Keeping the Autonomous Vehicles Accountable: Legal and Logic Analysis on Traffic Code

Dan M. Costescu(✉)

University "Politehnica" of Bucharest,
Spl. Independentei 313, 060042 Bucharest, Romania
dan.costescu@stud.trans.upb.ro

Abstract. The recent boost of the autonomous vehicles (AV) technology clearly outpaced the related regulating processes. Even for the already existing regulation like Traffic Code, opposable today to the human drivers, supposing to be maintained on medium term without important modifications, a major challenge pops-up. The content should by "translated" to a form enabling the engineers and authorities to keep also the autonomous vehicles accountable against the rules. The formalization methodology is consolidated, containing three major steps, practically implemented for the Overtaking as study case. Firstly, the Legal Analysis aims to eliminate the inherent redundancy of existing legal texts, clearly separate the responsibility of user and AV and finally to logically break them down in "*predicate precursors*". The following step, Logic Analysis was conceived as a bridge between legal and engineering aspects, shaping step by step the Overtaking maneuver by using tools like the Modal Logic Flow Chart (sequenced but still untimed events), Atomic Proposition Tables (multi-level hierarchy) and finally Linear Temporal Logic (LTL) Formulas timed over a Temporal Logic Diagram. At this point the goal of this paper has been achieved, the methodology delivering the appropriate preparedness for automation and for further improvements of expressivity using High Order Language (HOL) by performing Engineering Analyses for aspects not yet covered by literature.

Keywords: Autonomous vehicles · Legal analysis · Logic analysis · Traffic rules formalization

1 Introduction

Considering the complex multimodal scenarios featuring urban and inter-urban traffic, mixed categories of vehicle, at-grade intersections and less predictable human behavior even under clear traffic regulations, it is obvious that defining standards and achieving an airtight safety and security package to society is not as straightforward as expected for the autonomous vehicles (AV).

Although the terms safety and security are generally used as interchangeable, the literature makes a clear difference between them. According to Burns et al. [1] and Albrechtsen [2], security is protection against deliberate incidents and safety is

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protection against unintended incidents. A more general definition would define safety as addressing the ability of a system to avoid undesirable effects on its environment whilst the security refers the traits of an environment necessary to avoid undesirable effects on the system [3].

In spite of spectacular technology development, for a long period from now on the traffic will be still mixed, including both human operated and autonomous vehicles. A reasonable approach would be then to avoid any sudden and sharp change of traffic code that could break the principle of continuity and predictability of safety regulation. This is, for the next years the principles of keeping human drivers legally accountable will be maintained and accordingly that should equally apply to AVs. However, as the automation level of AV will increase gradually, the liability for already existing rules shall transfer from user to vehicle (manufacturer) according to the volume of automated functions (see Fig. 1) and on medium and long term it is anticipated that the traffic code will be completed with new technology specific rules. On both cases it is required a clear methodology of distributing responsibility between user and vehicle and then, for the rules applicable to AV to “translate” them from the legal idiom into a directly computable, free of ambiguities, language. This is the formalization of traffic rules, the topic present paper aims to contribute on.

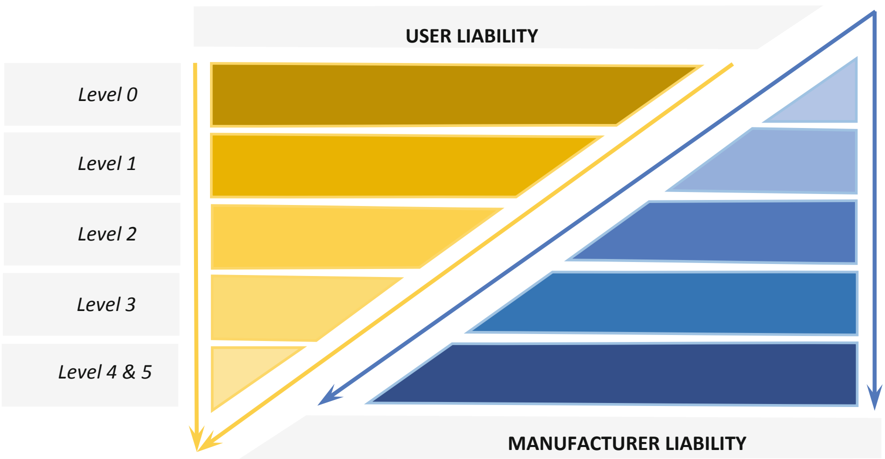

Fig. 1. The expected liability transfer from user to manufacture as automation level increases.

