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Review of Simulation Frameworks and Standards Related to Driving Scenarios

DISCLAIMER

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16 Abstract This paper presents the results of a review of simulation frameworks and standards that could be instrumental to testing and assessment of vehicles with SAE International driving automation Level 4 and 5 automated driving systems (ADSs). A simulation framework or standard describes the object level scenario data (the positions, orientations, and velocities of all the objects in the scene) along with roadway information such that the ADS can be tested in a simulation environment. This open framework could serve as an interface for reading and writing scenario data, allowing for development of a sharable scenario database. Such a database could aid companies, researchers, and developers in the development of ADS and in safely evaluating system performance in simulation. This literature review study showed no existing framework has been widely adopted among ADS stakeholders, though some are more broadly compatible across available simulation software platforms. Of the standards identified, the OpenX (OpenCRG, OpenDRIVE, and OpenSCENARIO) and RoadXML, which are standard formatted files that define roadways, road networks, and scenarios, appear to be the most widely supported by available simulation applications. However, these standards are still being developed to include elements of test scenarios that maybe needed to assess ADS performance in a simulated environment.		
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ACRONYMS, ABBREVIATIONS AND INITIALISMS

ACPS	automated cyber physical systems
ADS	automated driving system
ADAS	advanced driver assistance system
ASAM	Association for Standardization of Automation and Measuring Systems
API	application program interface
CRSS	Crash Report Sampling System
DCP	Distributed Co-Simulation Protocol
DDT	dynamic driving task
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FMU	functional mock-up unit
HD	high definition
HiL	hardware-in-the-loop
HLA	high-level architecture
JSON	JavaScript Object Notation
KPI	key performance indicator
MiL	model-in-the-loop
MUTCD	Manual on Uniform Traffic Control Devices
NCSA	National Center for Statistics and Analysis
ODD	operational design domain
OEDR	object and event detection and response
OEM	original equipment manufacturer
RTK	real-time kinematics
SAE	Society of Automotive Engineers (In 2006 this organization changed its name to SAE International, but keeps SAE as its initialism)
SiL	software-in-the-loop
SOTIF	safety of the intended functionality
SPU	sensor processing unit
VSSA	voluntary safety self-sssessments
ViL	vehicle-in-the-loop

EXECUTIVE SUMMARY

This paper presents the results from a literature review and market summary pertaining to simulation frameworks that can be used to describe scenarios that may be encountered driving automation systems. This review provides a background for the development of an open format[1] framework for describing the object level scenario data, such as the positions, orientations, directions, and velocities of all the objects in the scene, along with roadway and environmental information. Such a framework can be used to test the path planning and control subsystems of an automated driving system in simulation. Additionally, these programmable elements of an open format framework could be defined and accessed through a common interface for reading and writing scenario data, thereby enabling the development of a scenario database that could be exchanged among various stakeholders. The open format framework for defining scenario objects, a common scenario authoring interface, and scenario database with a common data structure could aid companies, researchers, and developers to develop ADS and to assess system performance downstream of the perception level in a simulated environment.

The literature review was initiated with a search of existing standards, standards under development, research projects, and frameworks that describe the object level scenario data and roadway information. These are tools that ADS developers have available to use as part of their overall validation, verification, and evaluation of the ADS performance. The market summary showed no existing open format framework can be readily used across all available simulation applications, though some are more broadly compatible. Of the standards available, OpenX and RoadXML standards for defining roads and scenarios, appeared to be the most widely supported by available simulation software. Both standards follow Extensible Markup Language (xml) rules for electronically encoding information in structured files that can be published or shared. Though partially supported, these standards are still in the process of being developed to define the elements of scenarios that could be instrumental in assessing ADS performance with simulation software.

Future work will include applying the knowledge from this review by using various simulation software to experiment with scenario description frameworks and assess their compatibility.

[1] https://en.wikipedia.org/wiki/Open_format: "An open format is a file format for storing digital data, defined by a published specification usually maintained by a standards organization, and which can be used and implemented by anyone. For example, an open format can be implemented by both proprietary and free and open-source software using the typical software licenses used by each"

1 INTRODUCTION

This paper presents results of a literature review of frameworks for describing simulation scenarios that could be relevant to developing and assessing the performance of vehicles with SAE International's Level 4 and 5 automated driving systems. Such a framework could enable scenario exchanges among stakeholders and facilitate more rapid development of a knowledge base around safety relevant scenarios.

Voluntary safety self-assessments published by ADS companies [1] indicate that computer simulation is an integral part of ADS development and validation. Simulation is documented as one of the principle pillars of designing, parametrizing, and testing ADS systems in conjunction with track-based testing and on-road testing. One reason simulation can be so beneficial to the development process is that a database of edge cases that have either been encountered on the road or artificially created can be repeatedly tested with new versions of software to ensure that revised software can still handle the full library of past scenarios of interest. Edge cases generally describe infrequently encountered higher risk situations that might be challenging to handle. It can take many miles of driving to encounter an edge case probabilistically on the road. Conditions for most of these edge cases are typically not easy to replicate in a controlled test track environment due to the required specific infrastructure, traffic, environment, and testing safety protocols. These edge cases, along with normal driving scenes, and other scenarios of interest in a given operational domain provide coverage of a variety of road layouts, environmental conditions, and traffic situations. A standard format for these scenarios would allow for the potential of scenario exchanges between interested parties and could further advance ADS development and performance assessment. Simulation-based testing typically offers high repeatability (absolute difference between a pair of repeated test results), reproducibility (the ability to replicate the results) and traceability (deterministic root-cause analysis) due to the controlled nature of the parametrized environment and vehicle systems. Simulation also faces some challenges, such as verifying that the simulated virtual world is an appropriate representation of the real world to provide useful insights. This topic is currently the subject of considerable research and could benefit from a common framework point of reference.

Figure 1 illustrates an example of how a generic simulation framework may fit within a holistic testing and validation process prior to and in conjunction with closed test track and public road testing. For this research, the ADS are treated as a "black box." This means that no internal information, therefore intellectual property, of the system needs to be known and testing is done at the system level by defining inputs and measuring outputs.[2] "Black box" testing reinforces the utility of standardization of inputs and outputs so that any ADS following these standards can be tested using a standardized method.

This research does not cover potential frameworks for the "simulator" block or the "unknown framework" simulator output block shown in Figure 1, nor does it cover the broader framework for how simulation may be used in conjunction with test track and public road testing. These frameworks maybe considered in future research efforts. Cybersecurity aspects of simulation are

[2] In contrast, "white box" testing allows for accessing internal information and intermediate outputs that is generally only available to developers by controlled access and/or with special interface services.

also out of scope for this research. Instead, this initial research effort focusses on methods and frameworks for implementing the "Road and Static Content" and "Dynamic Content" blocks shown in Figure 1. The "data sources" block shows that simulation scenarios can come from various sources, such as data gathered during public road testing, existing test track procedures, or crash data bases. An initial objective of this research is to focus on reviewing existing standards for describing scenario data, ("road and static content" and "dynamic content" blocks), so that data from these various data sources can be used by any simulator to aid in the development and testing of ADSs. It is believed that this will help future efforts to develop (open format, shareable) scenarios that could be used in a multitude of ways to improve trustworthiness and safety of ADSs.

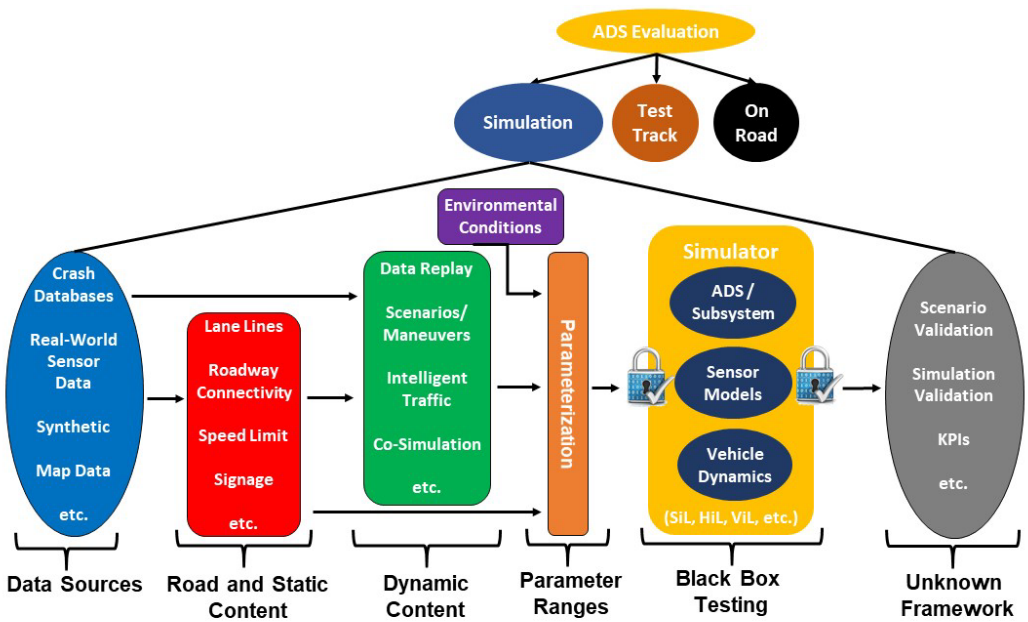

Figure 1. Generic ADS Testing Process

1.1 Definitions

Clear definitions and consistent use of terminology is critical to advancing the discussion around automation, including simulation. To date, a variety of terms (e.g., self-driving, autonomous, driverless, highly automated) have been used by industry, government, and observers to describe various forms of automation in surface transportation. This document uses the terms defined in SAE International standards, DOT policy documents, and uses "automation" and "automated vehicles" as general terms to broadly describe the topic, with more specific language, such as "Automated Driving System" or "ADS" are used when appropriate.

