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Ontology-Based Traffic Scene Modeling, Traffic Regulations Dependent Situational Awareness and Decision-Making for Automated Vehicles

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Abstract— **This paper presents a modular framework for traffic regulations based decision-making of automated vehicles. It builds on a semantic traffic scene representation formulated as ontology and includes knowledge about traffic regulations. The semantic representation supports traffic situation classification by reasoning, providing improved situational awareness for the automated vehicle. Decision-making rules are directly derived from traffic regulations and concepts used in the ontology are harmonized with concepts used in traffic regulations. Due to the modular structure of the developed ontology, switching between different sets of national traffic regulations becomes a simple process. The methodology is evaluated for a variety of traffic scenarios, building up from basic to complex urban scenarios containing intersections, traffic regulating police officers and crossing street railways.**

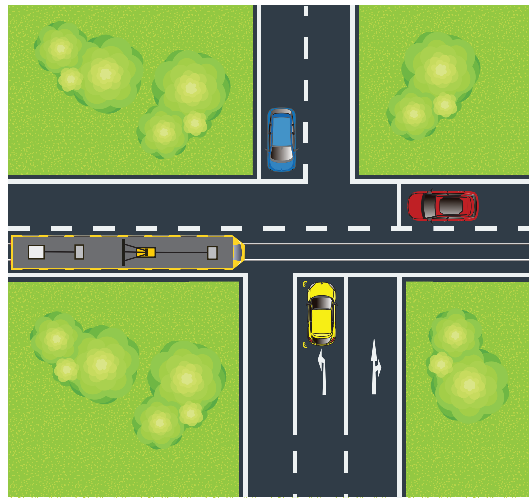

Fig. 1. Example of a complex intersection scenario including vehicles with special rights (tram) for ontology-based decision-making.

I. Introduction

Automated vehicles will face a huge variety of traffic scenarios of growing complexity. While most automated vehicles were developed and tested in one country only, for a phased roll-out all traffic scenarios have to be mastered in different regions with different traffic regulations[1].

The definition, description and classification of traffic scenarios[2] plays an important role during the entire development process. An iteratively improving traffic scenario catalog together with a description of the desired, situation dependent behavior becomes a solid foundation for the requirements engineering process of automated vehicles. Test cases need to be derived from these requirements and performed in simulation as well as real field tests, and the result of each test case needs to be verified with a combination of analytic analysis, simulations and field tests. A key role play software components involved in the decision-making process running online on the automated vehicle.

The complexity of automated vehicles and the huge variety of possible scenarios, lead to a significant increase of required development and testing efforts. Clear semantic scenario representations are both human- and machine-readable, enabling automatic scenario generation and simulations. Therefore, semantic scenario representations offer opportunities to reduce the necessary engineering effort for automated driving.

One of the requirements to an automated vehicle is that its behavior has to be in line with current traffic regulations at all times. From a software development and maintenance point of view, it is desirable to create software code which is modular with respect to traffic regulations: code fragments which are dependent on traffic rules should be in a separate module.

The planning components of the software running on an automated vehicle have to be able to distinguish different traffic situations in order to apply the traffic rules correctly. Many traffic rules are only applicable if certain conditions are met, while the same conditions might invalidate other rules, e.g. the presence of a traffic regulating police officer on an intersection. In this case, the right-of-way rules for uncontrolled intersections are invalidated and all the vehicles have to follow the commands given by the traffic regulating person.

Many of the rules of traffic regulations are formulated as concepts rather than clear definitions. For example, German traffic regulations use the concept of a "queue of vehicles"[3] to formulate a necessary condition to allow overtaking on the right on highways. A clear definition of the term is not given in the traffic regulations itself, but can be derived from

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[1] We use the term "traffic regulations" to describe a set of rules valid for a country, e.g. the German StVO or the British Highway Code, where traffic regulations consist of a set of "traffic rules", e.g. rules for right-of-way, overtaking, etc.

[2] We adopt the terminology for traffic scenarios, situations and scenes in the context of automated driving from [12].

[3] German traffic regulations (StVO §7(2)): "Fahrzeugschlangen"

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case-law[4], where a decision was taken to allow overtaking on the right if a queue of vehicles is moving with a maximum speed of 60 km/h. Nevertheless, no clear definition of additional conditions for a queue of vehicles is given, e.g. the minimum number of vehicles, and it would be left to the court to decide [3].

