U.S. Department
of Transportation
National Highway
Traffic Safety
Administration

NHTSA

DOT HS 812 623 September 2018

A Framework for Automated Driving System Testable Cases and Scenarios

DISCLAIMER

This publication is distributed by the U.S. Department of Transportation, National Highway Traffic Safety Administration, in the interest of information exchange. The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the Department of Transportation or the National Highway Traffic Safety Administration. The United States Government assumes no liability for its contents or use thereof. If trade or manufacturers' names are mentioned, it is only because they are considered essential to the object of the publication and should not be construed as an endorsement. The United States Government does not endorse products or manufacturers.

Suggested APA Format Citation:

Thorn, E., Kimmel, S., and Chaka, M. (2018, September). *A framework for automated driving system testable cases and scenarios* (Report No. DOT HS 812 623). Washington, DC: National Highway Traffic Safety Administration.

Technical Report Documentation Page

1. Report No. DOT HS 812 623	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle A Framework for Automated Driving System Testable Cases and Scenarios		**5. Report Date** September 2018 **6. Performing Organization Code**
7. Authors Eric Thorn,** Shawn Kimmel,*** Michelle Chaka*		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Virginia Tech Transportation Institute* 3500 Transportation Research Plaza (0536) Blacksburg, VA 24061; Southwest Research Institute** 6220 Culebra Rd. San Antonio, TX 78238; Booz Allen Hamilton*** 20 M St. SE Washington DC 20003		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE. Washington, DC 20590		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

This report describes a framework for establishing sample preliminary tests for Automated Driving Systems. The focus is on light duty vehicles exhibiting higher levels of automation, where the system is required to perform the full dynamic driving task, including lateral and longitudinal control, as well as object and event detection and response.

17. Key Words automated driving systems, fail-safe mechanisms, object and event detection and response, tests, operational design domain	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, www.ntis.gov.

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
-Unclassified	Unclassified	180	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Automated driving systems (ADS) are being developed to perform the primary functions of the dynamic driving task (DDT). These technologies hold great promise to improve safety and mobility for transportation. The goal of this research was to develop an example of a preliminary test framework for ADS that are in development and may come to market in the near to mid future. The following steps were conducted to support the development of the sample test framework.

1. Identify concept ADS
2. Identify attributes that define the operational design domain (ODD)
3. Identify object and event detection and response (OEDR) capabilities
4. Identify and assess failure modes and failure mitigation strategies

Technologies of interest in this work included light-duty automated driving functions that fell within Level 3 (L3) to Level 5 (L5) of the SAE[1] levels of driving automation (SAE International, 2016). The functions were identified based on prototype vehicles and conceptual systems. A literature review which included popular media, press releases, technical journals, and conference proceedings was performed. This review identified potential concept ADS being developed or proposed by original equipment manufacturers (OEMs), suppliers, technology companies, and other organizations. The identified ADS were categorized into a set of generic names. The terminology was modified to ADS features (as opposed to functions) to more closely align with the standardization community's language.

Twenty-four conceptual features were identified, and although a thorough search was conducted, the list is not exhaustive. The identified features were grouped into seven generic categories.

- L4 Highly Automated Vehicle/Transportation Network Company (TNC)
- L4 Highly Automated Highway Drive
- L4 Highly Automated Low Speed Shuttle
- L4 Highly Automated Valet Parking
- L4 Highly Automated Emergency Takeover
- L3 Conditional Automated Highway Drive
- L3 Conditional Automated Traffic Jam Drive

The generic names were developed to align with terminology from the SAE levels of driving automation (i.e., conditional driving automation [L3], high driving automation [L4], and full driving automation [L5]). Three of these generic features were selected to further support the development of an example of a testing framework for ADS (L3 Conditional Automated Traffic Jam Drive, L3 Conditional Automated Highway Drive, and L4 Highly Automated Vehicle/TNC).

[1] In 2006 the Society of Automotive Engineers changed its name to SAE International. It's standards are still called SAE standards.

The ODD describes the specific operating domains in which the ADS is designed to function. The ODD will likely vary for each ADS feature on a vehicle and specifies the condition in which that feature is intended and able to operate with respect to roadway types, speed range, lighting conditions, weather conditions, and other operational constraints. The ODD is specified by the technology developer, and the ADS should be able to identify whether it is operating within or outside of that ODD.

A literature review was performed for all the generic ADS features to identify the attributes that define the ODD. The review included popular media, press releases, technical journals, videos, and conference proceedings. An ODD taxonomy for this report was then defined. This taxonomy is hierarchical and includes the following top-level categories.

- Physical Infrastructure
- Operational Constraints
- Objects
- Connectivity
- Environmental Conditions
- Zones

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 from which the ODD can be further defined and delineated by the developer, and from which industry standards for ODD definition can be established.

OEDR refers to 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 International, 2016).

A notional concept of operations (ConOps) was considered for the three selected ADS features. This served as a basis to perform an evaluation of the normal driving scenarios each ADS feature may encounter, including expected hazards (e.g., other vehicles, pedestrians) and sporadic/fluctuating events (e.g., emergency vehicles, construction zones). Baseline ODDs were identified for each of the features to frame this analysis. These baseline ODDs and scenario analyses were used to identify important OEDR functional capabilities. This analysis, along with the survey of ADS features, helped to identify two key sets of behaviors for the selected ADS features.

- Tactical Maneuver Behaviors
- OEDR Behaviors

Tactical maneuver behaviors may be viewed as more control-related tasks (e.g., lane following, turning). OEDR behaviors may be regarded as perception and decision-making related tasks (e.g., detecting and responding to pedestrians). This analysis generated a list of fundamental objects that may be relevant to an ADS's driving task, as well as important events, which can be viewed as interactions with those objects. A list of potential responses the ADS could implement was identified, and these responses were mapped to the objects and events.

To develop a preliminary testing framework, existing test methods and tools were identified and evaluated to formulate an appropriate, comprehensive testing architecture. The evaluation resulted in three main components of a testing architecture for ADS, as well as advantages and disadvantages of each.

- Modeling and Simulation (M&S)
- Closed-Track Testing
- Open-Road Testing

A test scenario framework that fit flexibly within the test architecture was then identified and developed. The framework can be viewed as a multidimensional test matrix, with the following principal elements.

- Tactical Maneuver Behavior
- ODD Elements
- OEDR Behavior
- Failure Mode Behaviors

An ADS test scenario can be defined at a high level by these dimensions. Each of these dimensions can be viewed as a checklist of sorts to identify the maneuvers, ODD, OEDR, and failure mode behaviors that will outline the test setup and execution. Preliminary test procedures for a sampling of defined scenarios were then developed and these included, among other things, information on potential test personnel, test facilities, test execution, data collection, performance metrics, and success criteria that are translated from collected data and results.

Key challenges related to testing and evaluating ADS were also identified. These challenges were associated with the technology itself, as well as test setup and execution.

A high-level system failure mode and effects analysis (FMEA) was performed for a representative ADS. This representative ADS is described by a functional architecture under development by SAE International (Underwood, 2016). This notionally identified potential ADS failure modes, as well as their potential causes and effects. These failure modes were then mapped back to the selected ADS features. The FMEA focused on subsystems and processes related to the ADS, and the identified failure modes could largely be attributed to lack of information (e.g., resulting from a hardware failure) or poor/inadequate information (e.g., resulting from system latency). These potential failures could have significant impacts, ultimately resulting in collisions that could damage the vehicle or harm its occupants or other roadway users.

Potential failure mitigation strategies, including both fail-operational (FO) and fail-safe (FS) techniques, were then identified and analyzed. FS techniques are used when the ADS cannot continue to function, and may include options such as the following.

- Transitioning control to fallback-ready user
- Safely stopping in lane
- Safely moving out of travel lane/park

FO techniques can be used to allow the ADS to function at a reduced capacity, potentially for a brief period of time or with reduced capabilities, and may include options such as the following.

- Adaptive compensation – weighting data from a complementary component or subsystem more heavily (e.g., weighting camera data more heavily if lidar fails, etc.)
- Degraded modes of operation:
  - Reduced speed operation
  - Reduced level of automation operation
  - Reduced ODD operation
  - Reduced maneuver behavior operation
  - Reduced OEDR behavior operation

The appropriate failure mitigation strategy is highly dependent on the nature of the failure and the initial conditions under which the failure occurs. As such, implementing a hierarchy of techniques, which may include the list above, may be appropriate. ADS internal health-monitoring capabilities, such as measurement and indication of sensor and localization subsystem performance, were also identified as being important.

GLOSSARY OF TERMS AND ACRONYMS

4D/RCS	4-dimensional real-time control system
ACC	adaptive cruise control
ABS	antilock braking system
ADS	automated driving system
AEB	automatic emergency braking
ALC	automated lane centering
ASILS	ISO 26262 Automotive Safety Integrity Levels
BSW	blind spot warning
CBD	central business districts
ConOps	concept of operations
CV	connected vehicle
DARPA	Defense Advanced Research Projects Agency
DDT	dynamic driving task
DOD	Department of Defense
DSRC	dedicated short-range communication
ECU	electronic control unit
ESC	electronic stability control
FCW	forward collision warning
FHWA	Federal Highway Administration
FMEA	failure mode and effects analysis
FMECA	failure modes, effects, and criticality analysis
FMVSS	Federal Motor Vehicle Safety Standard
FO	fail-operational
FS	fail-safe
FTA	fault tree analysis
GPS	global positioning system
HAV	Highly Automated Vehicle
HazOP	Hazard and operability analysis
HIL	hardware-in-the-loop
HMI	human-machine interface
HOV	high-occupancy vehicle
HWD	highway drive
IMU	inertial measurement unit
INS	inertial navigation system
ISO	International Organization for Standardization
LDW	lane departure warning
LKA	lane keeping assist
LTAP/OD	left turn across path/opposite direction
M&S	modeling and simulation
MRC	minimal risk condition
MUTCD	Manual on Uniform Traffic Control Devices

NASA	National Aeronautics and Space Administration
ODD	operational design domain
OEDR	object and event detection and response
OEM	original equipment manufacturer
ORAD	SAE International's On-Road Automated Driving Committee
PATH	California Partners for Advanced Transportation Technology
POV	principal other vehicle
PS	pedestrian surrogate
RMS	root mean square
RPN	risk priority number
SIL	software-in-the-loop
SPaT	signal phase and timing
SV	subject vehicle
TJD	Traffic Jam Drive
TNC	transportation network company
UNECE	United Nations Economic Commission for Europe
V&V	validation and verification
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VIL	vehicle-in-the-loop
VRU	vulnerable road user
VSSA	voluntary safety self-assessment

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION AND BACKGROUND

PROJECT BACKGROUND AND PURPOSE

Since 1975, the first year that the Fatality Analysis Reporting System began collecting data, the rate of traffic fatalities per 100 million miles traveled in the United States has decreased by 66 percent, according to the National Highway Traffic Safety Administration's Traffic Safety Facts 2015 data (NHTSA, 2017b). Advancements in motor vehicle safety have been made through continuous engineering innovation, public education, industry agreements, safety regulations, and safety rating programs. There is, however, significant room for continued focus on motor vehicle traffic safety. In October 2017 NHTSA reported that traffic fatalities increased by 5.4 percent from 2015 to 2016 (35,485 to 37,461) for the United States (NCSA, 2017), which follows an 8.4 percent increase from 2014 to 2015 (32,744 to 35,485) (NHTSA, 2017b).

Many forces are at work in the automotive industry to advance safety technology. The worldwide automotive industry has recognized driver performance (e.g., error and choice) as a key factor that impacts safety and has begun to introduce systems that complement the driver in terms of enhanced perception with 360-degree vehicle views and rear video systems. Systems that monitor the operational environment seeking to enhance driver detection and response, such as forward collision warning and even assisted automation such as lane keeping assist, are becoming ubiquitous in newer model vehicles. Additionally, 20 automakers have committed to making automatic emergency braking a standard feature in new vehicles by 2022 (IIHS, 2016).

Recently, research activities by several companies to develop automated driving systems that can perform certain driving functions automatically have captured the Nation's attention. ADS have been the subject of multiple congressional hearings and the public has provided numerous responses to NHTSA's Federal Automated Vehicles Policy (Howe, Xu, Hoover, Elsasser, & Barickman, 2016), including over 1,100 responses from industry participants, State and municipal transportation agencies, policy groups, and citizens (Kyrouz, 2017). The United States Department of Transportation (USDOT) and NHTSA recently released an update to their Federal guidance for ADS that focused on their development and safe deployment and operation. NHTSA also continues to advance its ADS research. The research project summarized in this report sought to analyze aspects of ADS testing and develop examples of tests and evaluation methods for specific ADS features. A sample testing framework was developed that could further support the goals of improving safety for all users of the transportation network.

This project was accomplished in cooperation and consultation with NHTSA by completing the seven tasks described below.

Task 1: Revised Technical Work Plan

This work focused on reviewing, revising, and finalizing the work activities for the project. The project's objectives, planned course of actions, milestones and deliverables, and any concerns with the proposed approach were discussed with NHTSA staff. The work plan was updated based on feedback during a project team meeting with NHTSA.

Task 2: Identification of Sample Concept ADS Functions

The goal of this work was to identify sample concept ADS functions based on specific automation technologies. The analysis and results of this task are presented in Chapter 2. Technologies of interest focused on light-duty vehicle functions that fell within L3 through L5 of the SAE International levels of automation (SAE International, 2016). The functions were identified based on prototype vehicles and conceptual systems. A literature review which included popular media, press releases, technical journals, and conference proceedings was performed. From this review, concept ADS being developed or proposed by original equipment manufacturers, suppliers, technology companies, and other organizations were identified. The identified functions were categorized into a set of generic names to be used throughout the subsequent tasks. The terminology was modified to ADS "features" (as opposed to "functions") to be more in line with the standardization community's language.

Twenty-four conceptual features were identified, and although a thorough search was conducted, the list is not exhaustive. The identified features were grouped into seven generic categories. Although all generic ADS features are considered in subsequent tasks, a deeper analysis was conducted on three select features.