Advanced Driver-Assistance Systems: Systems designed to help drivers with certain driving tasks (e.g., staying in the lane, parking, avoiding collisions, reducing blind spots, and maintaining a safe headway). ADAS are generally designed to improve safety or reduce the workload on the driver. With respect to automation, some ADAS features could be considered SAE Level 1 or Level 2, but many are Level 0 and may provide alerts to the driver with little or no automation. (USDOT AV 3.0 [3])

Automated Driving System: The hardware and software that are collectively capable of performing the entire dynamic driving task on a sustained basis, regardless of whether it is limited to a specific operational design domain. This term is used specifically to describe Level 4 and 5 driving automation systems. (SAE J3016 [2])

ADS-Dedicated Vehicle: A vehicle designed to be operated exclusively by a Level 4 or Level 5 ADS for all trips. (SAE J3016 [2])

Dynamic Driving Task: All the real-time operational and tactical functions required to operate a vehicle in on-road traffic. (SAE J3016 [2])

Object List: A map of all the static and dynamic elements that the sensors of an ADS can detect that are not part of the map data. It may include the location, orientation, velocity, and acceleration of nearby vehicles and pedestrians, along with the location and height of roadside furniture. Building and maintaining an object list is the role of sensor fusion and processing in many ADS architectures.

Object and Event Detection and Response: The subtasks of the DDT that include monitoring the driving environment (detecting, recognizing, and classifying objects and events and preparing to respond as needed) and executing an appropriate response to such objects and events (i.e., as needed to complete the DDT and/or DDT fallback). (SAE J3016 [2])

Operational Design Domain: The specific conditions under which a given driving automation system or feature thereof is designed to function, including, but not limited to, driving modes. This can incorporate a variety of limitations, such as those from geography, traffic, speed, and roadways. (SAE J3016 [2])

High Definition Map: A type of map with up to centimeter-level precision and detailed roadway information. The roadway information may include the lane width, the location of street signs and traffic lights, directions of travel for each lane, road junction information, and speed limit information. [4]

Sensor Processing: Processing sensor data (in the form of, for example, a stream of RGB data, or lidar data represented as point clouds) and extracting object properties from it. These object properties may include spatial location and orientation, velocity and acceleration, category (such as bicycle, pedestrian, etc.), color, and others. Sensor processing may also include object tracking, i.e., associating object identity across data from different times, and the fusion of data from different sensors.

2 OVERVIEW

Before discussing the results of the literature review and market summary pertaining to formats for simulation environment data, an overview of a generic ADS and ADS simulation is presented for context.

2.1 Generic Example of an Automated Driving Systems

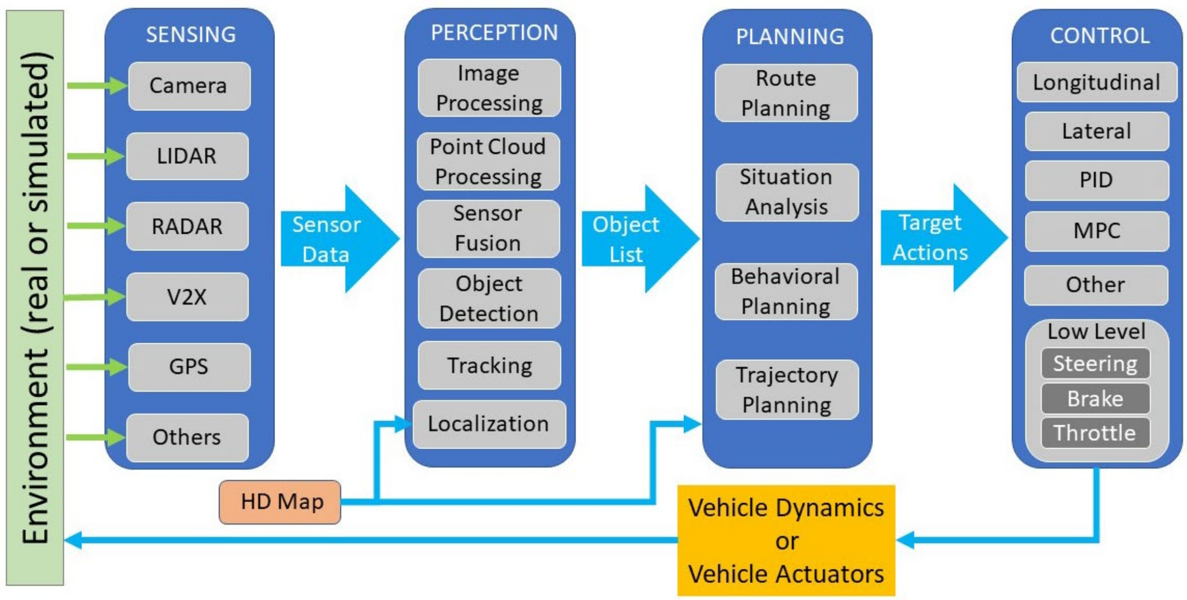

Figure 2. A Generic ADS Overview with Subsystems

Based on literature [5] and VSSAs published by ADS companies [1], a generic ADS may be considered to operate using four main subsystems; sensing, perception, planning, and control, as shown in Figure 2. These subsystems parallel human driving, which at its most basic level needs to answer the following questions: "What do I see?," "Where am I and what's around me?," "Where am I going?," and "How do I get there?."

As expressed in the "What do I see?" question, human drivers mainly rely on vision for sensing their surrounding environment. Human drivers also use other senses such as touch, sound, and vestibular feedback to provide information about the external and internal state of the car. Similarly, ADSs use sensors such as radars, cameras, lidars, and vehicle-to-x communication systems to receive and transmit information about the external environment. ADSs can also monitor the internal state of the car by using sensors, such as wheel speed sensors, IMU/GPS sensors, and brake/throttle/steering sensors. While this example shows many types of sensors, a specific automated vehicle that is intended for production may be equipped with any type and quantity of sensors.

The next step for a human driver is understanding where they are and what is around them. An ADS does this by providing the sensor data to the perception subsystem to understand the surrounding environment. Sensor processing units convert the sensor data into an object list. The object list data may include spatial location, orientation, velocity, acceleration, and category (such as bicycle, pedestrian, etc.) for objects surrounding the vehicle. Sensor fusion algorithms aid in confirming and refining the initial object list from various sensors into a final combined list of objects within sensor range of the vehicle. Perception can also include object tracking, i.e., associating object identity across data from different time intervals. In this example, another function that falls under perception is localization. Localization is the act of locating the vehicle's position, with up to centimeter accuracy, in the environment. This answers the question of "Where am I?." Human drivers do this by visually recognizing familiar features they have seen before and/or by referencing a map. ADS work in a similar way. ADSs can use RTK GPS to reference a map to find out where they are. They also can compare sensor data against a predefined sensor map to get a high accuracy estimate of position.

With information regarding where the vehicle is and what is around it, the next step for the ADS and human drivers is to plan a path. Just as human drivers plan a path based on the surrounding environment and the destination, the ADS's planning subsystem produces a trajectory that the vehicle should follow based on inputs from the perception subsystem and HD maps. This trajectory is based on current and predicted positions of the detected objects and obstacles, the road layout, traffic signs/signals, and the desired destination.

The last step for this generic ADS is controlling the vehicle along the desired path. The control subsystem considers the short-term desired trajectory, for the next few time stamps, and sends low level commands to the vehicle actuators or to a vehicle dynamics model to achieve the desired trajectory just as a driver would operate the brake, throttle, and steering wheel to achieve their desired path.

An ADS repeats this entire process of sensing, perception, planning, and control multiple times a second. These ADS subsystems are complex and are responsible for the complete DDT for a given ODD. This can result in adverse risks to safety without extensive validation. To aid in safety evaluation, simulation is considered a low risk tool that is often used with test track and road testing for a comprehensive and complimentary validation and verification framework.

