Definition of scenario in the context of the assessment of automated vehicles

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***Abstract*— The development of assessment methods for quantifying quality and performance aspects of Automated Vehicles (AVs) is important to not delay the deployment of AVs. As traditional methods for approving vehicles are not applicable for AVs, other approaches have been proposed. One such an approach is to perform scenario-based assessment, where the test cases are derived from real-world scenarios obtained from real-world driving data. To minimize any ambiguity regarding these test cases and scenarios, a clear definition of the notion of scenario is required. In this paper, we propose a more concrete definition of scenario, compared to what is known to the authors from the literature. This is achieved by proposing an ontology in which the quantitative building blocks of a scenario are defined. An example illustrates that the presented ontology is applicable for scenario-based assessment of AVs.**

I. Introduction

An important aspect in the development of automated vehicles (AVs) is the assessment of quality and performance aspects of the AVs, such as safety, comfort, and efficiency [1]–[8]. For legal and public acceptance of AVs, it is important that there is a clear definition of system performance and that there are quantitative measures for the system quality. The more traditional methods [9], [10], used for evaluation of driver assistance systems, are no longer valid for the assessment of quality and performance aspects of an AV [8]. Therefore, a scenario-based approach is proposed [4], [7]. For the scenario-based assessment, proper specification of scenarios is crucial since they are directly reflected in test cases used for scenario-based assessment [2]. This paper proposes an ontology for these *scenarios*.

The notion of scenario is frequently used in the context of automated driving [4]–[6], [11]–[17], despite the fact that an explicit definition is often not provided. However, as mentioned by various authors [2]–[4], [17]–[22], using a scenario in the context of the development or assessment of AVs requires a clear definition of a scenario. To this end, few definitions of a scenario in the context of (automated) driving have been proposed [21]–[23]. For the context of the assessment of AVs, however, a more concrete definition of a scenario is required to minimize any ambiguity regarding the scenarios.

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We aim for a definition of a scenario that is, on the one hand, broadly consistent with existing definitions [21]–[23] while, on the other hand, more concrete, such that it is applicable for scenario mining [23] and scenario-based assessment [2], [24]. We propose a definition that is concrete enough to be used in quantitative analysis required for assessment of AVs. This is achieved by defining quantitative building blocks of scenarios in the form of activities and events. An example is provided that illustrates the use of the ontology with a real-world case.

The outline of the paper is as follows. Section II specifies notions that are adopted from literature to define a scenario. Section III describes the ontology of real-world scenarios in the context of automated driving. In Section IV, an application example is provided to illustrate the use of the ontology with a real-world scenario. The paper is concluded in Section V.

II. Nomenclature

For the definition of *scenario* and *event*, several notions are adopted from literature. In this section, the concepts of *ego vehicle*, *actor*, *state*, *model*, *mode*, *activity*, *static environment*, and *dynamic environment* are detailed.

1) Ego vehicle: The ego vehicle refers to the perspective from which the world is seen. Usually, the ego vehicle refers to the vehicle that is perceiving the world through its sensors (see, e.g., [25]) or the vehicle that has to perform a specific task (see, e.g., [26]). In the latter case, the ego vehicle is often referred to as the system under test [2] or the vehicle under test [6].

2) Actor: An actor is an element of a scenario acting on its own behalf [22]. In practice, this can be a driver of a car, a bicyclist, a pedestrian, an automation system, or a combination of a driver and an automation system [21].

3) State: According to the IEEE Standard Glossary of Software Engineering Terminology [27], states are "[...] variables that define the characteristics of a system, component, or simulation". For example, a state could be the acceleration of an actor.

4) Model: Typically, a system is modeled using a differential equation of the form $\dot{x} = f_\theta(x(t), u(t), t)$ [28], where $x(t)$ represents the state vector at time t, $u(t)$ represents an external input vector, and the function $f(\cdot)$ is parametrized by θ.

5) Mode: In some systems, the behavior or evaluation of the system may all of a sudden change abruptly, e.g., due to a sudden change in an input, a model parameter, or the model function. Such a transient is called a mode switch. In each mode, the behavior of the system is described by a particular model with a fixed function f, parameter θ and smooth input $u(t)$ [29].

6) Activity: An activity refers to the behavior of a particular mode. For example, an activity could be described by the label 'braking' or 'changing lane'.

7) Static environment: The static environment refers to the part of a scenario that does not change during a scenario. This includes geo-spatially stationary elements [22]. Although one might argue whether light and weather conditions are dynamic or not [21], [30], in most cases it is reasonable to assume that these conditions are not subject to significant changes during the time frame of a scenario. Hence, light and weather conditions are considered to be part of the static environment.