Task 3: Identification of the Operational Design Domain

This work focused on identifying the ODD for all conceptual ADS. The analysis and results of this task are presented in Chapter 3. The ODD describes the specific operating domains in which the ADS is designed to function. The ODD will likely vary for each ADS feature on a vehicle, and specifies when that feature is intended and able to operate with respect to roadway types, speed range, lighting conditions, weather conditions, and other operational constraints. The ODD is specified by the technology developer, and the ADS should be able to identify whether it is operating within or outside of that ODD.

A literature review was conducted for all seven generic ADS features to determine the attributes that define the ODD. Three of the features were selected to further refine the ODD analysis. The review included popular media, press releases, technical journals, videos, and conference proceedings. The team then defined a hierarchical ODD taxonomy that could be used by government and industry to discuss ADS.

Some of the challenges associated with ODD elements include their variability (e.g., rain droplet sizes can vary greatly: light rain, moderate rain, heavy rain), as well as identifying or defining their boundaries. The work performed in this task to identify the ODD laid the foundation for subsequent tasks.

Task 4: Delineation of Object and Event Detection and Response Capabilities

This work sought to identify OEDR capabilities for the three selected ADS features that will enable them to function safely within their specified ODDs. The analysis and results of this task are presented in Chapter 4. OEDR refers to "the subtasks of the dynamic driving task (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 International, 2016).

A notional concept of operations – called ConOps -- was developed for each of the three selected ADS features. These served as a basis for performing an evaluation of the normal driving scenarios each ADS feature may encounter, including expected hazards (e.g., other vehicles, pedestrians) and sporadic/fluctuating events (e.g., emergency vehicles, construction zones). Baseline ODDs were defined for each of the selected features to frame this analysis. The baseline ODDs were developed by the research team by identifying relevant ODD attributes within the ConOps for each selected feature. These baselines were necessary because of the potential variability of ODDs for a given feature, as defined by their developers. These baseline ODDs and scenario analyses helped identify important OEDR functional capabilities.

Task 5: Development of Preliminary Tests and/or Evaluation Methods

This work sought to develop examples of preliminary tests and evaluation methods that could be used for ADS. The analysis and results of this task are presented in Chapter 5. Engineering judgments from previous test development experience, functional requirements, and use cases were used to identify test scenarios and preliminary procedures. These scenarios and procedures built upon the identified ADS features, ODDs, and OEDR capabilities.

Existing test methods and tools were identified and evaluated to formulate an appropriate, comprehensive testing architecture. A test scenario framework was then identified and developed that fit flexibly within the test architecture. The framework can be viewed as a multidimensional test matrix, with the dimensions encapsulating the principal elements from the other tasks (Feature, ODD, OEDR, Failure Modes). Preliminary test procedures — including information on potential test personnel, test facilities, test execution, data collection, and performance metrics, among other things — were developed for a sampling of these scenarios. No physical testing was conducted as part of this project.

Key challenges related to testing and evaluating ADS were also identified. These challenges were associated with the technology itself as well as test execution.

Task 6: Assessment of Fail-Operational/Fail-Safe Mechanisms

The goal of this work was to perform an assessment of fail-operational and fail-safe mechanisms for ADS. The analysis and results of this task are presented in Chapter 6. FO and FS mechanisms are used when an ADS fails, resulting in unintended functionality or behavior. Designing, testing, and validating these mechanisms ensures that an ADS can achieve a minimal risk operating condition that removes the vehicle and its occupants from harm's way in the event of a failure. For some features, the minimal risk condition may be to transition control back to a fallback-ready user; however, in other cases the ADS feature itself achieves that condition.

A high-level system failure mode and effects analysis for a representative ADS was performed. This representative ADS is described by a functional architecture under development by SAE International (Underwood, 2016). This analysis notionally identified potential ADS failure modes and their potential causes and effects. These failure modes were then mapped back to the selected ADS features. The FMEA focused on subsystems and processes related to the ADS, and the identified failure modes could largely be attributed to lack of information (e.g., resulting from a hardware failure) or poor/inadequate information (e.g., resulting from system latency). These potential failures could have significant impacts, ultimately resulting in collisions that could damage the vehicle or harm its occupants or other roadway users.

Failure mitigation strategies, including both FO and FS techniques, were identified and analyzed. FS techniques are used when the ADS cannot continue to function, while FO techniques allow the ADS to continue to function, although potentially at a reduced capacity or for an abbreviated period of time. The appropriate failure mitigation strategy is highly dependent on the nature of the failure and the initial conditions when the failure occurs. As such, a hierarchy of the techniques listed above may be appropriate. Health-monitoring capabilities were also identified as being important.

Task 7: Final Report

This task involved combining the results from the preceding tasks into a cohesive final report. The current report is the product of that effort.

This project contributes to the body of knowledge for ADS safety performance assessment, which could also play a role in system validation and verification. V&V includes methods and tools for determining whether design specifications and customer needs associated with the automated driving function have been met. Testing is critical in the development of an ADS, especially as it relates to safety performance and functionality. Testing occurs from the system-wide level all the way down to the individual unit level (e.g., camera sensor). This work focuses mostly on developing test cases that evaluate system-level functionality and capabilities (e.g., stay within a lane and stop at a stop sign).

Federal Automated Vehicles Policy

As mentioned above, NHTSA released the Federal Automated Vehicles Policy in 2016 (NHTSA, 2016a), which presents several key factors that play into the safe development and deployment of ADS, namely the following.

- Vehicle Performance Guidance
- Model State Policy
- NHTSA's Current Regulatory Tools
- New Tools and Authorities

In 2017 NHTSA released an updated version of the 2016 FAVP policy titled *Automated Driving Systems 2.0: A Vision for Safety* (NHTSA, 2017a), which responded to the public comments received while maintaining the overall goal of safe development and deployment of ADS. NHTSA plans to regularly update its guidance as the technology and deployment landscape evolve. Most of the research described in this report was conducted before ADS 2.0 was published, and therefore relies on the information contained in the 2016 FAVP document. The document's vehicle performance guidance section provides recommended best practices and expectations for the design, development, and testing stages for ADS. It applies to any entity performing activities related to ADS in any of those stages. It provides guidance on a number of ADS safety elements, including human-machine interfaces, vehicle cybersecurity, and crashworthiness, among others. It also provides guidance on four other areas that are specific to each individual ADS.

- ODD
- OEDR
- Fallback MRC
- Validation Methods

These four areas factor prominently in this research and in this report. The ODD, which is specified by the manufacturer or developing entity, describes the specific operating domains and conditions in which the system can function. Chapter 3 provides a thorough discussion of the importance and expansiveness of potential ODDs and presents a notional taxonomy for major ODD categories. OEDR refers to 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 International, 2016). Chapter 4 presents an analysis of OEDR and identifies specific OEDR capabilities that are applicable to many ADS within their specified ODDs. It is important for ADS to have a fallback strategy and be able to execute that strategy when things go wrong. The MRC is a state that places the vehicle and its occupants out of harm's way, to the best extent possible. Chapter 6 provides an analysis of potential failure modes for ADS and the potential mitigation strategies that ADS may be able to implement to achieve that MRC. Finally, existing testing and validation tools and methods may be insufficient to assess the safe operation of ADS, considering their added complexity and capabilities compared to traditional vehicles. The guidance suggests that developers should determine the appropriate testing methods and document their efforts and results to demonstrate that their systems are meeting performance expectations. Chapter 5 presents a discussion on potential methods for testing and validating ADS that seeks to assess safe performance and identify performance boundaries. The chapter also identifies several key challenges associated with testing ADS.

Stakeholder Engagement

Relevant stakeholders expressed significant interest in this research project from an early stage. Therefore, a stakeholder working group was established to solicit their feedback on the research materials. The motivation for establishing this working group included incorporating expert perspectives to inform the project framework and provide input to conclusions. Multiple OEMs and Tier 1 suppliers participated in the working group, as well as representatives from academia conducting research in ADS.

Outreach and materials were planned for the early research tasks, which, after review by NHTSA, were disseminated to the stakeholders. Feedback provided by the stakeholders was reviewed and facilitated follow-up discussions, as deemed necessary. Many of the stakeholders had multiple personnel reviewing the project materials. This included personnel with policy and strategic planning expertise, in addition to personnel with technical expertise related to ADS. Holistically, the stakeholder group provided a breadth of knowledge to comment on the issues evaluated in this research. Information shared by the stakeholders was treated as non-attributable as it was incorporated into the project and this report. While the stakeholders did not provide any proprietary information or data as part of the engagement, information was collected individually and was not shared between stakeholders.

In addition to per-task engagement, which was conducted largely in a virtual setting, an in-person workshop open to all stakeholders was organized and held near the end of the technical portion of the research project. The workshop was held immediately after the conclusion of the Automated Vehicles Symposium[2] in San Francisco, California, in July 2017. The goals of the workshop included providing an interactive venue for sharing insights about the concepts addressed by the research, providing a summary review of the project tasks, and offering an opportunity to work toward consensus on some of the elements of those tasks. Ten experts from the stakeholder working group participated in the workshop, along with five members of the research team. The experts agreed on the importance of the research and the potential need to consider a common set of test scenarios. They also provided many suggestions on the content of the resulting task materials. The suggestions and feedback are incorporated into the discussions in the following chapters.

[2] www.automatedvehiclessymposium.org/home

CHAPTER 2. AUTOMATED DRIVING SYSTEM FEATURES

OVERVIEW

This chapter describes the identification of sample concept ADS features that have been proposed for deployment. This analysis is focused on SAE Levels 3-5 ADS, such as Google's self-driving car project (i.e., Waymo), and others like it that focus on next-generation automation. This step is critical because the sample concept ADS features are used to identify ODDs and OEDRs, develop preliminary tests and/or evaluation methods, and assess FS and FO mechanisms, which form a foundation to begin considering validation and verification approaches for ADS.

This chapter is organized into four sections: the approach to identifying concept ADS features, a framework for defining concept ADS features (including behaviors), a list and description of concept ADS features, and a set of generic ADS feature categories used throughout the report.

APPROACH

A four-stage approach was followed to identify ADS features: (1) review the literature, (2) define a framework for discussing ADS features, (3) define features and behaviors, and (4) categorize the features. To guide later analysis, priority ADS features on which to focus were identified.

To support the identification of ADS features, a framework for describing ADS throughout the project was established and implemented. As part of this effort, industry stakeholders were engaged. The stages involved in ADS feature identification were as follows.

- Review the literature, including popular media, press releases, technical journals, and conference proceedings, to identify concept ADS features proposed by major OEMs, technology companies, suppliers, and cities.
- Define a framework for describing ADS features, including a functional architecture, behaviors, level of automation, ODD, and OEDR.
- Define ADS features, including operational concepts and behaviors; further description of the ADS features can be found in subsequent chapters (e.g., ODD in Chapter 3).
- Categorize ADS features into a set of generic ADS features.

Over 50 literature sources were reviewed, including OEM websites, press releases of vehicles being tested in specific domains, NHTSA pre-crash scenario analysis (Najm, Smith, & Yanagisawa, 2007), NHTSA's Fiscal Year 2017 budget request (NHTSA, 2016b), NHTSA L2 and L3 Human Factors Concepts (Blanco et al., 2015), Federal Highway Administration-managed lane use cases (FHWA, 2008), and technical and international publications, including proceedings of the 2015 and 2016 Automated Vehicles Symposiums and United Nations Economic Commission for Europe World Forum for Harmonization of Vehicle Regulations (WP.29) Automatically Commanded Steering Function working group. Research sponsored by

USDOT, such as the Crash Avoidance Metrics Partnership Automated Vehicle Research for Enhanced Safety (Christensen et al., 2015; NHTSA, 2016c), which details functional descriptions for on-road driving automation levels, was also used. Figure 1 depicts the stages involved in the ADS feature identification process.

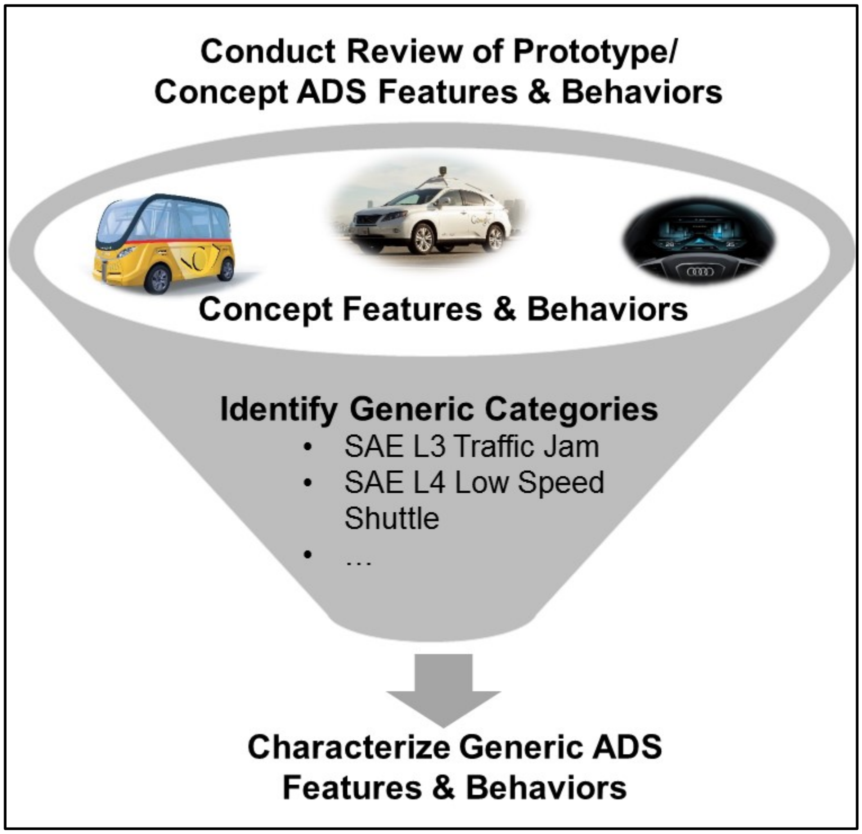

Figure 1. ADS Feature Selection Process

FRAMEWORK FOR DISCUSSING ADS FEATURES

The development of a framework for discussing ADS features began with defining the terminology and a reference functional architecture. The term ADS "feature" was selected to be used in place of "function" or "application" since it is the same term used by OEMs to market a vehicle's capabilities. While these terms have been used interchangeably, using "feature" is most consistent with existing descriptions of vehicle functionality in the marketplace. Using "feature" minimizes confusion when examining proprietary ADS offerings from OEMs in the literature review, as well as for future stakeholder engagement efforts with OEMs.

