Scenario-Based Safety Assessment Framework for Automated Vehicles

Jeroen Ploeg[1], Erwin de Gelder[1]*, Martin Slavík[2], Eley Querner[2],
Thomas Webster[3], and Niels de Boer[3]

[1] TNO Singapore, 2 Science Park Drive #02-07 Tower A, Singapore 118222
[2] TÜV SÜD Asia Pacific Pte Ltd, Singapore
[3] Nanyang Technological University, Singapore

Abstract Automated vehicles (AVs) are expected to increase traffic safety and traffic efficiency, among others by enabling flexible mobility-on-demand systems. This is particularly important in Singapore, being one of the world's most densely populated countries, which is why the Singaporean authorities are currently actively facilitating the deployment of AVs. As a consequence, however, the need arises for a formal AV road approval procedure. To this end, a safety assessment framework is proposed, which combines aspects of the standardized functional safety design methodology with a traffic scenario-based approach. The latter involves using driving data to extract AV-relevant traffic scenarios. The underlying approach is based on decomposition of scenarios into elementary events, subsequent scenario parametrization, and sampling of the estimated probability density functions of the scenario parameters to create test scenarios. The resulting test scenarios are subsequently employed for virtual testing in a simulation environment and physical testing on a proving ground and in real life. As a result, the proposed assessment pipeline thus provides statistically relevant and quantitative measures for the AV performance in a relatively short time frame due to the simulation-based approach. Ultimately, the proposed methodology provides authorities with a formal road approval procedure for AVs. In particular, the proposed methodology will support the Singaporean Land Transport Authority for road approval of AVs.

1 Introduction

The development of automated vehicles (AVs) has made significant progress. It is expected that before 2020, automated and autonomous vehicles will be introduced in controlled environments, whereas autonomous vehicles will be mainstream by 2040 [1] or earlier [2]. Especially in densely populated cities such as Singapore, there is a need for automated vehicles to increase traffic safety and traffic efficiency by enabling flexible, automated, mobility-on-demand systems [3], scheduled services for public transport needs, and automated freight and service vehicles to support 24 hours operations and labor shortage needs.

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* Corresponding author, e-mail: `erwin.degelder@tno.nl`.

An important aspect in the development of autonomous vehicles (AVs) is the safety assessment of the AVs [4–8]. For legal and public acceptance of AVs, a clear definition of system performance is important, as are quantitative measures for the system quality. The more traditional methods [9, 10], used for evaluation of driver assistance systems, are no longer sufficient for assessment of the safety of higher level AVs, as it is not feasible to complete the quantity of testing required by these methodologies [8]. Therefore, the development of assessment methods is important to not delay the deployment of AVs [4].

We propose a methodology for the safety assessment of AVs that includes functional safety [9], safety of the intended functionality [11], and behavioral safety [12], ultimately resulting in a qualitative and quantitative assessment of the safety of the AV. This is achieved by adopting a traffic scenario-based assessment [5, 7, 13]. The traffic scenarios are obtained through analysis of real-world driving data, after which the scenarios are verified regarding their relevance for the system under test. The scenarios are used for virtual and physical safety validation of the system under test, ultimately resulting in a safety report providing road approval authorities with quantitative measures regarding the safe performance of the system under test.

The proposed assessment methodology provides an efficient procedure for road approval for AVs, as the assessment methodology allows for three go/no-go decisions, based on the design review, the virtual safety validation, and, finally, a safety report based on all tests. Furthermore, using test scenarios derived from real-world driving data, the methodology provides quantitative measures regarding the safe performance of the AV in real-world traffic.

The proposed methodology provides authorities with a formal road approval procedure for AVs. In particular, the proposed methodology will be used by CETRAN[4] to support the Land Transport Authority from Singapore for road approval of AVs.

The structure of the paper is as follows. A background of relevant automotive safety notions are detailed in Section 2. Next, in Section 3, the proposed safety assessment pipeline is described. Section 4 provides more details on the method of scenario generation after which Section 5 summarizes the main conclusions.