2 Formalization of Legal Acts

Literature assigns the work on the “The British Nationality Act” as the first major attempt to formalize a law into a logic program [4]. It has been proved that there are a lot of similarities between law formulation and computer languages, the former including since centuries before computer era, elements similar to programming structures, specifications, database characterization and query, integrity constraints and even knowledge representation specific to artificial intelligence [5].

2.1 Legal Analysis of Traffic Rules

Definition of Legal Scope, Associated Set and Subsets of Regulation. Theoretically, in respect with the traffic, a comprehensive set of regulation $\{R\}$ should be defined, that could be further broken apart in two different, preferably disjoint subsets:

$$\{R\} = \{User\} \cup \{AV\} \tag{1}$$

$$\{User\} \cap \{AV\} = \emptyset \tag{2}$$

where $\{R\}$ is the traffic regulation set including all traffic rules, $\{User\}$ – the traffic rules subset assigned exclusively to the user, $\{AV\}$ – the traffic rules subset assigned exclusively to the autonomous vehicle.

Equation (1) indicates that the $\{R\}$ is a gaps free regulation set, meaning there is no traffic rule which is not assigned at least to one of the two subsets, $\{User\}$ and $\{AV\}$.

Equation (2) indicates that $\{R\}$ is a regulation set free of shared responsibilities which is the ideal legal setup, where the responsibility for every situation is entirely assigned, either to the user or to the autonomous vehicle.

The two concepts introduced above bring clarity in separation of responsibility areas. Despite the fact the latter one is an idealized case, when the two defined subsets were disjoint, which is obviously not the case in reality, its consideration eliminates ambiguity and helps defining a third subset of rules, that needs special attention. This is the intersection of the first two subsets (Eq. 2), where the responsibility is shared or needs further clarification (e.g. cases when AV gives back control to human operator).

Practically, the above formulated problem, starts from an already existing set $\{R\}$ of traffic rules, approved at national level and expressed in natural language, more specifically, in terms of a legal dialect which is a specialized language but still a natural one. Assuming that the subset $\{AV\}$ was appropriately extracted from the set $\{R\}$ the next issue to be tackled is that the natural language is in the most cases not suitable for assessing whether the AV obeys the traffic rules or not. This is, the sometime vaguely formulated rules as "adapting the speed to the extent of avoiding any dangerous situation" makes almost impossible in this form, the design or monitoring in traffic of an AV, which is actually a matter of position, time, speed and acceleration [6]. Further steps are required, in order to make the present traffic codes directly usable for *engineering purposes*, namely defining technical specifications and for *enforcement purpose*, namely monitoring behavior in traffic and liability topics.

A combination of legal, logic and engineering analyses should be employed with the declared aim to first ***filter the unnecessary and ambiguous information***, then ***codify the traffic rules*** into predicates as 'overtaking pre-check', 'do overtake', 'adapt speed' or 'safe distance' and thereafter perform their ***concretization***, interpreting from an abstract form to a clear and practicable one for an automated approach.

Traffic Rules Codification. The principles of *propositional logic* [7] have been used to generate *formulas*, generally constituted of *atomic propositions (AP)*, *as* statements without internal structure and *Boolean operators*. That technique is usually sufficient when preparing the "predicate precursors" for legal analysis. When propositional logic is not enough expressive to formalize the mathematics of engineering analysis, additional elements will be introduced, as *variables, arithmetic operators* and *relational operators*, and the resulted system of logic that can be interpreted on their basis is called a ***first-order logic*** or ***predicate logic*** [8]. For the cases where a finer distinction between a 'true' and 'false' value is needed, the ***modal logic*** is able to distinguish between statements that are *necessarily true* and those that are *possibly true.* For the specific processes of AVs, the ***temporal logic*** [9] as a form of modal logic proves to be more appropriate when time points should be referred, interpreting *necessarily* as *always* and *possibly* as *eventually*. Some of these formalisms will be used as *untimed* when time is referred only from the point of view of state ordering [10] whilst other formalisms will be employed further in the model because they allow declaring and using time values, mainly relative, but absolute as well [11].