SAE International's On-Road Automated Driving activities were used to develop a robust system to describe each feature. SAE J3016 defines an ADS feature as "a driving automation system's design-specific functionality at a specific level of driving automation within a particular Operational Design Domain." Referring to this definition, each feature can be described in terms of the following.

- Level of driving automation (using SAE International's levels of driving automation)

- Design-specific functionality, with a focus on the DDT, is defined in SAE J3016 as: "All of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and waypoints, and including without limitation the following.

    1. Lateral vehicle motion control via steering (operational)

    2. Longitudinal vehicle motion control via acceleration and deceleration (operational)

    3. Monitoring the driving environment via object and event detection, recognition, classification, and response preparation (operational and tactical)

    4. Object and event response execution (operational and tactical)

    5. Maneuver planning (tactical)

    6. Enhancing conspicuity via lighting, signaling and gesturing, etc. (tactical)

- ODDs in which it operates

- FS/FO capability

Per SAE J3016, DDT elements 3 and 4 can be collectively referred to as OEDR and are covered in Chapter 4 of this report. The remaining DDT elements 1, 2, 5, and 6 are discussed in this chapter, and are loosely described as "tactical and operational maneuvers." That term would typically include aspects of OEDR, but OEDR is covered in Chapter 4. It should be noted that nomenclature for many of these terms, such as behaviors, maneuvers, ODD, OEDR, and FS/FO can vary in their use throughout the literature in the context of ADS. There are ongoing efforts at SAE to clarify and standardize these terms. For example, the SAE ORAD Committee Task Force on Behaviors and Maneuvers is in the process of developing an information report to describe several of these terms and supporting taxonomies. Without an existing common framework, this report has been kept as consistent as possible with existing SAE efforts, but does consider other literature sources. More information on strategic, tactical, and operational levels of control will be provided below.

Levels of Driving Automation

SAE International, the Bundesanstalt für Straßenwesen, Organisation Internationale des Constructeurs d'Automobiles, and UNECE WP.29 have agreed upon common definitions for levels of driving automation, which are described in SAE J3016. SAE J3016 provides definitions for key terms, including MRC and ODD. It should be noted that J3016 was revised in September 2016, and now a joint SAE-International Organization for Standardization task force has been formed for future updates. Table 1 shows the SAE J3016 levels of driving automation for on-road vehicles. USDOT adopted these levels of driving automation into its policy guidance to establish standardization to aid in clarity and consistency.

Table 1. Summary of Levels of Driving Automation

Level	Name	Narrative Definition	DDT - Sustained lateral and longitudinal vehicle motion control	DDT - OEDR	DDT fallback	ODD
Driver performs part or all of the DDT						
0	**No Driving Automation**	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	*n/a*
1	**Driver Assistance**	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver and System*	*Driver*	*Driver*	*Limited*
2	**Partial Driving Automation**	The *sustained* and *ODD-specific* execution by a *driving automation system* of both the *lateral* or the *longitudinal vehicle motion control* subtask of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and supervises the *driving automation system*.	***System***	*Driver*	*Driver*	*Limited*
ADS ("System") performs the entire DDT (while engaged)						
3	**Conditional Driving Automation**	The *sustained* and *ODD-specific* performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user is receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle systems*, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	*Limited*
4	**High Driving Automation**	The *sustained* and *ODD-specific* performance by an **ADS** of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	*Limited*
5	**Full Driving Automation**	The *sustained* and unconditional (i.e., not *ODD-specific*) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	***Unlimited***

Design Specific Functionality

To best define the identified functions, a framework that references a functional system architecture was established and implemented. SAE International ORAD's J3131 work on functional architecture informed the approach. The draft J3131 functional architecture is shown in Figure 2.

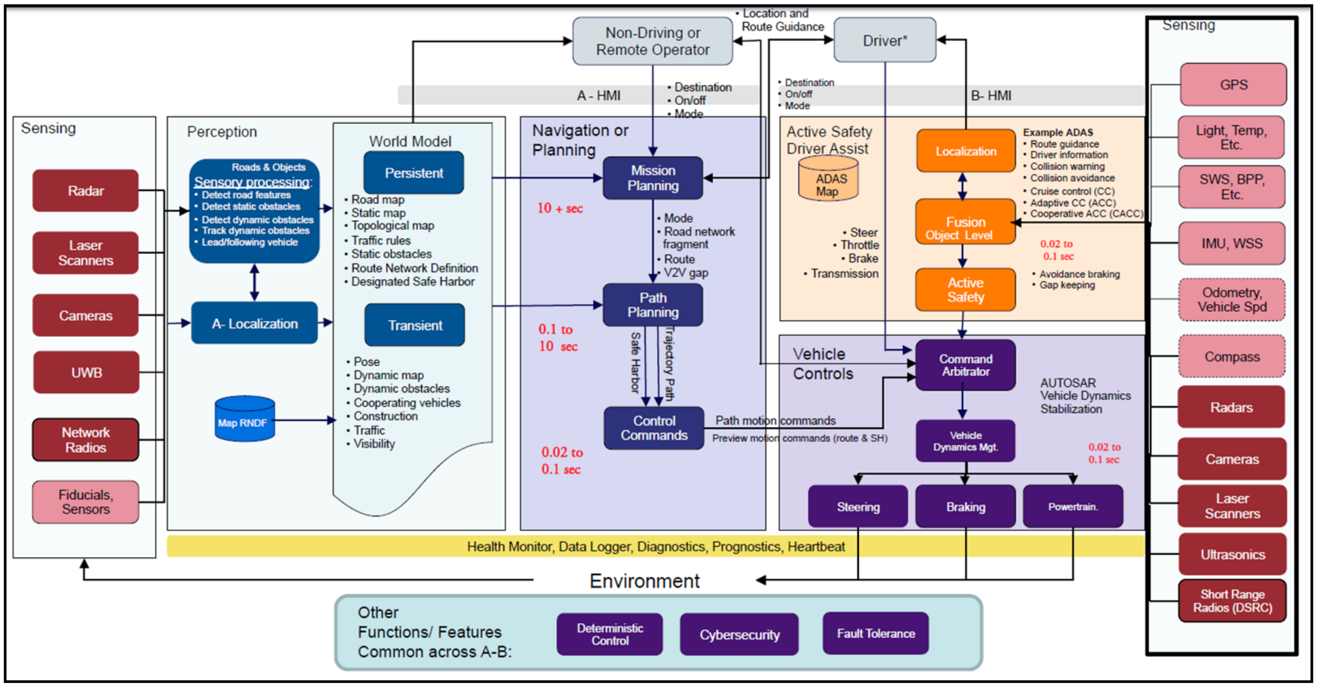

Figure 2. SAE International Autonomous Mode Functional Architecture Flow Diagram (Underwood, 2016)

The SAE International draft functional architecture (Figure 3) was adapted to describe system components (i.e., sensors, environment [ODD], perception, plan, act, etc.) and their interactions in relation to the technical analysis in this project. The functional architecture is helpful in structuring a definition of specific embodiments of ADS features. This architecture depicts the organization of vehicle software, electronics, and hardware, as well as the relationship to the external environment.

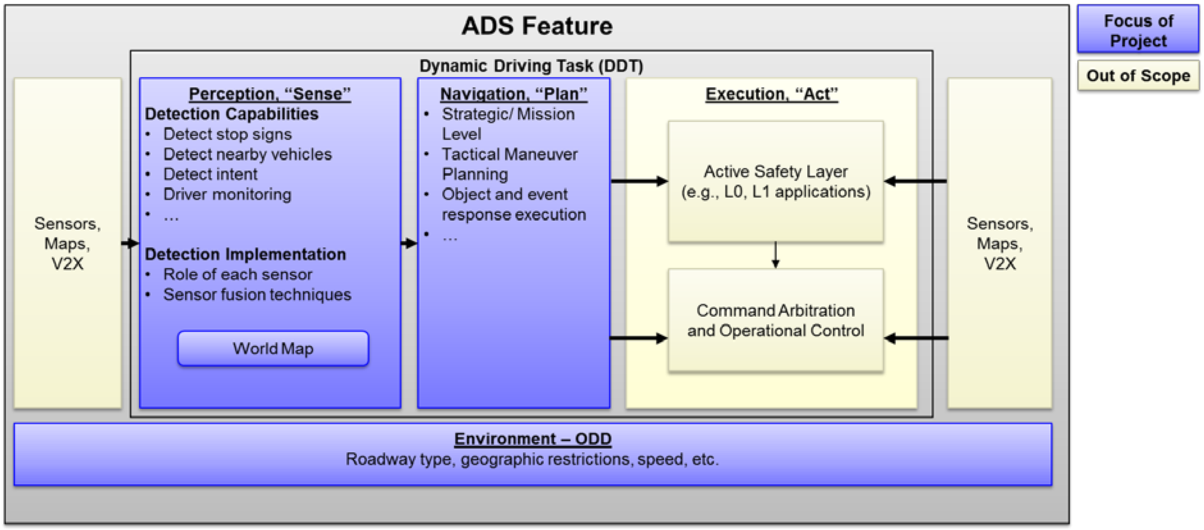

Figure 3. Generalized Functional Architecture for ADS Features

Behaviors can be used to help to define the functionality of each feature in terms of OEDR behaviors (described in Chapter 4) and other tactical and operational maneuvers (described in this chapter). Behaviors may be distributed within a hierarchy based on the duration of the behavior (as shown in Figure 4; note: the durations shown are rough order-of-magnitude estimates.) This work focuses on tactical and operational behaviors in the 1- to 10-s range, based on the logic that strategic/mission-level behaviors are not part of the DDT, and that active safety is out of the scope of this work because it is not specific to ADS.

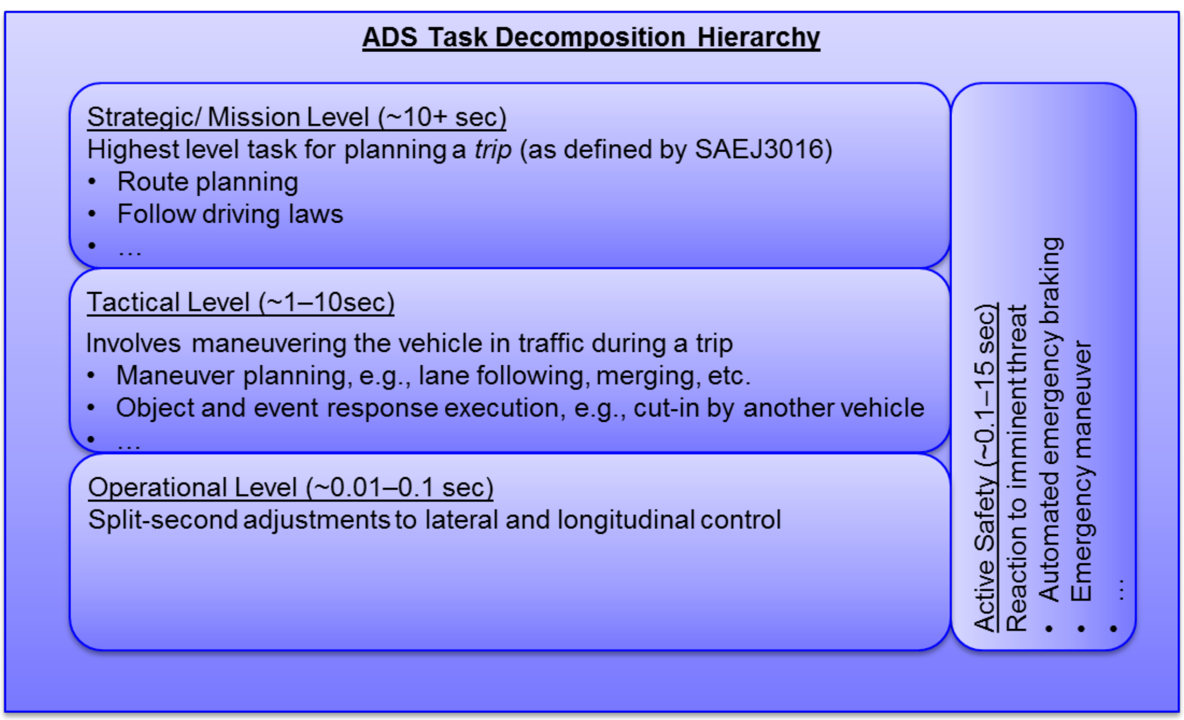

Figure 4. ADS Task Decomposition Distributed by Temporal Levels of the Control System

ADS Tactical and Operational Maneuvers

Through the literature review and analysis, a working list of tactical and operational maneuvers related to ADS driving control was created.

