DIGITAL INDUSTRIES SOFTWARE

Leveraging the Siemens autonomy toolchain

Testing and virtually validating advanced driver assistance systems and autonomous vehicle functions

Executive summary
Rapidly developing autonomous vehicles (AVs) requires robust testing and validation methods to ensure their safety and reliability. This white paper introduces the Siemens Digital Industries Software autonomy toolchain for testing and virtually validating advanced driver assistance systems (ADAS) and AV functions. The approach integrates scenario-based testing, virtual validation and compliance with the Safety of the Intended Functionality (SOTIF) standard to assess AV safety comprehensively. Leveraging the multi-pillar safety validation framework proposed by the United Nations Economic Commission for Europe (UNECE) and European Union (EU) regulations, manufacturers can use the Siemens toolchain for efficient scenario extraction, critical scenario creation and large-scale virtual validation. By addressing software infrastructure and scenario generation, Siemens enhances ADAS and AV system reliability and safety.

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Introduction

AVs hold immense promise for society, offering improved road safety and efficiency. However, recent incidents underscore the critical importance of ensuring the safety of these vehicles before their widespread deployment. Despite significant advancements, challenges persist in verifying and validating AVs, posing obstacles to their seamless integration into everyday transportation systems.

Introducing scenario-based testing and virtual validation

Scenario-based testing, virtual validation and adhering to the SOTIF standard play pivotal roles in assessing ADAS and AVs. These methods allow for thorough evaluation across a wide range of scenarios, mitigating the need for extensive public road testing. Whereas traditional validation methods fall short in capturing the complexity of real-world traffic scenarios, scenario-based testing and virtual validation provide insights into system performance under various conditions. By incorporating SOTIF alongside scenario-based testing and virtual validation, manufacturers can enhance the reliability and safety of ADAS and AV systems, facilitating their successful deployment and integration into transportation networks.

Safety validation of automated driving systems

Increased complexity requires a radical change of test methods and new concepts for comprehensive vehicle verification and validation (V&V) in the physical and virtual worlds, which regulations cover.

In February 2021, the UNECE presented the New Assessment/Test Method for Automated Driving (NATM),[1, 2] a framework that introduces a multi-pillar approach for safety validation of automated driving systems (ADS), which is shown in figure 1.

In August 2022, the EU Commission adopted the regulation 2022/1426 laying down rules for applying Regulation (EU) 2019/2144 of the European Parliament and of the Council as regards uniform procedures and technical specifications for the type-approval of the ADS of fully automated vehicles.[3, 4]

On July 7, new rules regarding active safety features in vehicles, including speed limiters, came into effect across the EU.

The New Vehicle General Safety Regulation (GSR2),[5] or Regulation (EU) 2019/2144, updates the minimum performance standards (type approval) for motor vehicles in the EU, requiring the addition of several ADAS.

