Structured Natural Language for expressing Rules of the Road for Automated Driving Systems

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Abstract—Automated Driving Systems (ADSs), like human drivers, must be compliant with the rules of the road. However, current rules of the road are not well defined. They use inconsistent and ambiguous language. As a result, they are not sufficiently formal for machine interpretability, a necessity for applications of verification and validation (V&V) of ADSs. Rules must be defined in a way that make them usable to a variety of stakeholders. While first-order and temporal logic forms of rules of the road are needed for monitoring and verification during simulation and testing, a structured natural language for these rules is necessary for consistent definition. They must also adhering to standard vocabulary taxonomies of Operational Design Domain (ODD) and behaviour. This paper contributes a structured natural language based on formal logic, that allows rules of the road to be defined in a natural, yet precise manner, using concepts of ODD and behaviour, making them usable in the V&V of ADSs. We evaluate the effectiveness of the language on a selection of rules from the Vienna Convention on Road Traffic and the UK Highway Code.

Index Terms—automated driving systems, rules of the road, natural language, logic, scenarios

I. Introduction

The benefits of moving towards Automated Driving Systems (ADSs) are known to include increased safety [1], improved traffic management [2], lowered emissions [3], and decreased workload for the driver [4]. To assess an ADSs safety it becomes crucial to define its capabilities and limitations. In this regard, a first step is the definition of the Operational Design Domain (ODD) of the ADS. The ODD defines the boundaries of the operating environment within which the ADS can operate, performing the Dynamic Driving Task (DDT) safely. BSI PAS 1883 [5] and ISO 34503 [6] have an ODD taxonomy, that covers environmental conditions, scenery elements such as drivable area, and dynamic element such as macroscopic traffic behaviour and designated speed of the subject vehicle [5]. It is crucial for an automated driving system (ADS) to ensure that:

1) it can operate safely within its ODD,
2) it will be primarily used within its ODD,
3) it can monitor whether it is inside/outside its ODD, and consequently react to it.

Furthermore, it is widely accepted that testing an ADS requires a quality-focused approach to testing, based on the quality of miles driven, as opposed to the quantity of miles driven. According to Ulbrich et al [7], a *scenario* is a 'temporal development between several scenes in a sequence of scenes. Every scenario starts with an initial scene. Action and events

Fig. 1: Applying Rules of the Road for V&V of ADS

as well as goals and values may be specified to characterise this temporal development in a scenario. Other than a scene, a scenario spans a certain amount of time.' By associating a scenario with ODD and behaviour tags (as relevant to the scenario), it becomes possible to index scenarios based on operational domain elements they address and behaviours they contain.

The scenario-based Verification and Validation (V&V) workflow for an ADS, as depicted in Figure 1, contains a testing component (consisting of scenario, environment) and a test evaluation component (certification/safety evidence and argument). The testing component uses scenarios to test the ADS on a possible variety of platforms (physical or virtual). In the test evaluation component of V&V (certification/safety evidence & argument), the outcomes of testing are assessed against safety criteria to determine if the ADS is safe to operate. Therefore, when assessing an ADS for safe behaviour, the natural question is; how should one define what safe behaviour means in the context of the ADS?

Assessing the correct and safe operation of an ADS requires it to be verified against both its functional requirements and it being able to drive a vehicle safely on the roads it must operate on. Regulating authorities define traffic rules to dictate safe and predictable behaviour protocols for all road actors. A vehicle operator obtains a license, that proves their knowledge of, and ability to adhere to, the respective region's traffic rules. In the same vein, an ADS must also be certified against a set of well-defined rules of the road. In this paper, we assume that a region's "rules of the road" define 'safe behaviour' for an ADS. For instance, in the UK, the Highway Code contains directions for the guidance of persons using roads and is intended to promote safety on the road.

Current rules of the road consist of unstructured natural language text that is designed for human driver interpretation. Further, they contains terms and phrases, that when considered from an ADS' perspective, are ambiguous, and unquantified.

Examples of this include statements such as, “slow down” (to what speed?), “road is clear ahead” (is this synonymous with stopping distance?), “when it is safe to do so” (how is safety defined?), “only when necessary” (what is considered necessary?). To assess an ADS against rules of the road, it becomes important to, have the rule-set in a form that is semantically clear, unambiguous, and enables automated analysis. Furthermore, rules of the road for an ADS need to be written in a manner that enables scenarios to be generated from a rule and subsequently used for testing against the rules. It is also crucial to be able to then index the rules consistently with scenarios and an ADS’ ODD / behaviour specification. Rules will contain essential terms that fall outside of the specification of ODD / behaviour, it is important that these properties be captured appropriately within a language for rule representation. Capturing instances of vehicular / driver properties such as ’visibility’ appropriately will play a crucial role in any rule language specification.