- **Parking –** ADS comes to a complete stop within a vacant parking spot; may be further qualified by parallel or perpendicular orientations, lot type (closed/open), initiation conditions, etc.
- **Maintain Speed –** ADS maintains a safe speed set through longitudinal control with acceptable following distances.
- **Car Following –** ADS identifies and follows a target vehicle at acceptable following distance while staying within a lane through longitudinal and lateral control.
- **Lane Centering –** ADS stays within a lane through lateral control.
- **Lane Switching/Overtaking –** ADS crosses lanes or overtakes an upcoming vehicle based on a projected path or hazard.
- **Enhancing Conspicuity –** ADS controls vehicle blinkers, headlights, horn, or other methods used to communicate with other drivers.
- **Obstacle Avoidance –** ADS identifies and responds to on-road hazards, such as pedestrians, debris, animals, etc.
- **Low-Speed Merge –** ADS merges into a lane below about 45 mph, for example from an exit ramp, by identifying a vacant lane position and matching speed.
- **High-Speed Merge –** ADS merges into a lane above about 45 mph, for example from an exit ramp, by identifying a vacant lane position and matching speed.
- **Navigate On/Off-Ramps –** ADS drives on on/off-ramps, which are typically one-way, steeply curved, and banked road segments.
- **Right-of-Way Decisions –** ADS obeys directional restrictions; for example, one-way roads and actively managed lanes.
- **Follow Driving Laws –** ADS obeys motor vehicle codes and local ordinances; for example, following distances, speed limits, etc. This may include driving norms that vary by region as well.
- **Navigate Roundabouts –** ADS determines right-of-way, enters, navigates, and exits a roundabout, and communicates with other road users as necessary.
- **Navigate Intersection –** ADS determines right-of-way, enters, navigates, and exits intersections, including signalized, stop signs, 4/3/2-ways, and communicates with other road users as necessary; may include left or right turns across oncoming traffic.
- **Navigate Crosswalk –** ADS determines right-of-way, enters, navigates, and exits pedestrian crosswalks, and communicates with other road users as necessary.
- **Navigate Work Zone –** ADS determines right-of-way and traffic patterns, enters, navigates and exits work zone, and communicates with other road users as necessary.
- **N-Point Turn –** ADS makes a heading adjustment that involves alternating between forward and reverse movement and adjusting steering to reposition the vehicle within a tight space.
- **U-Turn** – ADS determines right-of-way, initiates, and completes a U-turn, and communicates with other road users as necessary.

- **Route Planning –** ADS uses various information to define (and potentially update) a route network including road segments, turns, etc.

To serve as an example, Figure 5 displays some of the behaviors for L3 Nissan Piloted Drive.

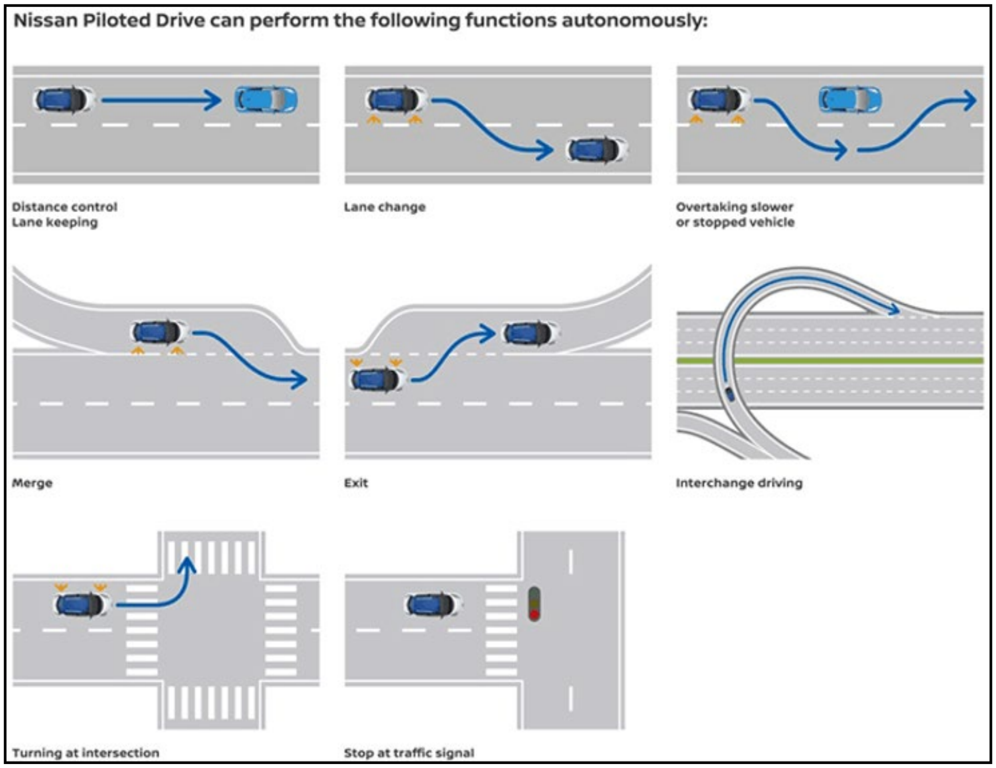

Figure 5. Sample Capabilities for Nissan Piloted Drive (Inside EVs, 2015)

IDENTIFICATION OF CONCEPT ADS FEATURES

Twenty-four concept ADS features were identified.

1. Audi Traffic Jam Pilot
2. Audi Highway Pilot
3. Auro Self-Driving Shuttle
4. Baidu Automated TNC[3]
5. Bosch Valet Parking
6. CityMobil2 Automated Shuttle
7. Bosch Highway Pilot
8. EZ10 Self-Driving Shuttle
9. Ford Automated TNC
10. GM Cruise Automation TNC
11. Google Car
12. Honda Automated Drive

[3] TNC: Transportation Network Company

13. Mercedes Highway Pilot Truck
14. Navya Arma Shuttle
15. Nissan Autonomous Drive
16. Olli Local Motors Shuttle
17. Otto Trucking
18. Tesla Self-Drive
19. Toyota Chauffeur
20. Toyota Guardian
21. Uber Automated TNC
22. Varden Labs Self-Driving Shuttles
23. Volkswagen I.D. Pilot
24. Volvo IntelliSafe Auto Pilot

These 24 features were categorized into the following seven generic categories.

1. L3 Conditional Automated Traffic Jam Drive
2. L3 Conditional Automated Highway Drive
3. L4 Highly Automated Low Speed Shuttle
4. L4 Highly Automated Valet Parking
5. L4 Highly Automated Emergency Take-Over
6. L4 Highly Automated Highway Drive
7. L4 Highly Automated Vehicle/TNC

Table 2 shows which ADS features belong to the seven generic categories.

Table 2. ADS Features by Generic ADS Category

Category	Generic ADS Feature	ADS Features
1	L3 Conditional Automated Traffic Jam Drive	Audi Traffic Jam Pilot
2	L3 Conditional Automated Highway Drive	Mercedes Highway Pilot Truck
3	L4 Highly Automated Low Speed Shuttle	Auro Self-Driving Shuttle, CityMobil2 Automated Shuttle, EZ10 Self-Driving Shuttle, Navya Arma Shuttle, Olli Local Motors Shuttle, Varden Labs Self-Driving Shuttles
4	L4 Highly Automated Valet Parking	Bosch Valet Parking
5	L4 Highly Automated Emergency-Take Over	Toyota Guardian
6	L4 Highly Automated Highway Drive	Audi Highway Pilot, Bosch Highway Pilot, Otto Trucking

7	L4 Highly Automated Vehicle/TNC	Baidu Automated TNC, GM Cruise Automation TNC, Waymo Automated TNC, Honda Automated Drive, Nissan Autonomous Drive, Tesla Self-Drive, Uber Automated TNC, Volkswagen I.D. Pilot, Volvo Intellisafe Auto Pilot, Ford Automated TNC, Toyota Chauffeur

Each of the concept ADS features is described below, organized by generic ADS feature categories. Each generic feature category is described in terms of ConOps and enabling technology, and each identified concept ADS feature is described in terms of tactical maneuver behaviors, commercial availability, and level of automation. The analysis was based largely on the literature review. Due to the incompleteness of the publicly available information, engineering judgment was used in some cases to predict certain data. In these cases, a "?" is provided in the accompanying table instead of an "X."

Category 1, L3 Conditional Automated Traffic Jam Drive Feature

L3 Traffic Jam Drive features autonomous travel for stop-and-go traffic. It allows the vehicle to act without input from the human operator at slower speeds if a preceding car can be followed. A human operator is the fallback for the DDT. The Audi Traffic Jam Pilot (Audi, 2015) uses adaptive cruise control and LKA to allow slow driving in traffic jams. The 2017 Audi A4 and Q7, which contain an early version of this feature (SAE International L2), follow the vehicle ahead and automatically operate the accelerator and brake within the limits of the system so the vehicle is kept in lane. The car steers, accelerates, and brakes automatically, and allows the driver to take his/her hands off the steering wheel in slow-moving traffic for 15 seconds at a time (Jaynes, 2016). The future version of the feature is expected to achieve L3 driving automation, and to be commercially available on the 2019 Audi A8.

Ford has announced that the company is finalizing their own traffic jam assist; however, they have offered no timeline for its debut. The traffic jam assist will be an autopilot that combines ACC and LKA, assisting the driver with steering, braking and acceleration (Ford Motor Company, 2015).

Table 3. L3 Conditional Automated Traffic Jam Drive Features

ADS Features and Tactical and Operational Maneuvers (X = demonstrated, ? = speculated)	**Commercially Available? (Y/N)**	**Level of Automation (SAE 1-5)**	Parking	Maintain Speed	Car Following	Lane Centering	Lane Switching/Overtaking	Enhancing Conspicuity	Merge	Navigate On/Off Ramps	Follow Driving Laws	Navigate Roundabouts	Navigate Intersection	Navigate Crosswalk	Navigate Work Zone	N-Point Turn	U-Turn	Route Planning
Audi Traffic Jam Pilot *(2019)*	N	3		X	X	X												

Category 2, L3 Conditional Automated Highway Drive Feature

L3 Highway Drive allows the vehicle to act without input from the human operator on highways (e.g., ACC and close-headway platooning). The feature enables the vehicle to travel at a desired speed and adjust the speed based on the surrounding traffic. The system is also able to overtake slower vehicles or merge at highway junctions.

Table 4. L3 Conditional Automated Highway Drive Features

ADS Features and Tactical and Operational Maneuvers (X = demonstrated, ? = speculated)	**Commercially Available? (Y/N)**	**Level of Automation (SAE 1-5)**	Parking	Maintain Speed	Car Following	Lane Centering	Lane Switching/Overtaking	Enhancing Conspicuity	Merge	Navigate On/Off Ramps	Right-of-Way Decisions	Follow Driving Laws	Navigate Roundabouts	Navigate Intersection	Navigate Crosswalk	Navigate Work Zone	N-Point Turn	U-Turn	Route Planning
Mercedes Highway Pilot Truck *(2020)*	N	3?		X	X	X	?		?			X							

Category 3, L4 Highly Automated Low-Speed Shuttle Feature

L4 Highly Automated Low Speed Shuttle is an automated shuttle that drives along a predetermined route. The system does not need an onboard driver control interface and is limited to speeds below 25 mph. For example, Olli (Local Motors, 2017) is a self-driving electric vehicle that has been tested in several locations in the United States and is currently deployed in Germany. Olli can be part of a fleet management system with a central operation center designed to solve the transportation needs of large campuses and municipalities. A smart phone application is available for users to find existing routes, share a ride, and input pick-up and drop-off locations for door-to-door service.

CityMobil2 (CityMobil2, 2017) piloted a platform for automated road transport systems, which was implemented in several urban environments across Europe. A large-scale demonstration in the Greek city of Trikala was completed in winter 2015. A fleet of six Robosoft vehicles drove at a speed of about 12.5 mph along a 1.5-mile itinerary that was integrated into the main city road network. During the last large-scale demonstration, automated shuttles operated in conditions close to normal traffic conditions, operating along with other road users, including cars, pedestrians, and cyclists. Almost 1,490 trips were recorded during the demonstration period. During this time, the vehicles covered more than 3,500 km and transported more than 12,000 passengers in the city center.

The French manufacturer Navya Technologies SAS's Arma (Navya, 2017) is a 100-percent electric, intelligent, and autonomous shuttle at the service of mobility, launched in October 2015. French specialists spent 10 years of research to achieve L4 driving automation. The Navya Arma does not require any driver or specific infrastructure, can avoid static and dynamic obstacles, and can transport up to 15 passengers and safely drive up to 28 mph. In terms of functional safety, the L4 Highly Automated Shuttle Feature could address some of the safety concerns (i.e., human error and situational awareness) associated with driving 15-passenger vehicles. Other safety concerns with vehicles of this size (such as tire pressure) could still pose a safety hazard if not checked regularly. Its batteries can be recharged by induction and can last from 5 to 13 hours, depending on the configuration and the traffic conditions.

Another French manufacturer, Easymile SAS, (EasyMile, 2017) is a start-up specializing in providing both the software powering autonomous vehicles and last-mile smart mobility solutions. Its EZ10 is an electric shuttle dedicated to smart mobility designed to cover short distances and predefined routes in multi-use environments. EZ10 can operate in three modes, needs only light infrastructure to operate, meets smart transportation requirements, and has operational and top speeds of 12 mph and 25 mph, respectively. The shuttle service runs on virtual tracks that can be easily configured to accommodate sudden shifts in demand. The service operator can set up new timetables and create new virtual stops to facilitate the flow of traffic. Using redundant embedded systems inspired by aeronautics, EZ10 ensures the safety of passengers and road users from road hazards and technical failures. Their hybrid sensing approach combines shuttle localization through vision, laser, and differential GPS data. This approach ensures smooth operation irrespective of infrastructure constraints, visibility, and/or weather conditions. Detection of static or moving objects and people relies on redundant perception systems. Following the detection of an object, the EZ10 adjusts its trajectory and speed, leading to obstacle avoidance. A "safety chain" as a stand-alone collision avoidance feature adds to vehicle and user safety. Additionally, fleet management software enables the remote and real-time monitoring and control of the fleet of EZ10 shuttles.

Table 5. L4 Highly Automated Low Speed Shuttle Features

ADS Features and Tactical and Operational Maneuvers (X = demonstrated, ? = speculated)	Commercially Available? (Y/N)	Level of Automation (SAE 1-5)	Parking	Maintain Speed	Car Following	Lane Centering	Lane Switching/Overtaking	Enhancing Conspicuity	Merge	Navigate On/Off Ramps	Follow Driving Laws	Navigate Roundabouts	Navigate Intersection	Navigate Crosswalk	Navigate Work Zone	N-Point Turn	U-Turn	Route Planning
Olli Local Motors *(Tampa, FL 2018)*	Y	4	X	X	X	X	X	X	?		X	?	X	?	?	X	X	X
CityMobil2 *(demo in multiple European cities, 2014-2016)*	N	4	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
Navya Arma Shuttle *(France/ Switzerland)*	Y	4	X	X	X	X	X	X	?		X	?	X	?	?	X	X	X
Auro Self-Driving Shuttle	N	4	X	X	X	X	X	X	?		X	?	X	?	?	X	X	X
Varden Labs Self-Driving Shuttles	N	4	X	X	X	X	X	X	?		X	?	X	?	?	X	X	X
EZ10 Self-Driving Shuttle	N	4	X	X	X	X	X	X	?		X	?	X	?	?	X	X	X

Category 4, L4 Highly Automated Valet Parking Feature

L4 Highly Automated Valet Parking involves a car, potentially unoccupied, that can find a parking spot and park itself. Bosch's Valet Parking feature is a future concept (release date unclear) offering a new laser technology that operates without the assistance of GPS signals. Drivers drop the vehicle off at a designated area near a parking garage entrance and pick it up at a designated area (Bosch, 2017). This feature combines a variety of different connected and automated parking solutions being developed by Bosch.