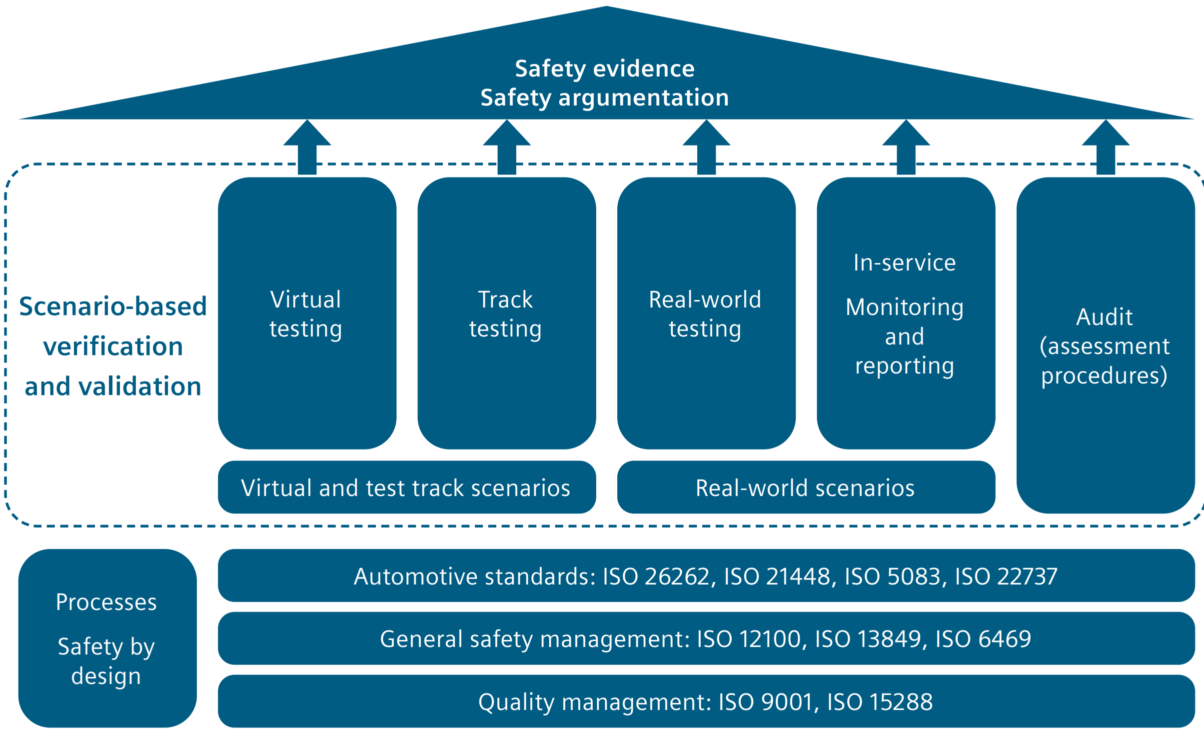

Figure 1. Siemens representation of the UN-ECE NATM multi-pillar safety validation of automated driving systems.

These required systems include intelligent speed assist (ISA), autonomous emergency braking (AEB), driver drowsiness and attention warning (DDAW) and emergency lane-keeping systems (ELKS).

The multi-pillar safety validation of automated vehicles specifies five certification pillars that support safety argumentation. Virtual testing, track testing and real-world testing are scenario-based, and as we move from virtual testing to real-world testing, the number of scenarios decreases and the realism of the scenarios increases.

After deployment, during the monitoring and reporting phase, you can record the relevant scenarios, and after scenario extraction and scenario selection, you can feed them back into the virtual testing, test track testing and real-world testing processes. Recording and extracting new scenarios enable the discovery of unknown-unsafe scenarios and continual improvement of the automated driving system.

Finally, it is important to note that the EU legislation and UNECE NATM (see the in-service and monitoring pillar) introduce a continuous integration and deployment workflow, which is well-known in the software industry (see development and operations (DevOps)).

Contributing to safer and more efficient ADAS and AVs testing

Siemens offers a suite of software tools and integrated toolchains that align with international standards and legislation, enabling scalable solutions for comprehensive safety validation workflows. The toolchain facilitates automated and efficient scenario generation, leveraging recorded data to extract known safe scenarios, generate known-unsafe scenarios and identify unknown-unsafe scenarios. By addressing the software infrastructure and scenario generation aspects, Siemens contributes significantly to streamlining the validation process and mitigating potential safety risks in ADAS and AV systems.

Siemens solution for scenario-based testing and virtual validation

Siemens provides a cutting-edge toolchain designed to systematically compile an extensive database of scenarios, assess the AV stack effectively and reliably using a combination of model-in-the-loop (MIL), software-in-the-loop (SIL) and hardware-in-the-loop (HIL) test platforms and reiterate the V&V process based on test results or new requirements.