2.2 ADS and Simulation Options

Testing ADSs in simulation can vary widely depending on the scope and goals of the simulation, as well as on the system/component being tested. As described in Section 2.1, ADS operation can be divided into four generalized subsystems; sensing, perception, planning, and control. These subsystems can be tested in simulation individually or in combinations. There are several methods for testing individual subsystems, combinations of subsystem, or even the complete ADS. These methods include model-in-the-loop, software-in-the-loop, hardware-in-the-loop, and vehicle-in-the-loop. Some commonly tested subsystems and combinations of subsystems, along with methods for testing them, are introduced in this section.

2.2.1 Perception Subsystem Simulation

Using a simulator to isolate and test the perception subsystem generally uses sensor data, like video data streams for cameras and point clouds for lidars, and feeds it into the respective sensor processing units, which generate independent object lists for each sensor. These objects lists are combined in sensor fusion to generate the overall object list output of the ADS. This can be done without simulation by using prerecorded sensor data. This approach has the limitations of not being able to change the vehicle's location or sensor location and type. This means that the prerecorded sensor data is only valid for the recorded vehicle trajectory and sensor set up.

The other option for testing the perception subsystem is using simulation to generate the raw sensor data. Setting up such a simulation is non-trivial, since the simulated sensor data needs to be both coherent, synchronized, and representative of the real-world. It also requires complex sensor models and graphics rendering to convert the ground truth object list to sensor data. The generated object list can then be compared to the ground truth data that was fed into the simulation to study the accuracy of the ADS's sensing and perception algorithms. This is beneficial compared to having to manually or semi-manually label ground truth data from recorded data. Sensor models are discussed in more detail in Section 2.3 below.

2.2.2 Sensor and Perception Subsystems Simulation

Such a simulation incorporates hardware like cameras, radars, GPS antennae, and other sensors into a HiL simulator. This increases the simulation complexity since the sensors need real-world-like situations presented to them to generate raw data. For radar, specialized equipment is available to generate radar data with appropriate Doppler shift and delay to simulate objects [6]. For cameras, the objects need to be rendered on a screen using appropriate image transforms to mimic real world objects. GPS simulators exist that can simulate real world-like GPS signals. Though these solutions exist, they add a lot of complexity to the simulation setup. Moreover, simulating actual geometries and material properties of the scene for lidars are still not feasible and generating the necessary signals to stimulate the lidar sensors is still an open research subject.

2.2.3 Planning and Control Subsystem Simulation

Using a simulator to isolate and test the planning and control subsystem involves providing the output of the perception subsystem, i.e., the object list, and a map to the ADS's planning subsystem. This can be used to check if the ADS is able to plan a safe trajectory for the given scenario. The output of the planner is then given to the control subsystem, and using a vehicle model within the simulation, the control subsystem can be tested.

2.2.4 Complete ADS Simulation

The complete ADS simulation enables the testing of the whole software stack of the ADS, including sensing, perception, planning, and control in a simulation environment. The challenge of establishing such a simulation setup is the complexity that comes with integrating all the subsystems and generating appropriate real-world-like data that is coherent and synchronized for all the various sensors.

2.2.5 ViL Simulation

Such a simulation, as the name suggests, incorporates the complete automated vehicle in the simulation environment. Two approaches for such a setup are discussed below.

2.2.5.1 ViL in Lab Simulation

Incorporating a ViL simulation in an indoor controlled laboratory setting requires extensive infrastructure capable of translating, rotating and tilting the whole automated vehicle as well as allowing for the vehicle's actuators to perform (i.e., wheels to rotate etc.). In addition, all the complexities of the sensor HiL simulation setup still exist. This considerably increases the cost and complexity of the setup. An example of such a setup is the Enable S3 - AVL DRIVINGCUBE [7].

2.2.5.2 Mixed/Augmented Reality ViL Simulation

Another form of ViL simulation is performed by operating a real automated vehicle on a test track and bypassing the sensors and injecting simulated sensor data or object list information to the ADS. This method is called mixed reality since it incorporates real world vehicle dynamics with simulated sensor/object data. Another similar simulation method is called augmented reality simulation. This is done by again operating a real vehicle on a test track and overlaying sensor data on top of incoming sensor data in a way that the ADS cannot distinguish the difference between the real and virtual objects/environment. By overlaying on top of the sensors the integration complexity is reduced. This option also allows for a partial evaluation of the sensing and perception subsystems on a test track in scenarios without the risk of crashing into test or real vehicles and without the need for complicated test vehicle coordination. Another benefit is that there is no need to develop vehicle dynamics models prior to testing. Since the actual vehicle is being used, this method produces high-fidelity vehicle dynamics. Also, other real vehicles can be used in low safety risk portions of test scenarios, like parked cars or easily sensed moving or stationary vehicles to supply realistic sensor data in conjunction with the virtual objects that are put in a high safety risk situation. An example of augmented reality testing is the work performed by Liu and Feng at the University of Michigan Transportation Research Institute [8].

2.3 Sensor Modeling

Some of the previously mentioned complexities of simulation can be overcome by introducing sensor models in software rather than using the actual sensor hardware. A sensor model is a mathematical representation of a physical sensor and its information manipulation process. Sensor models can vary in complexity and include ideal, probabilistic, and phenomenological or physics-based sensor models.

Ideal sensor models, or perfect sensor models, simply generate ground truth data for an object in range of the sensor. This means once an object comes in the field of view of the sensor, all the object list information relative to that sensor type (class for camera, relative distance and velocity for radar, distance for lidar, etc.) is obtained. Occlusion and confidence can still be applied during simulation with an ideal sensor.

A more realistic model uses a probabilistic approach to add uncertainty that is true in real sensors. An example of this for a radar model is modifying the object list data based on the radar datasheet and other parameters or disturbances to generate a realistic object list. This approach closes the gap between an ideal sensor output and the data generated from actual sensors.

The more complex phenomenological and physics-based sensor models are based on modeling and parametrizations of sensor physics. They are computationally intense and require increased processing power. A detailed description of environmental conditions (material properties, weather conditions, etc.) is needed to accurately model the physics of the sensor. The output of these models can be raw, analog signals comparable to that of the real sensor.

At this time, and for this research effort, the probabilistic sensor models may provide a more reasonable trade-off between complexity and computational efficiency since it reduces the number of properties that must be defined for a given scenario. This allows simulation tests to be performed faster than real time, while still allowing for applicable object list to be passed to the planning algorithm. This is important for efficiency, since the ADSs will be subjected to numerous scenarios with multiple configurations (speed, position, environment, etc.). It can be applied in SiL, HiL, or any other simulated environments. However, its idealistic sensing of the environment around the vehicle makes this choice less realistic when compared to actual situations encountered by ADSs. This tradeoff may be addressed in the future, as computer processing speed and cost efficiency continue to improve, and simulation products get more advanced capabilities. It's also noteworthy to mention that the simulation system does not require high-fidelity in every modeled component to provide useful information about performance of the vehicle and ADS. For instance, the sensor and perception subsystems could be further tested and validated in controlled test track scenarios that are complimentary to a subset of specific scenarios performed in simulation.

2.4 Vehicle Dynamics

To close the loop between the ADS and the simulated environment, a vehicle dynamics model must take the low-level commands from the ADS control subsystem and update the vehicle's position in the simulated environment. Therefore, the vehicle dynamics model influences the ADS performance and the more accurate the vehicle dynamics are to that of a real vehicle, the more realistic the ADS simulation can be. However, there is a trade-off between a high-fidelity vehicle model for accuracy and a lower fidelity model for computational cost and time. Balancing this trade off isn't a trivial problem. There has been some research conducted that aims to determine a minimum fidelity vehicle model required for a given maneuver severity, such as standard driving maneuvers verse crash imminent, highly dynamic maneuvers. There are also standards set to validate vehicle dynamic models for given maneuvers based on real world data. These vehicle dynamic validation methods and standards will be discussed in the literature review in Section 3.4.

2.5 ADS Maps

As discussed in the ADS overview, there are a variety of maps that can be used by an ADS for perception and planning. These maps can differ from traditional maps humans use for navigation. The first type of map that the ADS may use is commonly referred to as an HD map. HD maps contain detailed roadway information. The roadway information may include the lane width, the location of street signs and traffic lights, directions of travel for each lane, road junction information, and speed limit information. These HD maps are used for planning and to determine if the ADS is in its ODD.

Some ADSs use custom generated and continually updated sensor maps to assist in localization. These maps are constructed from historical sensor data. Such a pre-built sensor map is usually specific to an ADS's sensor setup. To localize, the ADS cross-references sensor data with the local historical sensor map to precisely estimate its current location on the road (GPS is usually fused with the sensor readings for robustness).

