Scenario-based Verification and Validation of Automated Transportation Systems

Birte Neurohr, birte.neurohr@dlr.de; and **Eike Möhlmann,** eike.moehlmann@dlr.de

■ ABSTRACT
The research and development activities performed by the DLR Institute of Systems Engineering for Future Mobility (DLR-SE) are organized via so-called assets. We present a scenario-based verification and validation process and relate selected research activities.

Verification and validation approaches of automated transportation systems based on driving a certain number of kilometers are infeasible. Therefore, the DLR-SE asset "Scenario-based Verification and Validation of Automated Transportation Systems" investigates methods and prototyping tools for verifying and validating automated transportation systems employing scenarios as the main structuring element to capture complex traffic evolutions. While there are many different approaches, our focus is formally specifying relevant abstract scenarios that are readable by humans while also being machine-readable. This allows us to automatize the verification and validation process, which increases confidence in, for example, the safety of the systems due to a dramatically increased number of executed tests while reducing the manual effort from humans.

■ KEYWORDS: automated systems; verification; validation; scenario-based testing; automated transportation systems; automated driving; safety

INTRODUCTION

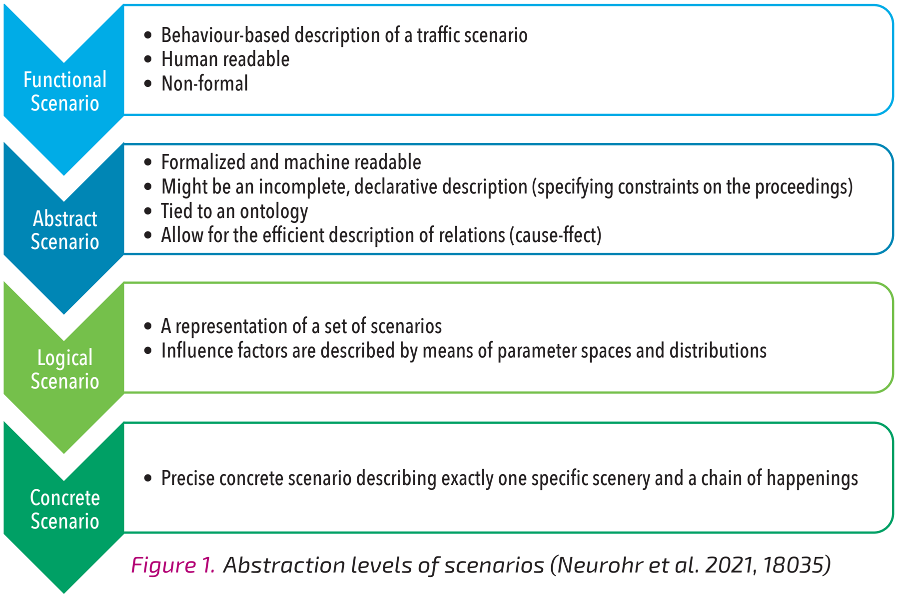
Automated and autonomous transportation systems are not only thought of as a way to make traveling more comfortable but also as a means to make it safer. To realize this and bring automated and autonomous transportation systems into the market, it is essential to guarantee their safe operation. This is a challenge as the systems as well as the input they receive (the environment) are highly complex and, further, depend on the targeted safety level. For instance, when human drivers are allowed to operate a vehicle, they have at least 17 years of experience with traffic, the expected behavior of other humans, and basic physical principles. Thus, the question arises of how to ensure a positive risk balance, including automated driving systems (ADS) causing fewer accidents than humans. Hence, for the validation and verification of automated transportation systems, it is not only necessary to develop them in a safe way but to test them extensively before rollout. These topics are addressed in the DLR-SE's asset "Scenario-based Verification and Validation of Automated Transportation Systems." The current focus of this asset is automated vehicles, but extension towards the maritime and the railway domain is ongoing.

Today's vehicles have been improved over decades, and human drivers can now drive relatively safely, thus, the average distance between accidents is very long. To demonstrate that a single automated driving system is safer than a human driver, the number of test kilometers necessary for statistical evidence amounts to several hundreds of millions of kilometers, depending on assumptions and the type of accident (Wachenfeld and Winner 2016, 442). To put this in perspective, all paved streets in the USA only form a network of 4.3 million km (World Factbook 2012). Even worse, — without further arguments — these tests would need to be performed with every newly developed or slightly modified automated driving system. Thus, an approach based on driving a distance to statistically show that an ADS is safer than a human-operated vehicle is infeasible in practice.

