right connected to the lane marking is a traffic lane.
- **Answer 2.3:** True

DISCUSSION

In this work, we showcased the German Technical Specification for Lane Markings as a reliable source of knowledge that can be formalized into an ontology. Knowledge, such as lane marking types, their forms, and their area of appearance were formalized and tested in exemplary use cases, which shows that formalized lane marking specifications can be used to enrich the driving situation. However, we must claim that we do not attempt to create a full ontology with all the aforementioned knowledge but rather to present a conceptual work to demonstrate the effectiveness of the ontology.

The demonstration of the uses cases shows that we can, i.e., infer information on the traffic area by querying possible traffic areas of detected lane markings or determine the type of a lane marking, that can take several lane markings forms, by using further contextual information. The Reasoning times for the first use case are short (below 100 ms) as the reasoner solely uses explicit facts and hierarchy inference to derive the traffic areas. For the second use case, the reasoning times are longer (above 10 s). Such long reasoning time does not meet the real-time requirements of a smooth traffic flow. This is due to the high number of axioms defined in the ASAM OpenXOntology and hardware constraints. We count more than 2000 axioms that the reasoner has to include to come to the correct conclusion for our query. Possible ways to improve the reasoning speed is to utilize pruning techniques on the core ontology, where large parts of concepts, relations, axioms can be removed or deactivated.

For a complete implementation we should further consider the formalization of the specific lengths of the ratios for broken lines of longitudinal markings. Ratios are implemented in the ontology and define the lane marking type, however, the lengths for these ratios are different in specific situations. The exemplary use case just showcased one situation where the general (urban) guiding line is distinguished with the guiding line to separate bicycle lanes by their ratios.

Another possible step is to formalize the conditions on when certain lane markings appear and when not. Here, we want to mention that guiding lines do not always appear on streets. If the street has only a small width or when the general traffic volume is low, guiding lines are not obligatory. Additionally, roadway boundaries are not needed, if the boundary of the roadway is clearly defined by the traffic infrastructure. An example is the curbside of a sidewalk that clearly designates the roadway boundary. Moreover, it could be formalized that a warning line always precedes a lane boundary, which is interesting information for trajectory planning. Further work should consider formalization of this knowledge into the ontology.

We deem the German Technical Specification as a reliable source of knowledge, however, it must be noted that this document has been created in 1980 and revised in 1993, hence it is old and not up to date in all aspects of lane markings. In 2019, a new document, called *Richtlinien für die Markierung von Straßen Teil A: Autobahnen* (RMS Teil A) [25], was released that amended parts of our document concerning the motorway area. This document is now state-of-the-art, covers the domain of the motorway in more detail, and clearly describes its scope. Further work should consider using this new Technical Specification to update the information on the domain of the motorway. Concerning the Urban and Non-Urban domains, new Technical Specifications are being developed, which will be published in the near future. They will be called *Richtlinien für die Markierung von Straßen Teil L Landstraßen und Teil S Stadt* (RMS Teil L/S). Together, these three Technical Specifications will supersede the current Technical Specification on Lane Markings completely. Hence, future work should focus on formalizing these new documents. Furthermore, the specifications are already more than 40 years old, but there are streets that have been constructed before the first version of these exact specifications has been published. Hence, some streets do not follow these documents and could appear in a different way, however, when streets are restored, depending on the construction body, the Technical Specifications must be followed.

This work presents the concept on formalization of knowledge from the German Technical Specification on Lane Markings. However, the Road and Transportation Research Association (FGSV) publishes many different Technical Specifications on the domain of road traffic. Further work should consider taking these different Technical Specifications of different domains and formalizing this knowledge in corresponding ontologies. There are Technical Specifications that handle further aspects on lane markings like, the Technical Specifications for Securing Work Sites on Roads in Accordance with Traffic Regulations (RSA 21) [26] and Recommendations for Cycling Traffic Infrastructure (ERA) [27]. For Technical Specifications for road signs, we recommend the Technical Specifications for Directional Signage on Motorways (RWBA) [28] and the Technical Specifications for Directional Signage outside Motorways (RWB) [29].

The last discussion point is the scope of countries. These specifications are strictly valid for Germany, hence other countries do not follow these guidelines on lane markings and have their own guidelines. While developing driving automation systems, it must be considered that this knowledge, and therefore the ontology, only applies for Germany and is not useful for other countries. Our suggestion is to create ontologies that are based on this knowledge in a modular way. The core ontology, here the ASAM OpenXOntology, shall remain the same for all countries and for each relevant country a more specific ontology can be created that can easily be integrated into the ASAM OpenXOntology. Corresponding documents must be identified for other countries and formalized as done in this work. If other countries do not have this kind of Technical Specifications, it is advisable to take this work as a template and formalize knowledge corresponding to the German Technical Specifications.

CONCLUSION

In this paper, we show that the formalization of normative knowledge, here the German Technical Specifications on Lane Markings from the Road and Transportation Research Association (FGSV), into an ontology, is a feasible way to support AI models to be rule compliant and more transparent and traceable. The German Technical Specification on Lane Markings is useful, albeit for now a little outdated document that includes information in a structured manner. As the knowledge is structured as hierarchical concepts and relations, complementing with a set of if-then rules, formalization using ontology is an ideal way to represent this knowledge. As the ASAM OpenXOntology is designed as an extensible framework, we can easily integrate our lane markings ontology, based on the German Technical Specifications, into the part of traffic domain ontology. Furthermore, we can extend the ontology with scenario specific concepts and rules to enhance situational awareness. Moreover, we showcased that the ontology can be used to infer information about the traffic area of appearance of lane markings and the type of lane markings using environmental context, despite their long inference time, which can be further improved using ontology pruning techniques.

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