3 LITERATURE REVIEW

An extensive literature review was conducted to identify existing frameworks and standards for scenario definitions. The literature review is structured as follows. First, existing simulation standardization projects are presented. This includes works from governments, standardization bodies, and industry that aim at providing methods and standards to aid in validating and verifying autonomous vehicles. Then literature regarding scenario specification will be discussed. Next, standards and frameworks for co-simulation are presented. Co-simulation standards provide methods to aid in subsystem testing as mentioned in Section 2.2. Then literature regarding simulation fidelity for vehicle dynamics is introduced. Finally, any applicable standards for general simulation and automated vehicle safety are presented along with industry reports.

3.1 Simulation Standardization Projects

With the rapid development and deployment of ADS, stake holders who have a vested interest in ensuring ADS safety have formed various consortiums and working groups with this common goal in mind. These groups have published significant research regarding ADS safety, including simulation methods for ADS safety. A review of existing groups that are working on simulation standardization is presented in this section. Increased collaboration with these groups may benefit and accelerate the standardization process.

3.1.1 RAND Corporation

The RAND Corporation is a research organization with a stated mission to “develop possible solutions to public policy challenges that help make communities throughout the world safer, healthier and more prosperous.” RAND has published several articles related to autonomous vehicles, including the often referenced *Driving to Safety: How Many Miles of Driving Would It Take to Demonstrate Autonomous Vehicle Reliability*? [9]. This report states that an ADS would have to be driven hundreds of millions, and sometimes hundreds of billions, of miles to demonstrate their reliability in terms of avoiding fatalities and mitigating injuries.

RAND also released a report titled *Measuring Automated Vehicle Safety: Forging a Framework* [10]. This report presents a framework for measuring safety in automated vehicles that could be used broadly by OEMs, policymakers, and the public. The authors addressed safety definitions, measurements, and a framework to communicate them to the general public. Given ADSs' limited total on-road exposures compared with conventional, human-driven vehicles, the authors also considered options for proxy measurements, i.e., factors that might be correlated with safety through simulation and on closed courses. It presents a structured framework/methodology to measure safety at different stages of an ADS's evolution. While acknowledging that the closely held nature of ADS data limits sharing of this data between companies and with governments, the report highlights the kinds of information that could be presented in consistent ways in support of public understanding of ADS safety.

Of interest to this research is the RAND report’s discussion on simulation limitations and validity. The report discusses confirmation bias as hurdle for simulation. Confirmation bias is defined as the tendency to interpret new evidence to confirm or reinforce one's existing beliefs and theories. This RAND report suggest that this confirmation bias can be combated by continual revision of safety measures based on new information and by creative interrogation of results to explore alternative explanations.

The report also notes that safety flaws can develop at the seams that exist between subsystems (typical ADS subsystems shown in Figure 2), notably as the result of misalignment of each subsystem's purpose and miscommunication of constraints but may go undetected in simulation. The report explains further that sensor simulation remains imperfect because of the complexity of simulating the details of the electromagnetic wave propagation that determines the performance of camera, lidar, or radar. Hardware and sensors can be added into more sophisticated simulations, but this artificial setting remains unable to provide the fidelity of real world environments. The authors refer to simulation validity as the ability of a test, scenario outcome, or other measure to determine safety.

For the simulation setting, validity depends on the correspondence between simulated and actual ADS performance. The authors mention internal simulation validity, which deals with the quality of the simulation software in terms of speed, bugs, faithfulness to present protocols and best practices. They also discussed external validity, which is how consistent the simulated ADS performance is with real-world performance under the same conditions, i.e., simulator fidelity. Simulations can be inaccurate or overly simplified versions of the real world. They also mention the inability to compare validity across types of simulations and simulators due to a lack of simulation standards, which is one of the topics covered in this project.

3.1.2 Catapult

The Catapult centers are a network of centers whose stated mission is to transform the United Kingdom's capability for innovation in specific areas and help drive future economic growth. Transport Systems Catapult is the UK's innovation center for intelligent mobility, where connected and autonomous vehicles research is one of its main activities.

In 2018 Transport Systems Catapult published a report titled *Regulating and Accelerating Development of Highly Automated and Autonomous Vehicles Though Simulation and Modeling* [11]. This report discusses the challenges in demonstrating confidence in ADS in the wide variety of environmental conditions they are expected to operate in. The authors mention that it is not realistic to test every combination of sensor input and driving situation with physical, real world testing. Therefore, the report proposes simulation, modeling, and testing as a potential solution to fill this gap and to enable rigorous, controlled, and timely evaluation of ADSs.

This Catapult report seeks to explore capabilities from the perspective of simulation and modeling for two categories; design/development and regulation/approval. For the design and development of ADSs, the authors describe the simulation capabilities that will enable accelerated ADS development. For regulation and approval, the authors note that a key challenge for regulators is determining whether ADSs, at the whole system level, are safe so that they can be approved for sale in the international market. The report proposes two phases of interventions that provide a framework for the testing and simulation of ADSs. The first phase addresses the short term needs to provide regulators with a means to assess the performance of an ADS. It relies on sensor processing being evaluated in the real world at a controlled test facility or proving ground, along with a simulated environment (e.g., a well-characterized digital twin of a test facility) to evaluate the ADS in simulation, and finally a physical test at a proving ground to evaluate ADS driving performance. The second phase addresses the longer-term needs of regulators and industry, building upon the prior phase. The report integrates sensor testing into a simulated environment that will ultimately enable the timely test and evaluation of over-the-air updates to ADS. The authors of the report anticipate that the dependence on physical testing will decrease progressively with time, while the extent and confidence in simulated testing grows. It is expected that an element of physical testing will always remain as part of the evaluation of ADSs.

Of specific interest relating to this project, the Catapult report proposes a target architecture for an ADS simulation test framework with three key elements: vehicle dynamics models, sensor models, and environmental models. The authors suggested that the vehicle dynamics models are well understood by the industry and lower fidelity models are sufficient for ADS simulated testing, however; sensor models are not yet mature enough for this task. As for the environmental models, the authors suggest that they should be “digital twins” of real world locations and that details regarding the level of fidelity needed in environmental models need to be addressed.

The report also discusses scenarios as key elements in the simulated testing of ADSs. The report states that scenarios are central to assuring the safety of ADSs and they can be easily understood by humans, are easy to convert to automated test cases, and can capture the characteristics of situations that are challenging to an ADS. The authors state the need for both normal driving and edge case scenarios with sensitivity testing to identify areas of weakness in ADS solutions that would not normally be found through field testing. Moreover, there should be an element of randomization in the selection of scenarios that an ADS-under-test is subjected to, to prevent “gaming” of the test (deliberate ADS design to just pass only the scenarios under consideration).

Standardized interfaces are required within any integrated test environment and several open issues need to be resolved, which are: How many scenarios are required? What should be the electronic format for scenario sharing? Should certain scenarios be prioritized? What level of detail should scenarios be stored at? (e.g., complete coordinates and speeds, or just “vehicle from the left lane cuts in front”). The authors state that a range of sources for scenarios already exist, and that there is a need for industry and regulators to collaborate and share insight to enable a central scenario repository to be established. Such a repository needs to grow as new challenging scenarios are being discovered, including near misses involving ADSs. The authors also recommend a “test oracle” to analyze the results of testing to remove the need for a human to monitor each vehicle under test. This thereby speeds up the process, removes human error, and enables more scenarios to be tested in a shorter time.

The report concludes by observing that the ADS simulation tools market is evolving fast and due to the large number of potential competing players adapting products from related areas, the market can expect to see consolidation and continuing alliances between tool vendors and providers to perform certain parts of the verification task. In the next 5 to 10 years, it may be possible that a common testing framework will emerge and, if so, this is likely to have an alliance of industry-leading simulation tool providers as its basis. Despite the authors interviews with stakeholders, the authors are still unclear if the key simulation tools for ADS design will be primarily bought off the-shelf or developed in-house by ADS developers. They suggest that for regulatory purposes, tools or frameworks that are independent of the system developers are likely to be required.

3.1.3 PEGASUS

PEGASUS joint project stands for: **P**roject for the **E**stablishment of **G**enerally **A**ccepted quality criteria, tools and methods as well as **S**cenarios and **S**ituations for the release of highly automated driving functions. PEGASUS' goal is to develop, a generally accepted and standardized procedure, for the testing and approval of automated driving functions to facilitate the rapid implementation of automated driving into practice.

The report states that the German automotive industry maintains the opinion that a standardized procedure in the field of testing and experimenting is necessary for securing the approval of higher levels of automation. For this reason, the PEGASUS project has brought together automotive OEMs, suppliers, small and medium-sized companies as well as research facilities to work towards the goal of developing a standardized ADS testing procedure.