8) Dynamic environment: As opposed to the static environment, the dynamic environment refers to the part of a scenario that changes during the time frame of a scenario. The dynamic environment is described using the activities that describe the way the states evolve over time. In practice, the dynamic environment mainly consists of the moving actors (other than the ego vehicle) that are relevant to the ego vehicle. Furthermore, road side units that communicate with vehicles within the communication range [31], are also part of the dynamic environment.

Note that it might not always be obvious whether a part of a scenario belongs to the static or dynamic environment. For example, the post of a traffic light can be considered as part of the static environment, while the signal of the traffic light can be considered as part of the dynamic environment. Most important, however, is that all parts of the environment that are relevant to the assessment are described in either the static or the dynamic environment.

III. Ontology

According to Gruber [32], an ontology is an "explicit specification of a conceptualization". As such, in this paper, several concepts are specified and their relations are further detailed. A summary of the ontology is presented in Table I. The characteristics of the terms *scenario class*, *scenario*, *event*, and *activity* are shown in the second column of Table I. The third column of the table shows the relation between the terms and other concepts. For example, a scenario class refers to multiple scenarios and a scenario contains one or multiple events and activities.

First, the context for which this paper describes the ontology is presented in Section III-A. In Section III-B, definitions of scenarios from literature are discussed. Based on this, the main features of a scenario are concluded. Finally, a definition of the term *scenario* is given. A discussion on the scenario classes is provided in Section III-C. The definition of the term *event* is presented in Section III-D.

A. Context of a scenario

Because the notion of scenario is used in many different contexts, a high diversity in definitions of this notion exists (for an overview, see [33], [34]). Therefore, it is reasonable to assume that "there is no 'correct' scenario definition" [33]. As a result, to define the notion of scenario, it is important to consider the context in which it will be used.

TABLE I
Summary of the ontology presented in this paper.

Term	Characteristics	Contents
Scenario class	Qualitative description of scenario	Scenarios Other (less generic) scenario classes One or multiple tags
Scenario	Quantitative description Time interval	One or multiple events One or multiple activities Ego vehicle Static environment Dynamic environment One or multiple tags
Event	Time instant Mode transition End or start of an activity	
Activity	Inter-event time interval Quantitative description of (changing) state Behavior of a particular mode	Model that describes the way the states evolve

In this paper, the context of a scenario is the assessment of automated vehicles. It is assumed that the assessment methodology uses scenarios (i.e., test cases) for which some resulting metrics are compared with a reference [2]. The ultimate goal is to build a database with all relevant scenarios that an AV has to cope with when driving in the real world [4]. Hence, a scenario should be a description of a potential use case of an automated vehicle.

In this paper, *scenario* can refer to either an observed scenario in (real-world driving) data, i.e., a real-world scenario, or a scenario that is used for testing AVs, i.e., a test case. Note that, typically, the difference between the two is that with a real-world scenario, the activity of all actors is described, while for a test case, some goals are specified for the system under test (e.g., the goal could be to drive from A to B) instead of its activity.

B. Definition of scenario

Go and Carroll [35] describe a scenario within the field of system design. They define a scenario as "a description that contains (1) actors, (2) background information on the actors and assumptions about their environment, (3) actors' goals or objectives, and (4) sequences of actions and events. Some applications may omit one of the elements or they may simply or implicitly express it. Although, in general, the elements of scenarios are the same in any field, the use of scenarios is quite different."

Geyer et al. [21] describe a scenario within the context of automated driving. They use the metaphor of a movie or a storybook for describing a scenario. Geyer et al. state that "a scenario includes at least one situation within a scene including the scenery and dynamic elements. However, [a] scenario further includes the ongoing activity of one or both actors." For a further explanation of the terms situation, scene, and scenery, see [21]. It is mentioned that the action of the driver and/or automation might be predefined. In [21], the meaning of action is not detailed.

Ulbrich et al. [22] also define a scenario in the context of automated driving. They define a scenario as "the temporal development between several scenes in a sequence of scenes. Every scenario starts with an initial scene. Actions & events as well as goals & values may be specified to characterize this temporal development in a scenario. Other than a scene, a scenario spans a certain amount of time." They state that actions and events link the different scenes. A further description of actions and events is not given in [22].

