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ORIGINAL RESEARCH

Traffic rules compliance checking of automated vehicle maneuvers

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Abstract

Automated Vehicles (AVs) are designed and programmed to follow traffic rules. However, there is no separate and comprehensive regulatory framework dedicated to AVs. The current Queensland traffic rules were designed for humans. These rules often contain open texture expressions, exceptions, and potential conflicts (conflict arises when exceptions cannot be handled in rules), which makes it hard for AVs to follow. This paper presents an automatic compliance checking framework to assess AVs behaviour against current traffic rules by addressing these issues. Specifically, it proposes a framework to determine which traffic rules and open texture expressions need some additional interpretation. Essentially this enables AVs to have a suitable and executable formalization of the traffic rules. Defeasible Deontic Logic (DDL) is used to formalize traffic rules and reasoning with AV information (behaviour and environment). The representation of rules in DDL helps effectively in handling and resolving exceptions, potential conflicts, and open textures in rules. 40 experiments were conducted on eight realistic traffic scenarios to evaluate the framework. The evaluation was undertaken both quantitatively and qualitatively. The evaluation result shows that the proposed framework is a promising system for checking Automated Vehicle interpretation and compliance with current traffic rules.

Keywords Automated vehicle · Defeasible deontic logic · Logical reasoning · Ontology knowledge base · Overtaking maneuver · Traffic rule formalization

1 Introduction

Automated Vehicles (AVs) are designed and programmed to follow traffic rules; it is therefore suggested that AVs would be the solution to traffic rule violations (Khorasani et al. 2013; Leenes and Lucivero 2015). AVs have the potential to reduce

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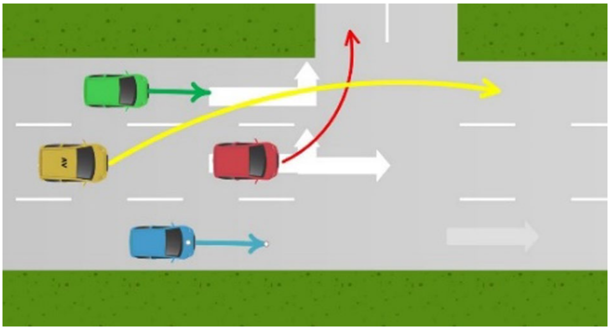


Fig. 1 Example of a complex overtaking maneuver

crashes, reduce traffic congestion, and improve driving efficiency (Ryerson et al. 2019). Undeniably, AVs could bring significant change to current transportation systems, such as smoother traffic flows and better fuel consumption and emissions, etc. (Fagnant and Kockelman 2015). Due to such impacts, it is not surprising that people are now considering these vehicles for their daily activities. Thus various companies such as Google, Uber, Toyota, Tesla, and Nissan, have begun the task of integrating automation into vehicles within a couple of years[1] (Sperling et al. 2018).

However, the transition from human-driven vehicles to AVs remains unclear as the debate on how AVs will fit into the existing regulatory framework is still open. There has been a debate about whether AVs can properly follow current traffic rules. Some scholars believe existing traffic rules and regulations are sufficient to address AV issues, while others think new rules and regulations are necessary (Brodsky 2016; Villasenor 2014). As the existing traffic rules are made for human drivers, AVs may not properly follow some terms and conditions (Brodsky 2016). For example, open texture expressions such as "approaching traffic", "clear view", "safely overtake", etc. appear in Queensland (QLD) traffic rules. AVs cannot interpret such expressions without clarifying the meaning and context of their use (Rizaldi et al. 2017). Also, an AV may not be able to follow the rules related to exceptions without additional interpretation. It is also unclear whether the AV can act appropriately in traffic scenarios where traffic rules conflict (Prakken 2017) and where traffic rules are implicitly defined (Leenes and Lucivero 2015). Currently, for some rules and situations, a human is more reliable in making the right decision than an AV (Schwarting et al. 2018). Therefore, AV technology deployment may not have the expected benefits (Dolgov 2016) unless AVs comply with relevant traffic rules and guidance (Brodsky 2016). Considering this issue, this research proposed an automatic compliance checking framework to check whether an AV complies with existing QLD traffic rules. Thus, it can be used to determine which traffic rules need additional pieces of interpretation for an AV to follow them correctly.

[1] http://www.businessinsider.com/companies-making-driverless-cars-by-2020-2016-8

Table 1 Queensland overtaking traffic rules[1]

Rule No	Rules about
140	General overtaking safety
141	Left overtaking rules
142	Right overtaking rules
143	Overtaking a vehicle displaying a "do not overtake turning vehicle sign"
144	Safe distance rules while overtaking
144A	Safe distance while passing bicycle
145	Speeding conditions for the overtaken vehicle

[1] https://www.legislation.qld.gov.au/view/html/inforce/current/sl-2009-0194#pt.11-div.3

Figure 1 shows an example of an overtaking maneuver. In this example, the AV (yellow) intends to overtake the red vehicle which is turning left. The green vehicle is moving forward, which may be another issue for the AV to consider while changing lanes to overtake the red vehicle. According to QLD overtaking traffic rules (see Table 1), to legally overtake the red vehicle, the AV must comply with traffic rules 145, 144, 141, and 140, as this is the left overtaking maneuver. According to the author's understanding, to perform this maneuver, the AV must deal with several open texture expressions and exceptions, such as "clear view of approaching vehicle", "safe to do so", and "must not overtake a vehicle to the left unless", etc.

Most of the approaches for formalizing traffic rules and monitoring methodologies (Aladin et al. 2019; Alves et al. 2019; Rizaldi et al. 2017) of AVs behaviour neglect handling and resolving traffic rules issues such as open textures, exceptions, and potential rule conflict. Accordingly, such approaches may not be capable to check AV behaviour compliance against traffic rules with the situation depicted in Fig. 1.

In this paper, we address the challenges and issues described above by adopting a traffic rule compliance-checking framework based on Defeasible Deontic Logic (DDL). DDL is an effective logical approach to handle exceptions and potential conflicts in rules as it works based on a suitable variant of defeasible logic. Indeed, DDL has been successfully applied to formalizing normative frameworks in different domains and applications (Governatori et al. 2020; Witt et al. 2021). The exercise of formalizing QLD traffic rules in DDL allows us to identify the 'open texture terms' in rules that need further interpretation. The formalization will be used in conjunction with a traffic ontology to provide the interpretation of the terms and concepts appearing in the traffic rules based on the traffic environment and AV's data. More specifically, each term in the rules has some data queries associated to it. The queries are created by domain experts and research in traffic literature to provide a bridge between the traffic rules and the environment in which an AV is situated. Consequently, queries provide the meaning for the 'open texture terms'. The paper integrates the approaches we developed in (Bhuiyan et al. 2019, 2020) for the formalization of traffic rules, and extend it with a methodology to evaluate such framework. More specifically, fhe framework is evaluated by an empirical experiment where overtaking maneuver by an AV are evaluated for legality by human. The experiment gives us a way to determine if the ‘open texture terms’ were properly captured (more details in Sect. 3.2.2). To the best of our knowledge this is the first experiment of this kind where the outcome of an automated compliance checker is robustly evaluated by human driver and domain experts.

This paper focuses on QLD overtaking traffic rules as a case study to check compliance. The main features of QLD overtaking traffic rules are similar to the other states of Australia (and in other jurisdictions around the world). So it can be assumed that the case study is generally relevant beyond QLD overtaking traffic rules.

There were several considerations in selecting overtaking traffic rules as a case study. To the best of the author’s knowledge, no research has been done on AV behaviour compliance checking with QLD traffic rules. In QLD traffic rules, overtaking rules are among the most challenging regulations with several complex terms and conditions. An empirical study of QLD traffic rules found that overtaking is referred to in around 15% of QLD traffic rules (3% explicitly and 12% implicitly). This high representation of overtaking in traffic rules shows the significance of overtaking in QLD traffic rules. Considering this level of references, overtaking traffic rules is a good case study to evaluate AV behaviour compliance checking within QLD traffic rules.

Overtaking is one of the most challenging and complex maneuvers for drivers and AVs. It is a complicated driving maneuver due to lateral and longitudinal motions involved while overtaking a leading vehicle (Naranjo et al. 2008). Depending on vehicle density on the road, and other surrounding vehicle speeds, overtaking often becomes a risky maneuver, and it is one of the significant, salient causes of road crashes (Hegedűs et al. 2019). However, this maneuver is considered one of road automation’s most required driving actions (Tsai and Chan 2019), as it keeps vehicle velocity consistent with the necessary road speed. There are two main types of overtaking: Left Overtaking and Right Overtaking.

Overtaking is the process of safely passing a vehicle on the road (Naranjo et al. 2008). This maneuver is performed for several reasons, including "the leading vehicle is driving slowly", "the leading vehicle is stationary", etc. The main requirement of overtaking is maintaining a safe distance from all other road entities (road islands, overtaken vehicles, and other vehicles) during operation. This maneuver can be legally performed on any road (freeway, motorway, highway, two-way, one-way, etc.) unless it is forbidden. The prohibition can be explicit given, for example, by the presence of an "Overtaking is not permitted" sign or by road or traffic conditions as codified in the relevant traffic rules.

Moreover, for the purpose of the formalization, the traffic rules regulating overtaking offers a good mixture of features: combination of open-texture and “black and white” terms (“black and white” terms are expressions whose truth can be computed directly from the environment and sensor data available by the AV), combination of different types of rules, and exceptions.

2 Related Work

This research focuses on the compliance checking of Automated Vehicle behaviour against traffic rules. Accordingly, the associated issue of this compliance checking is traffic rule formalization and legal reasoning of AV behaviour. Different factors make the formalization of traffic rules a challenging task. Some of these factors are: some rules are fuzzy, some lack specific details, some terms are not properly defined, and some rules might have a complex logical structure. For legal reasoning the main challenges concerns how to represent the traffic rules, how the formalized traffic rules interact with AV data to draw conclusions about the legal behaviour of an AV.

A summary of the most recent related research on AV behaviour compliance checking against traffic rules is provided in Table 2. The information presented in Table 2 includes the research method, goal, experiment, and compliance checking considered facts based on traffic rule formalization and legal reasoning. Most research focused on driving assistance systems for specific tasks such as lane change, overtaking, collision avoidance, decision-making in controlled and uncontrolled intersections, etc. A limited number of studies focused on assessing/compliance checking (Censi et al. 2019; Costescu 2018; Rizaldi et al. 2017) and monitoring/capture (Aladin et al. 2019; Alves et al. 2021) AV behaviour against traffic rules. In what follows we provide a quick overview of some related work relevant for the topic of this contribution.

Rizaldi and Althoff (2015) formalized traffic rules to identify which vehicle was liable for the collision. This work aimed to prove that an AV always obeys the traffic rules, and therefore, there was no chance for the AV to become responsible for the collision. The overall process was conducted mainly in three steps. First, a subset of Vienna traffic rules was formlaized and concretised in the Higher-Order-Logic (HOL). Second, a black box recorded the behaviour of the AV. Then, an unambiguous and formal compliance checking of traffic rules was performed regarding the AV behaviour. Later, the author extended the work and tried to solve the rule vagueness issue using the safe distance theorem (Rizaldi et al. 2016 2017). Costescu (2018) proposed a traffic rule formalization method to keep AVs accountable. This method worked in three major steps. First, implicit redundancy was eliminated from the legal text. Next, the AV and the user's responsibility was explicitly sorted out; and, finally, then they logically broke the rules into "*predicate precursors*". The proposed method also allows further development of expressivity of rules (codified traffic rules) using Higher Order Language. The methodology used the overtaking rules as a case study. In terms of precision, although the case study experiment was impressive compared to the natural language, it was not enough for immediate automation, and therefore further work was needed. Censi et al. (2019) proposed a rulebook, a formalism methodology for UK & Singapore rules, to make the self-driving vehicle behaviour compatible with the current traffic regulations. Rulebooks define driving behaviour by defining rules precisely and establishing a hierarchy of rules. The author experimented with this rulebook on three specific traffic scenarios: unavoidable collision, lane change near intersection and clearance and lane-keeping

Table 2 Summary of AV behaviour compliance checking studies

References	Methodological approach	Experiment process and experiment Scenarios	Goal	Compliance checking considered facts				
				Traffic rules formalization		Legal reasoning		
				Traffic rules cover	Methods	AV knowledge base		Reasoning methods
						AV information	Methods	
Hülsen et al. (2011)	Ontology modelling of traffic situations	• Simulation-based • Intersections	Advanced Driver Assistance System (ADAS)	Traffic signs (right-of-way, yield and stop) at the intersection, and Lane change	Description Logic (DL)	Vehicle, and infrastructure (roads, lanes, intersections)	Ontology, OWL, RDF	Logic Reasoning, Lean Ontology
Zhao et al. (2014)	Ontology-based Intelligent Speed Adaptation system	• Both Simulation and Real-world based • Intersections, KinderGarten, BusLane, OneWayLane, etc	ADAS (Overspeed detection)	Speed Limit	Semantic Web Rule Language (SWRL)	Vehicle, road and environment (intersection, lane,etc.)	Ontology, OWL, RDF	SPARQL, C-SPARQL, Jena, Pellet Reasoner, OWL
Armand et al. (2014)	Ontology Modelling	• Simulation-based • One dimensional road, Pedestrian Crossing, and intersection	Cotext awareness for Driving Assistance System (DAS)	14 specific rules regarding the experiment situation	SWRL	All road entities (Vehicles, pedestrian, road, etc.) and vehicles in one way direction	Ontology, OWL, RDF	SWRL, Pellet Reasoner
(Zhao et al. 2015a 2015b)	Ontology-based Knowledge Base	• Real-world based • Uncontrolled intersections (no traffic light)	ADAS to comply with traffic rules	Speed limit, Right-of-Way, Lane chane, and Intersection	SWRL	Vehicle, road and environment (intersection, lane,etc.)	Ontology, OWL, RDF	SPARQL, SWRL Reasoner

Table 2 (continued)

References	Methodological approach	Experiment process and experiment Scenarios	Goal	Compliance checking considered facts				
				Traffic rules formalization		Legal reasoning		
				Traffic rules cover	Methods	AV knowledge base		Reasoning methods
						AV information	Methods	
Mohammad et al. (2015)	Ontology-based framework	• Video based • Unpredictable road traffic environment	Risk assessment in road scene	Assume road users obey the traffic rules	-	Behaviour of all entities (vehicle, pedestrian, etc.) in the scene and environment	Ontology, OWL, RDF	SPARQL, Pellet Reasoner
Albert Rizaldi and Matthias Althoff (2015)	Logic-based formalizations of traffic rules	• – • –	Compliance Checking of AV behaviour	A subset of Vienna Traffic Rules	Isabella theorem, Higher-Order-Logic (HOL)	Vehicle behaviour, highway scenarios	Black Box, Isabella theorem, HOL	Isabella theorem, HOL
Xiong et al. (2016)	Ontology modelling for driving context	• Real-world based • Overtaking and lane change	Better understanding of traffic context and driving decision	Traffic signs, traffic lights, and speed limit on the experimented area	SWRL	Vehicle behaviour, road users (car, bikes, motorcycle, and pedestrians) lane information	Ontology, OWL, RDF	JESS CLIPS
Zhao et al. (2016)	Ontology Modelling	• Simulation-based • Uncontrolled intersections and narrow road	Fast decision-making system	Lane change, Stop, ToLeft GiveWay (right-of-way)	SWRL	Vehicle behaviour and driving environment around intersection	Ontology, OWL, RDF, Jena	SPARQL,C-SPARQL, SWRL Reasoner