2 Automotive safety

The field of automotive safety is very broad, characterized by many types of safety and definitions of the various aspects of safety. Nevertheless, on a high abstraction level, two types of safety are commonly distinguished, being *functional safety* and *safety of the intended functionality* (SOTIF). A third type of safety, being *behavioral safety* can also be identified, relating to how the AV is programmed to behave.

Functional safety, SOTIF, and behavioral safety can be jointly referred to as *operational safety*, as illustrated in Figure 1. This figure also mentions *best*

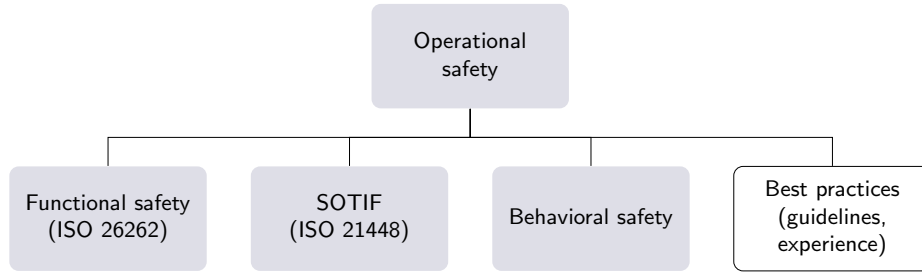[4] Centre of Excellence for Testing and Research of Autonomous Vehicles at NTU, Singapore.

Figure 1: Operational safety components

practices, which refers to the use of experience and (non-standard) guidelines, commonly included due to limitations of the ISO 26262 standard. SOTIF intends to address these limitations, but given the fact that the SOTIF standard is still under development, it is expected that best practices will remain useful, for the time being.

The three types of safety as introduced here, are briefly explained in the next sections.

2.1 Functional safety

Functional safety is defined in IEC 61508 as the absence of unacceptable risk due to hazards caused by malfunctioning behavior of systems. ISO/DIS 26262 [9], commonly referred to as ISO 26262, is an adaptation of the IEC 61508 for the automotive industry. It applies to safety-related electrical/electronic systems, specifically for road vehicles under 3500 kg.

The current ISO 26262 standard was introduced in 2011 and does not include automated vehicles. Advanced driver assistance systems (ADAS) will be included in the next release of ISO 26262, scheduled for 2018. In ISO 26262, the notion of functional safety has been defined as follows.

Definition 1 (Functional safety [9, 14]). *Functional safety is the absence of unreasonable risk due to hazards caused by malfunctioning behavior of electrical/electronics systems.*

According to this definition, functional safety is 'looking inwards', focusing on malfunctioning components of the vehicle. The process that must be followed according to the ISO 26262 to arrive at a functionally safe system design, the so-called 'safety lifecycle', is shown in Figure 2. In the scope of AV safety assessment, the validation processes included in this lifecycle are particularly relevant; These are briefly summarized as follows.