A. Related Work

A number of sources of legal text for traffic rules exist [8], [9]. The Vienna Convention on Road Traffic (VCoRT) from 1968 [8], a ratified source[1], and the national traffic rule set of the UK Highway Code (UKHC) [9], are the main sources of traffic rules in this paper.

There have been previous efforts to create formalised versions of traffic rules. One of the first attempt at codifying legal works was the formalisation of the British Nationality Act [10]. Since then, a variety of works on liability analysis and safety of ADSs have used formalized forms of VCoRT [11]–[14] and the German traffic regulations [13]–[17]. These studies view these rules as requirements for ADSs, while also acknowledging that existing traffic rules use lose and ambiguous language, that is not logically well-formed. The arguments in the rules are fuzzy and can be open to human interpretation, which makes them unsuitable for verification and validation of ADSs. The studies use assumptions to concretise notions such as visibility, distance, and safety, used in the rule text, to create formal symbolic representations of the rules.

Westohofen et al [17], that have formalised part of the German road traffic act, make reference to a congruence problem. The *congruence problem* refers to the equivalence of semantics between legal interpretation and a system’s implementation. They highlight the need to have an alignment of semantics for terms, to reduce uncertainty in the development process, and to create appropriate formalisms to express concepts unambiguously.

A language based on established logical structures (such as first-order and temporal logics [18]) is therefore necessary to have consistent alignment between legal text and its interpretation, both for use to human drivers and ADSs. Zhang et al [19] propose that a common underlying ODD and

[1] https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg no= XI-B- 19&chapter=11&clang= en

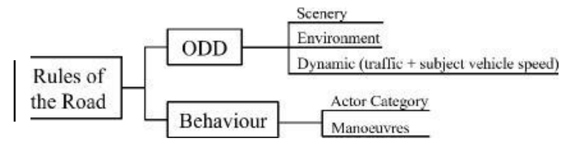

Fig. 2: ODD and Behaviour Context for Rules of the Road

behaviour domain model should be used by the language. This would allow all V&V activities to use a common interpretation for concepts across the scenario-based evaluation continuum. Rules of the road for ADSs expressed using such a language could then be used to both generate scenarios for testing, and as a safety evaluation criteria.

A language for traffic rules rooted in logic can then be easily formalised using establish symbolic languages such as first-order (predicate) logic, linear temporal logic (LTL), or other higher-order logics (HOL) [11]–[16], [20].

In this paper we do not focus on the symbolic expression of the rules, but on the source language in which rules of the road are expressed.

B. Contribution

Similar to scenarios, which have multiple levels of abstraction [21] so they may be usable across a variety of stakeholders, the same is true for rules of the road for ADS, which must be accessible to a variety of stakeholders.

This paper develops a language concept for formally expressing rules of the road for ADS in structured natural language. A logic-based natural language framework is defined, with a vocabulary that is consistent with international standard taxonomies of ODD and behaviour [5], [6]. This enables scenarios to be automatically generated from rules of the road, and a verification process that can be used to establish whether an ADS adheres to the “rules” during its operation. The language is defined from an ODD and behaviour perspective as depicted in Figure 2. The language is grounded in principles of first-order (predicate) logic. The activity of creating a language for a codified set of rules aims at facilitating the safety assurance process of ADSs and has the potential for other use cases such as run-time rule compliance monitoring during deployment.

The rest of this paper is organized as follows: Section II introduces the structured natural language for rules of the road for ADS, and defines its syntax and semantics. Section III presents case studies on using the language to express a selection of rules from the UKHC and VCoRT. In Section IV we provide our observations, discuss language usage, and rules of the road in the wider ADS scenario-based V&V context. Section V concludes the paper and proposes future directions.