Ontologies have been defined by Gruber [2] as "[...] specification of a conceptualization. That is, an ontology is a description (like a formal specification of a program) of the concepts and relationships that can formally exist for an agent or a community of agents." Ontologies are a powerful tool to model traffic situations and implement scenario-based decision-making rules. Because ontologies are built to represent and connect concepts, and concepts are the building blocks of traffic regulations, they are especially applicable in the context of traffic regulations. The way rules can be specified in a syntax which is both human- and machine-readable makes coding a very intuitive task.

Semantic descriptions have the advantage of being generalizable over a large amount of scenarios. Furthermore, information in a semantic representation is directly usable in Human-Machine Interfaces.

In this paper, after giving an overview on related work in Section II, we propose a method for a semantic description of traffic scenes using ontologies in Section III. We then present a method for improving situational awareness by using semantic classification conditions in Section IV. These conditions are easy to read and the classes defined by them can directly be linked to related traffic regulations (see Section V). An effective selection of modeled knowledge concepts leads to short and clear decision-making rules, which will be described for a selection of traffic scenarios (see Figure 1) in Section VI.

II. Related Work

Ontologies have already been used in the field of automated vehicles, driver assistance systems and robotics for the description of traffic scenarios and to implement decision-making rules for automated vehicles.

Hummel [6] developed a road network ontology for scene understanding using Description Logic (DL), the core logic used in OWL ontologies. The ontology was created using stereo vision input data, a digital map and a global positioning system (GPS). Object classification and detection as well as data association features were used to derive a semantic description of the road network. The method was tailored to German road networks and cannot be used for left-sided traffic without modification.

Huelsen et al. [5] developed a traffic intersection situation description ontology for advanced driver assistance systems. They performed reasoning about right-of-way rules with or without traffic signs or lights at an intersection. Using lean ontologies, the computational time needed could be reduced to allow real-time capabilities. However, the approach is not generic and needs to be adapted for left-sided traffic.

[4]BayObLG, 27.10.1977 - 1 ObOWi 555/77

Zhao et al. developed core ontologies for safe autonomous driving [14] and rules for ontology-based decision-making on uncontrolled intersections and narrow roads [16]. In [15] they focused on speeding up the decision-making process by using sub-ontologies to meet real-time requirements. Their rules were limited to Japanese traffic regulations and hence need to be extended to include other traffic regulations.

Morignot et al. [7] proposed an ontology-based approach for decision-making and relaxing traffic regulations in situations when crossing a solid lane marking is necessary, for example, to avoid being stuck in a deadlock behind an illegally parked vehicle. The framework demonstrated how SWRL rules can be used for decision-making, but was limited to a single scenario.

Regele [10] developed an ontology-based traffic model for efficient decision-making of automated vehicles. He used a generic approach, which allows reasoning about right-of-way rules, without having to consider different rules for right- or left-sided traffic with very simple rules. As a disadvantage, he concluded that it requires an additional processing step to generate this abstract traffic model, which is not a trivial task. He only provided rules for uncontrolled intersections and lane change maneuvers, and more complex intersection traffic scenarios were not with the scope of the paper.

Ulbrich et al. [13] proposed a hybrid approach of different, hierarchical information layers with geospatial information, topological relationships and a semantic information layer. The main application presented in [13] was map matching of objects, a task we considered as input to our framework. For this reason, we omit the geospatial layer. They further proposed an ontology for an automated vehicles' context model, where traffic rules are also treated as constraints.

Armand et al. [1] present an ontology-based context awareness framework for driving assistant systems and uses SWRL rules to infer knowledge about the interaction between road entities and the environment in which these are navigating. The framework is limited to a scenario of a straight road with a pedestrian crossing and French traffic regulations.

To conclude, some publications already exist which use ontology-based scenario modeling and decision-making. Mostly, they only consider a specific scenario or traffic regulations of one single country and mention that further work needs to be done to adapt it to other traffic regulations. We propose a framework to modularize software code and facilitate the application to other countries. This is realized by either introducing, whenever possible, a generic way of formulating rules, or by clearly linking traffic rules to decision-making rules. The latter is achieved using situational awareness classification.

III. Semantic traffic scene description

We use Protégé Version 5.0 [9] as a tool to model traffic scenes in the OWL 2 Web Ontology Language [8]. OWL 2 ontologies provide classes, properties, individuals and data values and are stored as Semantic Web Documents. OWL 2 corresponds to the $\mathcal{SROIQ}^{(\mathcal{D})}$ description logic.