3-7 *Hazard analysis and risk assessment (HARA)* — The HARA is a method to identify and categorize hazardous events, to specify safety goals, and to assign automotive safety integrity levels (ASILs) to system components, related to the prevention or mitigation of the associated hazards in order to avoid unreasonable risk.
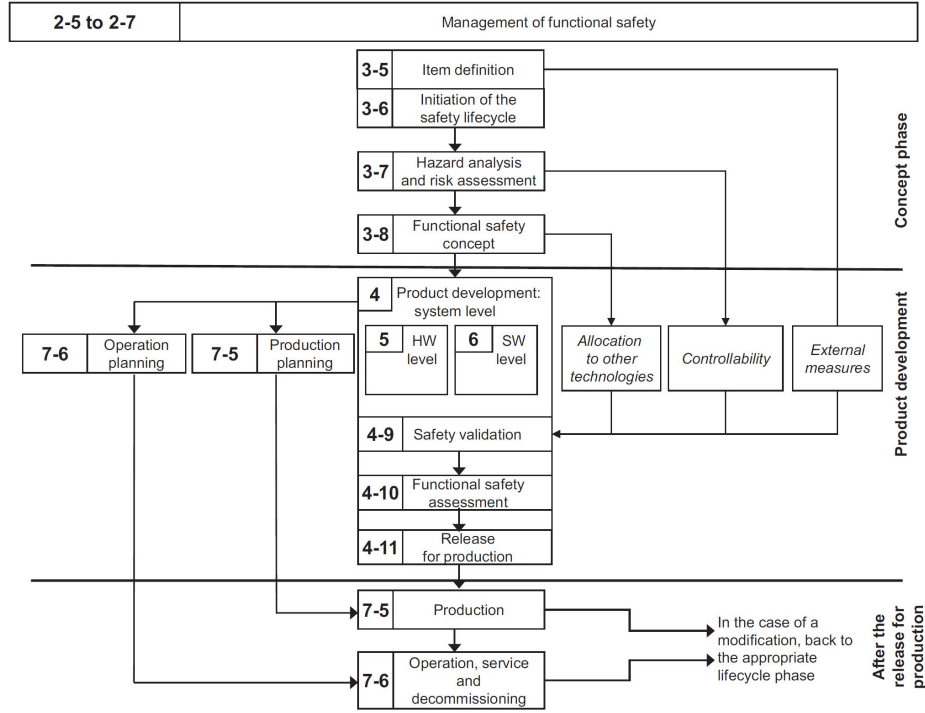
Figure 2: The ISO 26262 safety lifecycle (extracted from [9]).

3-8 *Functional safety concept* — This involves specification of functions and their interactions which are necessary to achieve the desired safe behavior. As such, it is a step in the design, rather than an assessment-oriented activity. However, *review* of the functional safety concept should certainly be part of the AV safety assessment framework. It is noted that the *technical safety concept* is omitted here, since that is typically part of the product development.

4-9 *Safety validation* — The safety validation checks, on a vehicle level, whether the safety goals are fulfilled. This is done through virtual and physical testing, representing the 'intended use cases', i.e., the traffic scenarios as they occur in the envisioned operational environment of the AV.

The key notion in the above list is *safety validation* which, in fact, is the ultimate objective of the proposed assessment framework presented in the next section. In ISO 26262, this notion is defined as follows.

Definition 2 (Safety validation [9]). *Safety validation is the assurance, based on examination and tests, that the safety goals are sufficient and have been achieved.*

When adopting the selected topics of the lifecycle, a first step is made towards a process for safety assessment of AVs from the perspective of functional safety;
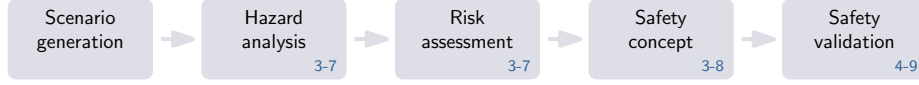
Figure 3: Functional safety assessment steps, inspired by the ISO 26262.

This is visualized in Figure 3, where the scenario generation component, which is not included in the original ISO process, aims to generate relevant traffic scenarios (either or not as part of overarching 'use cases').

In summary, it can be concluded that the ISO 26262 standard is oriented towards development of a certain automation functionality, as part of which verification and validation processes are implemented. The objective of the assessment framework, however, is not to design a safe AV but to assess the safety of a given design. Consequently, the process from Figure 3 needs to be further adapted, both in terminology and in contents, to better fit this objective.

2.2 Safety of the intended functionality (SOTIF)

As mentioned earlier, functional safety is 'inward looking', in the sense that it focuses on malfunctioning components of the vehicle's automation system. For AVs, however, it is also important to 'look outwards', i.e., to include inherent sensor and perception system limitations in the safety assessment framework and to take decision-making capabilities of the AV into account. These aspects of AV safety are covered by the notion of *safety of the intended functionality* (SOTIF).