The toolchain is composed of three main phases:

Requirements management and data collection – Requirements are gathered based on the operational design domain (ODD), the dynamic driving tasks (DDT) and applicable regulations and standards. Leveraging Siemens requirement management tools enables traceable and flexible integration of new requirements in the V&V process. Data collection in the ODD captures actor behaviors or patterns unique to the ODD. Siemens provides engineering services for sensor setup, data recording and data processing.

Scenario extraction and creation – Using the Siemens toolchain, including the Simcenter™ Autonomy Data Analysis solution and the patented critical scenario creation (CSC) workflow, enables the extraction of all categories of scenarios as per SOTIF. Simcenter is part of the Siemens Xcelerator business platform of software, hardware and services. Leveraging Simcenter Autonomy Data Analysis, you can analyze the data, extract known scenario types and apply safety thresholds to define safe and unsafe behavior. The patented critical scenario creation tool defines a search space over the recorded data. An optimization-based approach then systematically identifies known-unsafe and unknown-unsafe scenarios based on criticality and novelty.

Assessment – Using the Siemens physics-based simulator, Simcenter Prescan software, you can perform large-scale virtual validation of the AV based on the extracted scenarios with relevant protocol scenarios from standards and regulations. The result's reliability is further enhanced with Siemens offerings of HIL test beds.

Requirements management and data collection

Requirements for setting and defining a recording plan are the first steps in assessing the safety of ADAS and AV systems.

Requirements management

Developing an ADS starts with defining or describing the ODD and DDT. Next, gather applicable regulations and international standards and initiate the requirements definition of the automated driving system. Requirements are grouped in categories such as safety, system, hardware, software, user, etc. During the development process, existing requirements could change often and new requirements are defined; thus, using a requirements management tool is a must. Siemens supports requirements management with software tools like the Polarion™ portfolio, which is also part of the Siemens Xcelerator business platform.

Traceability, which refers to the ability to track and trace requirements to artifacts, test runs and anything else in the product lifecycle, is essential and mandatory in most cases (see figure 2).

Data collection

You can perform data collection for the ODD and the individual scenes using instrumented vehicles, static drone footage or infrastructure-mounted sensors. Siemens can assist with setting up a comprehensive sensor setup designed for recording real-world scenarios.

The collected data can contain errors due to noise, missed detections, occlusions, etc. Thus, some data processing is necessary to extract full trajectories and remove measurement noise.