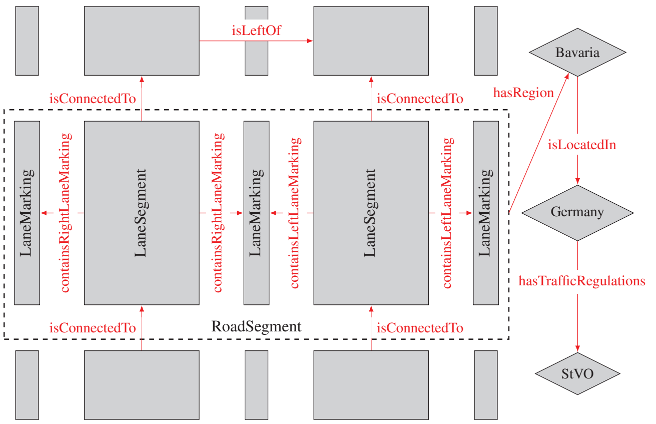

Fig. 2. Semantic description of a road segment with two parallel lane segments. Road segments are linked to traffic regulations in order to provide information e.g. about general road type dependent, country specific speed limits.

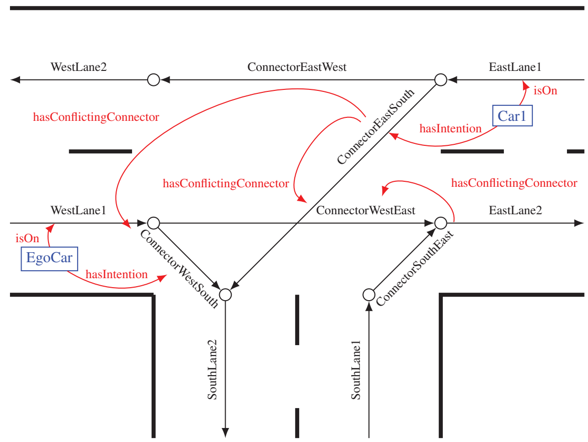

Fig. 3. Semantic representation of an intersection scene. The concept supports generic right-of-way rules independent of right- or left-sided traffic.

Classes are used to describe of which type of thing objects are. An example would be a class $Vehicle$ with subclasses Car, $Truck$, $Bicycle$. Individuals are objects of a certain class, for example $Car1$ and $Car2$ could be individuals of type Car. Object properties are used to give a semantic description of relations between objects, and are defined in triplets forming statements like $Car1$ $isBehind$ $Car2$. Data properties are linked to individuals to provide information about e.g. vehicle speed using a data property $Car1$ $hasSpeed$ 100, with the unit [km/h] being stored in the annotation property.

To infer knowledge from axioms and rules, we use the Pellet reasoner [11], a complete OWL 2 DL reasoner which also supports rules written in the Semantic Web Rule Language (SWRL) [4], supporting DL-safe reasoning. SWRL rules provide an easy-to-read syntax of type:

$$Vehicle(?v1) \wedge Vehicle(?v2) \wedge isOn(?v1, ?lane) \wedge isOn(?v2, ?lane) \Rightarrow isOnSameLane(?v1, ?v2)$$

to infer a new relation $isOnSameLane$ between all individuals $?v1$ and $?v2$ of type $Vehicle$, given that for both vehicles the $isOn$ relation exists to the individual $?lane$.

A. Semantic representation of road network and infrastructure

For a semantic traffic scenario representation, we defined the $TrafficScenarioOntology$, which contains the two main classes $TrafficScenario$ and $TrafficScenarioElement$. The latter contains the subclasses $Infrastructure$, $TrafficParticipant$ and $Obstacle$. Individuals of $TrafficScenarioElement$ are linked to a $TrafficScenario$ individual by the object property $isPartOf$.

Figure 2 shows a graphical illustration of the basic building block of a road, the $RoadSegment$. All the objects within a $RoadSegment$ are defined to have constant data properties, e.g. the maximum allowed speed, the curvature or the road slope. Similar to [13], it contains entities of type $LaneSegment$, which are connected to the lane segments of the successive road segments via the property $isConnectedTo$. The geo-spatial relation between lane segments in one direction is expressed by $isRightOf$ / $isLeftOf$ properties, and the right-/leftmost lane segment is defined using the property $hasRightMostLaneSegment$ / $hasLeftMostLaneSegment$ between a road- and lane segment of such type. The lane markings at each side of a lane are defined using the $containsLeftLaneMarking$ and $containsRightLaneMarking$ properties, where the individuals of type $LaneMarking$ are predefined individuals named $dotted\_line$ etc., with data properties describing if driving over the lane marking from either side is allowed.