SOTIF relates to hazardous behavior which is not caused by a malfunction. In particular for AVs, SOTIF is often related to environmental perception [15] since environmental sensors typically have inherent limitations, which may cause the AV to behave unsafely. Examples of such limitations are the occurrence of so-called 'ghosts' in radar measurements, or the blinding effect of direct sunlight in case of camera systems. This type of safety is described in the standard ISO/WD PAS 21448, in short referred to as ISO 21448, which is currently being drafted [11]. This draft standard defines SOTIF in a very broad sense as "the absence of unreasonable risk of the intended functions". In the scope of the assessment framework, a more precise definition will be adopted, as proposed below.

Definition 3 (Safety of the intended functionality). *Safety of the intended functionality (SOTIF) is the ability of the automation system to correctly comprehend the environmental situation and behave safely, by ensuring that the systems and components are operating within their design boundaries and, if they are not, by activating appropriate countermeasures.*
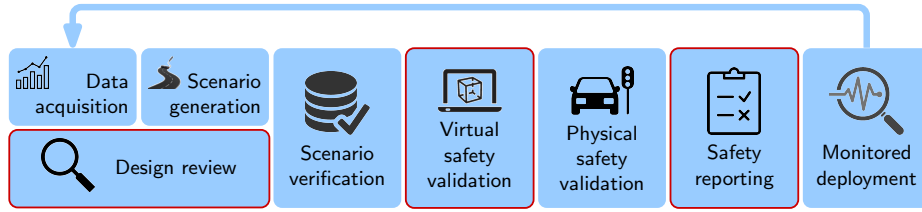
Figure 4: Outline of the safety assessment pipeline.

2.3 Behavioral safety

Next to SOTIF, in a recent report by Waymo [12], the notion of *behavioral safety* is introduced as "An aspect of system safety that focuses on how a system should behave normally in its environment to avoid hazards and reduce the risk of mishaps: for instance, detect objects and respond in a safe way (slow down, stop, turn, lane change, etc.)." This type of safety thus addresses the AV behavior as intentionally programmed by the developer, with all components and subsystems of the vehicle's automation system operating as intended. A relevant question in this context is, for instance, whether the AV follows the traffic rules. Since it is questionable if this type of safety will be part of the final version of ISO 21448, behavioral safety is regarded as a third type of safety.

The UN-ECE Automatically Commanded Steering Function group is drafting amendments to UN-ECE Regulation 79 which describes the expected behavior of a level 3 automated driving system [16]. However, the scope is limited to well-structured and controlled highways where there are no pedestrians/bicycles, at least two lanes in the direction of travel, and a physical separation between contraflow traffic. The authors are not aware of existing art describing the behavioral safety requirements for a level 4 automated driving system operating in complex urban environments, hence this study aims to provide some definition to the behavioral characteristics required for a vehicle using the context of Singapore's road traffic rules and traffic environment as the case study. The proposed assessment methodology makes use of traffic scenarios to assess the behavioral safety of the AV. The safety assessment pipeline, which is described in Section 3, sets out how the scenarios are defined from a design review exercise and from scenario generation using acquisition of real-world driving data. Next, the AV's behavioral performance is assessed through virtual and physical safety validation using these scenarios.

3 The safety assessment pipeline

The proposed AV safety assessment methodology is schematically outlined in Figure 4. This figure shows the assessment pipeline, which consists of eight steps (or 'components') as further introduced below.

1. *Design review* — During AV development, the AV developer must create a so-called *safety case* according to ISO 26262 standard on functional safety [9], which provides extensive information about the safety measures of the AV's automation system. This safety case serves a two-fold purpose in the scope of the assessment pipeline. First, the information contained in the safety case documents allows for a qualitative assessment of the functional safety of the AV, upon which a decision is made about the continuation of the safety assessment process. Second, the design review also yields insight into test scenarios that may be particularly challenging for the AV, or components of the automation system that pose a threat in case they fail (e.g., a 'single point of failure'). This knowledge, in turn, is helpful in defining and selecting the test scenarios to be simulated in the *scenario verification* component of the assessment pipeline.