Table 2 (continued)

References	Methodological approach	Experiment process and experiment Scenarios	Goal	Compliance checking considered facts				
				Traffic rules formalization		Legal reasoning		
				Traffic rules cover	Methods	AV knowledge base		Reasoning methods
						AV information	Methods	
(Buechel et al. 2017)	Ontology framework	• Simulation-based • 4-WAY uncontrolled intersections	Decision making	Intersection and Right-of-Way rules	SWRL	Vehicle behavior and traffic scenario in intersection	Ontology, OWL 2	SWRL, and Pellet Reasoner
Zhao et al. (2017)	Ontology-based Knowledge Base	• Real-world-based • Uncontrolled intersections and two-way narrow road	Decision Making	Intersection and Right-of-Way rules (14 rules)	SWRL	Vehicle behavior and driving environment (road segment, lane, crosswalk, etc.)	Ontology, OWL, RDF	SPARQL C-SPARQL SWRL Reasoner
Rizaldi et al. (2017)	Logic-based formalizations of traffic rules	• – • –	Monitor the compliance of traffic rules	German overtaking traffic rules	Linear Temporal Logic (LTL) using HOL	Vehicle behavior, surrounding information (ego vehicles) using V2V,and highway scenarios	Black Box, Isabella theorem, and HOL	Isabella theorem, HOL

Table 2 (continued)

References	Methodological approach	Experiment process and experiment Scenarios	Goal	Compliance checking considered facts				
				Traffic rules formalization		Legal reasoning		
				Traffic rules cover	Methods	AV knowledge base		Reasoning methods
						AV information	Methods	
Shadrin et al. (2017)	An expert traffic rule formalization mechanism	• Real-world based • –	Control autonomous vehicle in specific situation	800 traffic rules, road marking, road types, and traffic lights	A expert system includes multi-dimensional databases, data processing algorithm, and cognitive model	–	–	Logical reasoning
Costescu (2018)	Logic-based formalizations of traffic rules	• – • Complex multimodal scenarios in urban and inter-urban traffic, mixed categories of vehicle, and intersections	Keep the Autonomous Vehicle accountable	Overtaking Rule	Legal analysis and logically break the rules into "predicate cursor"	–	–	Logic Analysis (Modal Logic Flow Chart), Atomic Proposition, LTL, and HOL
Aladin et al. (2019)	Logic-based artificial intelligence system (Mivar expert system)	Simulation-based • Uncontrolled intersections, pedestrian crossing and so on	Monitor vehicle activities in real-time and inform the driver about traffic rules violations	–	Mivar knowledge base (Experts systems- Wi!Mi! Razumotor, Tel!Mi Robo!Razum.)	–	–	Trajectory control system, a simplified technical vision system, and a decision support system (DSS)

Table 2 (continued)

References	Methodological approach	Experiment process and experiment Scenarios	Goal	Compliance checking considered facts				
				Traffic rules formalization		Legal reasoning		
				Traffic rules cover	Methods	AV knowledge base		Reasoning methods
						AV information	Methods	
Alves and Dennis (2018), Alves et al. (2019)	Logic-based formalization of traffic rules	• – • –	Autonomous Vehicle control (route planning, obstacle avoidance, etc.)	Road junction rules (UK highway)	Description Language, and Temporal Logic	Vehicle behavior	BDI (Belief, Desire and Intention) agent and GWENDOLEN agent programming	Model Checking Agent Programming Lanugae (MCAPL), Agent Java Path Finder (AJPF)

based on 15 rules. However, the rulebook was domain-specific, and for a different nation, the priorities of the rules needed to be changed.

(Aladin et al. 2019) introduced a system, Mivar, that can monitor vehicle activities in real-time and can also inform the driver about violations of traffic rules. Mivar system consists of three main modules: a trajectory control system (lane position, a safe distance from other vehicles, etc.), a simplified technical vision system (road situation in real-time), and a decision support system (DSS). The Mivar control system was developed based on Razumator (Varlamov and Aladin 2018), a logic-based inference machine. This system processed the information (road situation) in real-time from data received from other assisted devices. Based on this information, it built the algorithms to monitor the driver's actions regarding the traffic rules. Alves et al. (2021) developed a double-level model to capture the correct behaviour of an AV concerning traffic laws and to minimise changes to present road junction rules in the UK Highway traffic rules, including road entities and traffic signs. The three-traffic junction regulations were explicitly tested in this model. The model was developed using the UPPAAL (timed automata model) and MCAPL (Model Checking Agent Programming language) techniques. The model experimented on three different scenarios of the road junction. However, a complete traffic environment (limitation of considering spatial information) was not considered while assessing AV behaviour.

None of these studies addresses the combination of open texture terms, exceptions, and potential conflict issues in rules, which are significant variant features of traffic rules and might create problems in compliance checking of AV behaviour. Comparing these and other works mentioned in Table 2, in terms of handling and resolving open texture terms, exceptions, and potential conflict in rules, we have proposed a DDL-based automatic compliance checking framework that can effectively handle these issues. Moreover, none of the above-mentioned related work evaluated their proposed approach by comparing results to other existing approaches or by evaluating human drivers. In contrast, we conducted a robust human evaluation, including domain experts, to evaluate our proposed compliance checking framework.

3 Compliance Checking Framework

The system architecture of the proposed Automatic Compliance Checking framework is shown in Fig. 2. It aims at checking the compliance of AV behaviour against the QLD Overtaking Traffic Rules. This unified framework relies on the use of a set of computational methods in an integrated manner. The framework includes simulator design, formalization, ontology definitions, and logical reasoning that are collectively used for automated reasoning. Defeasible Deontic Logic, Scanner Studio (AV Simulation—SCANeR™ studio 1.9), Protégé (Ontology – Owlready2 0.23 PyPI), and the Turnip Reasoner (DDL Reasoning) are used to support the computational process of the system. This system is built on a Python Platform (Version 3.8.0).

The framework consists of two main modules:

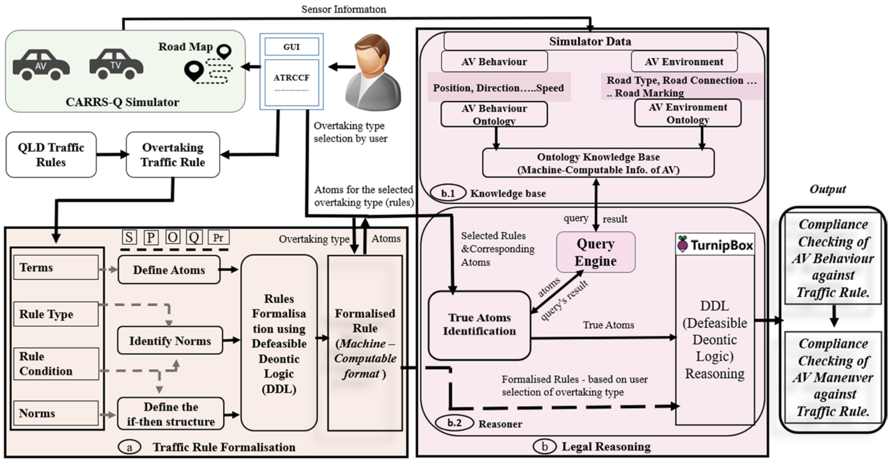


Fig. 2 Automatic traffic rule compliance checking framework (ATRCCF)

a. Traffic Rule Formalization and
b. Legal Reasoning.

The traffic rule formalization module formalizes traffic rules and send them to the legal reasoning module based on the requirement. The legal reasoning module creates a machine-computable (M/C) format of AV information (ontology knowledge base) and then performes the reasoning of this AV information with the formalized traffic rules. Finally, it checks the fof compliance of the AV behaviour against the traffic rules. A brief explanation of these two modules is given below.

3.1 Traffic Rule Formalization

Rule formalization (i.e., the representation of legal rules in a machine-computable format) is a crucial requirement for compliance checking, automatic reasoning, and legal validation (Wyner and Peters 2011). However, it is a difficult task because of the domain-specific sentence length, clause embedding, and structure. Rules contain thousands of provisions and norms, making the formalization work even more challenging (Banks and Banks 2010). Several studies have been conducted to address the issues of rule formalization (Biagioli et al. 2005; de Maat and Winkels 2010). In addition, several languages and products have been proposed to formally represent them. For example, LegalRuleML is a novel XML standard for the representation of norm (Monica et al. 2021). Several commercial products, such as Oracle Policy Automation (Oracle 2021), offer services to translate rules into executable language and give a user-friendly natural language online interface.

Traffic rules are generally written in natural language. Due to the complex and varying nature of traffic rules, it is a challenging task to formalize them. Any incorrect rule formalization might have a negative impact on the reasoning process. As a result, this study devised and implemented a Defeasible Deontic Logic

(DDL)-based formalization approach for translating traffic rules into a machine-computable (M/C) format. The resulting M/C format of traffic rules can be utilised for automatic traffic rule reasoning to evaluate AV behaviour to determine whether it is legal or not. The method incorporates the components and behaviour of regulations based on the rule's obligation, prohibition, and permission activities.

The proposed DDL-based traffic rule formalization methodology consists of four steps (Fig. 2a):

a. Define atoms,
b. Identify deontic modalites,
c. Define the if–then structure and
d. Rule formalization using DDL.

These steps were done manually. The methodology's input is a set of traffic rules in natural language. In the first step, atoms were defined from the rules. In the second step, norms were determined. Then, the if–then structure was identified from the rules in the third step. Finally, DDL was applied to the atoms, deontic modalities, and if–then structure to make the machine-computable (M/C) rules format. The steps are explained below.

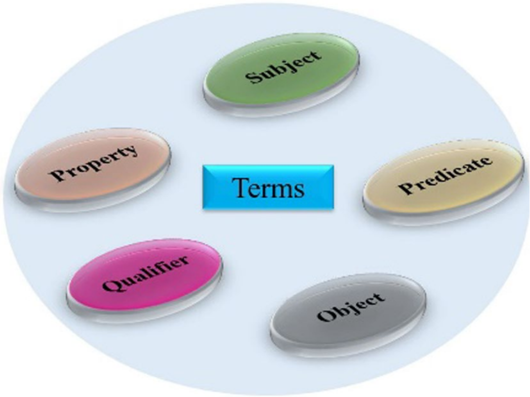
3.1.1 Define atoms

An *atom* is a predicate symbol including constants or variables that contains no logical connectives (Wolfson and Silberschatz 1988). Here, the atoms are extracted based on the occurrences of terms/expressions in the sentences or textual provision of the relevant traffic rules. A *term* is a *variable* or an (individual) *constant* in the textual provision (Gamut et al. 1991). This work deals with expressions (predicates, variables, and constants) that refer to subject (s), predicate (p), property (pr), object (o), and qualifier (q) in a rule sentence (Fig. 3). Before identifying terms, some text pre-processing was conducted on the rules; for example, modal verbs and connectives were excluded from the analysis. An atom is a combination of these terms/expressions that form a (prtimiteve) Boolean expression. For example, QLD Overtaking Traffic Rule 140, states "*the driver can safely overtake the vehicle*". In this rule, "driver" is the variable corresponding to the subject (entity) of the sentence. "overtake" is the predicate that refers to the action of the subject (entity). "can safely" is the qualifier that defines the predicate of this rule. "vehicle" is an individual variable that refers to the object of the rule. Integrating these four terms, an atom is defined as:

Predicate (subject, qualifier, object) ≡ Overtake (driver, CanSafely, vehicle): *driver_CanSafelyOvertake_vehicle*.

The current traffic rules use natural language to define the cases (events and facts) they are meant to regulate (terms, conditions, and legal provisions). Depending on the events, the description of these cases varies. There is no general structure in how traffic rules are written. Due to this heterogeneity of the rule information, the

Fig. 3 Terms



atom structure varies. Throughout the empirical study of the QLD Overtaking Traffic Rules, atoms were defined in five patterns[2] which are:

- Subject-Predicate-Object.
- Subject-Predicate-Qualifier-Object.
- Subject-Property.
- Subject-Predicate-Object-Object.
- Subject-Qualifier-Predicate-Object.

Based on these combinations, some examples of atoms are shown in Table 3.

The proposed methodology aims at improving the uniformity, consistency and repeatability of formalizing efforts. Witt et al. (2021) report very high (syntactic) variability of formalizings when they are done by a team of coders; moreover, they report that adopting a common naming convention and sharing a formalizing methodology greatly increase the agreement among the formalizings by the different coders. Also, fitting textual provisions in the patterns allows us to identify expressions that could have different syntactic structures but the same semantic meaning; such expressions will be formalized by the same atoms. Finally, as we will see in the rest of this section the actual form and name of an atom are not relevant for the reasoning tasks we are going to study. However, the identification of the components in an atom enables us to identify what are the elements of the ontologies and how they contribute to establishing when the atoms they are part of can be evaluated as true or false (see Sect. 3.2.2). Thus, they are relevant for how we query the AV data (see Sect. 3.2.2).

[2] These patterns are sufficient to cover the majority of cases of QLD overtaking traffic rules. While more patterns are possible, the patterns we present also offer guidance to capture more complex cases if needed.

Table 3 Example of atoms

Example	Rule	Defined atom
Ex-01	Part 11, Division 3 rule 151: 1 (a) driver must not overtake a vehicle	*NEG (driver_Overtake_vehicle)* (Subject-Predicate-Object)
Ex-02	Part 11, Division 3 rule 140: b "the driver can safely overtake the vehicle"	*driver_CanSafelyOvertake_vehicle* (Subject-Predicate-Qualifier-Object)
Ex-03	part 2 division 2, Rule 15: "A vehicle includes a bicyle"	*vehicle_Isabicycle* (Subject-Property)
Ex-04	Part 11 Division 3 rule 151A-1: a "motorbike between two adjacent lines"	*motorbike_InBetween_adjacentLine1_adjacentLine2* (Subject-Predicate-Object-Object)
Ex-05	part 19 rule 305: "A police vehicle is allowed not to display the light"	*police_vehicle_allowed_NotToDisplayTheLight* (Subject-Qualifier-Predicate-Object)

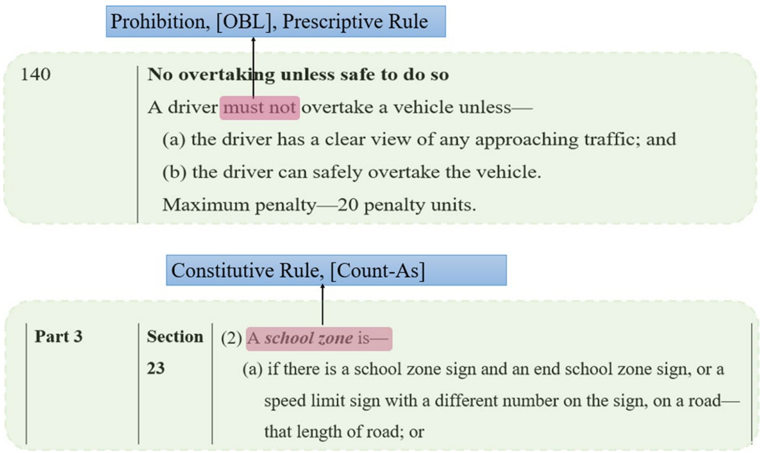


Fig. 4 Example of deontic modality (norms) identification

3.1.2 Identify deontic modalities

Deontic modalities are expressions in the traffic rule that (legally) qualifies terms and actions. They help us in determining the types of norms we are going to formalizes. Each norm is represented by one or more constitutive or prescriptive rules. *Constitutive rules* define terms specific to legal documents. *Prescriptive rules* prescribe the "mode" of the behaviour using deontic modalities: obligation, permission, and prohibition. Here we follow the definition given by LegalRuleML for obligation, prohibitions and permission (Monica et al. 2021). An obligation is an action or course that the subject must perform, whereas prohibition is an action or course that the subject must not perform. Permission is the state of an action that is not subject to a prohibition or an obligation. In this work, we identify norms based on both constitutive and prescriptive forms of rules. For example (Fig. 4), in the QLD Traffic Rules, part 11 division 3, rule 140 states that “a driver must not overtake a vehicle unless….”. In this statement we can identify the expression "must not" as a prohibition. An example of constitutive rule and identification of (Count-As) norm is shown in Fig. 4.