Road segments are connected to intersecting road segments with individuals of type $Intersection$. Similar to [10], $Connector$ elements are part of intersections and connect lane segments entering the intersection with all possible lane segments which can be reached from this lane. To facilitate reasoning on right-of-way rules, information about which lanes have to yield right-of-way to others is modeled as static information using the object property $hasConflictingConnector$ between the connectors (Figure 3). To create this information from geo-spatial map information, a method similar to the one described in Section V-A can be applied.

Infrastructure, like for example traffic lights or traffic signs, are linked to lane or road segments with the object property $contains$ or its inverse property $isPartOf$. If a lane segment contains a traffic sign, this means that it is located at the beginning of the segment and the attributes defined for the traffic sign will be valid for the entire segment. If it contains a traffic light, it must be at the end of the segment in driving direction and therefore at the beginning of the connected $Connector$s. The attributes of a road segment are inherited to all contained lane segments. The state of a traffic light is defined by a relation of type $TrafficLight1$ $hasColor$ $Green$, linking to a set of predefined color individuals. Further, the existence of a (functioning) traffic light in a scenario would be determined by the statement $Scenario1$ $containsTrafficLight$ $TrafficLight1$. A traffic regulating person would be causing relations of type $Lane1$ $isBlockedBy$ $PoliceOfficer1$ as well as $Scenario1$ $containsTrafficRegulatingPerson$ $PoliceOfficer1$, assuming that some environment detection module provides such information.

B. Traffic scene description

Dynamic scenario elements are linked to a traffic area by the $isOn$ property, stating that a vehicle is on a lane segment. The relations between vehicles are described using properties like $isOnSameLaneWith$ and $isBehind$, $isLeftOf$ and its inverse properties. More exact information about each vehicle's state, like its current position in a global frame or vehicle speed and acceleration information is stored in each individuals' data properties. Using the property $hasIntention$, the most likely lane or connector segment a vehicle intends to drive on is described. We assume this information to be provided by some intention prediction module.

Additionally, environmental conditions, like weather conditions, including ambient temperature or visibility parameters, are defined as data properties of an individual which is linked to the scenario using the relation $hasEnvironmentConditions$. For each of the parameters, valid ranges can be defined. This enables the implementation of traffic rules relating to environment conditions, such as reduced speed limits or prohibited overtaking on wet roads.

IV. Traffic situation classification

We use OWL‘s “defined classes” to classify a traffic situation in order to distinguish between situations in which different traffic rules have to be applied. For example, the same intersection with the same traffic participants could be in three different situations, depending on the presence of traffic lights, their current state and the presence of a traffic regulating police officer.

For each of those situations, different traffic rules have to be applied: the one(s) for uncontrolled intersections, the one(s) regulating intersections with traffic lights and the one(s) regulating how traffic participants have to behave in presence of a traffic regulating person. We define the class $UncontrolledIntersection$ by the exact cardinality restrictions:

$containsTrafficLight\ exactly\ 0\ TrafficLight$ and
$containsTrafficRegulatingPerson$
$exactly\ 0\ TrafficRegulatingPerson$

The class $TrafficLightIntersection$ is defined by the existential and the exact cardinality restriction:

$containsTrafficLight\ some\ TrafficLight$ and
$containsTrafficRegulatingPerson$
$exactly\ 0\ TrafficRegulatingPerson$

while $TrafficRegulatedPersonIntersection$ is formulated by the existential restriction:

$containsTrafficRegulatingPerson$
$some\ TrafficRegulatingPerson$

As shown later, we can use this classification to trigger selected decision-making rules which are valid for the defined situation. One advantage of the classification is, that each defined class can represent a concept described in the traffic regulations and therefore offer a possibility to separate conditions for a certain rule from the rule itself. As an example, a traffic rule might only be valid if our vehicle is in congestion, as stated in the traffic regulations. By creating a defined class $VehicleInCongestion$ we can directly use the concept of congestion as a condition for a certain rule to be applied, while leaving the question of how many vehicles form a congestion is left to the definition of the class. This separation enables to create software code which complies with traffic regulations while working with lawmakers to provide more detailed specifications needed for automated vehicles in future.

V. Traffic regulations ontology

We mentioned that the defined classes in the previous example can be used to distinguish traffic situations for which certain traffic rules have to be applied. We can provide the information about the traffic rule linked to the traffic scenario by a statement of type $TrafficScenario1$ $isRelatedTo$ $TrafficRule254$ with the TrafficRule being a part of a TrafficRegulations-subclass called for example $CaliforniaHighwayCode$ in the traffic regulations ontology. This helps to track requirements in the software development process.