2. *Data acquisition* — This component aims to obtain real-world driving data, ultimately providing a statistically accurate set of traffic scenarios relevant to the AV. Ideally, the driving data should be obtained by AVs, since manual traffic may behave differently in the presence of AVs, but this is not feasible in the early stages of AV deployment. The data includes, among others, ego vehicle data and object-level data of other traffic participants. The data acquisition involves converting the collected data to a standardized format, allowing for a smooth transition to the next step of the pipeline, and also includes data validation and 'cleaning' (e.g., removal of outliers).

3. *Scenario generation* — In this step, candidate test scenarios are generated from the acquired data for virtual evaluation of the AV performance. To this end, measured scenarios are decomposed into elementary 'events' and 'activities', enabling parametrization of the scenario data. Next, with a sufficient amount of measurement data, probability distributions of the scenario parameters are estimated. From these probability distributions, parameter sets can be sampled to obtain candidate traffic scenarios for virtual testing by re-creating variations of the original scenario. Here, safety-critical test scenarios are generated through parameter sampling which is biased towards safety-critical situations, i.e., the tails of the probability distribution.

4. *Scenario verification* — Scenario verification involves reducing the number of candidate test scenarios by retaining only those scenarios that are categorized as being safety-critical for the particular AV under test. This component takes the results of both the *scenario generation* and the *design review* components as inputs, while also taking into account the so-called 'safety of the intended functionality' (SOTIF) [11], and behavioral safety. On the other hand, the amount of test scenarios will be increased by introducing additional tests involving component failures, as dictated by functional safety considerations. The net result of this component is, therefore, a definitive set of test scenarios that provides quantitative information about all aspects of the operational safety of the AV when it is subjected to those test scenarios.

5. *Virtual safety validation* — The next component of the pipeline involves quantitative assessment of the AV safety through simulation of the selected test scenarios, employing a high-fidelity simulation environment capable of

simulating the AV, its perception and control software, other road users, and the static environment. The simulation results are quantitatively assessed by means of key performance indicators (KPIs). These KPIs are subject to pass/fail thresholds, upon which it can be objectively decided whether to proceed to the next step of the assessment process or not.

6. *Physical safety validation* — This component of the assessment pipeline aims to verify the AV performance through practical tests, employing functional safety and SOTIF requirements, formulated in terms of KPIs. The first aspect of the physical safety validation involves the selection of a subset of the virtual test scenarios to perform physical testing, which includes tests with the AV on a test track as well as field tests in relevant real-world situations. Similar to the virtual safety validation component, quantitative assessment of the AV safety performance is performed through KPIs with pass/fail criteria, thus providing an objective basis for approval regarding deployment of the AV in the intended operational environment.

7. *Safety reporting* — In this step, a comprehensive qualitative judgment, reflecting the overall impression, and a quantitative judgment, presenting the KPI values of previous assessment steps, are provided to the relevant authorities and the AV developer. Also, formal recommendations are given regarding the road approval of the AV to the relevant authorities.

8. *Monitored deployment* — After successful completion of the previous component, the AV is allowed to drive on public roads, possibly restricted to certain areas and/or certain conditions. During this deployment phase, the AV developer is required to upload driving data in a near real-time fashion to allow for monitoring the AV behavior. This is implemented for two reasons. First, also after completion of the assessment pipeline, road authorities need to be able to monitor safety continuously. Second, the uploaded data is, after anonymization, fed back to the data acquisition component. The latter allows for continuous extension and improvement of the scenario database, while also being able to adapt to new types of transportation such as personal mobility devices.

Remark 1. It is noted that the design review and the virtual safety validation include rating the AV safety level by means of pass/fail criteria, upon which the pipeline process will be continued or not. This is indicated in Figure 4 by means of solid red borders of the corresponding blocks. The physical safety validation, in fact, also includes a pass/fail rating, but the outcome will only be published in the safety report as the last step in the procedure.