Table 6. L4 Highly Automated Urban Valet Parking Features

ADS Features and Tactical and Operational Maneuvers (X = demonstrated, ? = speculated)	Commercially Available? (Y/N)	Level of Automation (SAE 1-5)	Parking	Maintain Speed	Car Following	Lane Centering	Lane Switching/Overtaking	Enhancing Conspicuity	Merge	Navigate On/Off Ramps	Follow Driving Laws	Navigate Roundabouts	Navigate Intersection	Navigate Crosswalk	Navigate Work Zone	N-Point Turn	U-Turn	Route Planning
Bosch Valet Parking *(2020)*	N	4	X	X	?	?		X			?		?	?		?	?	X

Category 5, L4 Highly Automated Emergency Takeover

In the event a driver is in impending danger, Emergency Takeover assumes control of the vehicle and guides it to a safe stop. Cameras inside the car track the driver's head movement, while software uses sensor data to estimate when a person needs help spotting or avoiding a potentially dangerous situation. Toyota's Guardian system is distinct from other ADS features and operates in parallel with a human rather than in series (Goreham, 2017). The system is designed to reduce complications of a handoff between the car and human driver, since the driver is expected to maintain control at all times.

Table 7. L4 Highly Automated Emergency Takeover Features

ADS Features and Tactical and Operational Maneuvers (X = demonstrated, ? = speculated)	**Commercially Available? (Y/N)**	**Level of Automation (SAE 1-5)**	Parking	Maintain Speed	Car Following	Lane Centering	Lane Switching/Overtaking	Enhancing Conspicuity	Merge	Navigate On/Off Ramps	Follow Driving Laws	Navigate Roundabouts	Navigate Intersection	Navigate Crosswalk	Navigate Work Zone	N-Point Turn	U-Turn	Route Planning
Toyota Guardian	N	4		X	X	X	X	X		X	X							

Category 6, L4 Highly Automated Highway Drive Feature

The L4 Highway Drive system handles the entire DDT on a highway route, allowing the passenger to engage in other tasks; the system is responsible for the fallback performance of DDT.

Bosch has publicly outlined its concept for its Highway Pilot system that can assume all driving duties on open highways, from entrance ramp to exit ramp. According to Bosch, emerging technology will be aided by vehicle-to-vehicle and vehicle-to-infrastructure communication. Bosch expects a fully self-driving Highway Pilot by 2020 (Stoklosa, 2016). Otto demonstrated a highly automated truck (Barber, 2016) in 2016 in coordination with the Colorado Department of Transportation that was intended as an SAE International L4 system operating on highways.

Table 8. L4 Highly Automated Highway Drive Features

ADS Features and Tactical and Operational Maneuvers (X = demonstrated, ? = speculated)	**Commercially Available? (Y/N)**	**Level of Automation (SAE 1-5)**	Parking	Maintain Speed	Car Following	Lane Centering	Lane Switching/Overtaking	Enhancing Conspicuity	Merge	Navigate On/Off Ramps	Follow Driving Laws	Navigate Roundabouts	Navigate Intersection	Navigate Crosswalk	Navigate Work Zone	N-Point Turn	U-Turn	Route Planning
Audi Highway Pilot	N	4		X	X	X	X	?	X		?							X
Bosch Highway Pilot *(2020)*	N	4		X	X	X	X	?	X		?							X
Otto Trucking *(demonstration 2016)*	N	4		X	X	X	X	?	X		?							X

Category 7, L4 Highly Automated Vehicle/Transportation Network Company (TNC) Feature

L4 Highly Automated Vehicle/TNC enables the vehicle to pick up passengers or goods and drive to a destination without the need for an onboard driver. This feature may operate within a broad ODD, which is explored in further detail in Chapter 3. However, confirmation has not yet been provided that these features will operate in all ODDs, and thus they are categorized as L4 as opposed to full driving automation (L5). For example, these vehicle fleets may initially be limited to the cities in which they are tested. OEMs developing this technology have stated that they intend to pursue full autonomy. This feature could become commercially available as soon as 2020. Examples of this feature include the Google Car (Waymo, 2017a), Tesla Self-Drive (Tesla, 2017), Volkswagen I.D. Pilot Mode (Nishimoto, 2016), Volvo IntelliSafe Auto Pilot (Volvo, 2017), and Nissan Autonomous Drive (Nissan, 2017).

Table 9. L4 Highly Automated Vehicle/TNC Features

ADS Features and Tactical and Operational Maneuvers (X = demonstrated, ? = speculated)	**Commercially Available? (Y/N)**	**Level of Automation (SAE 1-5)**	Parking	Maintain Speed	Car Following	Lane Centering	Lane Switching/Overtaking	Enhancing Conspicuity	Merge	Navigate On/Off Ramps	Follow Driving Laws	Navigate Roundabouts	Navigate Intersection	Navigate Crosswalk	Navigate Work Zone	N-Point Turn	U-Turn	Route Planning
Waymo Automated TNC	N	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Tesla Self-Drive	N	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Volkswagen I.D. Pilot	N	4?	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Volvo IntelliSafe Auto Pilot	N	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Nissan Autonomous Drive *(2020)*	N	4?	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
GM Cruise Automation	N	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Uber Automated TNC	N	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Honda Automated Drive *(2020)*	N	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Ford Automated TNC *(2022)*	N	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Baidu Automated TNC	N	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Toyota Chauffeur	N	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Summary of Generic ADS Features

Table 10 compares the generic ADS features. The tactical maneuver behaviors exhibited by each feature vary as a function of where and how they are intended to operate. Having more tactical maneuver behaviors does not necessarily indicate complexity. For example, low-speed shuttles may exhibit most of the tactical maneuver behaviors, but their ODD is limited by speed and reduces the complexity of the technical problem, thus enabling near-term deployment.

Table 10. Summary of Generic ADS Features

Generic ADS Features **and Tactical and Operational Maneuvers *(Summary)*** (X = demonstrated, ? = speculated)	**Commercially Available? (Y/N)**	**Level of Automation (SAE 1-5)**	Parking	Maintain Speed	Car Following	Lane Centering	Lane Switching/Overtaking	Enhancing Conspicuity	Merge	Navigate On/Off Ramps	Follow Driving Laws	Navigate Roundabouts	Navigate Intersection	Navigate Crosswalk	Navigate Work Zone	N-Point Turn	U-Turn	Route Planning
L3 Conditional Automated Traffic Jam Drive *(2018)*	N	3		X	X	X												
L3 Conditional Automated Highway Drive *(2020)*	N	3		X	X	X	X	X	X		X							X
L4 Highly Automated Low Speed Shuttle *(2018)*	Y	4	X	X	X	X	X	X	X		X	X	X	X	?	X	X	X
L4 Highly Automated Valet Parking *(2020)*	N	4	X	X	?	?		X			?		?	?		?	?	X
L4 Highly Automated Highway Drive *(2020)*	N	4		X	X	X	X	?	X		?							X
L4 Highly Automated Emergency Take-Over *(?)*	N	4		X	X	X	X	X		X	X							
L4 Highly Automated Vehicle/TNC *(2020)*	N	4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

SUMMARY

This chapter identified concept ADS features and illustrated how ADS functionality is emerging. Specifically, it described functionality and proposed timelines for commercial deployment across the different SAE International levels of driving automation. There is no clear correlation between level of driving automation and the timeline for commercial deployment. For L3 systems, conditional automated traffic jam drive is expected in 2018, while conditional automated highway drive is not expected until 2020. For L4 systems, highly automated low speed shuttles are expected in 2018, and other features are slated for 2020. A figure showing ADS deployment timelines from SAE J3016 is reproduced in Figure 6.

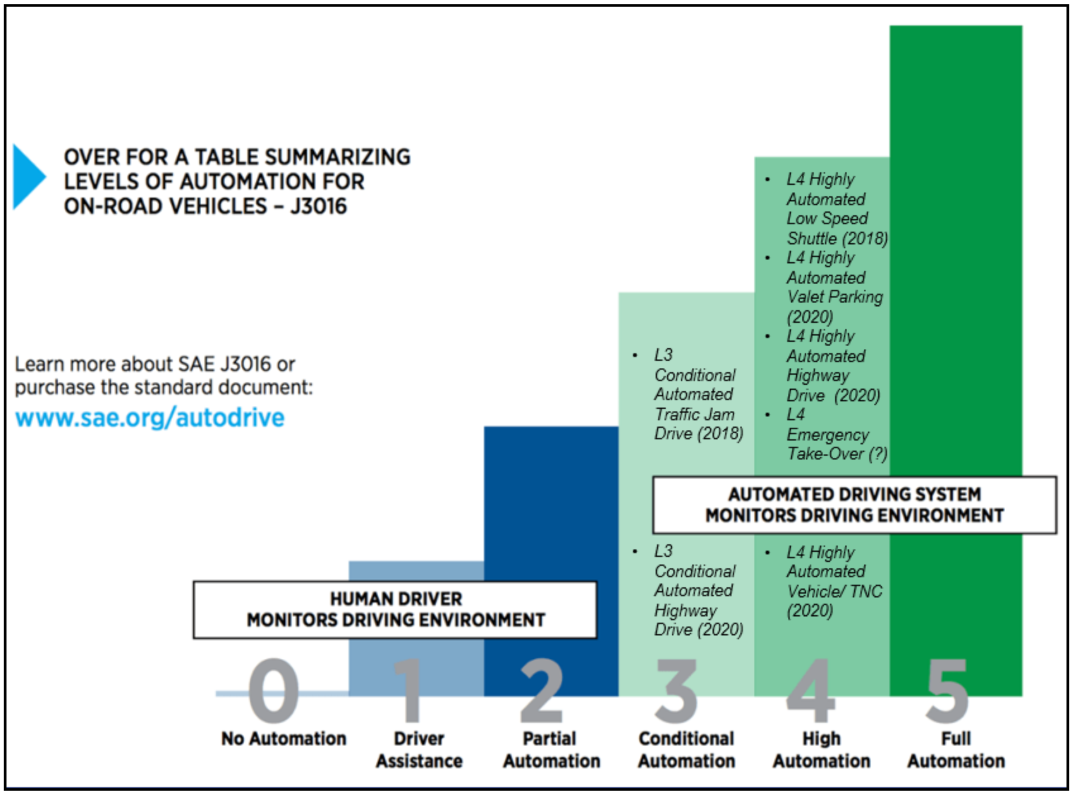

Figure 6. ADS Feature Timeline by Level of Driving Automation (SAE International, 2016)

The ADS features described in this chapter provide the basis for identifying ODD attributes in Chapter 3, OEDR capabilities in Chapter 4, test cases in Chapter 5, and FS/FO mechanisms in Chapter 6. Operational descriptions of the features provide insights into where and when an ADS can operate. The tactical maneuver behaviors describe the functionality that test cases will need to evaluate. The generic names provide a simple and consistent naming system that is referenced throughout to describe concept ADS features.

CHAPTER 3. OPERATIONAL DESIGN DOMAIN

OVERVIEW

This chapter describes the identification of attributes that can be used to define the ODDs for ADS. An ODD describes the specific operating domains in which an ADS feature is designed to function with respect to roadway types, speed range, lighting conditions (day and/or night), weather conditions, and other operations constraints. ODD will likely vary for each ADS feature, even if there is more than one ADS feature on a vehicle. The testing framework presented in this report considers the potential range of ODDs and how ODDs factor into developing potential test cases.

APPROACH

A three-stage approach was taken to define the ODDs.

1. Review the literature, including popular media, press releases, technical journals, and conference proceedings to identify key concepts, enumerate potential ODD characteristics, and examine approaches to ODD in other industries.
2. Define and categorize ODD into a taxonomy that can be used by DOTs and industry to discuss ADS.
3. Describe ODDs in which concept ADS features may operate based on literature review and engineering judgment.

Over 50 literature sources were reviewed, including OEM websites, press releases, USDOT documents, including NHTSA pre-crash scenario analysis and FHWA managed lane use case, as well as technical and international publications, including proceedings of the 2015 and 2016 automated vehicles symposiums. Additionally, the NHTSA fiscal year 2017 Budget Request to Congressional Appropriations Committees (NHTSA, 2016b) identifies several ADS use cases that were considered when defining the ODD for this analysis. It should be noted that given the emerging and highly competitive nature of ADS technology, it is inherently difficult to obtain explicit and complete information about the intended ODD of an ADS feature. In the absence of information about an ODD, engineering judgement was used at times to define the ODD taxonomy and identify the ODD for concept ADS features.