3.1.3 Define the if–then structure

Traffic rules specify the subject’s actions (or the conditions the subject must ensure hold). They consist of deontic modalities and conditions that control the subject’s behaviour. A rule comprises if (antecedent or premise) and then (consequent or conclusion). Therefore, a rule can be represented as:

if (antecedent)
then (consequent)

If the premise becomes true, then the consequent part of the rule triggers. A rule may have multiple antecedents joined by logical operators: OR, AND, and XOR. From a legal perspective, rules use conditions on some actions to achieve/mandate specific behaviours. Therefore, we identify the if–then structure from rules using atoms and deontic modalities for formalizing traffic rules. For example, in the QLD overtaking rules,

> Rule 140: A driver must not overtake a vehicle unless— (a) the driver has a clear view of any approaching traffic, and (b) the driver can safely overtake the vehicle.

The rule expresses an obligation norm for the driver to overtake. By defining atoms and identifying norms, the if–then structure of this rule can be defined as:

```
r_{140}:
IF
  \emptyset
THEN[F]
  %% must not overtake a vehicle %%
  NEG (driver_Overtake_vehicle)

r_{140-exc}:
IF
    %% the driver has a clear view of any approaching traffic %%
    driver_HasClearViewOf_approachingTraffic // atom
  AND
    %% the driver can safely overtake the vehicle %%
    driver_CanSafelyOvertake_vehicle // atom
THEN [P] // norm / deontic modality
    %% A driver must not overtake a vehicle UNLESS %%
    driver_Overtake_vehicle // atom

r_{140-exc} ≫ r_{140} // Superiority relation
```

3.1.4 Rule formalization using DDL

After defining and identifying atoms, deontic modalities and if–then structures for rules, the expressions are converted in DDL. DDL is an extension of Defeasible Logic with Deontic Operators and the compensatory obligation operator introduced by (Governatori and Rotolo 2006). DDL is a formalism that provides a conceptually approach to the formalization of norm and, at the same time, exhibits a computationally feasible environment to reason about them. DDL has been successfully used in legal reasoning to handle norms and exceptions, and it does not undergo the problems affecting other logic used for reasoning about compliance and norms (Antoniou et al. 2001; Governatori 2015). Below is a brief overview of Defeasible Logic and Deontic modalities and how we used them to represent traffic rules.

3.1.4.1 Defeasible logic Defeasible Logic is a non-monotonic, sceptical logic that prevents the derivation of contradictory conclusions. For example, suppose there is a piece of information that supports the conclusion A, but also there is a second piece of information that supports not A, preventing thus concluding A. DDL recognized the opposite conclusions and does not derive them. However, if A's support has priority over ¬ A, then it might be possible to conclude A.

Defeasible Logic is made up of five separate knowledge foundations: strict rules, facts, defeasible rules, defeaters, and superiority relations. (Maher 2001). Knowledge is organized in a theories, where a *theory* D is a triple (F, R, $\gg$) where F is a set of facts, R is a set of rules, and $\gg$ is a superiority relation in R.

Expressions in Defeasible Logic are built from a finite set of *literals*, where a *literal* can be either an atomic statement or its negation. Given a literal A, ~ A denotes its complement. That is, if A = B, then ~ A = ¬ B and if A = ¬ B, then ~ A = B. Facts (F) are unequivocal and conclusive statements. A fact represents a state of affairs (literal) or an act that has been performed and are believed to be true.

A *rule* (an element of R) specifies the relationship between premises and conclusion and can be characterised as its strength. Strict rules, defeasible rules and defeaters can be distinguished based on the relationship strength of the rules (Governatori 2018). The following expressions describe these rules: $A_1, \ldots, A_n \rightarrow B$ (Strict Rules), $A_1, \ldots, A_n \Rightarrow Y$ (Defeasible Rules) and $A_1, \ldots, A_n \rightsquigarrow$ (Defeaters) B, where $A_1, \ldots, A_n$ is the antecedent or premises (clauses), and Y is the consequent or conclusion (effect) of the rule.

Strict rules are rules in the classical sense: if the premises are unarguable (for example, a fact), then is the conclusion. For example, "a motorbike is a vehicle," formally:

Motorbike → Vehicle; this indicates that every motorbike is a vehicle.

Defeasible rules are rules that can be defeated by contrary evidence. For example, "a motorbike can edge filter", formally, can be written as:

$$\text{Motorbike} \Rightarrow \text{Edge\_Filtering\_Vehicle}.$$

Defeaters are rules that cannot be used to derive any conclusions on their own. Their purpose is to preclude some conclusions, i.e., to undermine some defeasible rules by supplying opposite evidence. For example, suppose a rule state that: "if a rider does not hold O type license, then the rider cannot edge filter".

¬ rider_HoldOTypeLicence¬ Edge_Filtering_Vehicle.

From this statement (and the previous one), it can be stated that a motorbike is an edge filtering vehicle, but if the rider of motorbike does not hold an O type licence, then it cannot edge filter on the road. This statement can prevent the conclusion of edge filtering. This is not also supporting the 'no edge filtering'.

The *superiority relation* ($\gg$) used the priority set among the rules, where one rule may override the other rule's conclusion. No conclusion can be made in such scenarios unless the rules are prioritised. For example, based on the following defeasible rules:

r_1: Motorbike ⇒ Edge_Filtering_Vehicle

r_2: Vehicle ⇒ ¬ Edge_Filtering_Vehicle

No conclusive decision can be made about whether a vehicle can edge filter. However, if we establish a superiority relation $\gg$ with $r_1 \gg r_2$, then we can state that the vehicle cannot edge filter. A complete definition of defesible logic reasoning mechanism can be found in (Antoniou et al. 2001).

3.1.4.2 Deontic Operators In addition to defeasibility, traffic rules contain extensive occuences of deontic concepts. This research considered Obligation [O], Prohibition [F] and Permission [P] deontic operators to formalize traffic rules. The deontic operators are modal operators. A modal operator applies to a proposition to create a new proposition where the modal operator qualifies the "truth" of the proposition to which the operator is applied. For instance, a proposition from QLD Overtaking Traffic Rule 142: *driver_OvertakeToTheRightOf_vehicle* means that the "driver is overtaking the front vehicle from its right side". We can distinguish this proposition based on the above deontic operators:

- *Overtake Right:* this is a factual statement that is true if the vehicle overtakes from the vehicle's right and false otherwise (¬ OvertakeRight is true).
- [O]*OvertakeRight:* this is a deontic statement meaning that the vehicle must overtake the right of the vehicle. The statement is true if the obligation to overtake is in force in the particular case.
- [F]*OvertakeRight:* this is a deontic statement meaning that the vehicle is prohibited from overtaking the vehicle on the right-hand side. The statement is true if the prohibition to overtake is in force in the particular case.
- [P]*OvertakeRight:* this is a deontic statement meaning that the vehicle has permission to overtake the right of the vehicle. The statement can be evaluated as true if the permission to overtake is in force in a particular case.

Moreover, to formalize traffic rules using DDL, we consider the traffic system as a normative system, which has a set of clauses (norms), where the causes/norms are represented as if…then rules. Every clause/norm is represented by one (or more) rule(s) with the following form: where, $X_1, \ldots, X_n$ are the conditions of applicability of the norm, and Y is the "effect" of the norm.

$$X_1, \ldots, X_n \Rightarrow Y$$

The above-mentioned ([O], [P], [F]) deontic modalities modelled the normative effects. We take the standard deontic logic relationships between these deontic modalities. These are described below (taking the concept of overtake, atom: overtake).

$$[F]\mathit{Overtake} \equiv [O]\neg\,\mathit{Overtake}$$

$$[O]\mathit{Overtake} \equiv [F]\neg\,\mathit{Overtake}$$

$$[P]\mathit{Overtake} \equiv \neg[O]\neg\,\mathit{Overtake}$$

Now, a complete example of traffic rule formalization using DDL is shown in Fig. 5. For this example, we use the QLD Overtaking Traffic Rule 142 (see also Table 1). The full formalization of QLD Overtaking Traffic Rules is shown in "Appendix".

Rules in DDL are defeasible. This means that, where a rule is applicable, we can assert the conclusion of the rule provided that all rules for the opposite are defeated or discarded. A rule is applicable if all the elements of its antecedent hold; a rule is discarded if at least one element of its antecedent does not hold; finally, a rule is defeated if a stronger applicable rule overrides it. A simple example from Rule 142 (Fig. 5) is, the driver is usually permitted to overtake from the right (r142_1); however, if the leading vehicle is turning right and is giving the right change of direction signal, then the driver (following vehicle) is not permitted to overtake (r142_1_a_ii>>r142_1). In this case, rule r142_1_a_ii is overriding rule r142_1. DDL is equipped with a superiority relation over rules establishing the relative strength between pairs or rules, to be used to solve conflicts when rules with opposite conclusions are applicable at the same time. For the full details of DDL, see (Governatori et al. 2013).

3.2 Legal Reasoning

Legal reasoning module consists of two components (Fig. 2(b)): knowledge base and reasoner. The traffic rule formalization module provides the required formalized rules to this legal reasoning module based on the compliance checking requirements (which rule or maneuver, such as left overtaking, right overtaking, lane change, speed, give way, etc.). The purpose of the ontology knowledge base is to provide the input to the reasoner for mapping the low level information available by an AV to the formalized traffic rules. A brief explanation of the ontology knowledge base and reasoner is provided below.

3.2.1 Knowledge Base

We created a knowledge base of AV information to facilitate the task of compliance checking the behaviour of an AV. The structure of the knowledge base is shown in Fig. 2b.1. Two ontologies were created from related AV information: AV behaviour and AV environment ontology, as shown in Figs. 6 and 7. The ontologies were used to provide the input (or case description) to the formalized traffic rules. These ontologies can be reused and easily extended based on requirements by adding other concepts. For the visual representation of these ontologies, we used Protégé.[3]

An ontology represents knowledge in a structured framework that consists of concepts (classes) and relationships (properties). It is a complete semantic network where concepts are in a hierarchy. An important characteristic of an ontology is that it represents knowledge in the machine-computable (M/C) format, for example, RDF (Resource Description Framework) data (Najmi et al. 2016). M/C knowledge representation in RDF can bridge the gap between AV perception and knowledge processing. Therefore, this work converted AV information (behaviour and environment) into ontologies (M/C knowledge base).

[3] https://protege.stanford.edu/

Rule 142: No overtaking to the right of a vehicle turning right etc.
(1) A driver must not overtake to the right of a vehicle if the vehicle is—
(a) turning right or making a U-turn from the centre of the road; and
(b) giving a right change of direction signal.

Formalization

Atom Initialisations:

Atom driver_OvertakeToTheRightOf_vehicle
Atom vehicle_IsTurningRight
Atom vehicle_IsGivingRightChangeOfDirectionSignal
Atom vehicle_IsMakingUturn
Atom vehicle_IsOn_centreOfRoad

Rules:

r142_1: => **[P]** driver_OvertakeToTheRightOf_vehicle
r142_1_a_i: vehicle_IsTurningRight => **[F]** driver_OvertakeToTheRightOf_vehicle
r142_1_a_ii: vehicle_IsTurningRight & vehicle_IsGivingRightChangeOfDirectionSignal => **[F]** driver_OvertakeToTheRightOf_vehicle
r142_1_a_iii: vehicle_IsMakingUturn & vehicle_IsOn_centreOfRoad => **[F]** driver_OvertakeToTheRightOf_vehicle
r142_1_a_iv: vehicle_IsMakingUturn & vehicle_IsOn_centreOfRoad & vehicle_IsGivingRightChangeOfDirectionSignal => **[F]** driver_OvertakeToTheRightOf_vehicle
r142_1_b: vehicle_IsGivingRightChangeOfDirectionSignal => **[F]** driver_OvertakeToTheRightOf_vehicle

r142_1_a_i >> r142_1
r142_1_a_ii >> r142_1
r142_1_a_iii >> r142_1
r142_1_a_iv >> r142_1

Fig. 5 Formalization of QLD traffic rule 142

Table 4 describes the metrics of these ontologies. These ontologies have 63 classes and 96 properties (object properties and data properties). The AV behaviour ontology was created using all AV behaviour information available in the simulator we use for this work (i.e., speed, direction, lane number, etc.). The environment ontology was created using road information (i.e., road marking, road type, etc.) and AV surroundings information (i.e., weather, other vehicles, etc.). In both ontologies (Figs. 6 and 7), the "timestamp" class is common. This class kept track of every timestamp's AV information. One driving maneuver can occur over hundreds of timestamps. For example, the scenario shown in Fig. 12 last 11.25 s; accordingly, given we record information every 0.05 s, this maneuver has 227 timestamps (and for each timestamp, we have the ontology data associated to it). Notice that not all timestamps may not be necessary to assess a maneuver. A compliance assessment results can be made from the evaluation of the AV's at specific timestamps.

Figure 6 (a) shows the driving behaviour ontology hierarchy. We have designed the ontology to include different types of vehicles, such as private, public, priority, etc. There are three main classes of this ontology which are "vehicle",

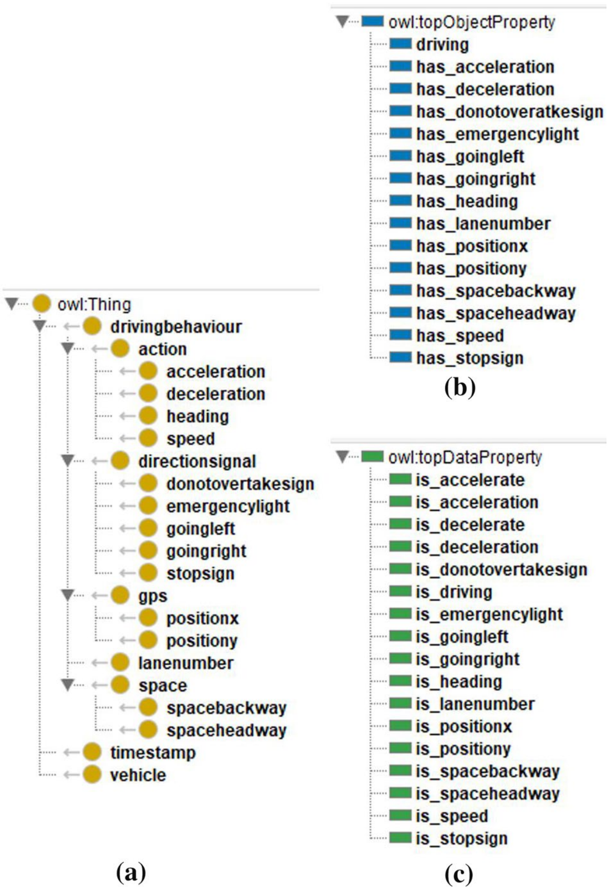


Fig. 6 **a** Class hierarchy of the behaviour ontology **b** Object properties of the Behaviour Ontology **c** Data properties of the Behaviour Ontology

"drivingbehaviour", and "timestamp". The "vehicle" class has a vehicle ids attribute. Through this id, the specific vehicle information could be tracked and retrieved. There are five major sub-classes in the “drivingbehaviour" class, such as "action", "directionsignal", etc. All these subclasses have several subclasses. The object and data properties of this behaviour ontology are shown in Fig. 6 (b) & (c). Object properties describe the relationship between the individuals among the classes. For example, the "driving" object property identifies which AV is driving in a specific time slot. The data properties were used to illustrate the value of the attributes of this ontology. For example, the vehicle’s "lane number" was used to identify the lane number of the vehicle.