4 Scenario generation

The objective of the scenario generation component is to generate candidate traffic scenarios for both virtual testing and physical testing with the ultimate goal to objectively and reproducibly assess operational safety of the AV[5]. The

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[5] Note that the generated scenarios are still 'candidate' scenarios. Only in the *scenario verification* component, the definitive test scenarios are selected.

scenario generation is based on a unified ontology for road traffic, in which road-traffic *scenarios* is an important notion, as further explained in the next two subsections.

4.1   Scenarios

The scenario-based approach is the key property of the assessment methodology, which is why a definition of the notion of scenario is presented first. Several definitions of the notion of scenario in the context of automated driving are proposed [17–20]. We adopt the definition of De Gelder et al. [20], as it is more applicable for the context of this paper. The definition of scenario is as follows.

Definition 4 (Scenario).   *A scenario is a quantitative description of the ego vehicle, its activities and/or goals, its static environment, and its dynamic environment. From the perspective of the ego vehicle, it contains all relevant events.*

Note that this definition is closely related to the definitions of Geyer et al. [17], Ulbrich et al. [18] and Elrofai et al. [19]. Definition 4 deviates from these existing definitions in the fact that it explicitly states that a scenario is a quantitative description. Similar (quantitative) scenarios can be abstracted by means of a qualitative description, referred to as *scenario class* [20]. A scenario class thus encompasses multiple scenarios.

To store measured scenarios in a structured way, such that they can be easily retrieved afterwards for test scenario generation, it is proposed to set up a hierarchical system of *tags*, corresponding to the aforementioned road traffic ontology[6]. As such, tags provide a semantic classification of the scenario in terms of, e.g., weather, road type, and target vehicle maneuvers. In accordance with the hierarchical approach, tags are arranged into *trees*, as illustrated in Figure 5. This figure shows three examples, relating to type of weather, road type, and target vehicle maneuver, respectively. Tags that are in the same layer are mutually exclusive, whereas different layers of a tree represent different levels of abstraction [22].

4.2   Events

A scenario can be decomposed into elementary building blocks, so-called *events* and *activities*. An event is defined as follows [20].

Definition 5 (Event).   *An event marks the time instant at which a mode transition occurs, such that before and after an event, the state corresponds to two different modes.*

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[6] Alternatively, a hierarchical system of types of scenarios may be created, thus directly classifying the scenario itself. However, scenarios may not be mutually exclusive. For instance, the same scenario might be relevant in highway and in urban environments. In case of direct scenario classification, this situation can only be solved by storing the same scenario multiple times, which is inefficient and prone to errors.
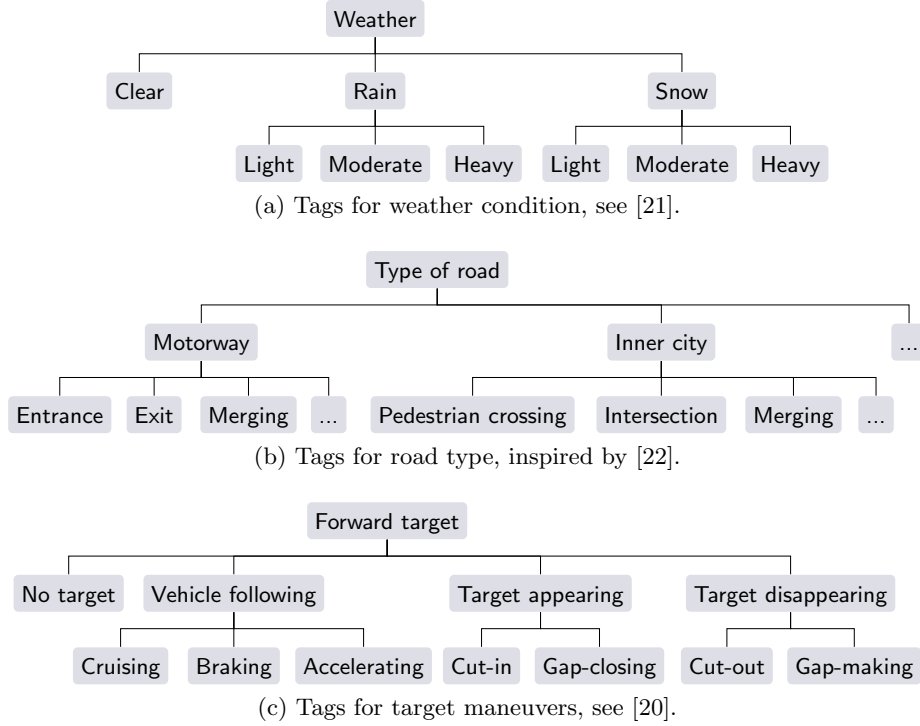
(a) Tags for weather condition, see [21].