Another definition of a scenario in the context of automated driving is given by Elrofai et al. [23]. They define scenario as "the combination of actions and maneuvers of the host vehicle in the passive [i.e., static] environment, and the ongoing activities and maneuvers of the immediate surrounding active [i.e., dynamic] environment for a certain period of time." They further mention that the duration of a scenario typically is in the order of seconds.

Before providing the definition of the notion of scenario, the characteristics of this notion are listed.

1) A scenario corresponds to a time interval: The aforementioned definitions [21]–[23], [35] state that a scenario corresponds to a time interval. Van Notten et al. [33] call such a scenario a chain scenario ("like movies"), as opposed to a snapshot scenario, i.e., a scenario that describes the state at a time instant ("like photos"). The duration of a scenario is in the order of seconds, as explicitly mentioned by Elrofai et al. [23]. Though the duration is not mentioned by Ulbrich et al. [22], the presented example is in the order of seconds. Furthermore, other scenarios regarding (automated) driving are also in the order of seconds, e.g., see [5], [6], [11]–[13], [17].

2) A scenario consists of one or several events [13], [21], [22], [30], [33], [35]–[38]: It can be helpful to develop scenarios using events [34]. Thus, a scenario could be defined as a particular sequence of events or, as Kahn [36] writes, "a scenario results from an attempt to describe in more or less detail some hypothetical sequence of events". Furthermore, Geyer et al. [21] and Ulbrich et al. [22] use the notion of event for describing a scenario, although they do not provide a definition of the term *event*. In Section III-D, we will elaborate on the notion of *event*.

3) Real-world traffic scenarios are quantitative scenarios: Regarding the nature of the data, a scenario can be either qualitative or quantitative [33]. Real-life traffic scenarios are quantitative scenarios, such that they are, e.g., suitable for simulation purposes. A scenario, however, can be described qualitatively, such that it is readable and understandable for human experts. Providing a qualitative description of a quantitative scenario has become known as a story-and-simulation approach [39]. Note that several quantitative scenarios might have the same qualitative description; thus a qualitative description of a scenario does not uniquely define a quantitative scenario. A qualitative description can be regarded as an abstraction of the quantitative scenario.

4) The time interval of a scenario contains all relevant events: According to Geyer et al. [21], "the end of a scenario is defined by the first irrelevant situation with respect to the scenario". In a similar manner, we require that the time interval of a scenario should contain all relevant events. Note that 'relevant' is subjective and, therefore, an event is considered to be relevant, if it is relevant to the ego vehicle.

5) A scenario can contain goal(s) of one or multiple actors: For describing a scenario in real-world data, it is not necessary to describe the goals and as such, Elrofai et al. [23] do not mention this. When describing a scenario that an AV has to cope with, however, its goals (i.e., its driving mission [21]) could be specified rather than its activities [22]. The same holds for other actors within the scenario.

6) A scenario includes the description of the environment: A scenario should include the description of the static and dynamic environment. The static environment does not change during a scenario. Although this is not a general prerequisite of a scenario, the description of the static environment is often included when speaking about traffic scenarios [15], [21]–[23], [26], [40]. Everything that changes during the time interval of a scenario is considered to be part of the dynamic environment.

Hence, we define a scenario as follows.

Definition 1 (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, a scenario contains all relevant events.*

Definition 1 deviates from existing definitions [21]–[23] in that it explicitly mentions that a scenario is quantitative. We use the term *scenario class* to refer to the qualitative description, see Section III-C.

Geyer et al. [21] and Ulbrich et al. [22] use the term *scene* to define a scenario, while Definition 1 describes the scenes implicitly. Thus the scenes do not have to be described explicitly.

Figure 1 provides a schematic overview of the various components of a scenario. As shown in the second row of Fig. 1, a scenario contains a description of the ego vehicle, the dynamic environment, and the static environment. As an example, possible activities of the vehicle in front, which is part of the dynamic environment, are detailed by considering the states 'heading' and 'speed'. The two rows of the activities show more generic descriptions and more detailed descriptions, respectively, of some possible activities.

C. Scenario classes

In this section, the notion of scenario class is introduced. As proposed above, a scenario in the context of the performance assessment of an AV needs to be quantitative. However, a qualitative description of each scenario exists. The qualitative description can be regarded as an abstraction of the quantitative scenario. As a result, for a qualitative description there is a virtually infinite number of scenarios.