II. Developing a Language for Rules of the Road

Each rule of the road describes the ODD (at a junction, near a pedestrian crossing, in the presence of foggy weather) and behaviour conditions (when overtaking, when parking), that when present, require the ADS to either take an action (stop, change lane, slow down, turn, move into a central

ODD Condition	**Simple**	***ODD element*** *(is | is not | are | are not)* ***Relation***
	Complex	***(Detail)? ODD element (Relation ((of)? ODD element)?)?*** *(is | is not | are | are not)* ***(Value | Relation | Behaviour)***
	Example	**Distance** of **Other Vehicle** to **Junction** is **less than 10m**
Behaviour Condition	**Simple**	*(performing)?* ***Behaviour*** | ***Behaviour*** *(is | is not | are | are not)* ***Relation***
	Complex	*(performing)?* ***Behaviour*** | ***Behaviour*** *(is | is not | are | are not)* ***(Value | Relation)***
	Example	performing **Overtake** | **Steering angle** is **less than 10°**
Property Condition	**Simple**	***Property*** *(is | is not | are | are not)* ***Relation***
	Complex	***(Detail)? Property (Relation ((of)? ODD element)?)?*** *(is | is not | are | are not)* ***(Value | Relation)***
	Example	**Distance** of **Visibility** to **Other Vehicles** is **less than 10m**

TABLE I: Syntax Variations for *Cause* Statements (for ODD, Behaviour, Property conditions): Syntax and Examples

reservation), set limits on its behaviour (speed limits) or affect its relationship with the ODD and other actors (slowing down or maintaining distance). Hence, a rule of the road may be viewed as having a *cause* component and an *effect* component, that is, the presence of a "cause" constrains or "effects" the behaviour of the ADS. While the complete set of rules is always applicable for the ADS when it is operating, at any particular moment, a specific rule (or set of rules) becomes active when the ADS' ODD and behaviour components match the ODD and behaviour component of a rule's condition.

The language architecture for codification must be designed for scalability and ease of extension. The language and its "rules" must be extendable to accommodate variations of environment, evolving actors, and behaviour specification. Scalability of the language architecture is a key element when making design decisions. The language architecture proposed in this section uses a hierarchical approach and has been designed top-down. It accommodates concepts associated with the ODD of an ADS (including scenery, operating environment, and behaviour). It also specifies domain terms, term properties and relationships between terms. It is important that the terms come from known standard taxonomies (such as the BSI PAS 1883 ODD taxonomy). This will result in a language that is comprehensive, consistent, and easy to analyse.

The key points to consider at this stage are as follows:

- A scenario plays out as a series of scenes.
- The Highway Code rules are applicable to a scene.
- Typical form a rule takes: IF the ODD/Behaviour meets *criteria* THEN do *something* NOW.

The language for rules of the road will be supported by authoring tools, similar to those already existing for the two-level abstraction scenario description language (SDL) [22], [23]. The tool will help rule authors by suggesting rule templates through an auto-completion feature, giving authors clear guidance on simple and unambiguous options for constructing the rule. The language also will have a companion level-2 formal symbolic logic format. This will be similar to the relationship the level-2 logical SDL has to its level-1 counterpart, which is a functional/abstract natural language SDL [24]. An automatic translation to the level-2 rules of the road format will also be made possible.

A. Language Overview

The language presented here aims to describe the rules of the road, in a structured format that maintains readability while introducing a programmatic structure that makes conversion to a machine readable format achievable. The structure builds on the very simple idea that every rule for the road has a cause and an effect. Using the UK highway code as inspiration, rules were studied from the perspective of a cause-and-effect framework, and a suitable syntax for the conditions that contribute to a cause, and the actions that make up an effect, were decided.

This language format provides the user with an exchangeable and consistent way to represent rules of the road. This includes the base structure for representing the cause and effect, a grammar which details the syntax of these two concepts, and guidelines for rule construction. As mentioned above, the implementation of this structure will need to be carefully considered in order to create verifiable rules; use of ambiguous terms, such as in current natural language descriptions, will be possible but should be avoided. The user will be able to represent any rule as they wish in this format, it should be noted that only certain uses of this structure will result in rules that are verifiable. Particular attention should be paid to this during implementation as choices during rule construction can have an effect on their programmatic use. Rules may also be represented in multiple ways using the format, allowing the user to adjust their language use to be more or less abstract, verifiable or unverifiable.

The simplest form of a rule, described using this concept, has the following syntax. The cause is denoted by **X** and the effect is denoted by **Y**:

*IF **X**, you **imperative (preposition)**?:*
  - **Y**
*(UNLESS **X**)?*

Conjunctions/disjunctions of both **X** and **Y** can be achieved using *AND*/*OR*. UNLESS in an optional inclusion that can be used to initiate a list of exceptions applicable to the IF block immediately preceding it. The bold-face text in the above description represents that the term needs expanding to construct a rule description; this convention will be maintained in all syntax definitions given throughout the paper. **Imperative** for instance can be one of the following: MUST | MUST NOT.