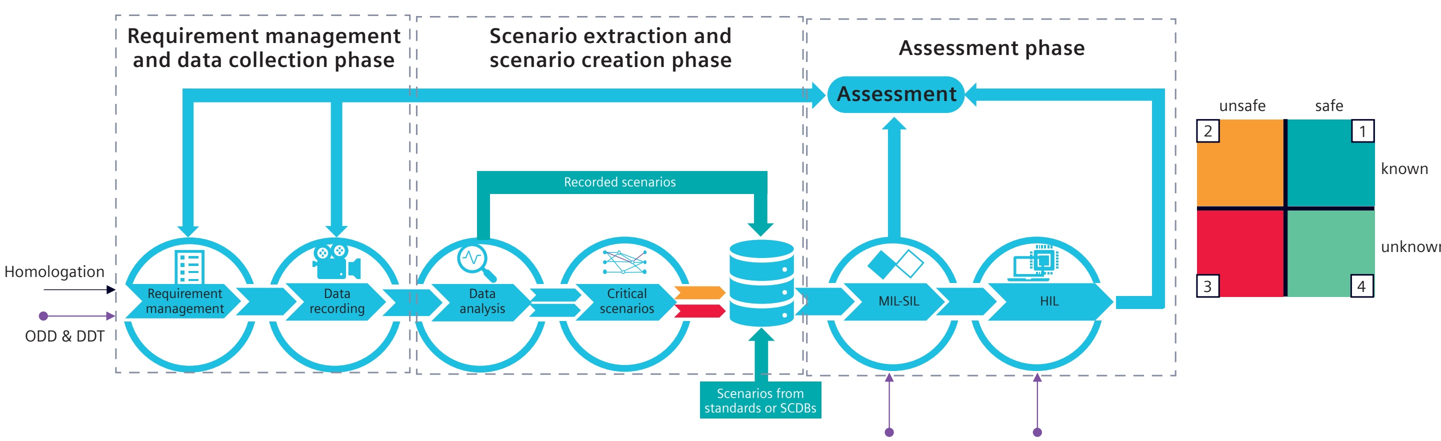

Figure 2. SOTIF scenarios (right) and the Siemens autonomy toolchain for V&V of ADAS/AV systems (left). The green arrows show scenarios from safe-known, and the orange and red arrows show the known-unsafe and unknown-unsafe scenarios, respectively. Purple arrows show the input of ODD and DDT to various tools.

Scenario extraction and creation

Using the Siemens toolchain, which includes Simcenter Autonomy Data Analysis and CSC, facilitates the extraction of all categories of scenarios in accordance with SOTIF requirements.

Data analysis
Simcenter Autonomy Data Analysis analyzes the recorded raw data, providing the following features (see figure 3):

- Extract and replay scenarios with perception algorithms of the environment
- Categorize scenarios and evaluate them based on key performance indicators (KPIs)
- Dive into the details of a categorized scenario and select data of interest manually
- Export raw data for replay or simulation via OpenDrive and OpenScenario, including validating the simulation models

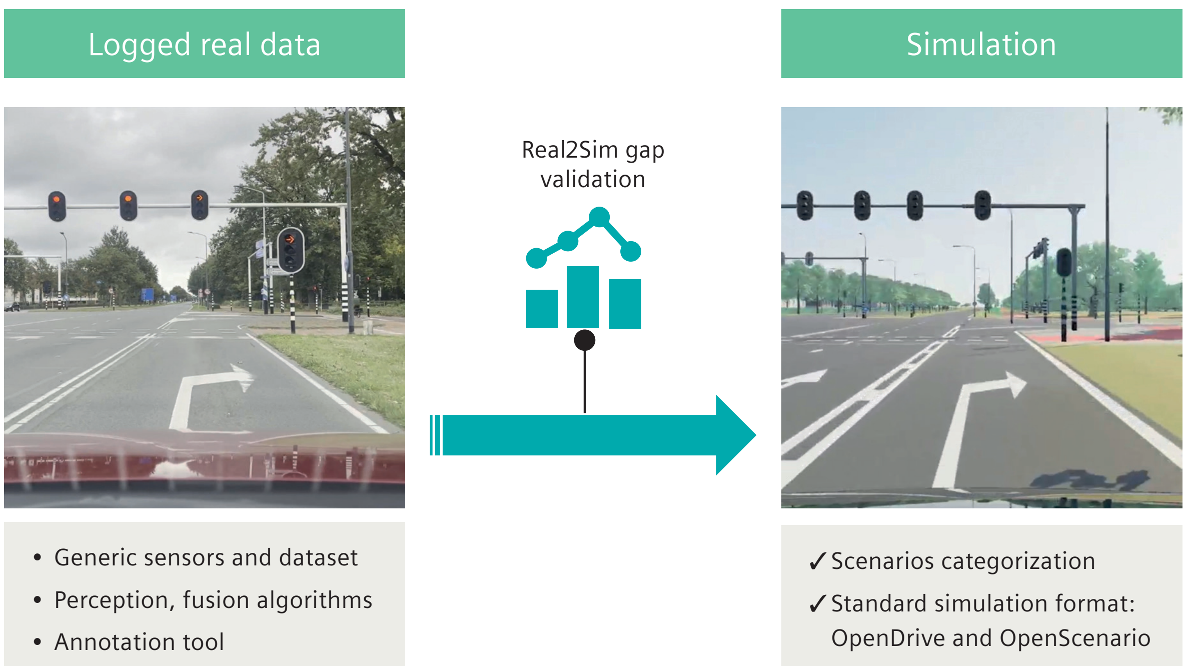

Figure 3. The real data analysis and virtualization Real2Sim process. The validation component is to quantify Real-Sim gap with dedicated metrics and guarantee a high-performance simulation model.