Furthermore, the complexity of the autonomous vehicles and their processes asks to migrate from the first-order logic able to quantify only variables ranging over individuals, towards superiors levels as *second-order logic* that quantifies over sets, towards *third-order logic* that quantifies over sets of sets, and finally towards ***higher-order logic*** (HOL) that delivers quantification over sets that are arbitrarily deeply nested, being actually a union of 1st-, 2nd-, …nth-order logic [12, 13].

The Romanian traffic code [14] was used as a working document in its form including the *main body*, and the related *regulation procedures*. To avoid confusion the articles of the former will be referred as Art. only with its number whilst the articles of the later with its number preceded by an "R. Art.".

One of the most complex manoeuvers on road is *overtaking*, that remains actually the major challenge for traffic rules formalization and it is also selected as the case for the present study. A summary of the relevant legal provisions is presented in Table 1.

Legal Analysis of Traffic Rules: Overtaking Maneuver. A compared analysis has been performed between the paragraphs selected as relevant for the study case in Table 1. The aim was ***to eliminate the inherent regulating redundancy*** and to retain only a concise and coherent foundation for subsequent formalization. Text in italic indicates those topics being already treated by other paragraphs or simply not relevant to the context and therefore excluded from further processing, as redundant.

The next step is what we will call from now on "***the logical break down***" of the law text as per Fig. 2, the Art. 45 (1, 2, 3) being used as example. It can be seen the legal text suffers only minor modification if any, but it is broken down in sentences semantically significant (*predicate precursors*) separated by Boolean operators.

3 Logic Analysis

It was conceived to enable a smooth transition from Legal to Concretization stage. After processing of all the retained articles according to Table 1, these are assembled sequentially for Overtaking in what we call from now on a "*Modal Logic Flow Chart*" represented in Fig. 3, in terms of concepts as *necessarily true* and *possibly true* specific to *modal logic*.

45 (1)	Overtaking is the manoeuver through which:

1.1.1.	→	which one vehicle passes another vehicle that is on the same lane
		OR
1.1.2.	→	an obstacle that is on the same lane

being executed by:

1.2.1.1.	→	changing the running direction
		AND
1.2.1.2.	→	leaving the initial lane

OR

1.2.2.1.	→	changing the running direction
		AND
1.2.2.2.	→	leaving the initial row of vehicles

45(2)	The driver engaging in an overtaking must make sure

2.1.	→	the forerunning vehicle has not initiated a similar manoeuver
		AND
2.2.	→	the following vehicle has not initiated a similar manoeuver

45(3)	When during the overtaking the central line is crossed, the driver must make sure that:

3.1.	→	no vehicle approaches from the opposite direction
		AND
3.2.	→	there is enough space to complete the overtaking and
		THEN
3.3.	→	return on the initial lane

Fig. 2. Logical break down of Art. 45 (1-3).

Table 1. Relevant traffic provisions regarding overtaking.

Art. No	Topic	Content	Comments
Art. 45 *(1) (2) (3)*	Overtaking	"(1) Overtaking is the manoeuver through which one vehicle passes another vehicle or an obstacle that is on the same lane, being executed by changing the running direction and leaving the initial lane or row of vehicles (2) The driver engaging in an overtaking must make sure the forerunning and the following	(1) Overtaking definition (1) Types of overtaking (2) Making sure (3) Making sure

(*continued*)

Table 1. (*continued*)