Simple	*(perform (a an)?)? Behaviour Behaviour (is is not are are not) Relation*
Complex	*(perform (a an)?)? Behaviour Behaviour (is is not are are not) (Value Relation)*

TABLE II: Action statement: Syntax of Behaviour action

Whereas, **preposition** can be one of the following: *make sure that* **|** *be aware that* **|** *be prepared for*.

B. Expressing Cause (X)

In the aforementioned literature review, and particularly from studying current driving rules in the UK highway code, it was discovered that rules revolve around 3 'types' of cause (**X**). These three types of cause have individual syntax' which can be fed into the structure presented above, in Section II-A.

These three types are defined as ODD conditions, Behaviour conditions and Property conditions. In Table I we describe the syntax associated with each condition type. Each syntax has a simple and complex format. The 'simple format' being the base form of the statement, in which a majority of terms are required. The 'complex format' introduces additional terms which can be used to represent more complicated conditions. In the following syntax definitions **bold type face** represents a 'category' of terms which can be selected from to complete a statement, and a '?' which follows a bracket is used to signify that the content within the brackets is optional.

As seen in Table I there are two variations of syntax for behaviour. These facilitate describing rules that focus on the performance of a behaviour as **X**, resulting in a series of actions or conditions; **Y**. As well as describing the a behaviour in the same way that an ODD element has been above. The **Behaviour** category itself has two separate options for use; **driving behaviours** and **driving context and supporting behaviours** which are detailed later in Section II-E.

Any combination of condition statement from Table I can be strung together to create as complicated a Cause (**X**) as is needed for the rule to be properly expressed.

C. Expressing Effect (Y)

The syntax for the Effect (**Y**) is categorised identically to that of the Cause (**X**), with the effect of the rule being described as an action or series of actions. For consistency these actions are described as ODD actions, Behaviour actions and Property actions.

There is little difference in the syntax between the conditions that make up the Cause (**X**) and the actions which make up the Effect (**Y**), with the primary differences being in how they are used. However, there is a difference in tense required for the Behaviour action; with the present participle **'performing'** becoming the present tense imperative **'perform'**. The resulting syntax for behaviour action in present in Table II. The remaining action syntax for ODD and Property are identical to their condition counterparts and can be read from Table I.

In the expression of simple rules it is likely that you will see the use of the simple format in the condition and the use of complex format in the listed effects.

. *Impact of "Preposition" on Effect (Y)*

As mentioned in Section II-A there are multiple prepositions which can be used to alter the meaning of a rule. Your selection of preposition has an effect on the type of Effect (Y) which can follow; it may restrict which of the 3 effect types can be used (ODD action, behaviour action or property action).

Three variations will be described to exemplify the relationship between preposition and effect. The three cases are, having no preposition, and the phrases 'make sure that' and 'be aware that'.

a) No preposition: When no preposition is used, the rule structure lends itself to describe a series of behaviours as the effects. Without a preposition given, the implication is that the imperative applies to the effects that follow it as things that MUST/MUST NOT be done, i.e. the use of no preposition requires the ADS to 'do' what follows. It therefore holds that, if no preposition is given, the syntax will typically align with the Behaviour effects syntax given in Section II-A.

An example expressing a rule in this format might look like the following.

IF Crossroad is Ahead you MUST:
- Reduce throttle input OR
- Apply brakes
- AND Slow down

b) 'Make sure that': When a preposition such as 'make sure that' is used, a verifiable effect must follow, such as the presence of an ODD element, or a property having a certain acceptable value. There is not a typical case in which a behaviour is described as an effect after this preposition is used, Verifiable behaviours of other actors can be described in using the complex format of the ODD effect as this appertains to another actor in the scenes behaviour, where the other actor is the focus of the effect statement. It therefore follows, that after this preposition, it is typical that only a selection of ODD effects or Property effects can be used.

An example expressing a rule in this format, with an ODD effect, might look like the following.