Critical scenario creation

Critical scenario creation contributes to the scenario generation process in two ways. First, it provides the possibility of generating known-unsafe scenarios (see orange arrow in figure 2) by optimizing the criticality of known-safe scenarios extracted using the Simcenter Autonomy Data Analysis solution in a previous step.

Second, it provides a tool to generate unknown-unsafe scenarios (see red arrow in figure 2). Figure 4 shows the main three steps of the tool and explained briefly here (more details about the tool can be found in the paper: A Systematic Approach for Creation of SOTIF's Unknown Unsafe Scenarios: An Optimization based Method).[6]

Extraction

Feature extraction provides a finite set of features that can describe the behavior of actors (for example, cars) in the scene. To extract features for actor behavior, the road layout is described as a graph and the probability distributions are determined for each parameter and node combination.

In equation 1, $P_{a,i}$ is the probability of a certain behavior from actor i and calculated as shown below.

$$P_{a,i} = P_{p,i} \times \prod_{j=1}^{m} P_{par,j}$$

Equation 1.

Additionally, in equation 1, m is the number of parameters extracted for actor i with the probability of $P_{par,j}$ aggregated from the collected data and $P_{p,i}$ is the probability of a path cluster for actor type i.

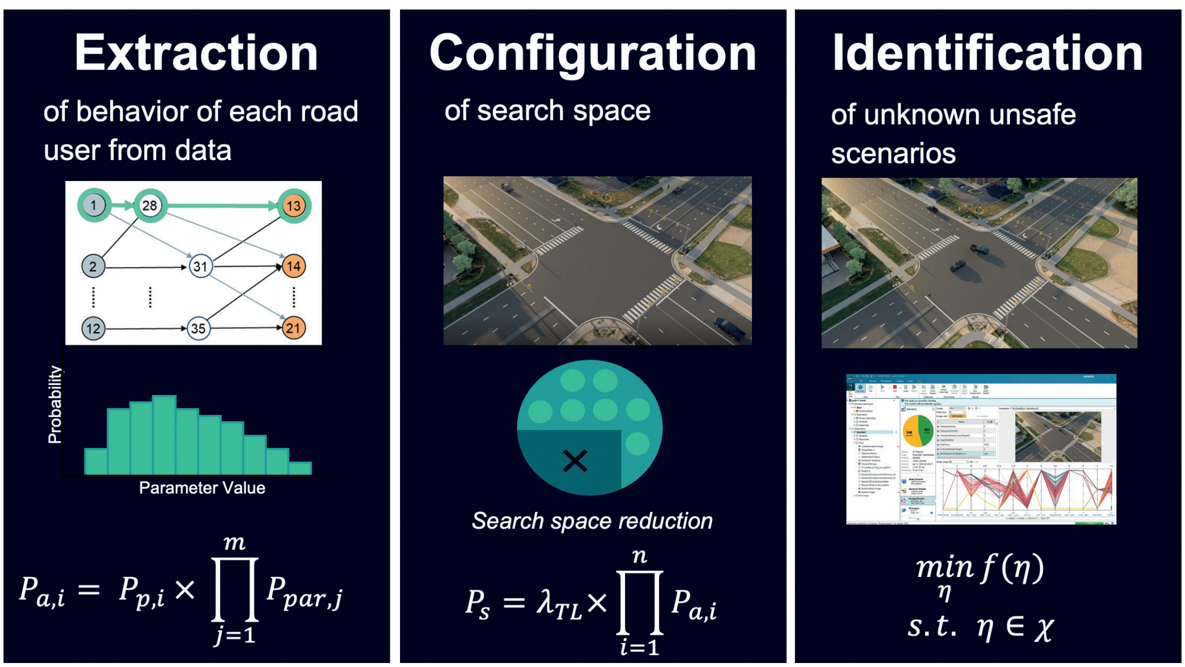

Figure 4. The main three steps of critical scenario creation.