Art. No	Topic	Content	Comments
		vehicle has not initiated a similar manoeuver (3) When during the overtaking the central line is crossed, the driver must make sure that no vehicle approaches from the opposite direction and there is enough space to complete the overtaking and return to the initial lane"	
Art. 54 *(1) (2)*	Manoeuvers	"Art. 54. (1) The driver of a vehicle changing the running direction, leaving or entering a raw of vehicles, changing the lane or (…) is obliged to timely signalize intention and make sure the traffic is not disturbed or the other road users are nor endangered through his manoeuvers (2) Signalization of any change in running direction shall be maintained during the entire duration of the manoeuver"	(1) Signaling obligation (1) Making sure *(dealt partially by 45(3),* except case of followers) (2) Signaling duration
R. Art. 116	Signalization	"*(1) The drivers shall signalize the changing of running direction, overtaking, stopping and putting into motion* (2) Intention of road users to change the running directions, to leave or enter a row of vehicles, to change the lane or (…) must be signalized by turning on the blinking lights with at least 50 m within urban areas and at least 100 m otherwise, before starting the manoeuver	*(1) Signaling obligation* *(d. by 54(1))* (2) Signaling distance
R. Art. 118	Overtaking	"The driver engaging in taking over is obliged to: *(a) Make sure the follower or forerunner did not signalize the intention of a similar manoeuvers and he can safely takeover without inducing any discomfort*	*(a) Making sure dealt also by 45(2)(3)* *(b) Signalizing dealt also by 54(1)* *(c) Lateral safe distance* *(d) Return obligation*

(*continued*)

Table 1. (*continued*)

Art. No	Topic	Content	Comments
		to the users running from opposite direction; *(b) Signalize overtaking intention;* (c) Keep during the manoeuver a sufficient lateral distance to the overtaken vehicle; (d) Return to initial lane or row of vehicles after making sure such a manoeuver is safe for all road users"	
R. Art. 120 (1) a ÷ k, (2)	Overtaking pre-check	A number of situations when the overtaking is forbidden are listed within this article. As it makes no difference and for the sake of concision, they will be further treated as a built in-set of conditions. However it worth to mention that the Pre-check set contains two subsets, one related to infrastructure R. Art. 120 {a, b, c, d, e, f, g, i} and one related to the other road users R. Art. 120 {j, k}. The later should be addressed together with Art. 45 (1), (2)	

A complete analysis of AV overtaking maneuver will be performed, to define the ***Atomic Propositions*** for the early stages of detecting, planning and making sure but also for the last stage of concretely performing the maneuver. Automation preparedness is improved by establishing a multilevel hierarchy. The logic formulas **for Linear Temporal Logic (LTL)** will be then expressed in terms of following: *Detecting-Need & Types-of-Overtaking, Pre-Check-Overtaking and Perform-Overtaking*. Finally, the ***Temporal Logic Diagram*** will be built, assigning time descriptions to the former untimed sequence of modal Logic Flow Chart and, by explicitly making use of the *temporal logic* concepts of *always true* and *eventually true*, allowing further development *in **High Order Language (HOL)***.

Modal Logic Flow Chart supplies sufficient information for further definition of atomic propositions as per Table 2, including both their interpretation and sequence. The three important phases, *Detecting Need & Type of Overtaking*, *Pre-Check Overtaking* and *Perform Overtaking* considered itself as level 1.

As described in logic interpretation, during the detection phase no maneuver is executed yet but the atomic propositions are assigned with the Boolean values in order