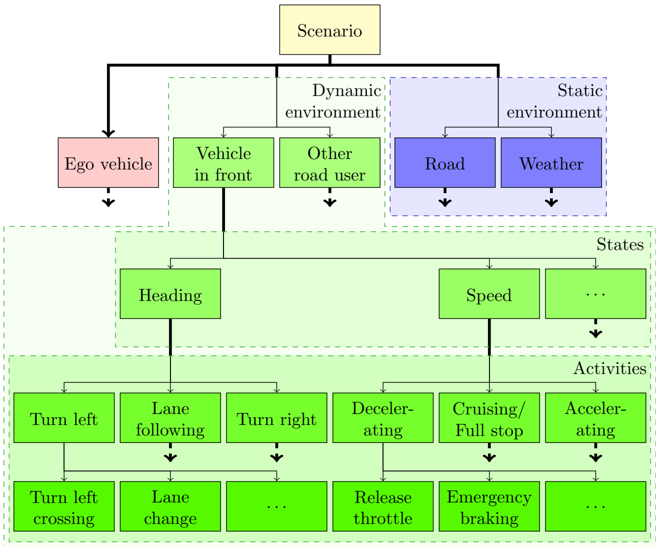

Fig. 1. Schematic overview of a scenario. Note that the dynamic environment is not limited to the 'vehicle in front' and 'other road user', while the static environment is not limited to 'road' and 'weather'.

Fig. 2. Examples of tree structures with *tags* for a scenario.

In literature, many different types of traffic scenarios are considered, such as a cut-in [5], [6], [14], braking of a predecessor [11], [14], [24], a near miss [6], a collision or a safety-critical scenario [6], [15], an urban scenario [17], a free-driving or vehicle-following scenario [5], a lane change [5], an overtaking action [12], a platoon merge [13], an intersection passing [13], a highway lane reduction [16], or urban intersection crossing [16]. In order to get a complete picture of all scenarios that are encountered in traffic, this list of scenarios should be expanded. However, when doing this, the following problems occur:

1) The scenario classes are not mutually exclusive, so it may be unclear how a scenario should be classified. For example, a scenario in which a predecessor brakes can be both a braking scenario and an urban scenario.
2) It might be difficult to determine whether the list of scenarios is complete.
3) There is a balance between having general scenario classes - and thus a high variety - and having specific scenario classes - and thus not much variety. For some systems, one is interested in very specific set of scenarios, while for another system one might be interested in a set of scenarios with a high variety.

The proposed solution is to adopt tree structures of tags that describe the scenario. A tag could be a label that describes the weather, the type of road, or a specific activity of a target vehicle, etc. The tags are structured according to different trees, see Fig. 2 for three examples. Tags that are in the same layer of a branch are mutually exclusive. For example, regarding the weather (Fig. 2a), it is not possible to have a scenario in which there is rain and snow at the same time. The different layers of the trees can be regarded as different abstraction levels [25].

The trees provide the possibility to define specific tags, while these specific tags belong to a more generic tag. For example, when examining the following behavior of an AV, one might want to test for all vehicle-following scenarios (see Fig. 2b), while in another case one might want to only test for the vehicle-following scenarios with braking involved.

D. *Definition of events*

A scenario, for which the definition is proposed in Section III-B, consists of events. Events can be seen as the building blocks of a scenario. The notion of event is extensively used in literature [29], [42]–[46]. In this section, a selected number of descriptions is presented. Next, a definition of event is given that suits our context.

The term event is used in many different fields, e.g.:

- In computing [42], an event is an action or occurrence recognized by software. A common source of events are inputs by the software users. An event may trigger a state transition.
- Jeagwon Kim, a philosopher, writes: "The term event ordinarily implies change" [43]. Kim states that an event is composed of three elements: objects, a property, and a time instant or a temporal interval.
- In probability theory, an event is an outcome or a set of outcomes of an experiment [44]. For example, a thrown coin landing on its tail is an event.

- In the field of hybrid theory, “the continuous and discrete dynamics interact at ‘event’ or ‘trigger’ times when the continuous state hits certain prescribed sets in the continuous state space” [45]. “A hybrid system can be in one of several modes, [...], and the system switches from one mode to another due to the occurrence of events” [29].
- In event-based control, a control action is computed when an event is triggered, as opposed to the more traditional approach where a control action is periodically computed [46].

Before providing the definition of an event, the following is concluded about an event:

1) An event corresponds to a time instant: Whether it is regarding computing, hybrid control, or event-based control, an event is happening at a time instant.

2) An event marks a mode transition: A mode transition may be caused by either an abrupt change of an input signal, a change of a parameter or a change in the model. For example, pushing the brake pedal may cause a mode transition and therefore, this may be regarded as an event.

Hence, we define an event as follows.