THE SCENARIO-BASED APPROACH

One possible solution for this dilemma is a scenario-based approach (Riedmeyer et al. 2020). A scenario describes a temporal evolution of traffic scenes, where a scene is a snapshot of the environment including its scenery (like lanes, obstacles and traffic signs) and dynamic objects (like cars, passengers and bicyclists) (Ulbrich et al. 2015).

Scenarios built the foundation of our verification and validation methods as they allow for structuring the complex environment consisting of an infinity of possibilities. They allow for reasoning the safe operation of an automated transportation system without relying solely on the num-



- Behaviour-based description of a traffic scenario
- Human readable
- Non-formal

- Formalized and machine readable
- Might be an incomplete, declarative description (specifying constraints on the proceedings)
- Tied to an ontology
- Allow for the efficient description of relations (cause-ffect)

- A representation of a set of scenarios
- Influence factors are described by means of parameter spaces and distributions

- Precise concrete scenario describing exactly one specific scenery and a chain of happenings

Figure 1. Abstraction levels of scenarios (Neurohr et al. 2021, 18035)

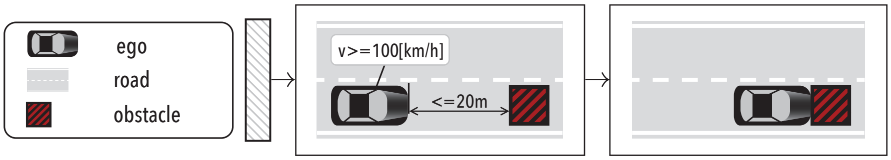


Figure 2. Car collides with an obstacle (specified as TSC) (Jan Steffen Becker, pers. Comm.)

ber of kilometers driven. Instead, they take advantage of the identification and understanding of which principles are essential for the safety of automated transportation systems. Thus, verification and validation methods can be structured and carried out in a more systematically than in a naïve distance-based approach with random test cases (Wachenfeld and Winner 2016, 442)

Scenarios can be described at different abstraction levels relevant at different stages in the V&V process (Menzel et al. 2018), (Becker et al. 2021, 3).

A *functional scenario* (Menzel et al. 2018) is human-readable and non-formal. It is a behavior-based description of a traffic scenario. Functional scenarios can be used in the very early phases of the verification and validation process.

Illustrative example: The ego vehicle is driving on the right lane of a two-lane highway below 100 km/h. There is one obstacle in front of the ego. Then the ego vehicle collides with the obstacle.

An *abstract scenario* (Neurohr et al. 2021) is formalized in a declarative way. Thus, it only specifies what is relevant to the described traffic scene and leaves out irrelevant aspects. It is always tied to an ontology and allows for describing alternatives and variance in objects and space. Abstract scenarios are used in the concept phase of the verification and validation process.

Illustrative example: As an example of an abstract scenario, we present a Traffic Sequence Chart (TSC) (Damm et al. 2017; Damm et al. Jan 2018; Damm et al. Jul 2018) in Figure 2. While it may look like a simple picture, it actually translates to a formula in a first-order multi-sorted real-time logic that machines can read and interpret. It should be noted that this TSC corresponds to a multitude of specific collisions.

The shown TSC captures only the relevant constraints and, hence, describes all traffic evolutions that (1) anything may happen, (2) a vehicle called ego with a velocity of 100 km/h (or higher) approaches an obstacle with a distance of at least 20m on a lane of a road with at least one more left lane, and (3) touches the obstacle. Note that aspects that are not constrained, such as the existence of other traffic participants, the shape of the road, the weather, the type of the vehicle, and the obstacle, are left open. Therefore, an infinity of concrete scenarios is described.

Logical scenarios (Menzel et al. 2018) have value ranges for parameters and parameter constraints that may also be given by specifying distributions. They may be used during system development.

In contrast to the example of an abstract scenario above, all parameters are specified (with a value range) here. For example, the width of the road is between 3m and 3,75m. This is not specified in the abstract scenario above.

Scenery, Concrete scenarios (Menzel et al. 2018) have concrete values instead of parameter ranges. Thus, they describe one specific *scenery* and chain of events.

These different abstraction levels of scenarios are used during verification and validation. The necessary level of abstraction depends on the phase of this process. Please note that the amount of described scenarios rise with the abstraction level.