A machine-computable road map was required to perceive the driving environments. For AV Environment Ontology, the road map was mainly considered where the AV is driving. The general structure of and relevant data for the road map was

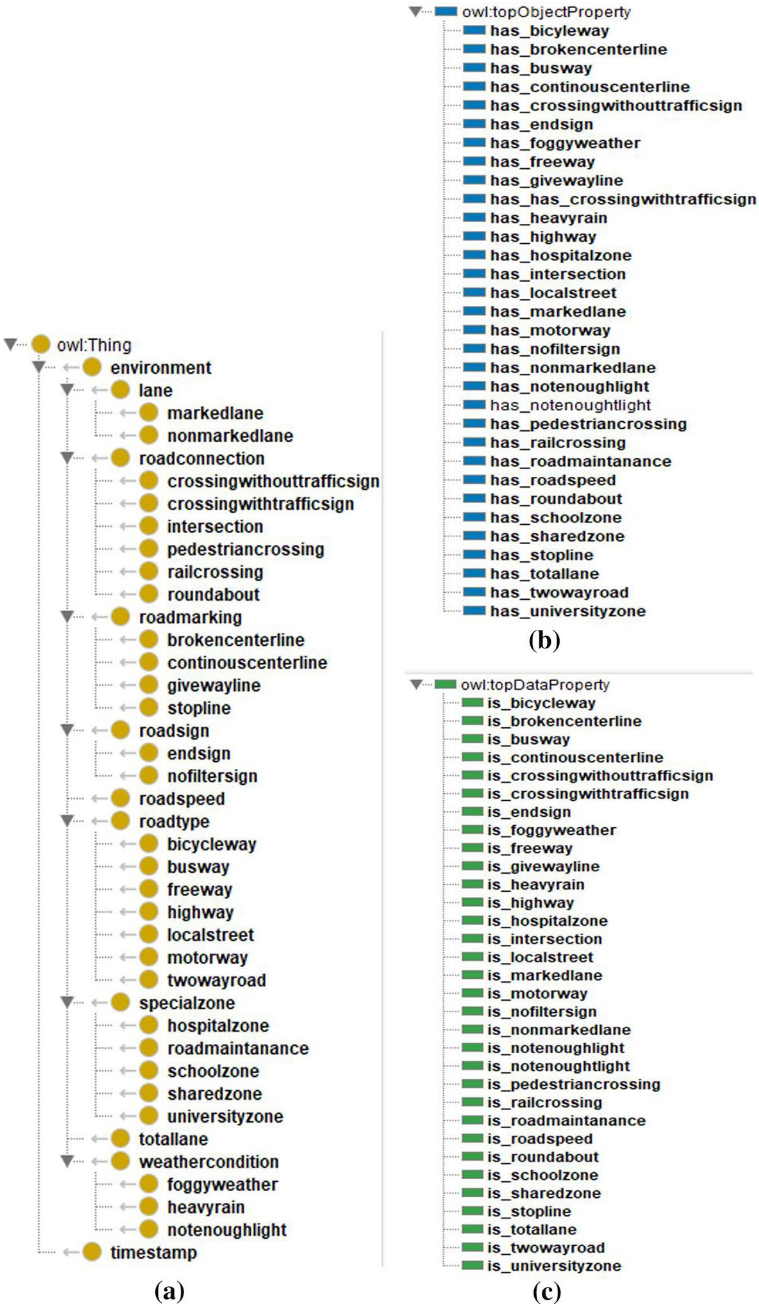


Fig. 7 **a** Class hierarchy of the environment ontology **b** Object properties of the environment ontology **c** Data properties of the environment ontology

Table 4 Metrics of ontologies

AV behavior ontology		AV environment ontology	
Class	22	Class	41
Object property	15	Object property	32
Data property	17	Data property	32
Individual count	18	Individual count	33

based on the road map information from the QLD transport and main roads website.[4] AV surrounding information about road and traffic was considered to design this ontology. Figure 7(a) presents the classes and properties of this ontology. "environment", and "timestamp" is the main two classes of this ontology. The "environment" class consists of nine subclasses, such as "lane", "roadconnection", "roadmarking", etc. There are also several subclasses of each of these subclasses. Figure 7(b) shows the detail of this ontology's object properties. For example, to know about the special areas where traffic rules are controlled in a particular way, several object properties were considered, such as "has_schoolzone", "hase_sharedzone", etc. Figure 7(c) shows this ontology's data properties. For example, when a vehicle is approaching to change the lane, it must follow the road speed and other safety issues according to the traffic rules. By using the data property "is_roadspeed", the speed limit of the road can be known.

3.2.2 Reasoner

The reasoner methodology is shown in Fig. 2 (b.2). The aim of this reasoner is to map and reason between formalized traffic rules and AV information (ontology knowledge base). Based on the compliance checking requirements, the Traffic Rule Formalization module (Sect. 3.1) sends the required formalized rules and atoms to this reasoner. Then, the reasoner uses the AV knowledge base (Ontology—Sect. 3.2.1) to verify whether the atoms were true/false. The output of this reasoning provides the compliance checking result of the AV behaviour against traffic rules. This reasoner works in two steps: true atom identification and DDL reasoning.

3.2.2.1 True atom identification This step determines what atoms (facts) are true for AV behaviour through the query result analysis. A query engine is used to fetch the information from the ontology knowledge base for every atom. The query engine has preset SPARQL queries for every atom. SPARQL is an effective and efficient query technique to access an ontology knowledge base.[5] It is recognized as the facto standard for a linked (ontology) knowledge base (Koutsomitropoulos et al. 2011). Here, we use SPARQL queries to retrieve AV information from ontologies. The number of queries varies depending on the queried atom. We designed and developed an algo-

[4] https://www.tmr.qld.gov.au/Travel-and-transport/Maps-and-guides

[5] http://www.w3.org/TR/rdf-sparql-query/

rithm to execute the queries optimally. Most of the queries, such as speed, acceleration, curvilinear coordinates, etc., are computed to determine an atom's characteristics (i.e., safe distance, approaching vehicle, etc.). An atom is evaluated as true when the corresponding queries (with possible pipelines of subqueries) return a positive outcome. Notice that the atom identification is the mechanism we use to address the issue of open texture terms. More specifically, the (computational) interpretation of an atom is given by the associated queries. Some of the atoms have a simple immediate query associate to it.

For example, the atom "vehicle_IsStationary" has the simple query checking if vehicle_speed is 0, then the atom is considered true.

The current traffic rule contains several "open texture" terms. As a result, some atoms contain these "open texture" terms. For example, in rule 141 (see "Appendix") *atom:* "*vehicle_CanBeSafelyOvertakenIn_markedLane*" has "open texture" term "safely". To deal with such a term, we had to solve (determine) two important characteristics of rules: safe distance and safe lane change. For safe distance and safe lane change, we used the methodology described in (Pek et al. 2017; Rizaldi et al. 2017). Eight queries were determined from an empirical study to determine safe distance and safe lane change (see Table 5). Only the linguistic format of these queries is shown for the atom to aid readability. Solving the safe distance and safe lane change eventually solves the "open texture" issue: "safely". Because by solving the safe distance and safe lane change issue, we eventually determined whether the *Atom:* "*vehicle_CanBeSafelyOvertakenIn_markedLane*" was true/false for the specific AV situation.

Also, some queries required some logical reasoning to determine whether the atom was true/false. For example, three queries were triggered to verify the *atom "markedLane_IsToTheLeftOf_vehicle"* (see Table 6). The answer to these queries indicates whether there is a marked lane left of the AV. Thus these queries answers verified whether the atom was true /false. If the answer reflects that the road is a marked lane, the overtaken vehicle's lane number > 1, and the road is multilane; then it can be stated that "*markedLane_IsToTheLeftOf_vehicle*" atom is true for the AV. Similarly, for all the atoms of QLD overtaking traffic rules (see Table 1), SPARQL queries were triggered and verified the corresponding atoms.

In this research, we conducted an experiment with 40 cases (more details in Sect. 4). The reasoning metrics (atoms, rules, and queries) of these cases are shown in Fig. 8. Each case was categorized into one of four overtaking types based on traffic rules to show the reasoning property metrics. In Fig. 8, for every overtaking type, the compliance system (ATRCCF) checked, on average, 31 rules and 350 queries of 37 atoms. Among these four types, the compliance checking of the 'long vehicle left overtaking' takes the longest time to compute as it requires around 494 queries of 50 atoms and reasoning with 48 rules.

3.2.2.2 DDL Reasoning The DDL reasoning mechanism works in two steps. In the first step, formalized traffic rules are selected for compliance checking based on the overtaking type. After that, formalized traffic rules and true atoms (received from the true atom identification step) are sent to TurnipBox to compute the legal conclusions in force and then compared against the corresponding state. TurnipBox is a tool

Table 5 Queries for the atom (Example-1)

Atom: *vehicle_CanBeSafelyOvertakenIn_markedLane*
Queries:
Query 1: Which vehicle is driving in time_1? (AV_Environment) *Query 2: How many lanes in the road? (AV_Environment)* *Query 3: What is AV (automated vehicle) Lane Number? (AV_Behaviour)* *Query 4: What is TV (target vehicle) lane number? (AV_Behaviour)* *Query 5: What is AV speed? (AV_Behaviour)* *Query 6: What is road allowed speed at time_1? (AV_Environment)* *Query 7: Is AV is in safe-distance? (AV_Behaviour)* *Query_7_Subquery_1: What is the AV curvilinear coordinates in time_1? (AV_Behaviour)* *Query_7_Subquery_2: What is TV curvilinear coordinates in time_1? (AV_Behaviour)* *Query_7_Subquery_3: What is the velocity of AV in time_1? (AV_Behaviour)* *Query_7_Subquery_3_Nested_Subquery_1: What is the speed of the AV in time_1? (AV_Behaviour)* *Query_7_Subquery_3_Nested_Subquery_2: What is the direction of AV in time_1? (AV_Behaviour)* *Query_7_Subquery_4: What is the velocity of AV in time_1? (AV_Behaviour)* *Query_7_Subquery_4_Nested_Subquery_1: What is the speed of the TV in time_1? (AV_Behaviour)* *Query_7_Subquery_4_Nested_Subquery_2: What is the direction of TV in time_1? (AV_Behaviour)* *Query_7_Subquery_5: What is the reaction time of AV and TV in time_1?* *Query 8: Can AV safely change lane? (AV_Behaviour) (AV_Environment)* *Query_8_Subquery_1: Is the road is marked lane? (AV_Environment)*

Table 6 Queries for the atom (Example-2)

Atom: *markedLane_IsToTheLeftOf_vehicle*		
Queries:		
Query 1: Is road is markedLane? (AV_Environment) prefix as:<http://www.semanticweb.org/bhu011/ontologies/2019/8/untitled-ontology-13#> SELECT ?markedlane_road WHERE { as:road as:markedlane_road ?markedlane_road.}	***Query 2****: What is vehicle Lane Number? (AV_Behaviour)* *prefix* *ab:<http://www.semanticweb.org/bhuiyanh/ontologies/2019/8/untitled-ontology-50#>* *SELECT ?lane_number* *WHERE {* *ab:vehicle ab:lane_number ?lane_number.}*	***Query 3****: How many lanes in the road? (AV_Environment)* *prefix* *as:<http://www.semanticweb.org/bhu011/ontologies/2019/8/untitled-ontology-13#>* *SELECT ?total_lane* *WHERE {* *as:road as:total_lane ?total_lane.* *}*

offering a run-time implementation of DDL.[6] Two simple examples of left overtaking showing the computation performed by TurnipBox are presented in Fig. 9. This type of left overtaking requires evaluating at least four traffic rules (145, 144, 141, 140) (more details about rules in Table 1 and formalization of rules in "Appendix"). However, for simplicity of representation, only the formalization of rule 141 formalization is given in this example. For left overtaking at a particular timestamp, Fig. 9c, shows the true atom at a particular timestamp over a left overtaking maneuver. Figure 9c reports that the AV is permitted ([P]) to overtake, and thus the manveuver is legal and the AV complies with the overtaking rules. On the contrary, if the true atoms are as in Fig. 9d, then overtaking is forbidden ([F]), thus the overtaking maneauver is illegal and the AV does not comply with the traffic rules.

[6] https://turnipbox.netlify.com/

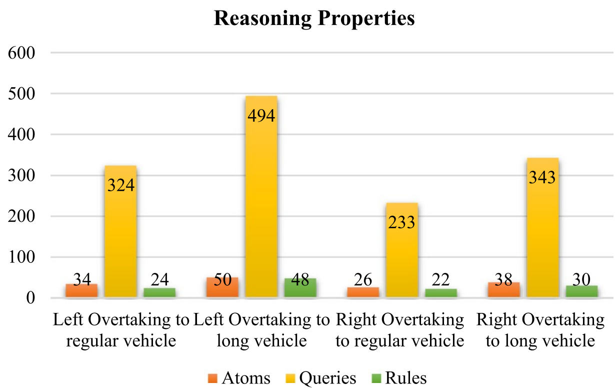


Fig. 8 Reasoning properties for QLD overtaking traffic rules

4 Experiment and evaluation

An experiment was conducted to evaluate the proposed Automatic Traffic Rule Compliance Checking Framework (ATRCCF). Forty cases of overtaking maneuvers were evaluated based on eight realistic QLD traffic scenarios. Every case is a specific overtaking maneuver. First, these overtaking maneuvers (40) were assessed by the proposed ATRCCF. Then participants (general drivers and domain experts) were asked to look at the maneuvers and to assess whether the behaviour was legal or illegal. After that, the ATRCCF performance (effectiveness) was determined based on how many participants agreed with the framework's evaluation. Two types of assessment had been conducted: legal/illegal assessment of every maneuver and reason assessment if the maneuver is illegal.

4.1 Experiment design

The CARRS-Q Advanced Driving Simulator [7] was used to design experiment scenarios. This simulator used SCANeR™ studio 1.9 software. Before making these scenarios, an empirical study was made of overtaking cases (maneuvers) that generally occur in Queensland. Based on this survey, eight types of scenarios were included in this evaluation. A portrait of each experiment scenario is shown in Fig. 10.