Overview of the PEGASUS projects main tasks:

1. Definition of standardized procedures for the testing and experimenting of automated vehicle systems in simulation, on test stands, and in real environments.
2. Development of a continuous and flexible tool chain for automated driving safety assurance.
3. Integration of the tests at an early stage of development processes.
4. Creation of a manufacturer independent method for the safety assurance of highly automated driving functions.

PEGASUS also provides some structure for defining scenarios. They break scenarios down into three abstraction levels: functional, logical, and concrete. For representation of functional scenarios, a structure for a linguistic description has been developed. This structure enables an abstract definition of scenarios. Logical scenarios define the parameter space to be tested and provide the essential information for test case generation. Concrete scenarios are then a specific instance of the logical scenarios and are used as input data for the simulation-based test. Concrete scenarios are represented by the quasi-standards OpenDRIVE and OpenSCENARIO.

3.1.4 Enable-S3

Enable-S3 is an industry consortium aimed at developing cost-effective verification and validation methods for automated cyber physical systems for various domains (automotive, aerospace, rail, maritime, health care and farming). The consortium recognizes that simulation cannot reproduce the environment with sufficient fidelity to replace real-world testing, due to limitations in modeling and computation. Since real-world testing can be expensive, time consuming, and potentially dangerous, their goal is to combine the strengths of both simulation and real-world testing in an optimized manner into an innovative solution. They demonstrate this capability in the automotive domain in five use cases: Highway Pilot, Intersection Crossing, Context-Aware In-Car Reasoning System, Traffic Jam Pilot with V2X Communication, and Valet Parking. For each of these use cases, they applied different test environments (HiL, ViL, DiL) and compared the results of varying levels of simulation and real-world testing. The main deliverables included an overall framework for testing ACPS that includes coupling hardware, software, and testing equipment. Scenario generation tools and performance metrics were incorporated into each case. The consortium also produces research articles regarding sensor modeling, test optimization, and standardization. Detailed information regarding criteria necessary for specific sensor simulation and stimulation is also presented.

3.1.5 Scottish Law Commission

On November 2018 the Law Commission of England and Wales, and the Scottish Law Commission released a joint paper on automated vehicles titled *Automated Vehicles: A Joint Preliminary Consultation Paper* [12]. The paper follows a request from the Centre for Connected and Autonomous Vehicles to review the UK's regulatory framework to enable the safe and effective deployment of automated vehicles on the UK's roads. This was the first paper released as part of the three-year project exploring the regulation of automated vehicles, which will run until March 2021. This paper focused on the use of automated vehicles for private passenger transport (i.e., not of regulated public transport or logistics). The paper covers three key themes; first, safety assurance before automated vehicles are placed on the market, as well as ongoing monitoring and maintenance requirements once on the road; second, criminal and civil liabilities; and finally, the need for the adaptation of road rules for artificial intelligence.

The main point of interest to this paper is that the UK government announced up to £15 million of funding for projects that use simulation and modeling in the development of approvals and standards for autonomous and connected vehicles. The results of these projects are of interest to this work and will be continually monitored.

3.1.6 Singapore Technical Reference 68

Singapore has released a set of national standards to guide the local industry in the safe development and rollout of automated vehicles. These standards include guidelines related to vehicle behavior, functional safety, cybersecurity, and data formats. The standards are called Technical Reference 68 (TR 68) The standards were developed by various representatives from the automated vehicle sector, research and education institutions, and government agencies.

Of interest is Standard TR 68 – 4, titled *Technical Reference for Autonomous Vehicles – Part 4: Vehicular Data Types and Formats* [13]. It specifies vehicular data types and formats, but not the interchange syntax, for the following purposes:

a) Data to be recorded by the data storage system for ADSs,
b) Reasonable and adequate use of ADS data to continuously improve safety,
c) Management of dynamic content (e.g., high-definition mapping, road traffic information),
d) Use in investigation and reporting of accidents and claim disputes, and
e) V2X information exchange for enhancing safety and efficiency.

3.2 Scenario Specification

This section contains literature focused on describing and categorizing scenario elements that an ADS would encounter in the real world. As previously mentioned, this research is focused on roadway information, static scenario contents, and dynamic scenario contents as shown in Figure 1. Another important scenario element shown in Figure 1 is the environmental conditions, which are mentioned in some of the following literature but not the focus of this work since these environmental conditions predominately influence the sensing and perception subsystems.

Roadway information includes the layout of the lanes, the lane boundaries, speed limits, road surface types, friction coefficients, lane widths, direction of travels, and road types to name a few. These properties change throughout the length of the road.

Once the roads are defined, the road networks, which include how the roads meet and intersect, need to be defined as a later step. Accurate descriptions of the intersection geometries and layouts are important for the ADS navigation planner.

Static scenario contents need to be defined in terms of category, location, orientation, and bounding boxes. It is also useful to know if this static content was part of the existing base map (i.e., pole or sign) or is a new static object (i.e., stopped/parked car). Other information for specific static content, such as traffic light timing, might be necessary.

Finally, dynamic contents include all objects capable of movement during the scenario. These could be pedestrians, bicyclists, animals, or various other types of road users. Depending on the scenario design, it might be required that the motion of these actors depend on a triggering event or the motion of the ADS vehicle or another actor. Details regarding category, location, orientation, bounding box, motion, velocity, and acceleration to name a few are needed for these objects.

3.2.1 Association for Standardization of Automation and Measuring Systems OpenX

The Association for Standardization of Automation and Measuring Systems consists of more than 200 member organizations worldwide. These member organizations are automotive OEMs, suppliers, tool vendors, engineering service providers, and research institutes. ASAM standardization seeks to incorporate requirements from many different global viewpoints to produce an efficient interface. Thus, ASAM standards allow users to choose tools by their capability, efficiency, and support, rather than by proprietary connections.

ASAM has taken ownership of the VIRES OpenSCENARIO, OpenDRIVE, and OpenCRG specifications and is working to improve and maintain these standards. These three specifications together are referred to as the OpenX standards and give a description of road networks for driving and traffic simulation, allowing for the specification of driving maneuvers and test scenarios in a standardized language, methodology, and file format.

OpenCRG defines a file format for the detailed description of road surfaces. OpenCRG data sets are designed to describe patches of road surfaces in a very detailed format so they can be for applications such as tire, vibration, and driving simulation.

OpenDRIVE defines a file format for the precise analytical description of road networks. This includes exact road geometry descriptions, marking, signs, and logical properties such as lane types and directions. It may also include surface properties from OpenCRG. Road data can be synthetically created, converted from map data, or converted from sensor-based scans of real world roads.

Finally, OpenSCENARIO defines a file format for the description of the dynamic content in the simulated environment. It can be used to describe, complex, synchronized maneuvers that involve many actors such as vehicles, pedestrians, and other road users. Descriptions include driver actions (e.g., lane change) or trajectories (e.g., derived from a recorded driving maneuver). Descriptions of subject vehicle, driver appearance, pedestrians, traffic, and environment conditions, are included in this standard as well.

These standards are in the initial stages of development. ASAM has published a road map detailing the conversion of these to official ASAM standards.

3.2.2 RoadXML

The RoadXML is an open file format for the logical description of road networks. The RoadXML is the initiative of OKTAL to open its own file format resulting from the compilation of proprietary formats originally from two main projects: the GRS file format co-developed by INRETS, OKTAL and PSA Peugeot Citroën since 1995 and the RNS/RS file format, native format of SCANeRII software since 1997, co-developed through the Eureka Truck Simulator TRaCS project between Renault, Thales, Volvo 3P (Renault Trucks), and AutoSim.

The ambitions of the RoadXML group are to take part in the standardization of road network format to enhance the interoperability between the simulators and to develop a unique gateway between driving simulators and traffic engineering applications. The RoadXML group states that it is the outcome of 15 years of research and development in collaboration with academic, research and industrial partners in the driving and traffic simulation domains.

The RoadXML format is an XML file format that states that it is designed to answer the needs of many simulator applications:

- Traffic simulation: entities acting on networks such as pedestrians, vehicles, and bicycles;
- Scenario control;
- Car, truck, motorbike, motorsport or military vehicle dynamics models;
- Motion platform control model;
- Sound control; and
- 3D road networks generation.

RoadXML offers a multi-layer description of the environment for fast data access for real time applications. Here are the four main layers of information

- Topological: element's location and connections with the rest of the network.
- Logical: element's signification in a road environment.
- Physical: element's properties (road surface or obstacles).
- Visual: element's geometry and 3D representation.

A road network in the RoadXML file format is compounded of a patchwork of sub-networks. Each sub-network is a collection of tracks linked by intersections. Each of these intersections and tracks are then enhanced with different layers of data.