Further, parameters which are defined by local traffic regulations are stored as data properties, for example left- or right sided traffic and general speed limits for certain types of roads.

Figure 2 illustrates that a $RoadSegment$ is defined to be in a certain region by the $hasRegion$ property. Our ontology contains a knowledge base about regions, states and the traffic regulations linked to them. Figure 2 demonstrates this for the region Bavaria, the federal state of Germany. The regional information allows linking a scenario to environment parameter data with region specific range values. Solely providing the region information to a road segment is enough that, using the knowledge base, it can be inferred that a traffic scenario containing this road segment must be subject to the according traffic regulations. This is realized using property chains, and it results in the property $hasTrafficRegulations$ between the traffic scenario and the regulations valid in this region. The property chain can be defined in Protégé as a “SuperPropertyOf(Chain)”:

$hasRegion\ o\ isLocatedIn\ o\ hasTrafficRegulations$

The information stored in the data properties of the traffic regulations individual can be accessed and used as constraints. An example is the value for the maximum allowed vehicle speed. This information can be used in some trajectory planning module or for validation purposes in an application for software testing.

A. Traffic regulation based, generic enhancement of road models

In order to create traffic regulations independent, generic rules to infer information about which lane(s) a vehicle is allowed to drive on or which vehicle has right-of-way, we want to enrich our static representation of the road network. The simple example of deriving information about the preferred lane on a road, in dependence of the road to be in a country with left- or right sided traffic, should illustrate this concept.

We stated that, for example, a road segment $Road1$ could contain three lane segments in the same direction called $Lane1$, $Lane2$ and $Lane3$. The geospatial relation is determined by the triplets $Road1\ hasRightMostLane\ Lane1$ and the $isLeftOf$ relations and its inverse between the lanes. We then use three SWRL rules of type

$$
\begin{aligned}
&RoadSegment(?road)\\
&\wedge preferredLane(?trafficregulations, \text{"}right\text{"})\\
&\wedge hasRightMostLane(?road, ?lane)\\
&\wedge hasTrafficRegulations(?road, ?trafficregulations)\\
&\Rightarrow\ hasPreferredLane(?road, ?lane)
\end{aligned}
$$

to infer the property triplet $Road1\ hasPreferredLane\ LaneX$, one for each of the possible values $left$, $right$ or any stored in the data property $preferredLane$ of the traffic regulations individual linked to this road segment[5]. In a similar way we can infer the relation $hasConflictingConnector$ on intersections as described in III-A. For performance reasons, we propose to perform these enhancement rules in a preprocessing step. This is feasible since the information is static, meaning it does not change during driving. The enhanced road network information should then be provided to a software module running on the vehicle for decision-making, as described in the next chapter.

VI. Traffic scenario examples and Decision-making rules

In order to demonstrate the capabilities of the proposed framework, various urban and freeway traffic scenarios of increasing complexity have been evaluated to apply the decision-making rules. First, we will have a look at a scenario on a 4-way intersection regulated by traffic lights. Then, we assume that the traffic lights on that intersection stop working due to technical failure, so that it becomes an uncontrolled intersection, where different right-of-way rules have to be applied (Figure 4). To increase complexity, the scenario also contains a tram with special rights, namely priority coming from both the left and right side. Then, as a third traffic situation, we assume that a traffic regulating police officer

[5]The full implementation further contains terms to distinguish between different types of roads or other conditions like the number of lanes. This is necessary to comply with traffic regulations e.g. in California, where free lane selection is only allowed on highways with more than 3 lanes.

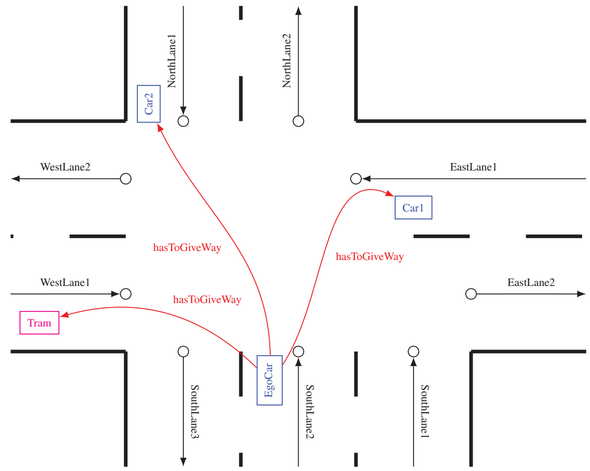

Fig. 4. Semantic representation of an intersection scene. The concept supports generic right-of-way rules independent of right- or left-sided traffic.

will start to regulate traffic, and yet another traffic rule has to be applied.