- Figure 10(1) shows an Automated Vehicle (AV) and three Target Vehicles (TV) driving in a marked multi-lane road. The AV is approaching to overtake TV-1
- One AV and two TVs are heading to an intersection [Fig. 10(2)]. The AV is approaching to overtake TV-2 (long-vehicle), and the TV-2 displays the "do not overtake turning vehicle" sign.

[7] https://research.qut.edu.au/carrsq/engage/research-infrastructure/

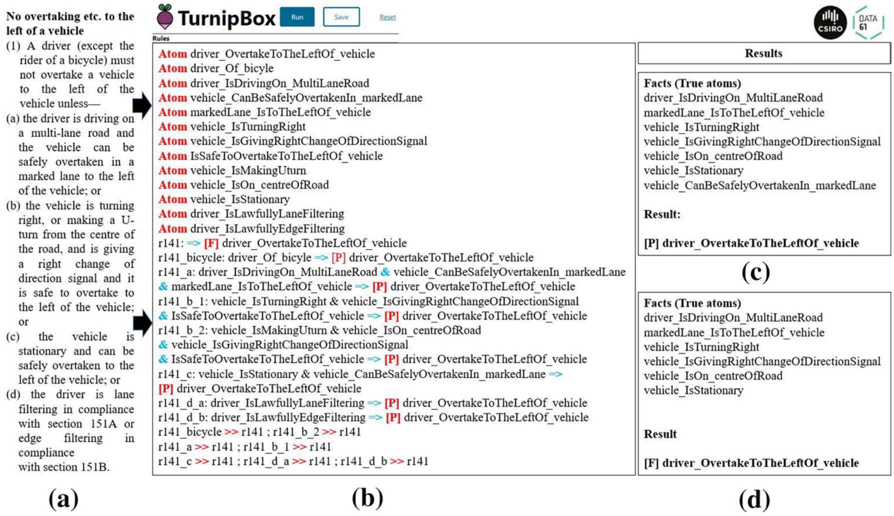


Fig. 9 **a** QLD traffic rule 141 **b** Formalization of the traffic rule 141 **c** Example of compliance checking where AV behaviour complies with traffic rules **d** Example of compliance checking where AV behaviour does not comply with traffic rules

- Five vehicles, including one AV, two TVs, and two bicycles, are driving in a marked multi-lane road [Fig. 10(3)]. The AV is approaching to overtake TV-1.
- An AV and two TVs are approaching an intersection in Fig. 10(4), where the road has both broken and continuous center lines. The AV intends to overtake TV-1.
- An AV and two TVs are heading to a T-intersection [Fig. 10(5)]. AV is approaching to overtake TV-1.
- An AV is about to overtake TV-2 after merging on a multi-lane road. However, TV-1 is approaching the AV's merge lane [Fig. 10(6)].
- In Fig. 10(7), an AV is about to overtake a stationary vehicle (TV-1). Another vehicle (TV-2) is approaching in a different lane towards the AV.
- In an unmarked two-way road, an AV and three TVs are driving [Fig. 10(8)], and AV is about to overtake TV-1.

The experiment was conducted with these eight scenario types. Both Left Overtaking (LO) and Right Overtaking (RO) cases were considered. Five different overtaking maneuvers were conducted for each scenario. Two of these maneuvers are examples of explicit legal and illegal driving action. The other three maneuvers are borderline maneuvers, where the classification of the maneuver as legal or illegal might depend on the perception of the observer. One of the main reasons to make these three different types of maneuvers is that traffic rules contain open texture terms (e.g., safe distance) requiring judgment by the drivers. Clearly, AVs need a deterministic and algorithmic approach. The determination if atoms corresponded

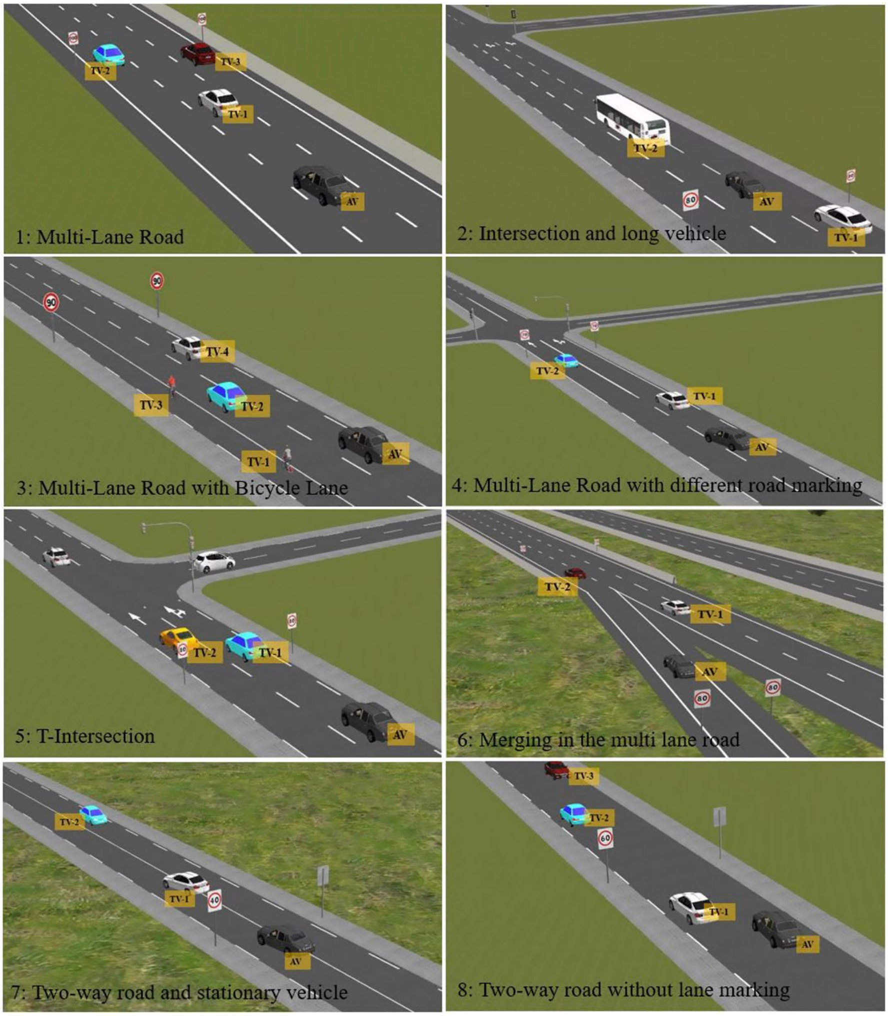


Fig. 10 Experiment scenarios

to open texture terms was delegated to the ontology and query method, where the queries implemented state-of-the-art techniques from traffic research. For example, we used the approach proposed by (Pek et al. 2017; Rizaldi et al. 2017) to compute whether the distance between two vehicles was safe or not. For the borderline cases, the parameters were set very close to the computed threshold, while for the clear cases, the value were far apart. For example, if the value for safe distance was computed as 25 m, values of 24 or 26 m were borderline, while 5 or 50 m were considered for clear cases.

AV Behaviour	Timestamp	AV speed	AV acceleration	--	AV Pos x	AV Pos y	--	TV-1 speed	--	TV-1 donotovertakesign	TV-1 goingright	--	TV-2 Pos y	--	TV-2 Lane number
	0	null	null	--	null	null	--	null	--	null	null	--	null	--	null
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	0.15	1.38	3.69	--	243.32	141.36	--	5.00	--	1	0	--	183.41	--	3
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	3.05	35.04	4.66	--	252.02	146.62	--	13.18	--	1	0	--	190.27	--	3
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	11.35	77.77	0.36	--	393.30	232.58	--	22.82	--	1	1	--	194.43	--	3

AV Environment	Timestamp	Road speed	--	Intersection	Roundabout	--	Broken centreline	--	Give way line	School zone	--	Total lane	Marked lane	--	Freeway	Foggy weather
	0	null	--	null	null	--	null	--	null	null	--	null	null	--	null	null
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	3	80	--	0	0	--	1	--	0	0	--	3	1	--	0	0
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	9.15	80	--	1	0	--	1	--	0	0	--	3	1	--	0	0
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	11.35	80	--	0	0	--	1	--	0	0	--	3	1	--	0	0

Fig. 11 Experiment data (AV information)

4.2 Experiment data

Figure 11 shows an 11.35 s snippet of experiment data (AV information). The CARRS-Q Advanced Driving Simulator was used to create this data. This simulator can provide the data under controlled and repeatable conditions, allowing for more useful and meaningful analysis. For every 0.05 s, AV behaviour (speed, acceleration, position, lane number, going right, going left, heading, etc.) and the AV environment (road speed, intersection, marked lane, continuous line, broken centerline, weather, other vehicle behaviours, etc.) information were provided by the simulator.

The information attributes (speed, position, marked lane, weather, etc.) were predefined in the simulator. These were scripted in the simulator based on the behaviour and environment ontologies. Some attributes, such as going right, going left, marked lane, continuous line, broken centerline, etc., were Boolean (1—true, 0—false). For vehicles, it was user-defined which vehicle was the AV and which were TVs. For numbered TVs, the distance from the AV was considered. The closest vehicle was designated 1, and the others were sequentially numbered based on the distance to the AV.

4.3 ATRCCF assessment

The ATRCCF assessed AV behaviour compliance for each maneuver, whether it was legal or illegal according to the traffic rules. If the assessment was illegal, then ATRCCF recorded the illegal actions of the AV. The result of these 40 cases is shown in Table 7. Every maneuver was considered as several driving actions. Each driving action was recorded as 0.05 s (timestamp) of data. AV behaviour compliance with traffic rules was validated for each maneuver for every timestamp. After validating all experiment timestamps, the legal result was determined. For a maneuver (experiment), the whole maneuver was considered legal if the driving action was permitted in all timestamps. However, among all timestamps, if any driving action was prohibited (unlawful action) for any timestamp, then the maneuver was considered an illegal maneuver.

For example, the compliance trajectory of Scenario-1, Maneuver-3 is shown in Fig. 12. In this maneuver, the AV is approaching to overtake TV-1. For every timestamp (0.05 s), the compliance result is shown for the AV. The red rectangle indicates that the AV behaviour does not comply with traffic rules, and the green circle indicates that AV behaviour complies with traffic rules. Figure 12 shows that from the beginning to 90 timestamps (4.5 s), the AV behaviour is legal (driving action permitted [P]) according to QLD overtaking traffic rules. However, between timestamp 92–110 (4.6–5.5 s), the AV behaviour is illegal (driving action prohibited [P]) while overtaking the target vehicle (TV-1). Thus, the whole maneuver is considered an illegal overtaking maneuver.

4.4 Manual assessment

The QUT Human Research Ethics Committee approved ethical clearance (Approval No.: 2021000109) for human participation in this research.

4.4.1 Participants

32 participants of all ages having a valid Australian driving licence evaluated the above-mentioned 40 overtaking maneuvers. Among these 32 participants, there were 8 driver trainers and 24 general drivers. Participants were considered irrespective of gender. Driver trainers participated as domain experts in this experiment as they should have a greater understanding of legal vehicle passing maneuvers in Queensland. Domain experts were recruited through their respective driving schools, and in-person and general drivers were recruited in person by the research team. Every domain expert evaluated 20 maneuvers in two stages. In the first stage, they evaluated 10 maneuvers, followed by a 10 min break and then another 10 maneuver assessments were completed in stage 2. Every general participant evaluated 10 maneuver videos. Maneuvers were allocated to the participant based on randomly chosen scenarios. To recognize their participation in this research, participants were compensated for their involvement ($25 for general participants and $150 for domain experts).

4.4.2 Procedure

General drivers and domain experts conducted the manual assessment. They assessed the legality of driving maneuvers from simulation video footage. Figure 13 shows an example of Scenario-3, Maneuver-3 video footage. For better understanding and evaluation, we integrated and combined three video views (driver, normal and bird's eye) in the footage. This enabled the participant to assess AV behaviour in all possible ways. Each maneuver was evaluated by 10 participants (6 general participants and 4 domain experts). Participants watched every video twice and evaluated whether the maneuver was legal or illegal according to their knowledge of QLD traffic rules and safe driving. If their assessment of any maneuver was illegal, then they provided reasons. The assessment result was recorded on paper. After completing all assessments, the researcher did the necessary post-processing and analysis and recorded the result. Based on this assessment, the performance of the ATRCCF was measured.

Table 7 ATRCCF compliance result

Experiment scenarios	Maneuver type	Proposed framework (ATRCCF)		Experiment scenarios	Maneuver Type	Proposed framework (ATRCCF)	
		Result	Reason if illegal			Result	Reason if illegal
Scenario – 1: Multi-Lane Road Situations Covered: Vehicles position dimensions, Multiple vehicles (4), Multiple lanes (3), Broken center line	Maneu -1	√	N/A	Scenario – 5: T-Intersection Situations Covered: Vehicles position dimensions, Multiple vehicles (5), Multiple lanes (2), Broken center line, T-Intersection	Maneu -1	√	N/A
	Maneu -2	X	1. Safe distance from other vehicles 2. Not clear view of the target vehicle		Maneu -2	X	1. Safe distance from the target vehicle 2. Safe distance from other vehicles 3. Not clear view of the target vehicle
	Maneu -3	X	1. Safe distance from other vehicles		Maneu -3	X	1. Target vehicle intended to go right 2. Not clear view of the target vehicle
	Maneu -4	X	1.1. Safe distance from other vehicles		Maneu -4	X	1. Safe distance from other vehicles
	Maneu -5	√	N/A		Maneu -5	√	N/A
Scenario – 2: Intersection and long vehicle Situations Covered: Vehicles position dimensions, Multiple vehicle (3), Multiple lanes (3), Broken center line, Long vehicle display do not overtake sign, intersection	Maneu -1	√	N/A	Scenario – 6: Merging in the multi-lane road: Vehicles position dimensions, Multiple vehicles (5), Multiple lanes (3), Solid Line, Broken center line, Merging in another route	Maneu -1	√	N/A

Table 7 (continued)

Experiment scenarios	Maneuver type	Proposed framework (ATRCCF)		Experiment scenarios	Maneuver Type	Proposed framework (ATRCCF)	
		Result	Reason if illegal			Result	Reason if illegal
	Maneu -2	X	1. Target vehicle intended to turn right 2. Target vehicle had do not overtake sign 3. Safe distance from the target vehicle 4. Not clear view of approaching traffic		Maneu -2	X	1. Safe distance from the target vehicle 2. Safe distance from other vehicles 3. Not clear view of approaching traffic
	Maneu -3	√	N/A		Maneu -3	X	1. Safe distance from the target vehicle 2. Not clear view of the target vehicle 3. Safe distance from other vehicles 4. Not clear view of approaching traffic
	Maneu -4	X	1. Target vehicle had do not overtake sign 2. Target vehicle intended to go right 3. Not clear view of approaching traffic		Maneu -4	√	N/A
	Maneu -5	X	1. Target vehicle had do not overtake sign 2. Target vehicle intended to go right 3. Safe distance from the target vehicle 4. Safe distance from other vehicles		Maneu -5	X	1. Safe distance from the target vehicle 2. Not clear view of approaching traffic

Table 7 (continued)