- The road profile is added on the track to define the pavement surface.
- Road signs and other local cognitive elements are attached to the track.
- Traffic and 3D description are carried by the road profiles.

The RoadXML file format is also extensible and allows users to add extra information into the format. Current commercial products that use the RoadXML format as advertised on the RoadXML website are: SCANeRstudio and SCANeRDT by AVSimulation and OKSimRail by OKTAL. The last update to the RoadXML format specification was RoadMXL 2.4.13 in 2016.

3.2.3 GeoJSON

GeoJSON is an open standard format designed for representing simple geographical features, along with their non-spatial attributes. It is based on JSON, the JavaScript Object Notation.

The features include points (addresses and locations), line strings (streets, highways and boundaries), polygons (countries, provinces, tracts of land), and multi-part collections of these types. GeoJSON features need not represent entities of the physical world only; mobile routing and navigation apps, for example, might describe their service coverage using GeoJSON.

The GeoJSON format differs from other GIS standards in that it was written and is maintained not by a formal standards organization, but by an Internet working group of developers.

3.2.4 SDF XML Format

SDF is an XML format that describes objects and environments for robot simulation, visualization, and control. Originally developed as part of the Gazebo robot simulator, SDF was designed with scientific robot applications in mind. Over the years, SDF has become a stable, robust, and extensible format capable of describing all aspects of robots, static and dynamic objects, lighting, terrain, and even physics.

Accurate descriptions of all aspects of a robot using SDF is possible, whether the robot is a simple chassis with wheels or a humanoid. In addition to kinematic and dynamic attributes, sensors, surface properties, textures, joint friction, and many more properties can be defined for a robot. These features allow for SDF to be used for both simulation, visualization, motion planning, and robot control.

Simulation also requires rich and complex environments in which models exist and interact. SDF provides the means to define a wide variety of environments. Multiple lights may be included in an environment, terrain (either fictional or based on a digital elevation model), streets from OpenStreetMaps, and any model provided from an online repository of 3D models can also be included.

3.2.5 Fatality Analysis Reporting System/Crash Report Sampling System

While not a formal standard for scenario description, the NHTSA Fatality Analysis Reporting System and Crash Report Sampling System databases provide some structure for defining road and environment information for a crash. NHTSA has collected motor vehicle traffic crash data since the early 1970s to support its mission to reduce motor vehicle traffic crashes, injuries, and deaths on our nation's traffic ways. FARS was conceived, designed, and developed by the National Center for Statistics and Analysis of NHTSA in 1975 to provide an overall measure of highway safety, to help identify traffic safety problems, to suggest solutions, and to help provide an objective basis to evaluate the effectiveness of motor vehicle safety standards and highway safety programs. Both FARS and CRSS data systems share a similar reporting format. Since these data systems already provide a large volume of important crash data that ADS systems could be tested against, any similarities between an open format framework for sharing simulation data and the FARS and CRSS data bases would increase the ease of accessing this important data.

The road and environment information that these data bases contain are split into pre-crash level data elements and crash level data elements. They are listed below.

Crash Level Data Elements

C8 – Crash Date

C9 – Crash Time

C10 – Trafficway Identifier – FARS Only

C11 – Route Signing – FARS Only

C12 – Land Use and Functional System – FARS Only

C14 – National Highway System – FARS Only

C15 – Special Jurisdiction – FARS Only

C16 – Milepoint – FARS Only

C17 – Global Position

C18 – Crash Events

C19 – First Harmful Event

C20 – Manner of Collision

C21 – Relation to Junction

C22 – Type of Intersection

C23 – Relation to Trafficway

C24 – Work Zone

C25 – Light Condition

Pre-Crash Level Data Elements

PC4 – Contributing Circumstances, Motor Vehicle

PC5 – Trafficway Description

PC6 – Total Lanes in Roadway

PC7 – Speed Limit

PC8 – Roadway Alignment

PC9 – Roadway Grade

PC10 – Roadway Surface Type – FARS Only

PC11 – Roadway Surface Conditions

PC12 – Traffic Control Device

PC13 – Device Functioning

PC14 – Driver's Vision Obscured By

PC15 – Driver Maneuvered to Avoid

PC16 – Driver Distracted By

PC17 – Pre-Event Movement (Prior to Recognition of Critical Event)

PC18 – Critical Event – Pre-Crash (Category)

Crash Level Data Elements

C26 – Atmospheric Conditions

C27 – School Bus Related

C28 – Rail Grade Crossing Identifier – FARS Only

C32 – Related Factors – Crash Level

C33 – Interstate Highway – CRSS Only

C34 – Stratum – CRSS Only

Pre-Crash Level Data Elements

PC19 – Critical Event – Pre-Crash (Event)

PC20 – Attempted Avoidance Maneuver

PC21 – Pre-Impact Stability

PC22 – Pre-Impact Location

PC23 – Crash Type

Further classification and more detailed explanation of each of these data elements is recorded in the actual databases. For example, for crash level data elements C21–relation to junction, attributes include non-junction, intersection, entrance/exit ramp, railway crossing, driveway access, shared-use path crossing, to name a few.

It is worth noting that other crash databases, such as the German In-Depth Accident Study and China In-Depth Accident Study have been used to reconstruct scenario in simulation for evaluating ADAS/ADS technology It would be beneficial if the FARS/CRSS database could also be converted to simulation scenarios. This might require more detailed information, such as trajectory level information of vehicles, than what is currently recorded in the FARS/CRSS. This would allow for an objective basis to evaluate the effectiveness of proposed ADS technology.

3.2.6 SAE J3049

SAE J3049 [14] is titled, "*Model Architecture and Interfaces Recommended Practice for Ground Vehicle System and Subsystem Dynamical Simulation*". It defines the architectural structure of a ground vehicle system dynamic model by partitioning it into subsystem models and by defining subsystem interfaces required to enable plug-and-play operation of dynamic simulation models. The overall hierarchal organization is:

1. **Environment**
    a. Atmospheric
    b. Road/Terrain
    c. Traffic/Surroundings
    d. Remote HMI
2. **Driver/Passengers**
    a. Driver
    b. Remote Driver
    c. Passengers
3. **Vehicle**
    a. Vehicle Supervisory Control
    b. Power
        i. Power Supervisory Control
        ii. Electrical
        iii. Thermal Management
        iv. Fuel
        v. Propulsion Power
        vi. Auxiliary Power
        vii. Transmission
        viii. Driveline
    c. Chassis
        i. Chassis Supervisory Control

ii. Steering
iii. Braking
iv. Wheels/Tracks
v. Suspension
vi. Body-Frame
vii. Body-Frame Supervisory Control
viii. Under Body
ix. Upper Body
x. Cabin Interior
xi. Cabin Climate
xii. Power Take-Off Accessories

d. Trailer

Some specific areas of interest for this research are how the environment subsystem and its corresponding subsystems interface with the driver/passenger and vehicle subsystems. One of the environmental subsystems is the road/terrain subsystem. The road/terrain subsystem defines the physical state of the ground surface at the contact patches of the wheels/tracks. It describes the road/terrain conditions (surface coefficient of friction, surface slope or gradient [surface pitch and roll], and surface geometry, etc.). Another subsystem of interest is the traffic/surroundings subsystem that defines the local traffic and infrastructure surrounding the vehicle. It describes the traffic conditions (position, velocity, and volumes/footprints of surrounding vehicles, pedestrians, other occupied spaces, and unoccupied spaces, etc.), the surrounding conditions of the infrastructure, (e.g., traffic lane configuration, lane width, clearance height, speed limits, traffic lights, etc.) and may have a traffic/surroundings controller within it to control test conditions according to defined test schedules as would be performed on test tracks, test trips, and/or on road courses in traffic.

SAE J3049 also mentions automated driver functions. These functions fall under the vehicle supervisory control subsystem. However, as a control subsystem, it could also include additional actuators and sensors. With these additional capabilities to sense and control, it may provide remote or automated driving operation, active safety functions, driver performance monitoring and compensation, and both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. As an example, for an automated driver function, the vehicle supervisory control subsystem would require additional sensors, such as radar, camera, etc., and additional actuators, such as brake/throttle actuators, vibrators, annunciators, lights or special displays, etc.

While these subsystem interfaces are of interest, there is no framework to represent a scenario topography and no details regarding data structures or file formats included in the SAE J3049 standard.

3.2.7 A Framework for ADS Testable Cases and Scenarios

This NHTSA report [15] describes a framework for establishing sample preliminary tests for ADS. The focus is on light duty vehicles exhibiting higher levels of automation, where the system is required to perform the complete dynamic driving task, including lateral and longitudinal control, as well as object and event detections and responses. Regarding scenario specification, the report identifies the attributes that define the ODD and its taxonomy. Scenario specification is broken down into a hierarchy of categories and subcategories, each with definitions and, where appropriate, gradations. This hierarchical taxonomy includes the following top-level categories.