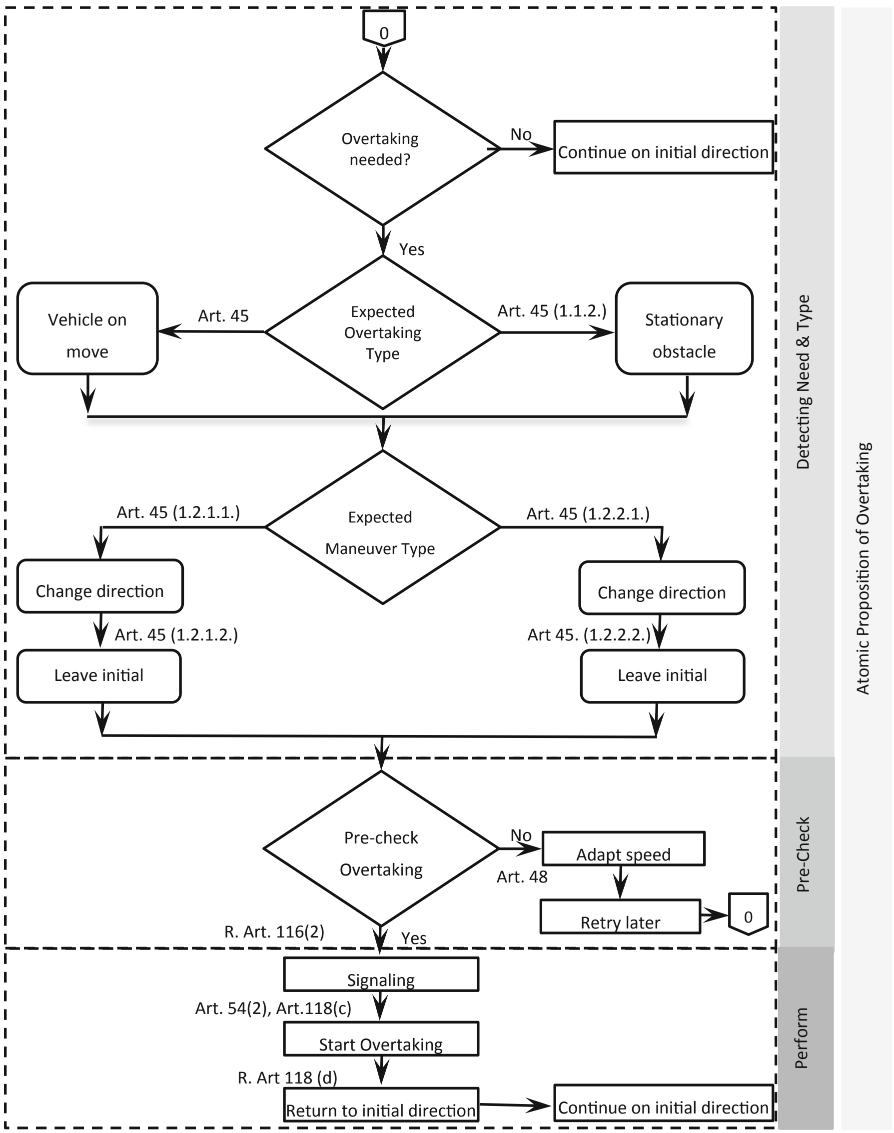

Fig. 3. Modal logic flow chart of overtaking.

to establish what type of overtaking if any, should be executed in a later phase. The assignments have following signification:

- for the level 2. AP *Overtaken-Needed?* value 1 and 0 simply indicates if AP is True or False,

Table 2. Atomic propositions, level and interpretations for *Detecting Need &Type of Overtaking*.

Level	Time	Atomic propositions (AP)	Logic interpretation
1.	$t_0 - t_3$	*Detecting-Need & Types-of-OT*	Determine if an OT is necessary and its type
2.	$t_0 - t_1$	*Overtaken-Needed?*	Determine whether an OT is necessary:{1, 0}
2.	$t_1 - t_2$	*Detect-Overtaken-Type*	Determine the type of overtaken entity:{m, n}. Coded as 1 when values m, n detected, 0 otherwise (before)
3.		*Vehicle-on-Move*	:=m, Coded as 1 if the entity to be overtaken is a vehicle on move, 0 otherwise
3.		*Stationary-Obstacle*	:=n, Coded as 1 if the entity to be overtaken is an stationary obstacle, 0 otherwise
2.	$t_2 - t_3$	*Detect-maneuver-Type*	Determine how to perform OT:{p, q, r} Coded as 1 when values p, q, r detected, 0 otherwise (before)
3.		*Change-Direction*	:=p, Coded as 1 if requested, 0 otherwise
3.		*Leave-Initial-Lane*	:=q, Coded as 1 if requested, 0 otherwise
3.		*Leave-Initial-Vehicle-Row*	:=r, Coded as 1 if requested, 0 otherwise

- for the level 2. APs, *Detect-Overtaken-Type* and *Detect-Maneuver-Type,* the value 1 means that the detection processes have been completed (the values m, n and respectively p, q, r were assigned with their Boolean values) and value 0 otherwise.