IF Overtaking you MUST make sure that:
- Road is Clear Ahead

c) 'Be aware that': If a preposition such as 'be aware that' is used, then the effect is not going to be verifiable. The widest range of syntax options for effect is available to describe this scenario. A behaviour can only be described in this scenario rather than be used an an instruction to perform. Therefore, of the two optional syntax representations for Behaviour effect, the syntax which enables behaviour description is used i.e

Behaviour (is **|** *is not* **|** *are* **|** *are not) Relation*

An example expressing a rule in this format, with a property effect, might look like the following:

IF Other Vehicles are Using fog lights you MUST be aware that:
- Visibility is Impaired

Strategic	**Syntax**	***Strategic behaviour*** *(value)?*
	Examples	**Overtake**, **Give way**, **Move** quickly
Tactical	**Syntax**	***Tactical behaviour*** *(value)?*
	Examples	**Turn** left, **Change lane** right, **Indicate** left, **Flash lights**
Operational	**Syntax**	*(qualifier)?* ***Strategic behaviour*** *(value)?*
	Examples	**Braking** distance, **Steering** angle, reduce **Throttle** input

TABLE III: Driving Behaviour: Syntax and Examples

*E. Describing Behaviour within Cause (**X**) and Effect (**Y**)*

In the preceding syntax definitions specified in this paper 'Behaviour' has not been expanded upon. Unlike its counterparts 'ODD element' and 'Property', 'Behaviour' does not represent the parent class of a leaf node attribute (not having further 'children'). This section expands upon what is meant by behaviour as it is classified into 'Driving behaviours' and 'Driving context and supporting behaviours', and further classified by abstraction level.

a) Driving behaviour: Driving behaviours are actions or events performed by the driver/system which contribute to the driving task. This is a broad definition which covers a range of activities which are defined in road rules at multiple levels of abstraction. These have been categorised for use into Strategic level behaviours, Tactical level behaviours and Operational level behaviours. These different levels describe behaviours at different levels of abstraction and have slight variations in syntax as a result, their individual definitions are be given bellow.

Strategic level behaviours describe a macroscopic manoeuvre of the vehicle, can be seen as planning or intended behaviours and could often be broken down into 'tactical behaviours' which specifically alter the vehicle heading.

Tactical level behaviours describe a lower level manoeuvre that directly results in an interaction with the vehicles environment, can be seen as action behaviours performed by the vehicle as a whole entity and could be further broken down into 'operational behaviours' performed by individual vehicle systems.

Operational level behaviours describe a lower level manoeuvre that directly results in an interaction with the vehicles environment, can be seen as action behaviours performed by the vehicle as a whole entity and could be further broken down into 'operational behaviours' performed by individual vehicle systems. The syntax and examples of the use of all aforementioned behaviour types can be seen in Table III.

b) Driving context and Supporting behaviours: These behaviours do not require a hierarchical breakdown.This category is defined as behaviours which support driving activities but do not specifically have an effect on the driving task. These behaviours are typically human actions which would not necessarily have a use in an automated approach to the driving task. The syntax and examples of its use are shown in Table IV.

Syntax	***Supporting behaviour*** *(context)?*
Examples	**Check** blind spot, **Look** out of rear, **Use** left lane

TABLE IV: Driving Context and Supporting Behaviours

*F. Grouping rule Effect's (**Y**'s)*

Rule description is often not a simple process, a single Cause (**X**) may result in multiple groups of Effects (**Y**), and some rules may have multiple nesting Causes that build upon each other having compounding Effects (**Y**s). Whilst the syntax is capable of representing road rules sufficiently, we propose some methods for its use; making the grouping of conditions easier and resulting in more readable rule representations. Three example methods for grouping Effects are detailed below, covering grouping by preposition type, temporal progression and nesting 'IF' conditions. In this subsection each of the three methods will be described.

a) Preposition type: As covered in Section II-D, there are multiple prepositions which can be used in the description of rules. This method of organising a rule the effects are clustered together by common preposition. A typical example of a rule written in this format would take the form:

*IF **X** you MUST make sure that:*
- Y
- ANDY

AND you MUST:
- Y

In this structure there are two things (**Y**s) that you must 'make sure' are true (typically ODD conditions) and one thing (**Y**) that must be done (a Behaviour condition).

b) Temporal progression: In some cases the effects of a rule are dependent on the temporal progression of the Cause (**X**). This is primarily found in cases where a Strategic behaviour, as defined in Section II-E, is the Cause of the rule (**X**). In this grouping method the Effects (**Y**s) are grouped by things which occur before **X**, during **X** and after **X**. A small addition to the syntax can be seen, this help improve a rule's readability. The example below shows a typical use of this format:

*IF **X**,*
<u>Before</u> you MUST:
- Y
- ANDY

<u>During</u> you MUST:
- Y
- then Y
- AND then Y

After you MUST make sure that:
- Y

c) Nesting 'IF' conditions: The complexity of some rules is increased by the inclusion of additional Causes that compound upon the original rule cause. Each additional Cause is made clear by an additional, 'nested' IF, this cause will have a corresponding Effect that only happens or is true if the original IF condition, and the nested IF condition are true. The example below shows how one might use this grouping method:

IF X you MUST make sure that:
- Y

AND IF X OR X you MUST:
- Y

G. Rule Verifiability

This paper has presented a structured natural language for representing rules. The syntax proposed enables user to represent rules with a structure that enables consistent understanding for readers. Rules represented in this language (level 1) will be able to be converted into a machine readable logic, however, there are multiple areas in the language where your representation of the rule will effect its verifiability. This should be considered during the construction of the rule.