1. **Physical Infrastructure**
    a. Roadway Types
    b. Roadway Surfaces
    c. Roadway Edges
    d. Roadway Geometry
2. **Operational Constraints**
    a. Speed Limit
    b. Traffic Conditions
3. **Objects**
    a. Signage
    b. Roadway Users
    c. Non-roadway Users
4. **Obstacles/Objects Connectivity**
    a. Vehicles
    b. Traffic Density Info
    c. Remote Fleet Management System
    d. Infrastructure Sensor and Comms
5. **Environmental Conditions**
    a. Weather
    b. Weather-Induced Roadway Conditions
    c. Particulate Matter
    d. Illumination
6. **Zones**
    a. Geofencing
    b. Traffic Management Zones
    c. School/Construction Zones
    d. Region/States
    e. Interference Zone

The hierarchy extends into multiple sublevels. For example, weather is further subdivided into rain, temperature, wind, and snow. Some of the challenges associated with ODD elements include their variability (e.g., rain droplet sizes can vary greatly: light rain, moderate rain, and heavy rain), as well as identifying or defining their boundaries. The work performed to identify the ODD lays a foundational framework that can be further defined and delineated so an industry standard for ODD definition can be established.

3.2.8 TNO StreetWise

TNO, an independent research organization in the Netherlands, recently published a report titled *Scenario-Based Safety Validation of Connected and Automated Driving* [16]. This document details StreetWise, a data-driven methodology that provides real-world scenarios and test cases for the development and assessment of ADASs and (connected) ADSs. StreetWise consists of a database in which all parameterized scenarios identified from real-world driving data is stored. The driving data was collected from various fleets of data collection vehicles. The database provides scenario selection with an overview of the probability density functions of the parameters showing how frequently a certain measured value of a parameter is found in the selection. From the scenario selection, test cases are generated by sampling parameter values, such as simply replaying the scenario as encountered on the road without sampling or using statistical methods like Monte-Carlo simulation. Test cases can be exported to the OpenSCENARIO and OpenDRIVE format.

Within StreetWise, the scenario definitions and the related scenario mining techniques are agnostic to the automated driving technology or the applied sensor technologies. Scenario specification is only limited by the ADS field-of-view, and the quality of target identification of the sensor system onboard. A scenario cannot be reliably described outside the field-of-view and for this reason, the sensor system limitations are stored in the database meta information with a reference to the resulting scenarios. Through off-line analysis, scenario mining algorithms can ‘look into the future’ and have a higher level of confidence than what a real-time analysis would provide.

3.3 Co-Simulation

Co-simulation is the distributed modeling and simulation of different subsystems that form a larger, coupled system. This allows for modeling to be done on the subsystems level while providing standard interfaces to connect these subsystems to the rest of the system. These standard interfaces include standard scenario descriptions for co-simulation of ADSs. This section discusses published co-simulation standards and interface tools for hardware and software that could be applied to simulators built to test ADSs. It also contains information for connecting separate simulations together with interactive communications. These co-simulation standards provide a common framework for developing, testing, and sharing multiple subsystems and tools that aid in the overall development of ADS. In contrast, many of the simulation options covered in Section 2.2 deal with a given subsystem.

3.3.1 IEEE 1516 - The High-Level Architecture

The IEEE High-Level Architecture (HLA) – Object Model Template (OMT) Specification [17] has been developed to provide a common architecture for distributed modeling and simulation. The HLA defines an integrated approach that provides a common framework for the interconnection of interacting simulations. The document published by IEEE defines the standard services of, and interfaces to the HLA runtime infrastructure. These services are used by the interacting simulations to achieve coordinated exchange of information when they participate in a distributed federation. The Object Model Template specification defines the format and syntax (but not content) of HLA object models.

3.3.2 ASAM XIL

ASAM XIL. is an API standard for the communication between test automation tools and test benches. The standard supports test benches at all stages of the development and testing process – most prominently MiL, SiL, and HiL. This has the advantage that it enables users to freely choose testing products according to their requirements and integrate them with little effort. Using ASAM XIL-compliant products allows users of test systems to mix and match the best components from different suppliers without having costly integration efforts. The standard furthermore decouples test-cases from real and virtual test systems. This allows for transfer between different test systems with little to no migration effort. Consequently, tests can be consistently standardized, easily re-used, and reproduced at different organizations and test systems.

3.3.3 Advanced Co-Simulation Open System Architecture

Advanced Co-Simulation Open System Architecture (ACOSAR) [18] provides a virtual system development/validation tool for real-time systems. ACOSAR uses a modular co-simulation approach, supporting flexible system development, to integrate domain-specific subsystems. ACOSAR focuses on the specification of a non-proprietary open RT-system interface, a so-called “Distributed Co-Simulation Protocol,” for sharing relevant information for efficient and safe operation of RT systems, e.g., testbeds. ACOSAR proposes to develop a system independent communication architecture as well as functional framework for coupling strategies, highly efficient data transmission, and support for semantic data processing.

3.3.4 FMI/FMU

The Functional Mock-up Interface (FMI) [19] standard is an open and tool-independent standard for exchange of models and co-simulation between tools. FMI defines a combination of XML-files and C-code interfaces that are implemented by an executable called a functional mock-up unit (FMU). A simulation environment can use the FMI to create an instance of the FMU and simulate it together with other FMUs or models native to the simulation environment. The development of FMI was driven by an aspiration to create a standard in which a modeling environment could generate C-code of a system model, which could then be utilized by other modeling and simulation environments, thereby making it easier to collaborate in modeling projects where different tools and workflows are used. FMI/FMU development is currently maintained by the Modelica Association Project, a nonprofit, independent organization with the aim of developing modeling and simulation of physical systems and processes.

3.3.5 Open Simulation Interface

The Open Simulation Interface (OSI) [20] contains an object-based environment description using the message format of the protocol buffers library developed and maintained by Google. OSI consists of two individual top-level messages defining the *GroundTruth* interface and the *SensorData* interface. The *GroundTruth* interface gives an exact view on the simulated objects in a global coordinate system. This message is populated using the data available internally and then published to external subscribers by a plugin running within the driving simulation framework. The *SensorData* interface describes the objects in the reference frame of a sensor for environmental perception. It is generated from a *GroundTruth* message and can either be used to directly connect to an automated driving function using ideal simulated data or may serve as input for a sensor model, simulating limited perception replicating real world sensor behavior. OSI provides a way to convert the complex data structures representing object and sensor data to the FMU/FMI standard. OSI helps ease the implementation of driving simulators by providing a generic interface between the function development framework and the simulation environment. This enables easy and straightforward compatibility between automated driving functions and the variety of driving simulation frameworks available.

3.4 Vehicle Dynamics Model Fidelity

ADS path planning and control simulation requires a vehicle dynamics model to close the loop between the ADS subsystems and the virtual world. Therefore, the vehicle dynamics model influences the ADS performance. Validation of accuracy and fidelity of vehicle dynamics models is an active area of research and some results are presented in this section.

3.4.1 Draft: ISO 22140

This International Organization of Standards draft standard is titled *Passenger Cars - Validation of Vehicle Dynamics Simulation - Lateral Transient Response Test Methods*. [21] This standard specifies methods for comparing computer simulation results from a vehicle mathematical model to measured test data for an existing vehicle according to ISO 7401. The comparison is made for validating the simulation tool when applied to variants of the tested vehicle. It is applicable to passenger cars as defined in ISO 3833.

3.4.2 Draft: ISO/AWI 11010-1

This draft ISO standard is titled *Passenger Cars - Simulation Model Taxonomy - Part 1: Vehicle Dynamics Maneuver* [22]. This document was developed in response to worldwide demand for standardization of simulation models and their requirements in specific driving maneuvers as use cases. During development and test of road vehicles, the question arises as to the fidelity needed for performing certain driving maneuvers. Without standardization, experts in different organizations develop their own methods and processes to answer this question. When it comes to comparability and model exchange between project partners, obstacles can occur. As drafted, the main purpose of this standard is to provide a framework that enables a systematic assignment of simulation model characteristics for certain driving maneuvers. The simulation models are classified into certain model classes, their fidelity level, and related characteristics. The assignment is the responsibility of the user or can be specified by other regulations and standards. The standard contains recommendations in the sense of an appropriate simulation quality in terms of performance tests.

3.4.3 FHWA-JPO-16-405

The Federal Highway Administration) along with the Joint Programs Office (JPO) published a paper titled *A Framework for Validating Traffic Simulation Models at the Vehicle Trajectory Level*. [23] For an emerging number of applications, including ADS, the realism of simulated driver dynamics at the second-by-second or sub-second trajectory level plays an important role. A framework to validate the realism of simulated vehicle dynamics at the trajectory level is presented in this report. Trajectory measures related to safety, comfort, vehicle kinematics, and traffic flow are presented. Example validation measures include time-to-collision (TTC), lane change urgency and rate, acceleration range, jerk (rate of acceleration), and root mean square of acceleration. Practitioners can use the validation framework to assess the realism of the simulated vehicle dynamics in a model.