Configuration

To streamline optimization, we configure actor behaviors and parameters to define the search space. However, considering all possibilities leads to a large and unmanageable space. We automatically identify noninteracting actor paths and parameters, then partition the remaining space based on discrete parameters. This creates manageable optimization studies.

Identification

The identification step evaluates risk severity using proprietary indicators to assess criticality and novelty. It employs an optimization algorithm to identify scenarios with the highest potential impact. The objective function, as seen in equation 2, incorporates three terms: a proprietary unexpectedness metric $\epsilon(\eta)$, with η representing the scenario parameters (for example, speed of actors, distances, etc.), to identify unknown scenarios (a constant value of two is added to the above objective function to ensure its value remains nonnegative), time-to-collision (TTC) to measure scenario safety and a function (G(P_s)) of scenario probability.

$$\boldsymbol{f(\eta) = G(P_s(\eta)) \times (2 - \epsilon(\eta) + TTC_{min}(\eta))}$$

Equation 2.

Equation 3 shows how to calculate P_s with λ_{TL} as the traffic light factor, which provides the probability of following traffic light schedule by the actor.

$$P_s = \lambda_{TL} \times \prod_{i=1}^{n} P_{a,i}$$

Equation 3.

The optimization problem can be formalized in equation 4, where χ defines the bounds on the parameter values, and ζ_{col} is a Boolean variable and is one in case of nonego vehicle collisions.

$$\begin{aligned} &\min_{\eta} \boldsymbol{f(\eta)} \\ &\boldsymbol{s.t.}\ \ \eta \in \chi \\ &\zeta_{col} = 0 \end{aligned}$$

Equation 4.

Standard scenarios

Various scenario databases are used during assessment, including those from standards, experts defining scenarios based on ODD, critical scenarios and accident databases. For ADAS systems, EURO NCAP, UN R131 (AEBS), UN R152 (AEBS) and UN R157 (ALKS) define test scenarios. For AVs, International Organization for Standardization (ISO) standards such as ISO 22737 and ISO/DIS 23374-1 describe test scenarios. Using the Siemens toolchain enables virtualization and testing of these scenarios before on-road testing. Although standards provide a baseline for safety and performance, additional requirements defined by experts are often necessary during development and post-deployment.

Assessment

All collected scenarios from the database are tested to reveal the behaviors of the digital twin under varied and complex conditions. Transitioning from virtual to physical, the AV system, embedded within an electronic control unit (ECU), faces the ultimate test. This transitioning process is executed in (at least) two steps, known as SIL and HIL.

Software-in-the-loop testing

For AV control software design, the sense-plan-act paradigm structures development into perception, planning and control algorithms. Each team develops a simplified model of the other two components, which are integrated to create the full software stack. Testing occurs in a virtual environment with vehicle dynamics, sensor models and infrastructure simulations. This integration presents challenges, particularly regarding sensor model quality, as simulated sensor readings must match real-world functionality to create realistic scenarios for the AV.

Hardware-in-the-loop testing

The final step before physical deployment in the vehicle entails HIL testing the advanced driving system software running in real time on the intended hardware platform. This allows for assessment of the advanced driving system's responses to the selected scenarios.

Additionally, the same virtual environment can be used for SIL testing with the added nontrivial requirement it has to run in real time. However, the real-time hardware platform also requires sensor inputs satisfying specific, and often sensor-dependent, communication protocols since it is the exact same platform that will be deployed in the real vehicle. Hence, the simulation environment must output the simulated sensor signals in these formats. Note you can scale the simulation hardware based on the sensor requirements of the AV system under test.