(b) Tags for road type, inspired by [22].

(c) Tags for target maneuvers, see [20].

Figure 5: Examples of hierarchical structures ('trees') of tags regarding (a) type of weather, (b) road type, and (c) target maneuvers.

A mode transition may be caused by an abrupt change of either an input signal, a parameter, or a state. For example, pushing the brake pedal may cause a mode transition and therefore, this may be regarded as an event. The inter-event time interval, i.e., the time period between two subsequent events, is characterized by the occurrence of a certain *activity*. For example, when the longitudinal acceleration is negative during such an inter-event time interval, the activity corresponds to braking.

In general, a scenario contains multiple events and activities, whose temporal properties are such that both parallel and serial activities can be distinguished. As an example, Figure 6 shows two consecutive scenarios in which the ego vehicle (the red vehicle) is being overtaken by a station wagon (first scenario), after which the ego vehicle overtakes a pickup truck (second scenario). Figure 7 shows the activities and events for this example, in which the behaviors of the three actors are characterized by a number of serial activities for the longitudinal and lateral behavior. Events and activities thus relate to actors.

The advantage of decomposing scenarios into elementary events and (inter-event) activities is threefold:

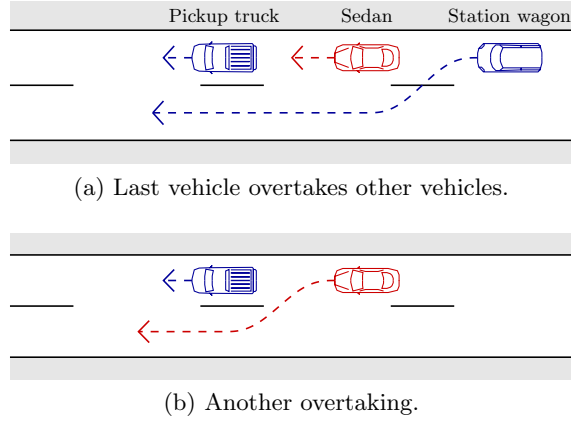(a) Last vehicle overtakes other vehicles.

(b) Another overtaking.

Figure 6: Schematic overview of two consecutive traffic scenarios. The sedan (red vehicle) is defined as the ego vehicle. First, the station wagon (the last vehicle in (a)) overtakes both vehicles. Next, the ego vehicle overtakes the pickup truck (first vehicle in (a)).

1. Whereas the amount of relevant scenarios might become very large over time, it is expected that only a *limited set of essentially different activities* will be obtained, being a direct consequence of the rather limited number of actions a vehicle can perform (basically change of speed and direction).
2. When analyzing measured data to extract scenarios, events are instrumental in *automatic scenario recognition*. Similarly, events can be directly detected by the ego vehicle in real life, providing a trigger for data logging.
3. The decomposition of a scenario into several activities allows for parametrization of scenarios, which, in turn, enables estimation of a (possibly multivariate) probability density function (PDF) of the parameters. This PDF can then be sampled in a specific way, e.g., emphasizing safety-critical situations or generating activities that are not actually encountered in the measurement data. Moreover, sampling from the PDF creates the possibility to automatically sample those situations from the parameter set during which the vehicle under test shows safety-critical behavior, without *a priori* knowledge of which scenarios are critical for the vehicle [13]. In other words, scenario parametrization allows for the systematic generation of candidate test scenarios for safety assessment of the vehicle under test.