For instance, use of the preposition *'be aware that'*, will render any Effect's that follow unverifiable, due to the nature of the preposition itself. There is no way to verify a system or driver's 'awareness' at any given point. There are examples of terminal choices within Behaviour and Relation that are also unverifiable, or will require additional data to become verifiable, it is the responsibility of the user to construct a rule in a way that suites their intended use. For instance, a rule could be written with the effect; 'distance to Junction is sufficient' or 'distance to Junction is greater than 10m'. Both of these rules are valid syntactically, however the later is represented in a way that is verifiable without any further data, the former would rely on additional data defining the term 'sufficient' for that particular effect, before it could be considered verifiable.

III. Case Studies

This section presents case studies based on a selection of rules from the UK highway code (UKHC) and the Vienna Convention of Road Traffic (VCoRT). For each rule, a snippet of the original rule text is first presented, as taken from the respective source, and then re-written using the proposed language.

A. Rule 162 (UKHC)

In unstructured natural language, as it appears in the UKHC.
"Before overtaking you should make sure:

- *the road is sufficiently clear ahead*
- *road users are not beginning to overtake you*
- *there is a suitable gap in front of the road user you plan to overtake."*

And represented in our structured rule language.

IF performing an Overtake,
Before you MUST be sure that:
- Road is Clear Ahead
- AND distance from Overtake Target to Vehicle in front is Suitable
- AND Vehicles to rear are not Overtaking

B. Rule 236 (UKHC)

In unstructured natural language, as it appears in the UKHC.
"You MUST NOT use front or rearfog lights unless visibility is seriously reduced (see Rule 226) as they dazzle other road users and can obscure your brake lights. You MUST switch them off when visibility improves."

And represented in our structured rule language:

IF Fog is present AND Visibility is not Seriously Reduced, you MUST NOT:
- Turn-on Fog lights

AND IF Fog is present AND Visibility is Seriously Reduced, you MUST:
- Turn-on Fog lights

And IF visibility improves you MUST:
- Turn-off Fog lights

C. Rule 227 (UKHC)

In unstructured natural language, as it appears in the UKHC.
"In wet weather, stopping distances will be at least double those required for stopping on dry roads (see 'Typical stopping distances'). This is because your tyres have less grip on the road. In wet weather

- *you should keep well back from the vehicle in front. This will increase your ability to see and plan ahead*
- *if the steering becomes unresponsive, it probably means that water is preventing the tyres from gripping the road. Ease off the accelerator and slow down gradually*
- *the rain and spray from vehicles may make it difficult to see and be seen.*
- *be aware of the dangers of spilt diesel that will make the surface very slippery (see Annex 6: Vehicle maintenance, safety and security)*
- *take extra care around pedestrians, cyclists, motorcyclists and horse riders."*

And represented in our structured rule language, the same information is presented in a structured format that maintains readability:

IF Wet Weather is present, you MUST be aware that:
- Stopping Distances are doubled
- AND Visibility is reduced

AND IF Vehicles are ahead you MUST:
- Keep well back

AND IF Steering is unresponsive you MUST:
- Reduce Throttle input
- AND Slow down gradually

AND IF Pedestrians OR Motorcyclists OR Cyclists OR Horse Riders are present you MUST:
- Take extra care

AND IF Spilt Diesel is present you MUST be aware that:
- Road surface is Very slippery

D. Article 11, Rule 9 (VCoRT)

In unstructured natural language, as it appears in the VCoRT.

"A vehicle shall not overtake another vehicle which is approaching a pedestrian crossing marked on the carriageway or signposted as such, or which is stopped immediately before the crossing, otherwise than at a speed low enough to enable it to stop immediately if a pedestrian is on the crossing."