Definition 2 (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.*

An event according to Definition 2 is related to an event described in hybrid control [29], where an event describes the transition from one mode of operation to another mode of operation. In our application, i.e., events in traffic scenarios, “mode of operation” is described by a certain model with parameters assigned to it.

The inter-event time interval, i.e., the time in between two events, corresponds to a certain activity. For example, when the longitudinal acceleration is negative during an inter-event time interval, the activity can be described by the label ‘braking’.

IV. Application Example

To illustrate the ontology, a real-world example is presented. A schematic overview of the example is shown in Fig. 3. Two vehicles are considered: a pickup truck and a sedan. The example can be described in words as follows. The ego vehicle (i.e., the sedan) accelerates towards its predecessor (i.e., the pickup truck), such that the distance between the ego vehicle and its predecessor becomes smaller. At some point, the ego vehicle brakes, such that it reaches approximately the same speed as the pickup truck’s speed. From then on, the ego vehicle cruises, such that the distance between the two vehicles remains approximately constant. The pickup truck drives at a constant speed.

In the presented example, two scenarios are identified. The scenarios can be qualitatively described as ‘gap-closing on rural road with clear weather’ and ‘cruising behind target vehicle on rural road with clear weather’, respectively. The first scenario ends when the ego vehicle starts cruising.

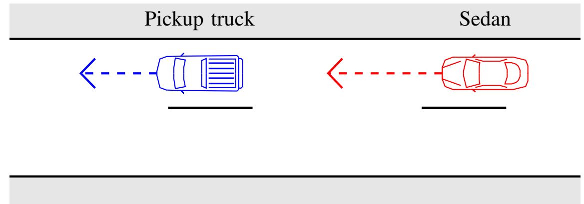

Fig. 3. Schematic overview of the traffic scenarios. The sedan (red, right vehicle) is defined as the ego vehicle. Initially, the ego vehicle accelerates towards the pickup truck (blue, left vehicle).

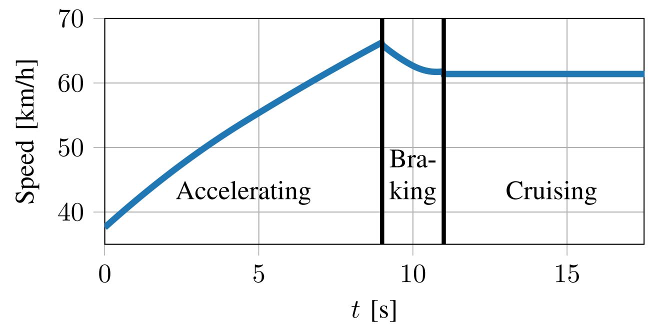

Fig. 4. Activities of the ego vehicle considering its speed. The black vertical lines indicate the events. The three different activities that can be qualitatively described as ‘accelerating’, ‘braking’, and ‘cruising’, respectively.

The activities of the ego vehicle are shown in Fig. 4, in which the speed is shown with respect to time t. Regarding the speed, two events are identified. At the first event, the ego vehicle’s longitudinal acceleration transits from being positive to negative, i.e., the ego vehicle starts braking. As there are two events identified regarding the speed, three different activities are to be modeled, qualitatively described as ‘accelerating’, ‘braking’, and ‘cruising’, respectively.

Whereas the definitions from Geyer et al. [21], Ulbrich et al. [22], and Elrofai et al. [23] do not state when a scenario ends, Definition 1 states that a scenario contains all the relevant events. Therefore, it follows from Definition 1 that the first scenario ends at the second event.

For a scenario-based assessment, test cases have to be defined. These test cases can be derived from real-world scenarios [2], [17], [24]. For example, based on the first scenario, a test case can be defined where the ego vehicle’s objective is to follow the pickup truck while maintaining a safe distance and where the ego vehicle’s initial speed is higher than the speed of the pickup truck. Other conditions can be applied for the test case, e.g., bad weather conditions that might cause a late detection, to assess the driving capabilities of the AV in different scenarios.

V. Conclusion

The performance assessment of AVs is important for the legal and public acceptance of AVs. Since scenarios for testing are crucial for the assessment, a clear definition of a scenario is required within this context. We have proposed a new definition of a scenario in the context of the assessment of the quality of an AV. The definition states that a scenario is a quantitative description of the ego vehicle, its activities and/or goals, its static environment and its dynamic environment. The attributes of a scenario are further specified in the proposed ontology. The ontology is illustrated with an example. The presented ontology is applicable for scenario mining and scenario-based assessment and therefore, this paper provides a step towards the scenario-based performance assessment of AVs.

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