Any change of *Overtaken-Needed?* from 1 to 0 reset to 0 the APs *Detect-Overtaken-Type* and *Detect-Maneuver-Type* while any change of *Overtaken-Needed?* from 0 to 1 trigger restarting their assessment. If an overtaking is requested, at the final of detecting process, all three Level 2. APs should have value 1 (true) and the overtaking vector OT (o m n p q r) should be fully evaluated. E.g. an OT (1 0 1 1 0 1) means that an overtaken is requested, the obstacle is not a vehicle on move but stationary and the maneuver should be done by changing direction and not leaving the initial lane but only leaving the initial row of vehicles.

Formulation of traffic rules in Linear-Temporal-Language (LTL) based on atomic propositions completes the codification process, facilitates the logic automation and allow a formal model checking [9]. The resulted formulas for *Detecting Need & Type of Overtaking*, specific to above defined time intervals, are:

1. Overtaking identified as necessary:

$$\mathcal{F}_{(0-1)} = f(\text{Overtaken-Needed?}), \tag{3}$$

where $\mathcal{F}_{(0-1)}$ is the formula evaluated between the time points [t_0, t_1], $f(AP)$ – the function assessing the atomic proposition AP always as true.

2. Overtaking is the maneuver through which one vehicle passes another vehicle or an obstacle that is on the same lane -Art 45, (1.1.1) & (1.1.2):

$$\mathcal{F}_{(1-2)} = f(\text{Detect-Overtaken-Type}\rightarrow\text{Vehicle-on-Move} \oplus \text{Stationary-Obstacle}) \quad (4)$$

3. Overtaking is the maneuver (..) being executed by changing the running direction and leaving the initial lane or row of vehicles - Art 45 (1.1.1.1) & (1.1.1.2) & (1.1.2.1) & (1.1.2.2):

$$\mathcal{F}_{(2-3)} = f(\text{Detect-Maneuver-Type}\rightarrow ((\text{Change-Direction} \wedge \text{Leave-Initial-Lane}) \oplus (\textit{Change-Direction} \wedge \textit{Leave-Initial-Vehicle-Row}) \quad (5)$$

4. When overtaking identified as necessary that is the maneuver through which one vehicle passes another vehicle or an obstacle that is on the same lane, being executed by changing the running direction and leaving the initial lane or row of vehicles – Art 45 (1) & (2):

$$\mathcal{F}_{(0-3)} = f(\text{Detecting-Need \& Types-of-Overtaking}\rightarrow\text{Overtaken-Needed?}\rightarrow\text{Detect-Overtaken-Type}\rightarrow\text{Detect-Maneuver-Type}) \quad (6)$$

For the brevity the similar formulation of *Pre-Check of Overtaking* and *the Perform-Overtaking* are not included in the present work. The final logic formulas of them are:

1. Overtaking is safe as both conditions related to infrastructure and other users are fulfilled R. Art. 120 (1) (2):

$$\mathcal{F}_{(3-5)} = f(\textbf{Pre-Check-Overtaking}\rightarrow (\text{Pre-Check-Infrastructure} \wedge \text{Pre-Check-Road-Users}) \quad (7)$$

2. Perform overtaking according to Art 45 (1), (2), (3), R. Art. 116 (2), R. Art. 118, c - d:

$$\mathcal{F}_{(5-9)} = f(\textbf{Perform-Overtaking}\rightarrow\text{Signaling}\rightarrow\text{Start-Overtaking}\rightarrow\text{Advance-Overtaking}\rightarrow\text{Complete-Overtaking}) \quad (8)$$

Finally, the logic formulation of Overtaking maneuver in Linear Temporal Language is expressed as follows:

$$\mathcal{F}_{(0-9)} = f(\textbf{Overtaking} \rightarrow \textbf{Detecting-Need \& Types-of-Overtaking} \rightarrow \textbf{Pre-Check-Overtaking} \rightarrow \textbf{Perform-Overtaking}) \quad (9)$$

and the Overtaking is now fully coded from the moment t_0 when the need is identified, till t_9 when the maneuver is completed. The processes' sequence related to the above described atomic propositions and logic formulas is graphically presented in Fig. 4.