Experiment scenarios	Maneuver type	Proposed framework (ATRCCF)		Experiment scenarios	Maneuver Type	Proposed framework (ATRCCF)	
		Result	Reason if illegal			Result	Reason if illegal
Scenario – 3: Multi-Lane Road with Bicycle Lane Situations Covered: Vehicles position dimensions, Multiple vehicles (5), Multiple lanes (4), Broken center line, Solid line, Bicycle Lane, Bicyclists (2)	Maneu -1	√	N/A	Scenario – 7: Situations Covered: Two-way Road and stationary vehicle. Vehicles position dimensions, Multiple vehicles (3), Stationary vehicle, Two-way lane, Solid line	Maneu -1	√	N/A
	Maneu -2	X	1. Safe distance from other vehicles 2. Not clear view of the target vehicle		Maneu-2	X	1. Safe distance from the target vehicle 2. Not clear view of approaching traffic
	Maneu -3	X	1. Not clear view of the target vehicle		Maneu -3	X	1. Safe distance from the target vehicle
	Maneu -4	X	1. Safe distance from other vehicles 2. Not clear view of the target vehicle		Maneu -4	X	1. Safe distance from the target vehicle 2. Safe distance from other vehicles
	Maneu -5	X	1. Not clear view of the target vehicle		Maneu -5	X	1. Safe distance from the target vehicle 2. Not clear view of approaching traffic

Table 7 (continued)

Experiment scenarios	Maneuver type	Proposed framework (ATRCCF)		Experiment scenarios	Maneuver Type	Proposed framework (ATRCCF)	
		Result	Reason if illegal			Result	Reason if illegal
Scenario – 4: Multi-Lane Road with different road marking, Situations Covered: Vehicles position dimensions, Multiple vehicles (3), Multiple lanes (3), Broken center line, Continuous line, intersection	Maneu -1	√	N/A	Scenario – 8: Situations Covered: Two-way Road without lane marking. Vehicles position dimensions, Multiple vehicles (4), Multiple lanes (2), Unmarked lane, Two-way lane	Maneu -1	√	N/A
	Maneu -2	X	1. Crossed solid line 2. Safe distance from other vehicles		Maneu -2	X	1. Safe distance from the target vehicle
	Maneu -3	X	3. Safe distance from other vehicles 4. Crossed solid line		Maneu -3	X	2. Safe distance from the target vehicle 3. Not clear view of the target vehicle
	Maneu -4	√	N/A		Maneu -4	√	N/A
	Maneu -5	X	1. Safe distance from the target vehicle 2. Safe distance from other vehicles		Maneu -5	X	1. Safe distance from the target vehicle 2. Not clear view of the target vehicle

* √ = Legal and X = Illegal

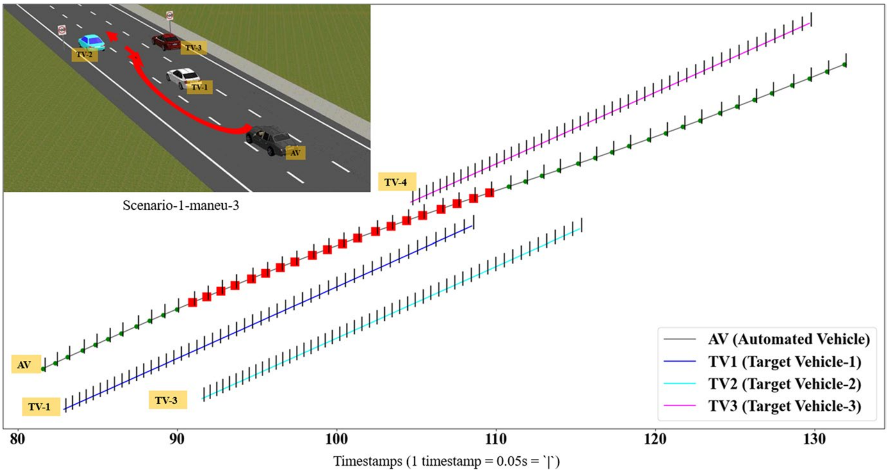


Fig. 12 An example of AV overtaking compliance checking trajectory (scenario-1, maneu-3). The green circle indicates legal action (Permission [P]) of AV in a specific timestamp. The red rectangle indicates illegal action (Prohibition [F]) of AV in a specific timestamp

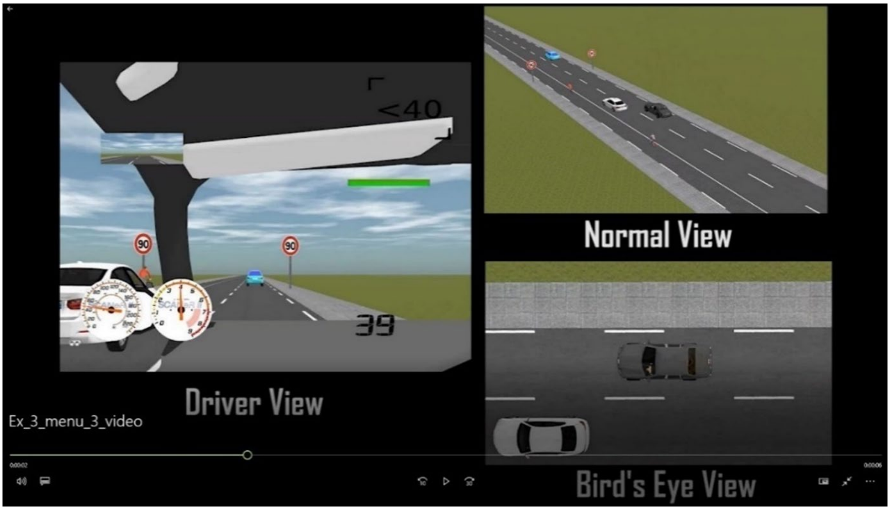


Fig. 13 An example of the video footage used for evaluation (Scenario-3, maneuver-3)

4.5 Result analysis

In this section, the performance of the proposed ATRCCF was evalauted based on how many participants agreed with the framework evaluation. The ATRCCF assessment result is shown in Table 7, and the participant's agreement rate is shown in Tables 8 and 9.

Table 8 For legal/illegal assessment, participant's agreement rate with ATRCCF evaluation

Experiment scenarios	Cases	General participants (%)	Domain experts (%)	Experiment scenarios	Cases	General participants (%)	Domain experts (%)
Scenario -1	Clear	91.67	70.00	Scenario -5	Clear	75.00	62.50
	Borderline	50.00	75.00		Borderline	83.33	58.33
Scenario -2	Clear	91.67	87.50	Scenario -6	Clear	83.33	100.00
	Borderline	44.44	66.67		Borderline	44.44	66.67
Scenario -3	Clear	83.33	88.00	Scenario -7	Clear Cases	100.00	62.50
	Borderline	66.67	41.67		Borderline	27.78	33.33
Scenario -4	Clear	83.00	100.00	Scenario -8	Clear	91.67	87.50
	Borderline	72.22	91.67		Borderline	61.11	66.67

4.5.1 Legal/illegal assessment

Table 8 shows the participant's agreement rate with the ATRCCF evaluation of legal/illegal action of the AV. Equation (1) determined the participant's agreement rate regarding ATRCCF evaluation.

$$Participant^{'}s\,agreement\,rate = \frac{Number\,of\,participant\,assessments(Legal/Illegal)\,similar\,as\,ATRCCF}{Total\,number\,of\,assessments} \quad (1)$$

a. **Clear Cases**: For scenarios 2, 3, and 8, the agreement rate of domain experts and general participants with the ATRCCF evaluation is around 88%. For scenarios 4 and 6, the agreement rate of domain experts regarding ATRCCF assessment is 100%, where the general participant's agreement rate is approximately 83%. However, in scenarios 1 and 7, the opposite trend is seen, where the average agreement rate of general participants and domain experts is 95.8% and 66.25% concerning framework evaluation. For scenario 5, both participants agreement rate is comparatively poor than other scenarios.
b. **Borderline cases**: Compared to clear cases, participants agreement rate with ATRCCF evaluation for borderline cases is lower. For scenario 4, the general participants and domain experts agreement rate regarding ATRCCF assessment is 72.22% and 91.67%. On the contrary, for scenario 7, the agreement rate of both participants is very poor, which are 27.78% and 33.33%. For scenarios 1, 2 & 6, the agreement rate of domain experts with the system evaluation is higher than general participants. The opposite bias is seen for scenarios 3 and 5, where the

Table 9 For reason assessment, participant's agreement rate with ATRCCF evaluation

Experiment scenarios	Cases	General participants (%)	Domain experts (%)	Experiment scenarios	Cases	General participants (%)	Domain experts
Scenario -1	Clear	100.00	100.00	Scenario -5	Clear	80.00	100.00
	Borderline	50.00	60.00		Borderline	80.00	100.00
Scenario -2	Clear	90.00	100.00	Scenario -6	Clear	100.00	100.00
	Borderline	33.33	75.00		Borderline	100.00	50.00
Scenario -3	Clear	100.00	100.00	Scenario -7	Clear	100.00	66.67
	Borderline	66.67	60.00		Borderline	33.33	50.00
Scenario -4	Clear	100.00	100.00	Scenario -8	Clear	20.00	25.00
	Borderline	85.70	37.50		Borderline	16.67	50.00

agreement rate is well regarding general participants. For scenario 8, the agreement rate is almost similar regarding both participants assessments.

4.5.2 Reason assessment (when the maneuver is illegal)

The participant agreement rate with ATRCCF reason assessment was determined based on Eqs. (2) and (3). For a specific maneuver, if S = {a, b, c, d, e, f} is a set of ATRCCF identified reasons and P = {u, v, x, y, z} is a set of participants given reasons, then if there is any common element between the two sets, then we considered that the participant's assessment is similar to the framework's assessment.

$$\text{Reason similarity} = \text{S} \cap \text{P} \neq \{\emptyset\} \tag{2}$$

$$\text{Participant's agreement rate} = \frac{\text{Number of reason similarity}}{\text{Total number of assessments those given reasons for illegal actions}} \tag{3}$$

a. **Clear cases**: For all scenarios, the average agreement rate of general participants and domain experts is almost equal to the ATRCCF assessment, which is around 86%. In scenarios 1, 3, 4 and 6, both participants agreement rate is 100% with the ATRCCF evaluation. For scenarios 2 and 5, general participants agreement rates are 90% and 80% with the ATRCCF evaluation, while the domain expert agreement rate is on average 100%. However, in scenario 8, both participant's agreement rate with the framework assessment is very low, which is on average 22%.

b. **Borderline cases**: In borderline cases, the participant's agreement rate is lower than in clear cases. The average agreement rate of both participants is around 59% regarding system evaluation. In scenario 6, the general participant's agreement rate with the ATRCCF evaluation is double of domain experts. A similar trend is shown in scenario 4. In scenario 3, the agreement rate of domain experts with ATRCCF assessment is slightly lower compared to general participants. In scenarios 2, and 8, the domain experts agreement rate with ATRCCF evaluation is more than double of general participants. Also, in scenarios 1, 5, and 7, domain experts agreement rate with ATRCCF assessment is relatively higher than general participants.

5 Discussion

Figure 14 shows the performance of the proposed Automatic Traffic Rule Compliance Checking Framework (ATRCCF). This performance is measured based on how many participants agreed with the ATRCCF assessment. In clear cases, on average, there is 84% legal/illegal agreement and 86% reason assessment between participants and the ATRCCF assessment. In borderline cases, participant average agreement rates with the framework's legal/illegal assessment and reason assessment are almost identical at 59%. In this context, the agreement rates show that the proposed ATRCCF is a promising approach for checking AV interpretation and compliance with traffic rules. It shows that the proposed interpretations of the open texture expressions are aligned with the participant's perception. Moreover, the experiment methodology suggests that the proposed framework can be beneficial for evaluating other possible interpretations of open texture terms. For example, in our work the way we compute safe distance was based on (Rizaldi et al. 2016), but the methodology could be used to evaluate other approaches in the road safety literature to compute the same parameter. All one has to do is to replace the queries for computing "safe distance" with a new set of queries implementing the alternative computation.

However, Fig. 14 shows that for clear cases, on average, around 15% of participants disagree with the framework's legal/illegal and reason assessment. For borderline cases, the difference ratio average is around 41% between the framework and participants. Table 10 shows the differences in evaluations between ATRCCF and participants. For legal/illegal assessment, 40 overtaking maneuvers were evaluated 400 times (240 times by 24 general participants and 160 times by 8 domain experts) by 32 participants (details in Sect. 4.4). Table 10 shows that for legal/illegal assessment, in 40 maneuvers, there are 122 dissimilarities between participants and ATRCCF assessments. Most of these dissimilarities (77.87%) occur in borderline cases. In addition, most differences appear when the ATRCCF assesses the maneuver as illegal. A similar trend is seen in the case of reason assessment between ATRCCF and participants. For the reason assessment, 25 illegal maneuvers were evaluated 156 times (88 times by 24 general participants and 68 times by 8 domain

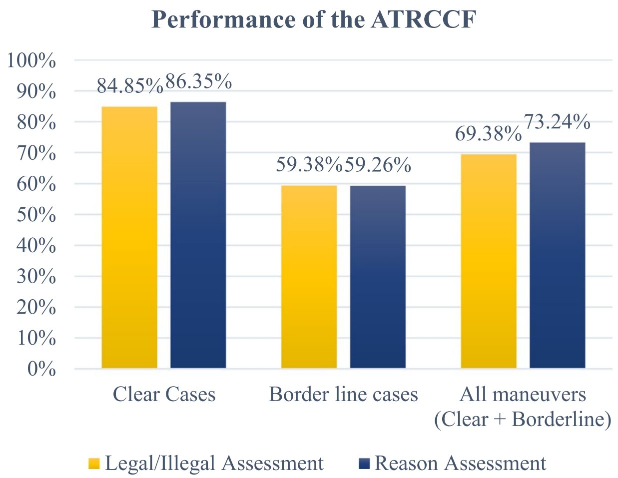


Fig. 14 Overall performance of the ATRCCF assessment

Table 10 Differences in assessments between ATRCCF and Participants

Metrics		Cases	Number of maneuvers	Number of participants assessments, unlike with ATRCCF assessments		Total dissimilarities
				General participants assessment	Domain expert's assessment	
Legal\illegal assessment	ATRCCF assessment is legal	Clear	8	4	7	11
		Borderline	7	9	9	18
	ATRCCF assessment is illegal	Clear	8	8	8	16
		Borderline	17	50	27	77
	Total	All cases	40	71	51	122
Reason assessment	ATRCCF reason assessment (maneuver is illegal)	Clear	8	6	4	10
		Borderline	17	18	17	35
	Total	All cases	25	24	21	45

experts) by 32 participants. Most of the differences (77.78%) arise in borderline cases.

After analyzing participant assessments, it is seen that some participants overlook critical issues in some cases and assess those maneuvers as legal, although they are illegal. Likewise, some participants exaggerate assessments by overthinking and assessing legal maneuvers as illegal. Moreover, sometimes participants seem to have a knowledge gap about traffic rules. For example, some participants, including domain experts, mentioned that a specific maneuver is illegal because there is overtaking from the left side even though left overtaking is legal in Queensland. The empirical observation shows that such differences occur due to several characteristics of participants, such as misunderstanding of traffic rules, misunderstanding of legal/illegal vehicle actions, etc.