Using the enhanced semantic road network description, we are able to provide several generic rules to infer traffic regulation based information. In the situation of (functioning) traffic lights present, the according SWRL rule

$$
\begin{aligned}
&TrafficLightRegulatedIntersection(?scen1)\\
&\wedge Vehicle(?vehicle1)\ \wedge\ isOn(?vehicle1, ?lane)\\
&\wedge isPartOf(?vehicle1, ?scen1)\\
&\wedge containsTrafficLight(?lane, ?light)\\
&\wedge hasColor(?light, Red)\\
&\Rightarrow\ hasToWaitForTrafficLight(?vehicle1, ?light)
\end{aligned}
$$

will be triggered using the scenario classification from Section IV to infer statements like $vehicle1\ hasToWaitForTrafficLight\ light1$.

If the traffic light stops working and right-of-way rules at an uncontrolled intersection have to be applied, they can be inferred by the rule:

$$
\begin{aligned}
&UncontrolledIntersection(?scen1)\\
&\wedge Vehicle(?vehicle1)\ \wedge\ Vehicle(?vehicle2)\\
&\wedge isPartOf(?vehicle1, ?scen1)\\
&\wedge hasConflictingConnector(?c1, ?c2)\\
&\wedge hasIntention(?vehicle1, ?c1) \wedge hasIntention(?vehicle2, ?c2)\\
&\Rightarrow\ hasToGiveWay(?vehicle1, ?vehicle2)
\end{aligned}
$$

This rule is only applied for situations classified as $UncontrolledIntersection$ and uses the property $hasConflictingConnector$ to derive the relation $hasToGiveWay$, meaning that a vehicle in the subject will have to yield right-of-way to the vehicle in the object of the expression. The rule does not contain any term dependent on right or left sided traffic and hence the same rule can be used for both traffic regulations. The rule will provide information about right of way for any number of traffic participants with any possible intentions. A similar rule can be applied for vehicles with green traffic lights in the traffic light scenario.

In case a police officer starts regulating traffic on the intersection, the rule:

$$TrafficRegulatedPersonIntersection(?scen1) \wedge Vehicle(?vehicle1) \wedge contains(?scen1, ?vehicle1) \wedge isOn(?vehicle1, ?lane1) \wedge isBlockedBy(?lane1, ?police) \Rightarrow hasToWaitForTRP(?vehicle1, ?police)$$

will become active and provide the information that the vehicle has to wait in case a police officer is blocking its lane.

VII. Conclusion and Outlook

We proposed an extended framework for traffic scenario modeling and decision-making. The semantic traffic scenario description includes knowledge about traffic regulations of different countries. The implementation as an ontology allows to use the same concepts as used in the traffic regulations and is both human and machine readable. The modular framework facilitates the application of automated vehicles in different countries with different traffic rules. A rule set is further capable of enhancing the static map information dependent on traffic regulations, which allows to implement generic decision-making rules for a subset of traffic rules like the preferred lanes in right- or left sided traffic.

Another main contribution is an ontology-based classification method which allows improved situational awareness and to apply traffic situation dependent decision-making, for example only if the conditions for a specific traffic rule are fulfilled. This enables traffic regulation compliant driving in complex traffic scenarios and supports the development process, since this framework can be used to build a traffic scenario catalog for testing purposes.

The framework was validated with a variety of traffic scenarios, both urban as well as on highways. The urban traffic scenarios included complex intersections with uncontrolled traffic, intersections with traffic lights, traffic regulating persons and vehicles with special rights.

As future work, we plan to extend the framework to contain all necessary traffic rules for the regions of interest. The complete ontology would contain useful information about existing definitions of concepts used in the traffic regulations and also to demonstrate where there are inconsistencies. This knowledge base could be used as a foundation in the dialog with law making bodies in order to discuss how today's traffic regulations have to be extended or modified to pave the way for automated driving.

From a technical point of view, a next step is to integrate the framework into a vehicle architecture. For real-time application, reducing the computational complexity might be necessary, where an approach using lean ontologies similar to [15] can be evaluated. An alternative might be to translate the rules to another, faster programming language, not necessarily needing to support first order logic.

We further plan investigations on how the framework can be exploited to support the development process from requirements engineering to testing.

Acknowledgment

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