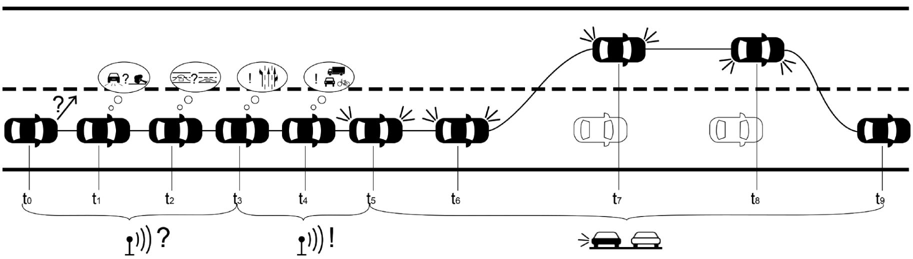

Fig. 4. Temporal logic diagram.

The three major phases of overtaking were logically coded over their validity time intervals: *Detecting-Need & Type-of-Overtaking* ($t_0 \div t_3$), *Pre-Check-Overtaking* ($t_3 \div t_5$) and *Perform-Overtaking* ($t_5 \div t_9$) and they are now fully prepared for automation.

4 Conclusions and Future Work

The Traffic Code Violating Monitor was proposed in order to keep the autonomous vehicles accountable against the traffic rules. Usually these rules are consolidated in National Traffic Codes and approved as laws by the authorities, being therefore expressed using legal specific terms, syntax and semantic which improve the precision comparing with natural language but not enough to allow an immediate automation.

A *Legal Analysis*, as a first step to resolve ambiguity is required but a concrete approach is still missing by now in recent literature. The author proposed separation of the traffic code in two major subsets of rules, concerning the responsibility of the user and AV, respectively. Two concepts are newly introduced, first being the *Gaps Free Set of Regulation,* meaning there is no traffic rule which is not assigned at least to one of the two subsets, which is important to consider for innovative and disruptive technologies. The second concept is that of a *Set of Regulation Free of Shared Regulation* meaning that the responsibility for every situation is entirely assigned, either to the user or to the autonomous vehicle. That is an idealized case, when the two defined subsets were disjoint, which is obviously not the case in reality, but its consideration helps defining a third rules subset, the intersection of the first two major subsets, that needs special attention.

Mandatory steps of legal analysis were defined and then implemented for the Overtaking case study, namely the *Elimination of inherent regulation redundancy* and *Logical break down of legal text.*

The *Logic Analysis* was conceived as the transition from Legal to Engineering Analysis and it consist of *Modal Logic Flow Chart* that assemblies sequentially the elements of the modelled maneuver, making use explicitly of *modal logic* concepts of *necessarily true* and *possibly true*.

Consequently, a complete analysis of AV's overtaking has been performed, generating for the first time the *Atomic Propositions* not only for the last stage of concretely performing the maneuver but also for the early stages of detecting, planning and making sure. For helping automation, a multilevel hierarchy has been proposed within the *Atomic Proposition Table.*

The logic formulas for Linear Temporal Logic (LTL) have been expressed in terms of atomic propositions for *Detecting-Need & Types-of-Overtaking, Pre-Check-Overtaking and Perform-Overtaking*. Finally, the *Temporal Logic Diagram* is constructed assigning time descriptions to the former untimed sequence of Modal Logic Flow Chart and allowing further development in High Order Language (HOL) by making use explicitly of the *temporal logic* concepts of *always true* and *eventually true.*

After facilitating a *better automation* through the logic analysis of overtaking rule, the *expressivity* should be enabled by *Engineering Concretization* in a future work. The author proposed to develop for the first time the overtaking model for three vehicles where at least the overtaken vehicle is AV, as a basis for Traffic Code Violating Monitor.

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