Such differences in participants evaluation may not happen if it was possible to recruit appropriate participants after examining their knowledge of traffic rules and safe driving. However, recruiting participants is a challenging task. It is difficult to find expected participants through interviews (examining). Moreover, assessment from video footage is a challenging task. Sometimes it might be hard to observe everything perfectly from video footage. It becomes harder for someone while watch three views at the same time. The way and limitation of watching every video twice may also impact the participant assessment.

6 Conclusion and future work

This paper aims to develop a unified framework to check Automated Vehicle compliance with current QLD traffic rules. Also, through this assessment, it can be determined which current traffic rules need additional interpretation for AV to follow them correctly. To achieve this, first, we studied the problem of the current traffic rules mentioned in the literature review. Then we developed the system, "Automatic Traffic Rule Compliance Checking Framework (ATRCCF)." This system works in two steps. First, it formalizes traffic rules using Defeasible Deontic Logic (DDL) so that AVs can process this formal specification (machine-computable) of traffic rules. The main advantage of using DDL is resolving open texture terms, exceptions and potential conflicts in rules. We then build AV information ontologies (machine-computable format of AV information). The formalised rules use the ontology terms and conditions to provide input for reasoning about AV legal requirements in the situation identified by the data available to the AV. A reasoning engine is developed using the Turnip reasoner to map and reason between machine-computable AV information (ontology knowledge base) and formalized traffic rules.

We conducted a comprehensive experiment to evaluate this framework. We evaluated this framework using 40 test cases based on eight realistic Queensland traffic scenarios. The framework assessment is then evaluated by general participants and driver trainers (domain experts). Based on their evaluation (agreement rate with ATRCCF evaluation), the performance of the proposed ATRCCF is determined. Based on the overall performance, it can be stated that the proposed ATRCCF is a promising framework for checking Automated Vehicle interpretation and compliance with current Queensland traffic rules.

The outcome of this research shows great potential for supporting the legal operation of AVs according to traffic rules. As a next step, we plan to do a real-life experiment in level 4 Automated Vehicle. Furthermore, we will enhance the scope and scale of this proposed formalization mechanism by covering other traffic environments such as giving way, roundabouts, intersection crossing, U-turns, etc.

Appendix: Formalization of QLD overtaking traffic rule

See Tables 11, 12, 13, 14, 15, 16, 17, 18.

Table 11 Formalization of QLD Traffic Rule 140

Rule 140: No overtaking unless safe to do so
A driver must not overtake a vehicle unless—
(a) the driver has a clear view of any approaching traffic; and
(b) the driver can safely overtake the vehicle.

Formalization

Atom Initialisations:
Atom driver_HasClearViewOf_approachingTraffic
Atom driver_CanSafelyOvertake_vehicle
Atom driver_Overtake_vehicle

Rules:

r140: => **[F]** driver_Overtake_vehicle
r140exc: driver_HasClearViewOf_approachingTraffic & driver_CanSafelyOvertake_vehicle
=> **[P]** driver_Overtake_vehicle

r140exc >> r140

Table 12 Formalization of QLD Traffic Rule 141

Rule 141: No overtaking etc. to the left of a vehicle

(1) A driver (except the rider of a bicycle) must not overtake a vehicle to the left of the vehicle unless—

(a) the driver is driving on a multi-lane road and the vehicle can be safely overtaken in a marked lane to the left of the vehicle; or

(b) the vehicle is turning right, or making a U-turn from the centre of the road, and is giving a right change of direction signal and it is safe to overtake to the left of the vehicle; or

(c) the vehicle is stationary and can be safely overtaken to the left of the vehicle; or

(d) the driver is lane filtering in compliance with section 151A or edge filtering in compliance with section 151B.

Formalization

Atom Initialisations:

Atom driver_OvertakeToTheLeftOf_vehicle
Atom driver_Of_bicyle
Atom driver_IsDrivingOn_MultiLaneRoad
Atom vehicle_CanBeSafelyOvertakenIn_markedLane
Atom markedLane_IsToTheLeftOf_vehicle
Atom vehicle_IsTurningRight
Atom vehicle_IsGivingRightChangeOfDirectionSignal
Atom IsSafeToOvertakeToTheLeftOf_vehicle
Atom vehicle_IsMakingUturn
Atom vehicle_IsOn_centreOfRoad
Atom vehicle_IsStationary
Atom driver_IsLawfullyLaneFiltering
Atom driver_IsLawfullyEdgeFiltering

Rules:

r141: => **[F]** driver_OvertakeToTheLeftOf_vehicle
r141_bicycle: driver_Of_bicyle => **[P]** driver_OvertakeToTheLeftOf_vehicle
r141_a: driver_IsDrivingOn_MultiLaneRoad & vehicle_CanBeSafelyOvertakenIn_markedLane & markedLane_IsToTheLeftOf_vehicle => **[P]** driver_OvertakeToTheLeftOf_vehicle
r141_b_1: vehicle_IsTurningRight & vehicle_IsGivingRightChangeOfDirectionSignal & IsSafeToOvertakeToTheLeftOf_vehicle => **[P]** driver_OvertakeToTheLeftOf_vehicle
r141_b_2: vehicle_IsMakingUturn & vehicle_IsOn_centreOfRoad & vehicle_IsGivingRightChangeOfDirectionSignal & IsSafeToOvertakeToTheLeftOf_vehicle => **[P]** driver_OvertakeToTheLeftOf_vehicle

r141_c: vehicle_IsStationary & vehicle_CanBeSafelyOvertakenIn_markedLane => **[P]** driver_OvertakeToTheLeftOf_vehicle
r141_d_a: driver_IsLawfullyLaneFiltering => **[P]** driver_OvertakeToTheLeftOf_vehicle
r141_d_b: driver_IsLawfullyEdgeFiltering => **[P]** driver_OvertakeToTheLeftOf_vehicle

r141_bicycle >> r141
r141_a >> r141
r141_b_1 >> r141
r141_b_2 >> r141
r141_c >> r141
r141_d_a >> r141
r141_d_b >> r141

Table 13 Formalization of QLD Traffic Rule 142

Rule 142: No overtaking to the right of a vehicle turning right etc.
(1) A driver must not overtake to the right of a vehicle if the vehicle is—
(a) turning right or making a U-turn from the centre of the road; and
(b) giving a right change of direction signal.

Formalization

Atom Initialisations:

Atom driver_OvertakeToTheRightOf_vehicle
Atom vehicle_IsTurningRight
Atom vehicle_IsGivingRightChangeOfDirectionSignal
Atom vehicle_IsMakingUturn
Atom vehicle_IsOn_centreOfRoad

Rules:

r142_1: => **[P]** driver_OvertakeToTheRightOf_vehicle
r142_1_a_i: vehicle_IsTurningRight => **[F]** driver_OvertakeToTheRightOf_vehicle
r142_1_a_ii: vehicle_IsTurningRight **&** vehicle_IsGivingRightChangeOfDirectionSignal => **[F]** driver_OvertakeToTheRightOf_vehicle
r142_1_a_iii: vehicle_IsMakingUturn & vehicle_IsOn_centreOfRoad => **[F]** driver_OvertakeToTheRightOf_vehicle
r142_1_a_iv: vehicle_IsMakingUturn **&** vehicle_IsOn_centreOfRoad **&** vehicle_IsGivingRightChangeOfDirectionSignal => **[F]** driver_OvertakeToTheRightOf_vehicle
r142_1_b: vehicle_IsGivingRightChangeOfDirectionSignal => **[F]** driver_OvertakeToTheRightOf_vehicle

r142_1_a_i >> r142_1
r142_1_a_ii >> r142_1
r142_1_a_iii >> r142_1
r142_1_a_iv >> r142_1

Table 14 Formalization of QLD Traffic Rule 143 (left overtaking)

Rule 143 (Left Overtaking): Passing or overtaking a vehicle displaying a do not overtake turning vehicle sign

(1) A driver must not drive past, or overtake, to the left of a vehicle displaying a do not overtake turning vehicle sign, unless—

(a) if the vehicle is turning left and is giving a left change of direction signal

(b) otherwise—

(i) the driver is driving on a multi-lane road and it is safe to pass, or overtake, in a marked lane to the left of the vehicle; or

(ii) the vehicle is turning right, or making a U-turn from the centre of the road, and is giving a right change of direction signal and it is safe to pass, or overtake, to the left of the vehicle; or

(iii) the vehicle is stationary and it is safe to pass, or overtake, to the left of the vehicle; or

(iv) it is otherwise safe to pass, or overtake, to the left of the vehicle.

Maximum penalty—20 penalty units.

Formalization

Atom Initialisations:

Atom vehicle_IsTurningLeft
Atom vehicle_IsMakingUturn
Atom vehicle_IsOn_centreOfRoad
Atom vehicle_IsStationary
Atom driver_IsDrivingOn_MultiLaneRoad
Atom vehicle_IsGivingLeftChangeOfDirectionSignal
Atom vehicle_Display_doNotOvertakeTurningVehicleSign
Atom MarkedLane_IsToTheLeftOf_vehicle
Atom IsSafeToPassIn_MarkedLane
Atom IsSafeToOvertakeIn_MarkedLane
Atom IsSafeToPassToTheLeftOf_vehicle
Atom IsOtherwiseSafeToPassToTheLeftOf_vehicle
Atom IsSafeToOvertakeToTheLeftOf_vehicle
Atom IsOtherwiseSafeToOvertakeToTheLeftOf_vehicle
Atom driver_DrivePastToTheLeftOf_vehicle
Atom driver_OvertakeToTheLeftOf_vehicle

Rules:

r143_1_1:vehicle_Display_doNotOvertakeTurningVehicleSign => **[F]**
driver_DrivePastToTheLeftOf_vehicle

r143_1_2:vehicle_Display_doNotOvertakeTurningVehicleSign => **[F]**
driver_OvertakeToTheLeftOf_vehicle

r143_1_1_a: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsTurningLeft &
vehicle_IsGivingLeftChangeOfDirectionSignal
=> **[F]** driver_DrivePastToTheLeftOf_vehicle

r143_1_2_a: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsTurningLeft &
vehicle_IsGivingLeftChangeOfDirectionSignal
=> **[F]** driver_OvertakeToTheLeftOf_vehicle

r143_1_1_b_i_1: vehicle_Display_doNotOvertakeTurningVehicleSign &
driver_IsDrivingOn_MultiLaneRoad & IsSafeToPassIn_MarkedLane
& MarkedLane_IsToTheLeftOf_vehicle & **[P]** driver_Overtake_vehicle => **[P]**
driver_DrivePastToTheLeftOf_vehicle

r143_1_1_b_i_2: vehicle_Display_doNotOvertakeTurningVehicleSign &
driver_IsDrivingOn_MultiLaneRoad & IsSafeToOvertakeIn_MarkedLane
& MarkedLane_IsToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => **[P]**
driver_DrivePastToTheLeftOf_vehicle

Table 14 (continued)

r143_1_2_b_i_1: vehicle_Display_doNotOvertakeTurningVehicleSign & driver_IsDrivingOn_MultiLaneRoad & IsSafeToPassIn_MarkedLane & MarkedLane_IsToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_OvertakeToTheLeftOf_vehicle
r143_1_2_b_i_2: vehicle_Display_doNotOvertakeTurningVehicleSign & driver_IsDrivingOn_MultiLaneRoad & IsSafeToOvertakeIn_MarkedLane & MarkedLane_IsToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_OvertakeToTheLeftOf_vehicle
r143_1_1_b_ii_1: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsTurningRight & vehicle_IsGivingRightChangeOfDirectionSignal & IsSafeToPassToTheLeftOf_vehicle & [P]driver_Overtake_vehicle => [P] driver_DrivePastToTheLeftOf_vehicle
r143_1_1_b_ii_2: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsTurningRight & vehicle_IsGivingRightChangeOfDirectionSignal & IsSafeToOvertakeToTheLeftOf_vehicle & [P]driver_Overtake_vehicle => [P] driver_DrivePastToTheLeftOf_vehicle
r143_1_1_b_ii_3: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsMakingUturn & vehicle_IsOn_centreOfRoad & vehicle_IsGivingRightChangeOfDirectionSignal & IsSafeToPassToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_DrivePastToTheLeftOf_vehicle
r143_1_1_b_ii_4: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsMakingUturn & vehicle_IsOn_centreOfRoad & vehicle_IsGivingRightChangeOfDirectionSignal & IsSafeToOvertakeToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_DrivePastToTheLeftOf_vehicle
r143_1_2_b_ii_1: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsTurningRight & vehicle_IsGivingRightChangeOfDirectionSignal & IsSafeToPassToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_OvertakeToTheLeftOf_vehicle
r143_1_2_b_ii_2: vehicle_IsTurningRight & vehicle_IsGivingRightChangeOfDirectionSignal & IsSafeToOvertakeToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_OvertakeToTheLeftOf_vehicle
r143_1_2_b_ii_3: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsMakingUturn & vehicle_IsOn_centreOfRoad & vehicle_IsGivingRightChangeOfDirectionSignal & IsSafeToPassToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_OvertakeToTheLeftOf_vehicle
r143_1_2_b_ii_4: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsMakingUturn & vehicle_IsOn_centreOfRoad & vehicle_IsGivingRightChangeOfDirectionSignal & IsSafeToOvertakeToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_OvertakeToTheLeftOf_vehicle
r143_1_1_b_iii_1: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsStationary & IsSafeToPassToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_DrivePastToTheLeftOf_vehicle
r143_1_1_b_iii_2: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsStationary & IsSafeToOvertakeToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_DrivePastToTheLeftOf_vehicle
r143_1_2_b_iii_1: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsStationary & IsSafeToPassToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_OvertakeToTheLeftOf_vehicle
r143_1_2_b_iii_2: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsStationary & IsSafeToOvertakeToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_OvertakeToTheLeftOf_vehicle

Table 14 (continued)

r143_1_1_b_iv_1: vehicle_Display_doNotOvertakeTurningVehicleSign & IsOtherwiseSafeToPassToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_DrivePastToTheLeftOf_vehicle
r143_1_1_b_iv_2: vehicle_Display_doNotOvertakeTurningVehicleSign & IsOtherwiseSafeToOvertakeToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_DrivePastToTheLeftOf_vehicle
r143_1_2_b_iv_1: vehicle_Display_doNotOvertakeTurningVehicleSign & IsOtherwiseSafeToPassToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_OvertakeToTheLeftOf_vehicle
r143_1_2_b_iv_2: vehicle_Display_doNotOvertakeTurningVehicleSign & IsOtherwiseSafeToOvertakeToTheLeftOf_vehicle & [P] driver_Overtake_vehicle => [P] driver_OvertakeToTheLeftOf_vehicle
r143_1_1_a >> r143_1_1 r143_1_2_a >> r143_1_2 r143_1_1_b_i_1 >> r143_1_1 r143_1_1_b_i_2 >> r143_1_1 r143_1_2_b_i_1 >> r143_1_2 r143_1_2_b_i_2 >> r143_1_2 r143_1_1_b_ii_1 >> r143_1_1 r143_1_1_b_ii_2 >> r143_1_1 r143_1_1_b_ii_3 >> r143_1_1 r143_1_1_b_ii_4 >> r143_1_1 r143_1_2_b_ii_1 >> r143_1_2 r143_1_2_b_ii_2 >> r143_1_2 r143_1_2_b_ii_3 >> r143_1_2 r143_1_2_b_ii_4 >> r143_1_2 r143_1_1_b_iii_1 >> r143_1_1 r143_1_1_b_iii_2 >> r143_1_1 r143_1_2_b_iii_1 >> r143_1_2 r143_1_2_b_iii_2 >> r143_1_2 r143_1_1_b_iv_1 >> r143_1_1 r143_1_1_b_iv_2 >> r143_1_1 r143_1_2_b_iv_1 >> r143_1_2 r143_1_2_b_iv_2 >> r143_1_2 r143_2_exception_i >> r143_2_i r143_2_exception_i >> r143_2_iii r143_2_exception_ii >> r143_2_ii r143_2_exception_ii >> r143_2_iv

Table 15 Formalization of QLD Traffic Rule 143 (right overtaking)

Rule 143 (Right Overtaking): Passing or overtaking a vehicle displaying a do not overtake turning vehicle sign

(2) A driver must not drive past, or overtake, to the right of a vehicle displaying a do not overtake turning vehicle sign if the vehicle is turning right, or making a U-turn from the centre of the road, and is giving a right change of direction signal, unless it is safe to do so.