4.3 Scenario generation topics

Having introduced the notions of scenario, event, and activity, the scenario generation component of the assessment pipeline can now be described in terms of the different topics below, adding more detail to the brief description in Section 3.

1. *Event detection* — This involves the automated detection of events, either during off-line analysis of measurement data, or in real-time during data
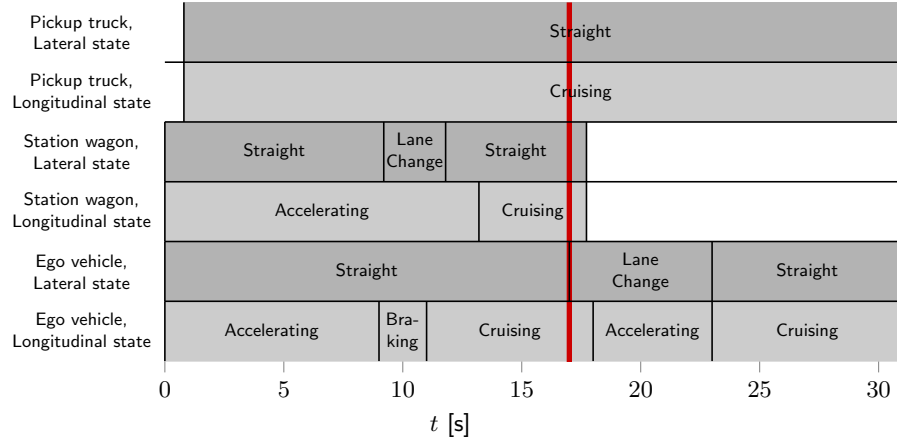
Figure 7: Example of a scenario decomposition into parallel and serial activities. The vertical lines represent the events. The red vertical line at $t = 16\,\text{s}$ indicates the end of the first scenario and the start of the second scenario.

  collection. Since the inter-event time intervals relate to the activities, the detection of events automatically result in the detection of the inter-event activities.

2. *Activity parametrization* — Next, detected activities will be parametrized and the PDF of the parameters will be estimated.

3. *Scenario mining* — Next, based on certain 'patterns' in detected activities and events, they will be clustered into full scenarios. This topic also includes scenario tagging.

4. *Test scenario generation* — Finally, (candidate) test scenarios can be generated by selecting scenario classes of interest, using the tagging system, upon which instances of those scenario classes are generated by drawing samples from the probability distribution of the activity parameters[7]. Here, an 'instance of a scenario class' is the quantitative scenario description. As explained in Section 4.2, the sampling is biased towards the tails of the probability distribution, representing the most extreme and/or rare situations.

5   Conclusion

The need for automated vehicles (AVs) in a dense city such as Singapore will require to have an assessment methodology for road approval authorities in place. Therefore, we proposed an assessment methodology for the safety assessment of AVs that includes functional safety, safety of the intended functionality, and

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[7] It is still a topic of research which and how many test scenarios need to be sampled from the total set of real-world scenarios. These questions are covered by the notion of *completeness*.

behavioral safety. This, ultimately, results in a qualitative and quantitative assessment of the safety of an AV when operating in real-world traffic.

The proposed methodology adopts a scenario-based assessment, using real-world data to employ a scenario database with scenarios that an AV might encounter when operating in real life. Next to a qualitative assessment of the AV, i.e., the design review, a quantitative assessment is performed by using the scenarios for virtual and physical safety validation. By monitoring the deployment of AVs, new data is acquired that can be used for continuous extension and improvement of the scenario database.

Ultimately, the proposed methodology provides authorities with a formal road approval procedure for AVs. In particular, the proposed methodology will be used to support the Land Transport Authority from Singapore for road approval of AVs.

Acknowledgment

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