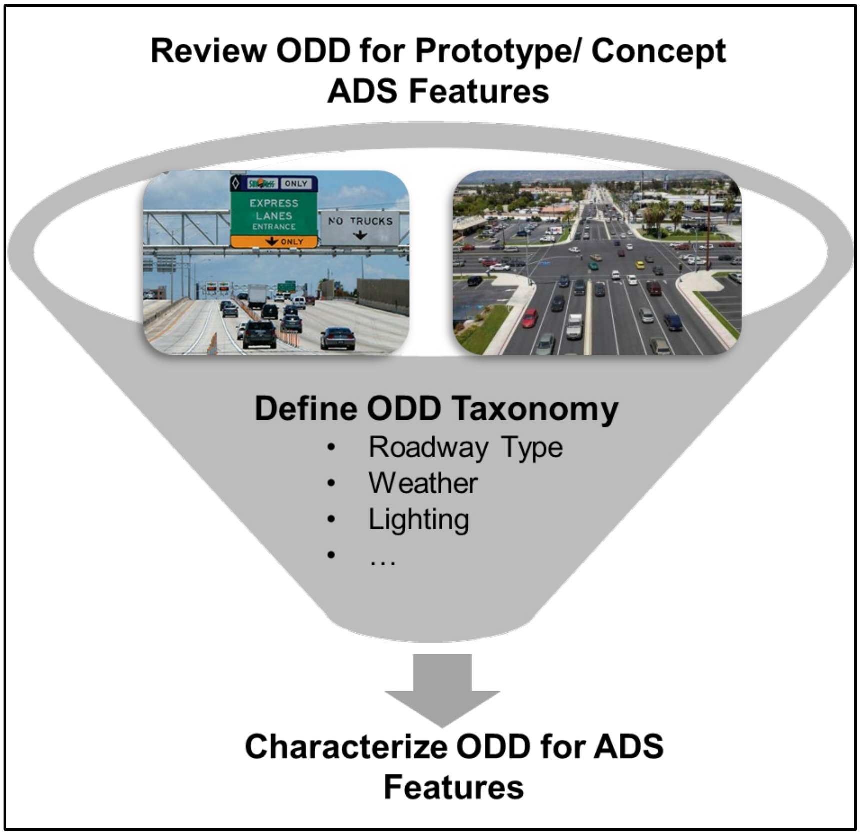

Figure 7. The ODD Defining Process

Certain pieces of information in the literature and media were particularly helpful with ODD identification and taxonomy definition, including the following.

- Descriptions in the product literature
  - In some cases, ODDs have been explicitly defined in the product literature and through prototype testing and deployment materials, especially roadway types and speeds.
- Videos
  - Videos provide visual documentation of vehicles being tested in specific domains (e.g., weather conditions, physical infrastructure, shared road users, etc.), which serves as the basis for inferring the potential ODDs for these ADS features.
  - Videos range from official marketing material to product research and testing videos to independent videos of released products for many different ADS features that are being tested or introduced by OEMs.
- Perception systems
  - Sensor suites drive ODD boundaries and limitations (e.g., dusty conditions hinder cameras more than radar). The perceptions systems proposed for the different ADS features were considered when identifying ODDs.
- Testimonials
  - Anecdotal reports provide insights into what features of the environment are important, especially reports of systems having trouble with specific ODDs, including poor lane markings, hill crests/curves, etc.

- ODDs from other domains
  - ODDs from other domains inform categorization and approach (e.g., aviation includes airspace classes and transitions, presence of ground crews, workload on operator, etc.).

Influences for Defining the ODD Framework

The literature revealed several early efforts to define and frame ODDs. The concepts put forth are not in complete agreement and take the form of everything from public policy to industry guidelines to research. This section discusses sources that were influential in advancing the framework put forth in this report.

Automated Driving Systems 2.0 – A Vision for Safety

The USDOT definition of ODD is given in Federal guidance and is adopted for the purposes of this report. The definition indicates that ODD should be identified by the manufacturer, and includes example ODD categories.

> Entities are encouraged to define and document the Operational Design Domain (ODD) for each ADS available on their vehicles as tested or deployed for use on public roadways, as well as document the process and procedure for assessment, testing, and validation of ADS functionality with the prescribed ODD.

The definition goes on to describe how the ODD's boundary influences ADS operation.

> The ODD would include the following information at a minimum to define each ADS's capability limits/boundaries: Roadway types (interstate, local, etc.) on which the ADS is intended to operate safely; Geographic area (city, mountain, desert, etc.); Speed range; Environmental conditions in which the ADS will operate (weather, daytime/nighttime, etc.); and other domain constraints (NHTSA, 2017a).

2016 SAE J3016

SAE J3016 has been adopted by USDOT and defines and describes ODDs. The concepts put forth in J3016 are adopted in this research and are consistent with USDOT's policy. ODD is not explicitly related to level of driving automation, except that for L5, the ODD is described as "unlimited."

J3016 provides the following definition of ODD: "The specific conditions under which a given driving automation system or feature thereof is designed to function, including, but not limited to, driving modes."

J3016 also provides example categories (see Figure 8).

> An ODD may include one or more driving modes. For example, a given ADS may be designed to operate a vehicle only on fully access-controlled freeways and in low-speed traffic, high-speed traffic, or in both driving modes.[3]

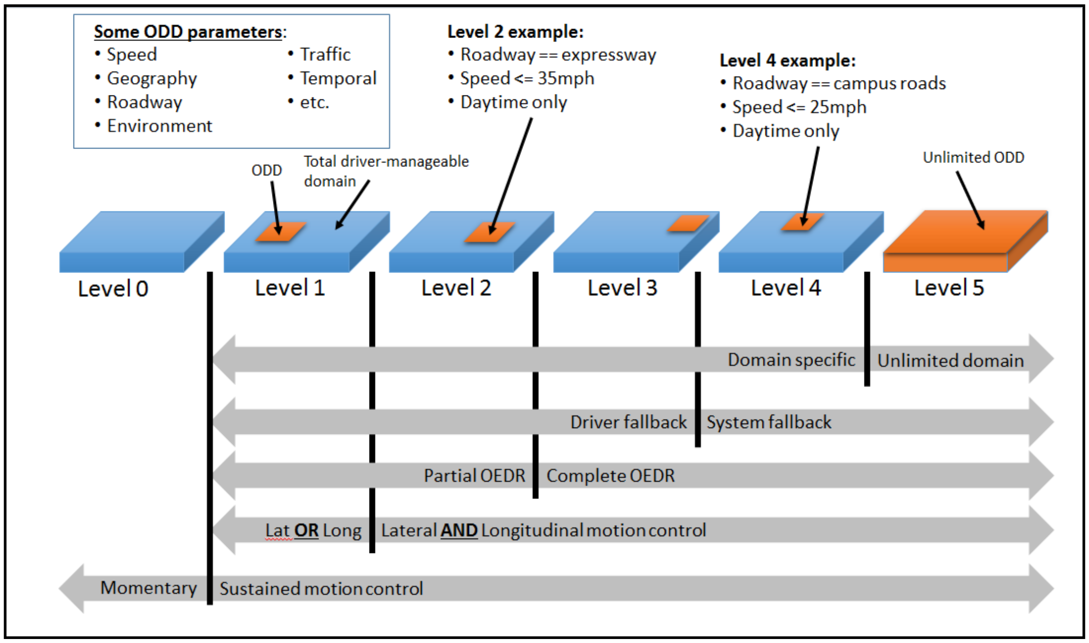

Figure 8. ODD Relative to Levels (SAE International, 2016)

There have been questions and critiques regarding J3016. For example, the National Society of Professional Engineers (Austin, 2016) commented that:

> The operational design domains proposed in SAE J3016 are overly broad and do not adequately reflect the myriad of subdomains a vehicle may be required to enter and exit in the course of a single route within an overall domain (e.g., toll roads).

Another question that has arisen is whether the concept of an "unlimited" ODD at L5 should be taken to the extreme (e.g., whiteout snow conditions) or whether it is limited in practice (e.g., to the same level as a reasonable human driver). SAE J3016 is currently working on an update to the document in conjunction with ISO that will clarify several points, including concepts that relate to ODDs.

California Policy

Similar to USDOT and SAE International, California draft regulations (CA DMV, 2017) describe a concept for ODD that defines the boundary between ADS and human operation, and state that the ODD is to be specified by the manufacturer.

> [The manufacturer] shall identify in the application the operational design domain in which the subject autonomous vehicles are designed to operate and certify that the vehicles are designed to be incapable of operating in the autonomous mode in areas outside of the disclosed ODD.

The policy goes on to note that ODD elements can be identified as subtractive:

> …identify any commonly occurring or restricted conditions including but not limited to: snow, fog, black ice, wet road surfaces, construction zones, and geo-fencing by location or road type, under which the vehicles are either designed to be incapable of operating or unable to operate reliably in the autonomous mode and certify that the vehicles are designed to be incapable of operating in autonomous mode under those conditions.

It also discusses the relationship with local legal codes within the geographically defined ODD:

> …a reference to the ordinances or resolutions from local authorities that specifies the operational design domains within the jurisdiction of the local authorities that the vehicles may be operated.

In support of the California policy, California PATH conducted an analysis (University of California PATH Program, 2016) that gathered expert feedback on "areas of operation," which were defined as Rural, Urban, and Freeway/Highway. This classification scheme was found to be too blunt and indiscriminate and was replaced by ODD. This analysis also identified the challenge of handling the wide range of environmental, weather, and lighting conditions, and suggested using a complementary functional safety plan to address difficult-to-quantify scenarios.

PEGASUS Project

The PEGASUS Project is aimed at "establishing generally accepted quality criteria, tools and methods, as well as scenarios and situations for the release of highly automated driving functions (Winner, Wachenfeld, & Junietz, 2016)." The effort is focused on highway driving, and the PEGASUS research team has identified several elements of a scene that pertain to ODD, including traffic infrastructure (e.g., lanes, regulations, geometry), environmental conditions (e.g., surface grip from wetness, light, sun, fog, sensor obstacles), and traffic (Hungar, 2017).

Others Referenced

While not central to this analysis, influences from other industries were considered. These include aviation and the Department of Defense.

The aviation industry manages operational domains for traffic in the national airspace and space flight. Airspace volumes are designated into several classes, which specify operational characteristics and procedures. To operate in certain airspace domains, airplanes may be required to have certain equipage (e.g., transponders), and pilots may need to follow certain procedures (e.g., instrumented flight rules versus visual flight rules). These operational domain designations are influenced by complexity of the airspace and potential risks. For automobiles, ODD is similarly influenced by complexity (e.g., speed, traffic level), risks, equipage (e.g., sensors), and procedures (e.g., toll lanes).

NASA's missions operate in a limited domain that help to constrain design; for example, missions that are restricted to specific geographic areas or types of objects that may be encountered (Wang & Hussein, 2012). For automated flight systems, there are certain domain considerations, such as air traffic, hazardous weather, terrain, and other obstructions and safety maneuvers (Hayhurst, Maddalon, Miner, DeWalt, & McCormick, 2006).

The DOD considers operating domains for the design and use of unmanned systems; for example, roadways, littoral areas, forested areas, and various operating speeds (National Research Council, 2005).

Guiding Principles

Several guiding principles were developed based on the literature to identify and characterize the ODDs:

- **Need for an ODD taxonomy** – A large variety of ODD dimensions exist, and a structure is needed to organize categories and facilitate discussion of system requirements, capabilities, and testing.
- **Account for variations in operational environments** – ODDs may vary in nature. Some can be predetermined (e.g., roadway type), while others change in time (e.g., traffic conditions). Some can be divided into discrete categories (e.g., signage), while others vary along a continuous scale and may be difficult to quantify (e.g., rain, light, fog).
- **Define what constitutes "operational scenario" –** An operational scenario is described in part by a set of ODD characteristics that describe the environment in which the feature is designed to perform.
- **Identify ODD boundaries –** ODD defines where the ADS can and cannot operate. ODD limits may vary by sub-trip or operational scenario due to confounding variables (e.g., weather and illumination), non-deterministic software, design and testing, etc. (Bojarski, et al., 2016)
- **Identify Current ODD State (Self-Awareness) –** An ADS feature should be able to identify whether it is within the ODD and detect and respond to system engagement and disengagement restrictions (University of California PATH Program, 2016). This may include identifying transitions between certain ODD states (e.g., roadway type).

Defining an ODD Taxonomy

While the literature provided many examples of ODD elements, no classification framework was identified. This work takes an initial step towards developing a taxonomy to organize the many ODD elements identified in research. This ODD taxonomy takes the form of a hierarchy of categories and subcategories, each with definitions and, where appropriate, gradations. This taxonomy is meant to be descriptive, not normative, as it is envisioned that these elements may be organized into several different groupings. The taxonomy offers a structured approach to organize and identify various ODDs for ADS features, especially when there are several different possible combinations. Figure 9 shows the broad range of top-level categories and immediate subcategories.

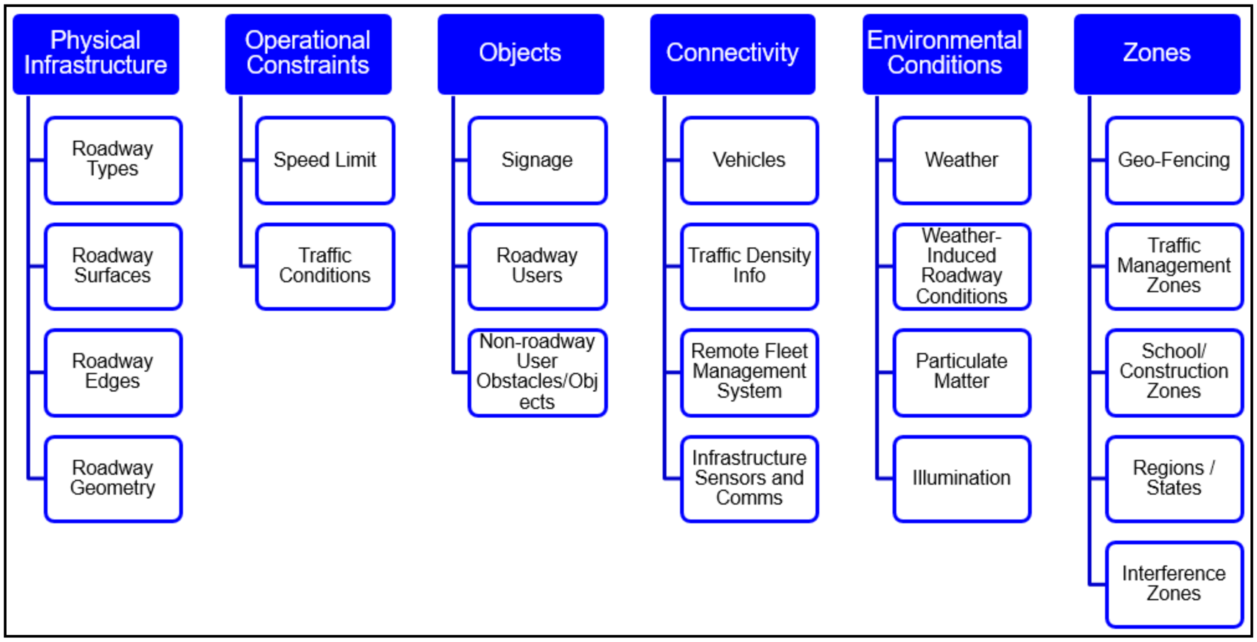

Figure 9. ODD Classification Framework With Top-Level Categories and Immediate Subcategories

The hierarchy extends into multiple sublevels, as shown in Figure 10. The "Environmental Conditions" category was divided into four subcategories: weather, illumination, particulate matter, and road weather. Weather is further subdivided into rain, temperature, wind, and snow. For this research project, it was helpful to further subdivide rain into gradations to capture the data that were collected on ADS features. For example, some ADS features had been tested in light rain, while others had been tested in heavy rain. Although the application of this taxonomy has been useful in the context of this research project, further research and stakeholder engagement would be beneficial in refining and objectively quantifying the categories and gradations.