And represented in our structured rule language, the same information is presented in a structured format that maintains readability:

> *IF Pedestrian crossing is ahead of Vehicle Infront OR (Vehicle Infront is stopped AND Pedestrian Crossing is ahead) you MUST NOT:*
> - Perform Overtake
>
> *UNLESS speed of Overtake is sufficiently slow AND immediate Stop is possible*

IV. Discussion

A set of codified rules of the road can be used for numerous purposes. Some of which have been enumerated earlier. These include,

- *Scenario generation* – creation of scenarios that specifically target testing the ADS performance against a Highway Code rule (or set of rules).
- *Validation during Simulation* – The Highway Code rules may be used as an oracle to deduce if any rule is violated, how, and to what extent.
- *In-System Advice* – Use of the Highway Code to suggest safe action.
- *Safety Argument* – The adherence of the ADS to the Highway Code is a strong argument for its safety. This would require that the ADS is adequately tested against the various conditions that trigger each applicable Highway Code rule, which would ensure rule coverage.

Unlike scenario representation, and to some extent ODD description, rule representation has seen little attention in the context of developing and validating ADSs.

As exemplified in the case studies, the language concept can appropriately describe real world rules of the road. If adopted by industry a structured language format for representing rules of the road could benefit the development of ADSs going forward; forming an excellent tool in the testing of developing systems and construction of safety cases.

The concept presented in this paper serves as a first step towards the codification of the rules of the road. It is presented as the first level of a two-level abstraction model for codified rules of the road, with a foundation in mathematical logic. A second level which advances the codification using formal symbolic logic is being developed as a counterpart to this structured natural language concept and will be able to utilise descriptions of this format through an automated language translation tool similar to our existing translators for scenario languages [23], [24].

Efforts into ensuring the effective use of a language structure for codifying highway rules will be supported via parsers and semantic validators [24]. The suggested concept has been developed with a capable enough structure for complex and scale-able rule description, but the use of unverifiable and abstract terms will limit the usefulness of this representation for achieving most of the above benefits.

V. Conclusions

This paper presents a structured natural language for representing the rules of the road for ADS. The language is rooted in logic fundamentals and aligned with ADS ODD and behaviour concepts and taxonomies. Constraints that cannot be addressed as either ODD or behaviour are classified as general property conditions, and this paper also distinguishes between rules (or components of rules) that are verifiable and non-verifiable. The argument put forward for the importance of establishing a codified format for rules of the road, while particularly emphasising its relevance as the industry makes steps towards achieving autonomy. The language is a first step towards a codified set of rules of the road which would offer a multitude of benefits to the development and deployment of ADS vehicles. A codified rule-set could offer a source of testing scenarios, a method of validating ADS behaviour in simulation, and act as a strong piece of evidence to be leveraged in safety argumentation. The language is evaluated on a set of example rules, ranging from simple to complex, chosen from the Vienna Conventions on Road Traffic and the UK Highway Code.

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References

[1] D. J. Fagnant and K. Kockelman, "Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations," *Transp. Res. Part A Policy Pract.*, vol. 77, p. 167–181, 2015.

[2] S. Le Vine, X. Liu, F. Zheng, and J. Polak, "Automated cars: Queue discharge at signalized intersections with 'Assured-Clear-Distance-Ahead' driving strategies," *Transp. Res. Part C Emerg. Technol.*, vol. 62, p. 35–54, 2016.

[3] D. J. Fagnant and K. M. Kockelman, "The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios," *Transportation Research Part C: Emerging Technologies*, vol. 40, pp. 1–13, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0968090X13002581

[4] N. Balfe, S. Sharples, and J. R. Wilson, "Impact of automation: Measurement of performance, workload and behaviour in a complex control environment," *Applied Ergonomics*, vol. 47, pp. 52–64, 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0003687014001410

[5] BSI, "Pas 1883:2020 operational design domain (odd) taxonomy for an automated driving system (ads) — specification," 2020. [Online]. Available: https://www.bsigroup.com/en-GB/CAV/pas-1883/

[6] ISO, "ISO/DIS 34503 Road Vehicles — Test scenarios for automated driving systems — Specification for operational design domain," 2023.

[7] S. Ulbrich, T. Menzel, A. Reschka, F. Schuldt, and M. Maurer, "Defining and Substantiating the Terms Scene , Situation , and Scenario for Automated Driving," *Proc. of the 2015 IEEE 18th 18th Int. Conf. on Intelligent Transportation Systems*, pp. 982–988, 2015.