For example, figure 5 shows the HIL setup, which assumes a limited sensor set consisting of two cameras and a lidar. The environment contains the vehicle dynamics and the sensor models. Since these high-fidelity models are computationally expensive, you could implement them in a federate architecture. The camera models output their data in a dedicated packet-based protocol operating at a fixed-link rate (GMSL2), whereas the lidar employs the standard user datagram protocol (UDP) as implemented by a Network Interface Controller (NIC). As a result, the control system ECU receives the data in the same way it would physically.

After assessing the real-time performance, you can update the data recording plan based on the previous assessment to ensure readiness against the unpredictable nature of real-world driving.

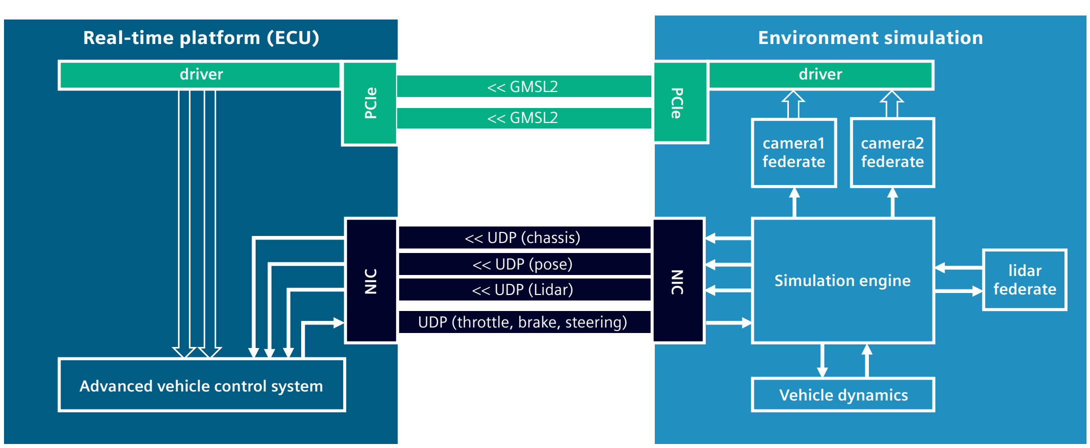

Figure 5. The HIL architecture with limited sensor suite of two cameras and a lidar.

Conclusion

Using the Siemens autonomy toolchain offers a comprehensive solution to accelerate deploying AVs while ensuring their safety and reliability. By uncovering unsafe scenarios as per SOTIF standards, the toolchain:

- Accelerates deploying AVs using robust testing methodologies
- Enhances system robustness by increasing scenario coverage
- Increases confidence in system performance for internal and regulatory KPIs
- Reduces development costs by streamlining validation processes

Overall, leveraging the Siemens toolchain provides a seamless and scalable approach covering three key areas of SOTIF scenarios, paving the way for the widespread integration of AVs into transportation systems while prioritizing safety and reliability.

References

1. UNECE The New Assessment/Test Method for Automated Driving (NATM), unece.org/sites/default/files/2022-04/ECE-TRANS-WP.29-2022-58.pdf, consulted in November 2023.
2. UNECE Guidelines and Recommendations Concerning Safety Requirements for Automated Driving Systems WP.29-187-10e.pdf (unece.org), consulted in November 2023.
3. EU-REGULATION (EU) 2019/2144 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R2144&from=EN, consulted in November 2023.
4. EU-2022/1426 - COMMISSION IMPLEMENTING REGULATION (EU) 2022/1426, Publications Office (europa.eu), consulted in November 2023.
5. GSR2: New rules to improve road safety and enable fully driverless vehicles in the EU, https://ec.europa.eu/commission/presscorner/detail/en/ip_22_4312
6. Singh, T., Van Hassel, E., Sheorey, A. and Alirezaei, M., "A systematic approach for creation of SOTIF's unknown unsafe scenarios: An optimization based method", SAE Technical Paper, 2024.

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