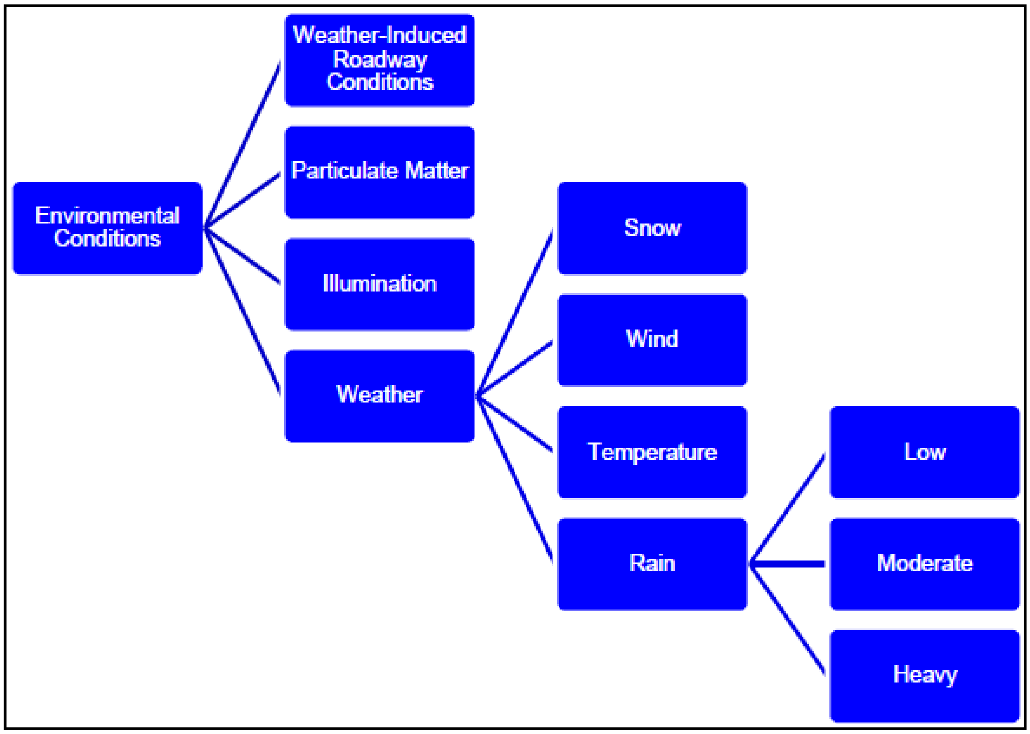

Figure 10. Example of Hierarchical Levels in the Environmental Conditions Category

ODD CATEGORY DESCRIPTIONS

Physical Infrastructure

Physical infrastructure refers to facilities and systems that serve a country, city, or area and enable its economy to function. Physical infrastructure is typically characterized by technical structures, such as roads, bridges, tunnels, water supply, sewers, electrical grids, telecommunications, etc., that are for the most part interrelated. ADS features may depend on such infrastructure elements, which are a critical part of the ODD environment. Subcategories of the main physical infrastructure elements are listed below; illustrative photos are provided in Figure 11.

Roadway Types

- Divided highway, undivided highway, arterial, urban, rural, parking, multi-lane, single lane, high-occupancy vehicle (HOV) lane, on/off ramps, emergency evacuation routes, one-way, turn-only lanes, private roads, reversible lanes, intersections (signaled, U-turns, 4-way/2-way stop, roundabout, merge lanes, turn-only lanes, crosswalk, toll plaza, railroad crossing) (FHWA, 2012).

Roadway Surfaces

- Asphalt, concrete, mixed, grating, brick, dirt, gravel, scraped road, partially occluded, speed bumps, potholes, grass (Gibbons, 1999).

Roadway Edges

- Line markers, temporary line markers, shoulder (paved or gravel), shoulder (grass), concrete barriers, grating, rails, curb, cones (Sage, 2016).

Roadway Geometry

- Straightaways, curves, hills, lateral crests, corners (regular, blind corners), negative obstacles, lane width (Huang, 2010).

Figure 11. Examples of Physical Infrastructure Elements

Operational Constraints

There are several operational constraints that need to be considered when designing and testing ADS applications. These include elements such as dynamic changes in speed limits, traffic characteristics, construction, etc. For example, an ADS entering a school zone is subjected to lower speed limits and must respond appropriately to ensure the safety of its passengers and other road users. Some examples of the operational constraints are listed below. Illustrative photos are provided in Figure 12.

Speed Limit

- Minimum and maximum speed limit (absolute, relative to speed limit, relative to surrounding traffic) (Elpern-Waxman, 2016).

Traffic Conditions

- Minimal traffic, normal traffic, bumper-to-bumper/rush-hour traffic, altered (accident, emergency vehicle, construction, closed road, special event) (University of California PATH Program, 2016).

Figure 12. Examples of Operational Constraints

Objects

For an ADS to properly navigate within an ODD, it must detect and respond to certain objects, which is referred to as OEDR. OEDR is the focus of Chapter 4, but is discussed here in the context of identifying objects that can reasonably be expected to exist within the ODD. For example, a pedestrian may be expected at an intersection but rarely on a freeway. Examples of objects and descriptions are provided in the text below and in Figure 13.

Signage

- Signs (e.g., stop, yield, pedestrian, railroad, school zone, etc.), traffic signals (flashing, school zone, fire department zone, etc.), crosswalks, railroad crossing, stopped buses, construction signage, first responder signals, distress signals, roadway user signals, hand signals (FHWA, 2012).

Roadway Users

- Vehicle types (cars, light trucks, large trucks, buses, motorcycles, wide-load, emergency vehicles, construction equipment, horse-drawn carriages/buggies), stopped vehicles, moving vehicles (manual, autonomous), pedestrians, cyclists (CA DMV, 2016).

Non-roadway User Obstacles/Objects

- Animals (e.g., dogs, deer, etc.), shopping carts, debris (e.g., pieces of tire, trash, ladders), construction equipment, pedestrians, cyclists

Figure 13. Examples of Objects

Environmental Conditions

Environmental conditions play a crucial role in the safe operation of a variety of ADS applications, and pose one of the biggest challenges to deployment, particularly early deployment. The environment can impact visibility, sensor fidelity, vehicle maneuverability, and communications systems. Today, ADS technologies are tested most often in clear, rather than adverse, weather conditions. On average, there are over 5.7 million vehicle crashes each year. Approximately 22 percent of these crashes—nearly 1.3 million—are weather-related (Erdman, 2015). Weather-related crashes are defined as crashes that occur in adverse weather (i.e., rain, sleet, snow, fog, severe crosswinds, or blowing snow/sand/debris) or on wet, snowy, or icy pavement. Weather acts through visibility impairments, precipitation, high winds, and temperature extremes to affect driver capabilities, vehicle performance (i.e., traction, stability, and maneuverability), pavement friction, roadway infrastructure, crash risk, traffic flow, and agency productivity (FHWA, 2017a). It is thus important to consider a variety of environmental conditions as part of the ODD. A few of these conditions are described below, and examples are shown in Figure 14.

Weather

- Wind, rain, snow, sleet, temperature
- On freeways, light rain or snow can reduce average speed by 3 to 13 percent. Heavy rain can decrease average speed by 3 to 16 percent. In heavy snow, average freeway speeds can decline by 5 to 40 percent. Free-flow speed can be reduced by 2 to 13 percent in light rain and by 6 to 17 percent in heavy rain. Snow can cause free-flow speed to decrease by 5 to 64 percent. Speed variance can fall by 25 percent during rain (FHWA, 2017c).

Weather-induced Roadway Conditions

- Standing water, flooded roadways, icy roads, snow on road
- Capacity reductions can be caused by lane submersion due to flooding and by lane obstruction due to snow accumulation and wind-blown debris. Road closures and access restrictions due to hazardous conditions (e.g., large trucks in high winds) also decrease roadway capacity (FHWA, 2017).

Particulate Matter

- Fog, smoke, smog, dust/dirt, mud
- Low visibility can cause speed reductions of 10 to 12 percent. Visibility distance is reduced by fog and heavy precipitation, as well as wind-blown snow, dust, and smoke. Low-visibility conditions cause increased speed variance, which increases crash risk. Each year, over 38,700 vehicle crashes occur in fog. Over 600 people are killed, and more than 16,300 people are injured in these crashes annually (FHWA, 2017b).

Illumination

- Day (sun: overhead, back-lighting, and front-lighting), dawn, dusk, night, street lights, headlights (regular and high-beam), oncoming vehicle lights (overhead lighting, back-lighting, and front-lighting) (FHWA, 2017a).

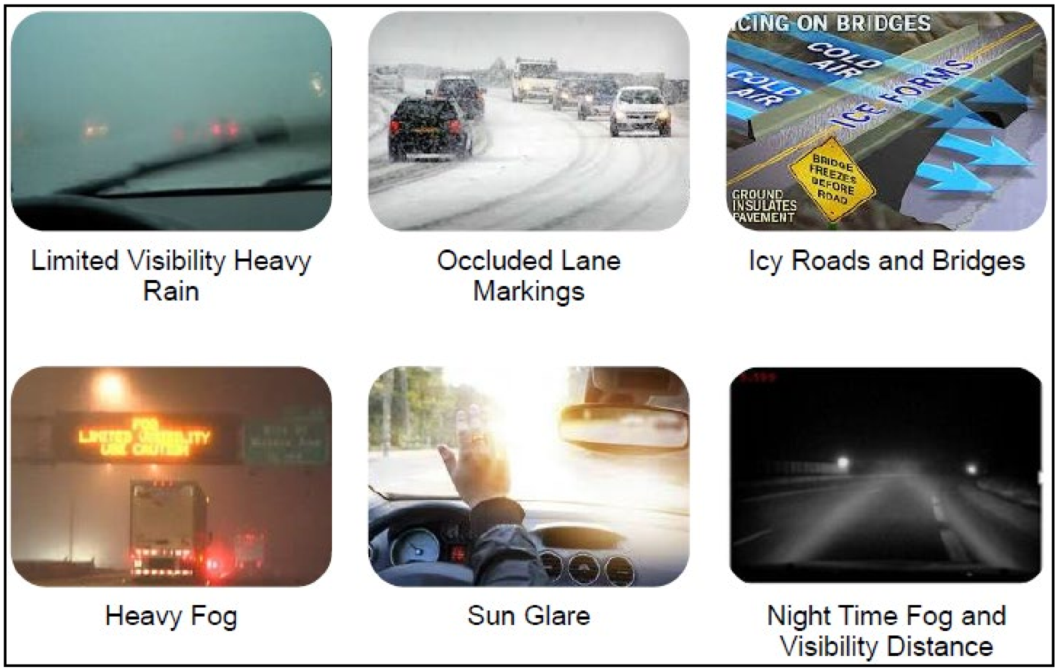

Figure 14. Examples of Environmental Conditions

Connectivity

Connectivity and automation are increasingly being integrated into cars and trucks with the objective of improving safety, mobility, and providing a better driving experience. Connectivity is an enabling technology that may define where an ADS feature can operate. For example, low-speed shuttles may depend on traffic light signal phase and timing messages to reduce the dependence on sensors alone to detect the signal. Other operational examples include eco-approach and departure or coordinated ACC (Michel, Karbowski, & Rousseau, 2016). Connectivity constitutes a communications link between other vehicles, road users, remote fleet management operators, and physical and digital infrastructure elements. Some of these elements are described below. Illustrative photos are provided in Figure 15.

Vehicles

- V2V communications (e.g., DSRC, Wi-Fi), emergency vehicles

Traffic Density Information

- Crowdsourced data (e.g., Waze) and V2I

Remote Fleet Management System

- A vehicle may be supported by an operations center that can perform remote operation. (Aljaafreh et al., 2011)

Infrastructure Sensors and communications

- Work zone alerts, vulnerable road user, routing and incident management, GPS, 3-D high-definition maps (Ellichipuram, 2016), pothole locations, weather data, data on the cloud, etc.