3.5 Other Simulation Standards

Many reports and literature discussing ADS safety, whether using simulation or not, reference ISO 26262 and "safety of the intended functionality, SOTIF. They are briefly introduced here for completeness. Also, the changes to the FHWA's MUTCD in reference to NHTSA's AV 3.0 to better support ADS are discussed.

3.5.1 ISO 26262

ISO 26262 [24] outlines processes useful for validating the safety of automotive electrical, mechanical, and electronic systems (hardware and software) in the face of internal failures and provides guidance for software quality and functional safety. It also provides a framework for evaluating associated tools, such as MiL, SiL, and HiL simulations. An ADS system that perfectly fulfills its design specifications according to ISO 26262 still could cause or be involved in road crash and harm. ISO 26262 functional safety is determined by the design and development process that the manufacturer follows and does not call for specific performance testing. Efforts to complement ISO 26262 have been underway to develop a new standard known as SOTIF ISO Standard 21448.

3.5.2 Draft: ISO/PAS 21448:2019

The absence of unreasonable risk due to hazards resulting from functional insufficiencies of the intended functionality or by reasonably foreseeable misuse by persons is referred to as the "safety of the intended functionality," SOTIF. This draft standard [25] provides guidance on the applicable design, verification, and validation measures needed to achieve SOTIF. This document does not apply to faults covered by the ISO 26262 series or to hazards directly caused by the system technology (e.g., eye damage from a laser sensor). This document is intended to be applied to intended functionality where proper situational awareness is critical to safety, and where that situational awareness is derived from complex sensors and processing algorithms; especially emergency intervention systems (e.g., emergency braking systems) and L1 and L2 ADAS. This edition of the document can be considered for higher levels of automation, however additional measures might be necessary. This document is not intended for functions of existing systems for which well-established and well-trusted design, verification and validation (V&V) measures exist at the time of publication (dynamic stability control [DSC] systems, air bag, etc.). Some measures described in this document are applicable to innovative functions of such systems, if situational awareness derived from complex sensors and processing algorithms is part of the innovation. Intended use and reasonably foreseeable misuse are considered in combination with potentially hazardous system behavior when identifying hazardous events.

3.5.3 AV 3.0 update to MUTCD for ADSs

FHWA administers the Manual on Uniform Traffic Control Devices [26]. The MUTCD is recognized as the national standard for all traffic control devices installed on any street, highway, bikeway, or private road open to public travel. Traffic control devices generally refer to signs, signals, markings, and other devices used to regulate or guide traffic on a street, highway, or other facilities. FHWA, in partnership with key stakeholder associations and the practitioner community, conducts research and device experimentation for overall improvements to the manual, and to better understand the specific needs of the emerging automated vehicle technologies. Incorporating existing interim approved devices, experimentations, and other identified proposed changes into the updated MUTCD will help humans and emerging automated vehicles to interpret the roadway. FHWA uses research to supplement knowledge regarding different sensor and machine vision system capabilities relative to interpreting traffic control devices. As part of this effort, FHWA proposes to update the 2009 MUTCD taking into consideration these new technologies and other needs. Any updates to traffic control devices will need to be reflected in simulation.

3.6 Industry Reports

Although there are currently no formal requirements for ADS safety, some ADS companies have been active in publishing information regarding their ADS safety verification and validation. One main source of such reports is in response to NHTSA AV 3.0 request for voluntary safety self-assessments. Other than these VSSA, some companies have published reports on their own regarding ADS safety. This section will cover the VSSA and other industry published safety reports.

3.6.1 Voluntary Safety Self-Assessment

Numerous companies have released VSSA [1] in response to NHTSA's guidelines titled "*Automated Vehicles 3.0: Preparing for the future of Transportation* [3]. The self-assessments follow the VSSA template, addressing NHTSA's 12 safety design elements.

1. System Safety
2. Operational Design Domain
3. Object and Event Detection and Response
4. Fallback (Minimal Risk Condition)
5. Validation Methods
6. Human Machine Interface
7. Vehicle Cybersecurity
8. Crashworthiness
9. Post-Crash ADS Behavior
10. Data Recording
11. Consumer Education and Training
12. Federal, State, and Local Law

These self-assessments address simulation as a key in developing safe ADS. Some provide additional test scenarios and scenario definitions beyond the NHTSA behavioral competencies.

3.6.2 FiveAI

FiveAI, a European automated mobility company, published a paper, *Certification of Highly Automated Vehicles for Use on UK Roads: Creating an Industry-Wide Framework for Safety* [27], The paper discusses the creation of regulation that promotes high safety standards and encourages all companies developing self-driving tech to share their safety findings, including scenarios. The authors stress that scenario sharing needs an agreed upon format by industry and government for the way data is stored and shared. This sharing would not only allow each ADS company to demonstrate a safe self-driving system for its own most challenging scenario test cases, but also for those of its competitors too.

The framework also aims to place high-fidelity software simulation at the heart of the process. To ensure safety, the simulation environment must itself be validated. The authors call for greater transparency to allow the industry, regulators, and the public to know that a given simulation is trustworthy and conducive to safety. For a simulation to be trustworthy, the simulator used must portray an appropriately accurate representation of reality. It is the opinion of the report's authors' that the simulator needs to test the full stack self-driving system, not just the prediction, behavior and control ("motion planning"') aspects of the software. This requires a model of the vehicle's sensor limitations and their ability to perceive the driving environment.

4 MARKET SUMMARY OF SIMULATION SOFTWARE FOR ADS RESEARCH

The ADS simulation software market, like the ADS supplier and manufacturer market, is undergoing rapid development and growth with new companies and large updates to products being introduced regularly. With such a quickly evolving market landscape, any market research performed will be outdated soon. The authors of this report found more than 50 commercial and several free simulation software sources. This review included publicly available literature and sometimes meetings with the companies' technical experts to build a more complete view of the current available technologies. These meetings were focused on gaining information regarding scenario descriptions and use of open standards. Another purpose of this market research was to determine the vitality and maturity of the simulation software options that could be used to carry out ADS simulation testing. This review showed that the market for simulation software appears to be well supported given the number and variety of simulation packages available for developing and testing ADS. Many of these simulation companies are mature and have years of simulation experience, yet the simulation of ADS provides new challenges and growth for these more mature companies while also supporting the creation of numerous new start-up simulation companies. The VSSAs submitted by various ADS companies also support this claim and provide proof that simulation plays a key role in the development and testing of ADS.

5 CONCLUSIONS AND FUTURE WORK

This paper presents initial findings from a literature review and market summary pertaining to frameworks used to describe scenarios for ADS simulation. This includes descriptions of roadway information, static, and dynamics content. Any open format framework is required to be simulator agnostic and be able to unambiguously describe all the necessary information for ADS path planning and control subsystem for a variety of simulation/testing methods. This review showed no existing open framework has reached maturity to be widely adopted by ADS stakeholders, though some are more broadly compatible. Of the standards available, the OpenX and RoadXML, which are xml-based standards for defining roadways, road networks and scenarios, appear to be the most widely supported by simulation software. Though supported, there are still elements that are needed for ADS simulation that these frameworks do not support completely.

ASAM has taken over the development and maintenance of OpenX (OpenCRG, OpenDRIVE, and OpenSCENARIO) frameworks and is working to improve them based on industry feedback and transform them into a formal standard. OKTAL is continuing to update the RoadXML standard, with the last update, RoadXML 2.4.13, in November 2016. Other organizations like the PEGASUS Project and the Enable S3 consortium are also working on standardizing simulation frameworks to improve quality and shareability. Given that none of the frameworks are widely adopted, the authors suggest experimenting with a diverse set of frameworks for sharing scenarios for the time being and evaluate their capabilities while continuing to monitor the progress off all the standardization work.

5.1 Future Work

Future work will include applying knowledge from this review by using various simulation software to experiment with scenario description frameworks and their compatibility with existing and developing standards. This will be implemented by developing several scenarios with simulation software to gain insights into scenario schema and electronic file formats that can be shared. The scenarios themselves will be chosen to maximize coverage from the behavioral competencies detailed by California Path, NHTSA's ADS Testable Cases and Scenarios [15], and the VSSA test cases provided by industry. Other sources, such as the Catapult Transport System Taxonomy of Scenarios for Automated Driving [28] will be considered. Scenario design will consider crash data, published test procedures, on road test data and other sources to challenge the ADSs. These scenarios may then be tested in several simulators to check feasibility and uniqueness.

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