A simplified framework of a scenario-based approach based on the work of the research projects ENABLE-S3 (www.enable-s3.eu) and PEGASUS (www.pegasusprojekt.de/en) can be seen in Figure 3 (Neurohr et al. 2020). The first step, scenario elicitation, consists of deriving adequate scenario classes to be tested. The requirement elicitation process equips the scenarios with the corresponding requirements. Testing will then be carried out virtually in simulations and physically

Table 1. Illustrative example of a logical scenario

Right lane width $[m]$	$[3,\ldots,3{,}75]$
Left lane width $[m]$	$[3,\ldots,3{,}75]$
Speed Ego vehicle $[\frac{km}{h}]$	$[100,\ldots,150]$
Long. position Ego vehicle $[m]$	$[80,\ldots,100]$
Long. position of obstacle $[m]$	$[80,\ldots,100]$
Long. position Ego vehicle < Long. position obstacle	

Table 2. Illustrative example of a concrete scenario

Right lane width $[m]$	[3,75]
Left lane width $[m]$	[3,75]
Speed Ego vehicle $[\frac{km}{h}]$	[125]
Long. position Ego vehicle $[m]$	[80]
Long. position of obstacle $[m]$	[92]
Long. position Ego vehicle < Long. position obstacle	

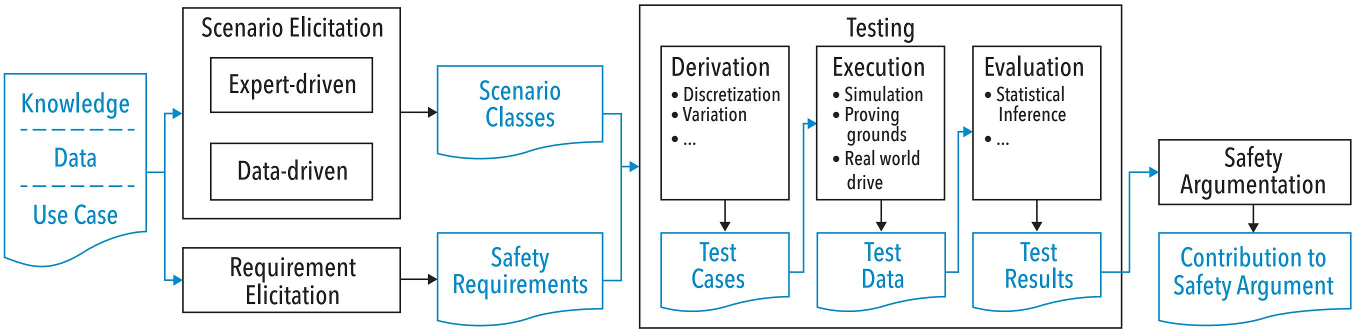


Figure 3. Simplified framework around scenario-based testing (Neurohr et al. 2020, 122)

on proving grounds and in the targeted environment. Finally, the results are integrated into an overarching safety argumentation (c.f. Koopmann et al. 2019), contributing to the safety case.

The focus of this asset lies in the scenario elicitation and execution part of this framework. Albeit the process and framework can incorporate different test techniques such as model-, software-, hardware-, and vehicle-in-the-loop, we, however, focus on computer simulations (MiL, SiL) as a virtual test bench.

CURRENT CHALLENGES THE ASSET IS ADDRESSING

While the idea of a scenario-based approach is well established and has already found its way into standardization organizations (ISO 21448; UL 4600), there are still many open questions about applying it.

On the one hand, knowing which scenarios are relevant is difficult. Using scenarios very similar to each other, like "driving on a highway with a yellow car in front of the ego" and "driving on a highway with a red car in front of the ego," does not add much value to the verification and validation process. Thus, it is imperative to identify scenarios that add value by identifying what makes a scenario relevant and critical (Zhang et al. 2022).

Scenarios are the foundation to reduce the search space for verification and validation approaches for automated transportation systems (Kalisvaart et al. 2020). This reduction is based on a fundamental principle: Myriad similar concrete scenarios can be described by one abstract or logical scenario. The process of determining abstract scenarios is called "Scenario-Mining." It can be approached either based on data, expert knowledge, or combining the best of both worlds. These approaches are addressed in the asset.

Closely related is the "Criticality-Analysis" (Neurohr et al. 2021), aiming to determine relevant phenomena and explain the underlying causality. This also contributes to determining which scenarios should be considered relevant for testing, however, from a different perspective. The criticality analysis strives to map the infinite-dimensional domain onto a finite and manageable set of artifacts that capture and explain the emergence of critical situations for automated vehicles. In the asset, we target a combined approach of expert-based and data-driven methods that leverages an ontology.

On the other hand, the question of how to correctly specify scenarios still needs to be fully answered because of the open context automated vehicles must operate. That means it is impossible to fully specify the operation environment at design time as it is highly complex and subject to constant change. Hence, human experts cannot carry out validation and verification methods for automated transportation systems alone, and methods for monitoring the satisfaction of requirements are needed. Additionally, monitors are needed to detect novelties and anomalies in order, for instance, to detect missing scenarios (addressing the open-world problem and, hence, incompleteness of any scenario set) and model inaccuracies as well as to activate fallback strategies like degraded operation modes and minimum risk maneuvers.