Formalization

Atom Initialisations:

Atom vehicle_IsTurningRight
Atom vehicle_IsMakingUturn
Atom vehicle_IsOn_centreOfRoad
Atom vehicle_IsStationary
Atom driver_IsDrivingOn_MultiLaneRoad
Atom vehicle_IsGivingRightChangeOfDirectionSignal
Atom vehicle_Display_doNotOvertakeTurningVehicleSign
Atom IsSafeToPassIn_MarkedLane
Atom IsSafeToOvertakeIn_MarkedLane
Atom IsSafeToPassToTheRightOf_vehicle
Atom driver_DrivePastToTheRightOf_vehicle
Atom driver_OvertakeToTheRightOf_vehicle

Rules:

r143_1_1:vehicle_Display_doNotOvertakeTurningVehicleSign => **[F]** driver_DrivePastToTheRightOf_vehicle

r143_1_2:vehicle_Display_doNotOvertakeTurningVehicleSign => **[F]** driver_OvertakeToTheRightOf_vehicle

r143_2_i: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsTurningRight & vehicle_IsGivingRightChangeOfDirectionSignal => **[F]** driver_DrivePastToTheRightOf_vehicle

r143_2_ii: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsTurningRight & vehicle_IsGivingRightChangeOfDirectionSignal => **[F]** driver_OvertakeToTheRightOf_vehicle

r143_2_iii: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsMakingUturn & vehicle_IsOn_centreOfRoad
& vehicle_IsGivingRightChangeOfDirectionSignal => **[F]** driver_DrivePastToTheRightOf_vehicle

r143_2_iv: vehicle_Display_doNotOvertakeTurningVehicleSign & vehicle_IsMakingUturn & vehicle_IsOn_centreOfRoad
& vehicle_IsGivingRightChangeOfDirectionSignal => **[F]** driver_OvertakeToTheRightOf_vehicle

r143_2_exception_i: vehicle_Display_doNotOvertakeTurningVehicleSign & IsSafeToPassToTheRightOf_vehicle & **[P]** driver_Overtake_vehicle => **[P]** driver_DrivePastToTheRightOf_vehicle

r143_2_exception_ii: vehicle_Display_doNotOvertakeTurningVehicleSign & IsSafeToPassToTheRightOf_vehicle & **[P]** driver_Overtake_vehicle => **[P]** driver_OvertakeToTheRightOf_vehicle

r_{143.2.exception.i} > r_{143.2.i}
r_{143.2.exception.i} > r_{143.2.iii}
r_{143.2.exception.ii} > r_{143.2.ii}
r_{143.2.exception.ii} > r_{143.2.iv}

Table 16 Formalization of QLD Traffic Rule 144

Rule 144: Keeping a safe distance when overtaking
Subject to section 144A(1), a driver overtaking a vehicle—
(a) must pass the vehicle at a sufficient distance to avoid a collision with the vehicle or obstructing the path of the vehicle; and
(b) must not return to the marked lane or line of traffic where the vehicle is travelling until the driver is a sufficient distance past the vehicle to avoid a collision with the vehicle or obstructing the path of the vehicle.

Formalization

Atom Initialisations:

Atom driver_IsOvertakingByCrossingADividingLine_anotherDriver
Atom driver_isDrivingOn_twoWayRoad
Atom driver_HasPassed_anotherDriver
Atom anotherDriver_IncreaseTheSpeed
Atom driver_IsOvertakingByCrossingToTheRightOfTheCentreOfTheRoad_anotherDriver
Atom anotherDriver_IsDrivingOn_markedLane
Atom driver_HasReturnedTo_markedLane
Atom anotherDriver_IsDrivingOn_lineOfTraffic
Atom driver_HasReturnedTo_lineOfTraffic
Atom driver_IsAtASufficientDistanceToAvoidACollisionInFrontOf_anotherDriver

Rules:

r144_a_1:driver_IsOvertaking_vehicle => **[O]**
driver_PassAtSufficientDistanceToAvoidCollisionWith_vehicle

r144_a_2:driver_IsOvertaking_vehicle => **[O]**
driver_PassAtSufficientDistanceToAvoidObstructingThePathOf_vehicle

r144_b_1_1:driver_IsOvertaking_vehicle & vehicle_IsTravellingOn_markedLane
& ~ driver_IsAtSufficientDistancePastToAvoidCollisionWith_vehicle => **[F]**
driver_ReturnTo_markedLane

r144_b_1_2:driver_IsOvertaking_vehicle & vehicle_IsTravellingOn_markedLane
& ~ driver_IsAtSufficientDistancePastToAvoidObstructingThePathOf_vehicle => **[F]**
driver_ReturnTo_markedLane

r144_b_2_1:driver_IsOvertaking_vehicle & vehicle_IsTravellingOn_lineOfTraffic
& ~ driver_IsAtSufficientDistancePastToAvoidCollisionWith_vehicle => **[F]**
driver_ReturnTo_markedLane

r144_b_2_2:driver_IsOvertaking_vehicle & vehicle_IsTravellingOn_lineOfTraffic
& ~ driver_IsAtSufficientDistancePastToAvoidObstructingThePathOf_vehicle => **[F]**
driver_ReturnTo_markedLane

Table 17 Formalization of QLD Traffic Rule 144A

144A Keeping a safe lateral distance when passing bicycle rider

(1)The driver of a motor vehicle passing the rider of a bicycle that is travelling in the same direction as the driver must pass the bicycle at a sufficient distance from the bicycle.

(2) A ***sufficient distance from the bicycle*** is—

(a) if the applicable speed limit is not more than 60km/h—a lateral distance from the bicycle of at least 1m; or

(b) if the applicable speed limit is more than 60km/h—a lateral distance from the bicycle of at least 1.5m.

(3) For subsection (2), the lateral distance is the distance between the following points—

(a) the furthermost point to the left on the driver's vehicle or any projection from the vehicle (whether or not attached to the vehicle);

(b) the furthermost point to the right on the bicycle, any bicycle trailer towed by the bicycle, the rider or any passenger in or on the trailer.

Example of what is part of a bicycle for paragraph (b)—

a basket or pannier bags attached to the bicycle

Example of what is not part of a bicycle for paragraph (b)—

a flag or stick, whether or not flexible, attached to the bicycle, that projects sideways from the bicycle

Formalization

Atom Initialisations:

Atom rider_Passing_bicycle
Atom rider_KeepingASafeLateralDistance_bicycle
Atom driver_Of_motorVehicle
Atom rider_Of_bicycle
Atom driver_Passing_rider
Atom driver_TravellingInSameDirectionOf_rider
Atom driver_IsPassing_bicycle
Atom driver_IsAtASufficientDistanceFrom_bicycle
Atom applicableSpeedLimit_LessEqualThan_60kmsPerHour
Atom vehicle_HasLateralDistanceGreaterEqualThan1MetreFrom_bicycle
Atom driver_IsAtASufficientDistanceFrom_bicycle
Atom applicableSpeedLimit_GreaterThan_60kmsPerHour
Atom vehicle_HasLateralDistanceGreaterEqualThan1.5MetreFrom_bicycle
Atom vehicle_LateralDistance_fromTheBicycle
Atom isLateral_Distance_between
Atom LeftOnTheDriver'sVehicle
Atom furtherMost_Point_toTheLeftOnTheDriver'sVehicle
Atom aSufficient_Distance_fromTheBicycle
Atom theVehicle
Atom projection_From_theVehicle
Atom RightOnTheDriver'sVehicle
Atom furthermost_Point_TotheRightOnthebicycle
Atom bicycle_Towed_byTheBicycleRider
Atom bicycle_Towed_byThePassenger
Atom the_Rider_onTheTrailer
Atom the_Rider_inTheTrailer

Table 17 (continued)

Rules:
r_144A: rider_Passing_bicycle => [O] rider_KeepingASafeLateralDistance_bicycle
r_144A_1: driver_Of_motorVehicle & rider_Of_bicycle & driver_Passing_rider & driver_TravellingInSameDirectionOf_rider & driver_IsPassing_bicycle => [O] driver_IsAtASufficientDistanceFrom_bicycle
r_144A_2_a: applicableSpeedLimit_LessEqualThan_60kmsPerHour & vehicle_HasLateralDistanceGreaterEqualThan1MetreFrom_bicycle => driver_IsAtASufficientDistanceFrom_bicycle
r_144A_2_b: applicableSpeedLimit_GreaterThan_60kmsPerHour & vehicle_HasLateralDistanceGreaterEqualThan1.5MetreFrom_bicycle => driver_IsAtASufficientDistanceFrom_bicycle
r_144A_3_a_i: vehicle_LateralDistance_fromTheBicycle & isLateral_Distance_between & LeftOnTheDriver'sVehicle & furtherMost_Point_toTheLeftOnTheDriver'sVehicle => aSufficient_Distance_fromTheBicycle
r_144A_3_a_ii: vehicle_LateralDistance_fromTheBicycle & isLateral_Distance_between & theVehicle & projection_From_theVehicle => aSufficient_Distance_fromTheBicycle
r_144A_3_b_i: vehicle_LateralDistance_fromTheBicycle & isLateral_Distance_between & RightOnTheDriver'sVehicle & furthermost_Point_TotheRightOnthebicycle & bicycle_Towed_byTheBicycleRider => aSufficient_Distance_fromTheBicycle
r_144A_3_b_ii: vehicle_LateralDistance_fromTheBicycle & isLateral_Distance_between & RightOnTheDriver'sVehicle & furthermost_Point_TotheRightOnthebicycle & bicycle_Towed_byTheBicycleRider & the_Rider_onTheTrailer => aSufficient_Distance_fromTheBicycle
r_144A_3_b_iii: vehicle_LateralDistance_fromTheBicycle & isLateral_Distance_between & RightOnTheDriver'sVehicle & furthermost_Point_TotheRightOnthebicycle & bicycle_Towed_byTheBicycleRider & the_Rider_inTheTrailer => aSufficient_Distance_fromTheBicycle
r_144A_3_b_iv: vehicle_LateralDistance_fromTheBicycle & isLateral_Distance_between & RightOnTheDriver'sVehicle & furthermost_Point_TotheRightOnthebicycle & bicycle_Towed_byThePassenger => aSufficient_Distance_fromTheBicycle
r_144A_3_b_v: vehicle_LateralDistance_fromTheBicycle & isLateral_Distance_between & RightOnTheDriver'sVehicle & furthermost_Point_TotheRightOnthebicycle & bicycle_Towed_byThePassenger & the_Rider_onTheTrailer => aSufficient_Distance_fromTheBicycle
r_144A_3_b_vi: vehicle_LateralDistance_fromTheBicycle & isLateral_Distance_between & RightOnTheDriver'sVehicle & furthermost_Point_TotheRightOnthebicycle & bicycle_Towed_byThePassenger & the_Rider_inTheTrailer => aSufficient_Distance_fromTheBicycle
r_144A_1 ≫ r_144A

Table 18 Formalization of QLD Traffic Rule 145

Rule 145: Driver being overtaken not to increase speed
If a driver is overtaking another driver on a two-way road by crossing a dividing line, or crossing to the right of the centre of the road, the other driver must not increase the speed at which the driver is driving until the first driver—
(a) has passed the other driver; and
(b) has returned to the marked lane or line of traffic where the other driver is driving; and
(c) is a sufficient distance in front of the other driver to avoid a collision.

Formalization

Atom Initialisations:

Atom driver_IsOvertaking_vehicle
Atom driver_PassAtSufficientDistanceToAvoidCollisionWith_vehicle
Atom driver_PassAtSufficientDistanceToAvoidObstructingThePathOf_vehicle
Atom driver_IsAtSufficientDistancePastToAvoidCollisionWith_vehicle
Atom driver_IsAtSufficientDistancePastToAvoidObstructingThePathOf_vehicle
Atom vehicle_IsTravellingOn_markedLane
Atom vehicle_IsTravellingOn_lineOfTraffic
Atom driver_ReturnTo_markedLane

Rules:

r145_a_1: driver_IsOvertakingByCrossingADividingLine_anotherDriver &
driver_isDrivingOn_twoWayRoad
& ~ driver_HasPassed_anotherDriver => [F] anotherDriver_IncreaseTheSpeed

r145_a_2: driver_IsOvertakingByCrossingToTheRightOfTheCentreOfTheRoad_anotherDriver &
driver_isDrivingOn_twoWayRoad
& ~ driver_HasPassed_anotherDriver => [F] anotherDriver_IncreaseTheSpeed

r145_b_1: driver_IsOvertakingByCrossingADividingLine_anotherDriver &
driver_isDrivingOn_twoWayRoad & anotherDriver_IsDrivingOn_markedLane
& ~ driver_HasReturnedTo_markedLane => [F] anotherDriver_IncreaseTheSpeed

r145_b_2: driver_IsOvertakingByCrossingToTheRightOfTheCentreOfTheRoad_anotherDriver
& driver_isDrivingOn_twoWayRoad & anotherDriver_IsDrivingOn_markedLane
& ~ driver_HasReturnedTo_markedLane => [F] anotherDriver_IncreaseTheSpeed

r145_b_3: driver_IsOvertakingByCrossingADividingLine_anotherDriver
& driver_isDrivingOn_twoWayRoad & anotherDriver_IsDrivingOn_lineOfTraffic
& ~ driver_HasReturnedTo_lineOfTraffic => [F] anotherDriver_IncreaseTheSpeed

r145_b_4: driver_IsOvertakingByCrossingToTheRightOfTheCentreOfTheRoad_anotherDriver
& driver_isDrivingOn_twoWayRoad & anotherDriver_IsDrivingOn_lineOfTraffic
& ~ driver_HasReturnedTo_lineOfTraffic => [F] anotherDriver_IncreaseTheSpeed

r145_c_1: driver_IsOvertakingByCrossingADividingLine_anotherDriver
& driver_isDrivingOn_twoWayRoad & ~
driver_IsAtASufficientDistanceToAvoidACollisionInFrontOf_anotherDriver
=> [F] anotherDriver_IncreaseTheSpeed

r145_c_2: driver_IsOvertakingByCrossingToTheRightOfTheCentreOfTheRoad_anotherDriver
& driver_isDrivingOn_twoWayRoad & ~
driver_IsAtASufficientDistanceToAvoidACollisionInFrontOf_anotherDriver
=> [F] anotherDriver_IncreaseTheSpeed

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