[0] E. C. for Europe: Inland Transport Committee, "Vienna convention on Road Traffic," Nov 1968. [Online]. Available: https://unece.org/fileadmin/DAM/trans/conventn/crt1968e.pdf

[1] U. K. Department for Transport, "The Highway Code," Road Safety and Vehicle Rules, July 2022. [Online]. Available: https://www.gov.uk/guidance/the-highway-code

[2] M. J. Sergot, F. Sadri, R. A. Kowalski, F. Kriwaczek, P. Hammond, and H. T. Cory, "The british nationality act as a logic program," *Commun. ACM*, vol. 29, no. 5, p. 370–386, may 1986. [Online]. Available: https://doi.org/10.1145/5689.5920

[3] A. Rizaldi and M. Althoff, "Formalising traffic rules for accountability of autonomous vehicles," in *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, 2015, pp. 1658–1665.

[4] C. Pek, P. Zahn, and M. Althoff, "Verifying the safety of lane change maneuvers of self-driving vehicles based on formalized traffic rules," in *2017 IEEE Intelligent Vehicles Symposium (IV)*, 2017, pp. 1477–1483.

[5] S. Maierhofer, A.-K. Rettinger, E. C. Mayer, and M. Althoff, "Formalization of interstate traffic rules in temporal logic," in *2020 IEEE Intelligent Vehicles Symposium (IV)*, 2020, pp. 752–759.

[6] K. Esterle, L. Gressenbuch, and A. Knoll, "Formalizing traffic rules for machine interpretability," in *2020 IEEE 3rd Connected and Automated Vehicles Symposium (CAVS)*, 2020, pp. 1–7.

[7] A. Rizaldi, J. Keinholz, M. Huber, J. Feldle, F. Immler, M. Althoff, E. Hilgendorf, and T. Nipkow, "Formalising and monitoring traffic rules for autonomous vehicles in isabelle/hol," in *Integrated Formal Methods*, N. Polikarpova and S. Schneider, Eds. Cham: Springer International Publishing, 2017, pp. 50–66.

[8] S. Maierhofer, P. Moosbrugger, and M. Althoff, "Formalization of intersection traffic rules in temporal logic," in *2022 IEEE Intelligent Vehicles Symposium (IV)*, 2022, pp. 1135–1144.

[9] L. Westhofen, I. Stierand, J. S. Becker, E. Möhlmann, and W. Hagemann, "Towards a congruent interpretation of traffic rules for automated driving - experiences and challenges," in *International Workshop on Methodologies for Translating Legal Norms into Formal Representations (LN2FR)*, G. Borges, K. Satoh, and E. Schweighofer, Eds., December 2022, pp. 8–21. [Online]. Available: https://elib.dlr.de/193009/

[10] S. Russell and P. Norvig, ""artificial intelligence — a modern approach"."

[11] X. Zhang, S. Khastgir, and P. Jennings, "An ODD-Based Scalable Assurance Framework for Automated Driving Systems 2023-01-0574," SAE International, Tech. Rep., 2023. [Online]. Available: https://www.sae.org/publications/technical-papers/content/2023-01-0574/

[12] ASAM, "ASAM OpenDRIVE® Standard," 2021. [Online]. Available: https://www.asam.net/standards/detail/opendrive/

[13] C. Neurohr, L. Westhofen, M. Butz, M. Bollmann, U. Eberle, and R. Galbas, "Criticality Analysis for the Verification and Validation of Automated Vehicles," *IEEE Access*, vol. 9, no. i, 2021.

[14] X. Zhang, S. Khastgir, and P. A. Jennings, "Scenario Description Language for Automated Driving Systems: A Two Level Abstraction Approach," in *2020 IEEE Int. Conf. Systems, Man, and Cybernetics*, pp. 973–980.

[15] A. A. B. da Costa, P. Irvine, X. Zhang, S. Khastgir, and P. Jennings, "Translating automated vehicle test scenario specifications between scenario languages: Learnings and challenges," in *Proceedings of the Driving Simulation Conference 2022 Europe VR*, A. Kemeny, J.-R. Chardonnet, and F. Colombet, Eds. Strasbourg, France: Driving Simulation Association, 2022, pp. 65–72.

[16] A. A. B. da Costa, P. Irvine, X. Zhang, S. Khastgir, and P. A. Jennings, "Writing accessible and correct test scenarios for automated driving systems," in *IEEE International Conference on Systems, Man, and Cybernetics, SMC 2022, Prague, Czech Republic, October 9-12, 2022*. IEEE, 2022, pp. 1356–1363. [Online]. Available: https://doi.org/10.1109/SMC53654.2022.9945564