Here again, the abstract scenarios come into play. An abstract scenario covers infinite concrete scenarios. They focus on complex interrelations, especially cause-and-effect relationships, which are essential for a scenario-based approach. As the TSCs mentioned above are not only machine-interpretable but also easily interpretable by humans, they may build a solid basis to support humans in the verification and validation process and, hence, increase confidence in safety by being able to execute more tests while reducing the needed manual effort.

This asset's basis and the connecting element is the concept of abstract scenarios. Thus, a central goal is further developing and tailoring the TSC language. Currently, it has an automotive focus. Ongoing work is to extend the language towards the maritime and the rail domain and include more language features to increase the expressiveness.

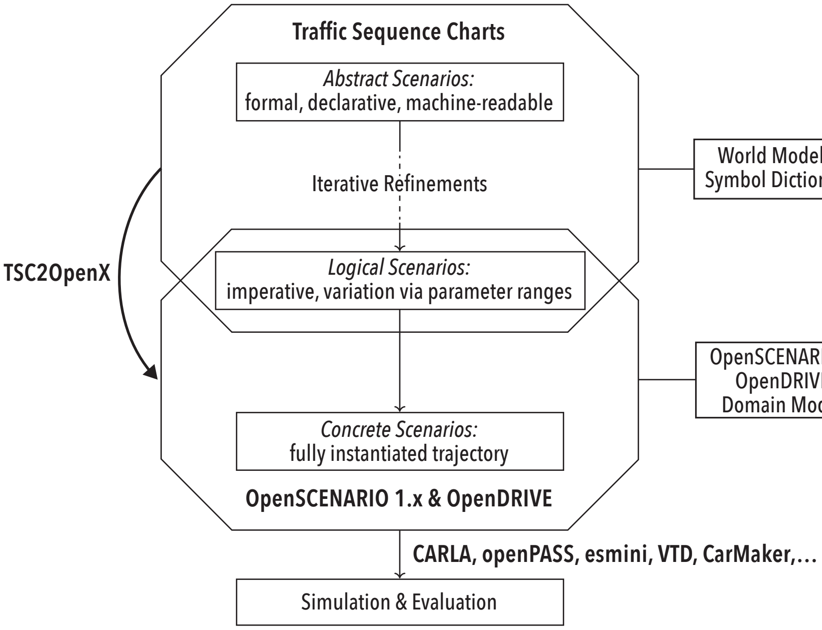


Figure 4. TSC Toolchain (Becker et al. 2020)

Furthermore, a prototypical tool for creating and evaluating TSCs is developed to do consistency analysis for TSCs and other automated reasoning. This prototypical tool specifies TSCs in a well-defined format that serves as an input for other TSC-related tools like TSC2OpenX. The aim of TSC2OpenX (see Figure 4 is to transfer abstract scenarios from TSCs into concrete scenarios in the industrially relevant formats OpenDRIVE (https://www.asam.net/standards/detail/opendrive/) and OpenSCENARIO (https://www.asam.net/standards/detail/openscenario/). These, in turn, can be simulated by most of the simulation platforms, thus reducing the manual effort of deriving concrete scenarios to be tested.

A test platform is needed to test or assess the safety of a given system. Within this asset, methods and different prototypes of scenario-based testing platforms for simulating the derived concrete OpenDRIVE and OpenSCENARIO are developed. These also guide the simulation into concrete scenarios with identified weaknesses, making them more meaningful for risk estimation.

Last but not least, when using simulation (relying, for example, on dynamic models) to assess the system's safety, we need to make sure that simulation results are transferrable to reality. Knowledge about this relation is a prerequisite for basing a safety argumentation for automated transportation systems on simulative tests within any verification and validation process. Thus, within the asset, we also investigate methods that help determine a simulation's validity, the used simulation models, and the obtained simulation runs.

OUTLOOK

For many of the challenges above, we are working on ideas, methods, and prototypical tools on how to tackle them. Automated transportation systems pose significant risks when they are not thoroughly verified and validated. This would put humans and our environment in danger and, consequently (and rightfully so), threaten their acceptance by society. Thus, we must develop methods and tools that help system and test engineers deal with the enormous complexity of traffic situations during design and assessment to obtain sufficient confidence in the safety of automated vehicles. While our research focuses on the mobility domain, we expect that gained insights (for instance, using scenarios for testing) can be transferred to other domains like health (https://enable-s3.eu). ■

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