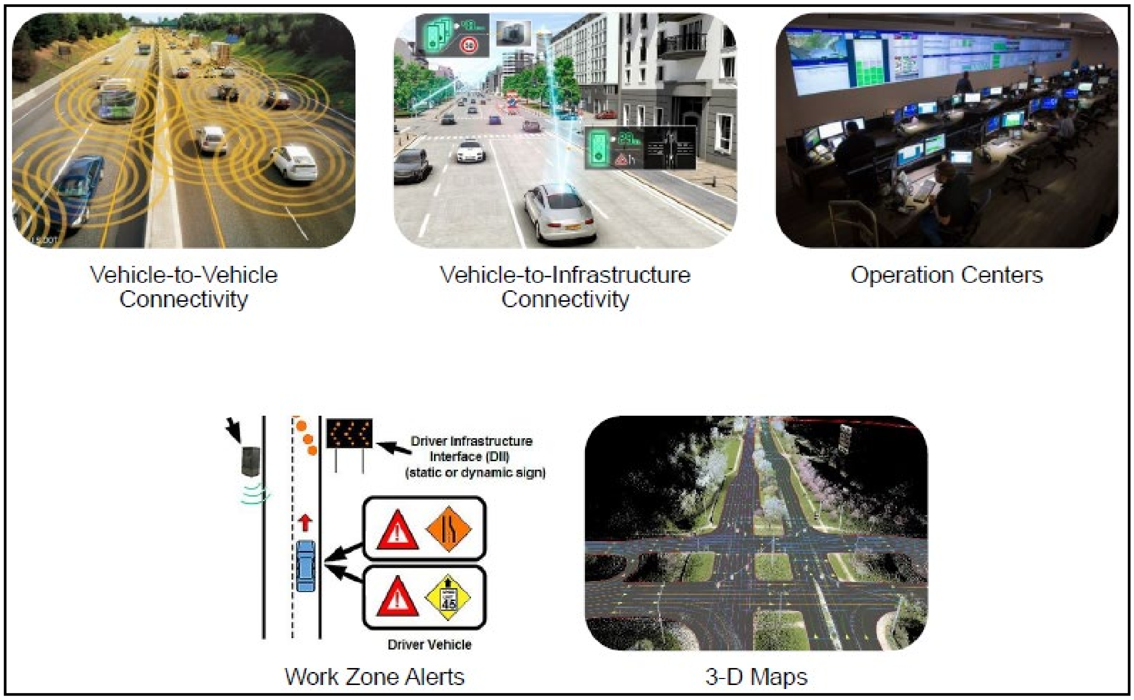

Figure 15. Examples of Connectivity

Zones

ADS features may be limited spatially by zones. The boundaries of these zones may be fixed or dynamic, and conditions that define a boundary may be based on complexity, operating procedures, or other factors. One example is work zones, which can confuse ADS as the road configuration (pavement markings and new lane alignments) differs from typical conditions. In a work zone, cones may replace double yellow lines, bollards may replace curbs, and construction worker hand signals may overrule traffic lights. These cues designed for human drivers can challenge advanced computer systems (Marshall, 2017). There are several other types of zones that are important to consider as potential elements of an ODD (see text below and Figure 16).

Geo-fencing (Crosbie, 2017)

- Central business districts, school campuses, and retirement communities (for example, CityMobil2 is fixed route and includes < 20 mph (CityMobil2, 2013) routes both on-road and off-road on pedestrian walkways).

Traffic Management Zones

- May include temporary lane closures, dynamic traffic signs, variable speed limits, temporary or non-existent lane markings, human-directed traffic, loading/unloading zones

School/Construction Zones

- Dynamic speed limit, erratic pedestrian and vehicular behaviors (Marshall, 2017)

Regions/States

- Any legal, regulatory, enforcement, tort, or other considerations (e.g., following distance, licensing, etc.) (Bomey & Zambito, 2017)

Interference Zones

- Tunnels, parking garages, dense foliage, limited GPS due to tall buildings, atmospheric conditions

Figure 16. Examples of Zones

ODD Identification for ADS Features

The ODD taxonomy lends itself to serving as a checklist for identifying the ODD of an ADS feature. A comprehensive ODD checklist was generated based on the ODD taxonomy described above. To demonstrate a potential application of the checklist, the checklist was filled out for three theoretical ADS features. The generic L3 Conditional Traffic Jam Drive, L3 Conditional

Highway Drive and L4 Highly Automated Vehicle/TNC features were selected. The results are presented in Appendix A. It should be noted that currently the manufacturer would determine the ODD for a feature, and the ODD may vary for similar ADS features. The theoretical features presented here are purely demonstrative, not representative of any commercially marketed ADS feature. An excerpt of the checklist for L3 Conditional Traffic Jam Drive is shown in Table 11, with the other ODD categories presented in the Appendix. Additional supporting material is provided in Appendix A.

Table 11. Extract from ODD Checklist Defined for a Generic L3 Conditional Automated Traffic Jam Drive Feature

<table>
<tr><th colspan="2">ODD CHECKLIST: L3 Conditional Traffic Jam Drive</th></tr>
<tr><th colspan="2">PHYSICAL INFRASTRUCTURE</th></tr>
<tr><td colspan="2">Roadway Types</td></tr>
<tr><td>Divided highway</td><td>Y</td></tr>
<tr><td>Undivided highway</td><td rowspan="5">N</td></tr>
<tr><td>Arterial</td></tr>
<tr><td>Urban</td></tr>
<tr><td>Rural</td></tr>
<tr><td>Parking (surface lots, structures, private/public)</td></tr>
<tr><td>Managed lanes (HOV, HOT, etc.)</td><td>Y</td></tr>
<tr><td>On-off ramps</td><td rowspan="2">N</td></tr>
<tr><td>Emergency evacuation routes</td></tr>
<tr><td>Intersections</td><td>N</td></tr>
<tr><td colspan="2">Roadway Surfaces</td></tr>
<tr><td>Asphalt</td><td rowspan="2">Y</td></tr>
<tr><td>Concrete</td></tr>
<tr><td colspan="2">Roadway Edges & Markings</td></tr>
<tr><td>Lane markers</td><td>Must be clear</td></tr>
<tr><td>Temporary lane markers</td><td>N</td></tr>
<tr><td>Shoulder (paved or gravel)</td><td>Limited to divided highway</td></tr>
<tr><td>Shoulder (grass)</td><td>Limited to divided highway</td></tr>
<tr><td>Lane barriers</td><td>Barrier, concrete or metal</td></tr>
<tr><td>Rails</td><td>Barrier, concrete or metal</td></tr>
<tr><th colspan="2">OPERATION CONSTRAINTS</th></tr>
<tr><td colspan="2">Speed Limits</td></tr>
<tr><td>Minimum speed limit</td><td>0 mph</td></tr>
<tr><td>Maximum speed limit</td><td>< 37 mph</td></tr>
<tr><td colspan="2">Traffic Conditions</td></tr>
<tr><td>Traffic density</td><td>Only heavy traffic with preceding vehicle to follow and convoy in adjacent lane</td></tr>
</table>

SUMMARY

The ODD defines when and where a vehicle is designed to function. This chapter reviewed the ODD literature, developed an ODD taxonomy, as reconciled with the OEM's current definitions, and identified ODDs for ADS features. The ODD framework presented here lays the foundation for Chapter 4 (OEDR) and Chapter 5 (Scenarios).

To test a vehicle's ability to operate safely, ODD is considered in test development and execution. Scenarios consider a combination of ODD elements that can be used to describe conditions for test cases and scenarios; for example, a highway with a concrete surface with a light mist. Test facilities are limited in their ability to re-create certain ODDs (e.g., urban environments, hill crests) and may need to be upgraded with new infrastructure to support testing. Some ODD elements are difficult to quantify and re-create (e.g., weather), and may be addressed through functional safety design practices and on-road testing. Other examples of ODDs are shown in Figure 17. A figure showing the significance of ODD relative to levels of driving automation from SAE J3016 is reproduced in Figure 18.

Figure 17. Other Examples of ODD

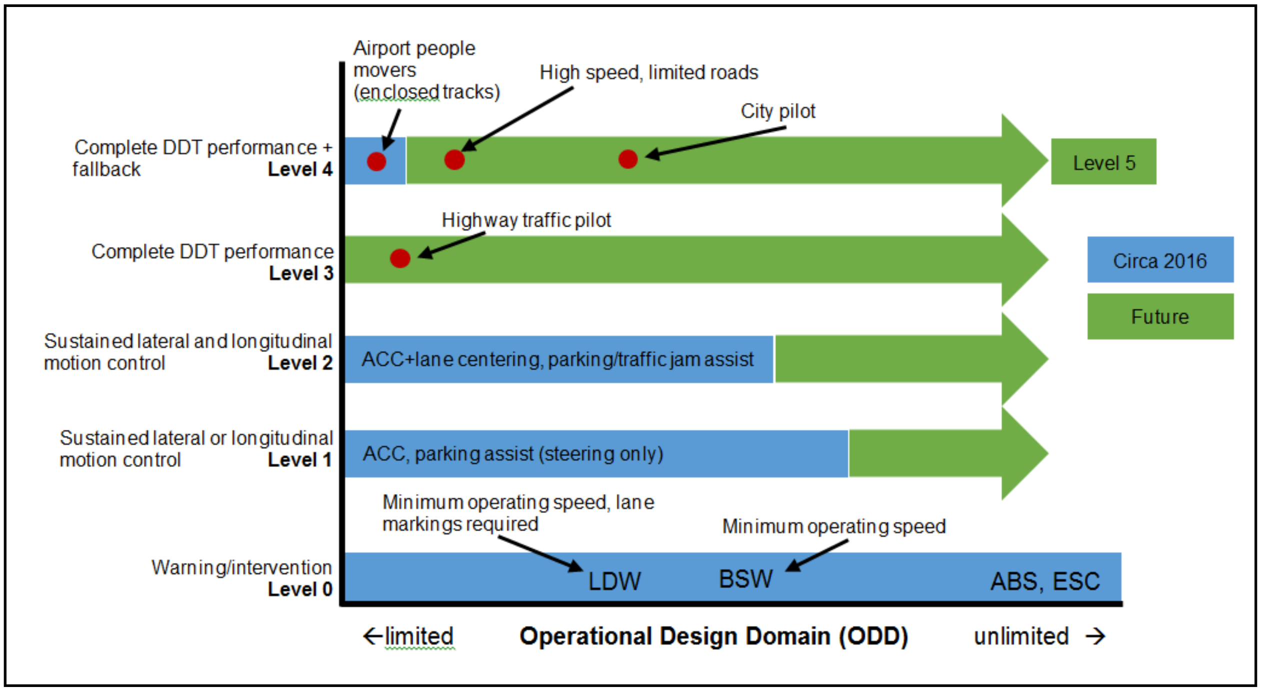

Figure 18. Illustrates the Significance of ODD Relative to the Levels of Driving Automation (SAE International, 2016)

There are several aspects to consider to expand upon the defined ODD characteristics. Comparisons with other ODD characterizations and working with OEMs to develop a consensus for definitions could improve the robustness of this taxonomy. Further investigation of ODD boundary conditions, and how ADS can detect these boundaries will be important to understanding disengagement events. For example, a minimal risk maneuver might differ based on on-board sensor configuration and availability of shoulders. Further, potential events like a leaf obstructing a sensor or bird excrement on a windshield obstructing line of sight when the driver is involved in part of the driving task need to be taken into account. There is thus a need to consider a more exhaustive list and potential classifiers for MRCs and other non-roadway users. Automation experts in both automotive and aviation industries have cautioned that the differences in ODD between automobiles and airplanes are so significant that the cross-learning opportunities are quite limited. Finally, monitoring the reports from the PEGASUS project in Europe is suggested.

CHAPTER 4. OBJECT AND EVENT DETECTION AND RESPONSE CAPABILITIES

OVERVIEW

This chapter describes the identification of OEDR capabilities that enable ADS to function safely within their prescribed operational ODD. OEDR refers to "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 International, 2016). OEDR capabilities will play a key role in developing sample tests for ADS.

Tactical maneuver behaviors were identified in Chapter 2 for conceptual ADS features. These behaviors largely focus on the elements of the DDT related to real-time functions specified in SAE J3016 (SAE International, 2016). These behaviors notionally represent the control-related tasks that are used as the ADS navigates to reach its prescribed destination. While performing these tactical maneuver behaviors, ADS will inevitably interact with a variety of static and dynamic physical objects that may alter how these behaviors are executed. SAE J3016 identifies the following real-time functions as elements of the DDT related to addressing these interactions with objects.

- Object and event detection, recognition, and classification
- Object and event response

These functions can be generalized under the term OEDR. OEDR represents the ability of the ADS feature to detect any circumstance that is immediately relevant to the driving task and implement an appropriate response. One of the factors that determines the level of driving automation of an ADS is whether the human driver or ADS is responsible for monitoring the driving environment. ADS, which are the focus of this report, range from SAE International L3 through L5, which means that the ADS feature is completing all aspects of monitoring the driving environment.

The elements of the ADS functional architecture shown in Figure 3 that are specifically relevant to OEDR generally include hardware and software components that support the following.

- Sensing (e.g., radar, laser scanners, cameras, etc.)
- Perception (e.g., road feature classification, object segmentation and classification, etc.)
- World modeling (e.g., persistent data mapping, dynamic obstacle tracking, and prediction, etc.)
- Navigation and planning (e.g., path planning and motion control commands to implement responses)

The sensing and perception elements of the architecture specifically support detection of relevant objects. World modeling supports the aggregation of perception and other information to identify and understand events that may occur through interactions with those objects. Navigation and planning supports determination of the appropriate response to those events and interactions, and the generation of control commands to implement that response.

APPROACH

Three of the generic ADS features identified in Chapter 2 were selected for this OEDR analysis. This allowed for an evaluation of a cross-section of operating environments and conditions, as well as driving scenarios. The three features selected were the following.

- L3 Conditional Automated Traffic Jam Drive
- L3 Conditional Automated Highway Drive
- L4 Highly Automated Vehicle/TNC

These features were selected to provide a cross-sectional representation of the wide variety of ODDs presented in Chapter 3. The L3 Conditional Automated Traffic Jam Drive feature can generally be expected to function in low-speed, stop-and-go traffic in areas where traffic jams are common (e.g., highways, urban roads). The L3 Conditional Automated Highway Drive feature can generally be expected to function on higher speed roads (e.g., highways, limited access freeways) with typical levels of traffic. The L4 Highly Automated Vehicle/TNC feature can generally be expected to function in denser urban areas at low to moderate speeds and be exposed to a wide variety of interactions with other vehicles and vulnerable road users. These features were also selected based on their expected timeline for availability to the public. The two L3 features were considered near-term ADS that will likely become available in the next few years. The L4 feature was considered a mid-term ADS, albeit one that is currently the subject of significant research.

Using these selected conceptual ADS features from Chapter 2 and the notional ODDs identified in Chapter 3 and expanded upon in Chapter 7.Appendix A for the selected features, this chapter will review the process undertaken to identify notional capabilities for OEDR for ADS. This process can be broken down into the following steps.

- Review the literature to evaluate and leverage prior research.
- Identify notional operational descriptions for features.
- Perform analysis to identify baseline ODDs.
- Perform driving scenario analysis.
- Perform analysis to identify OEDR behaviors and corresponding responses.

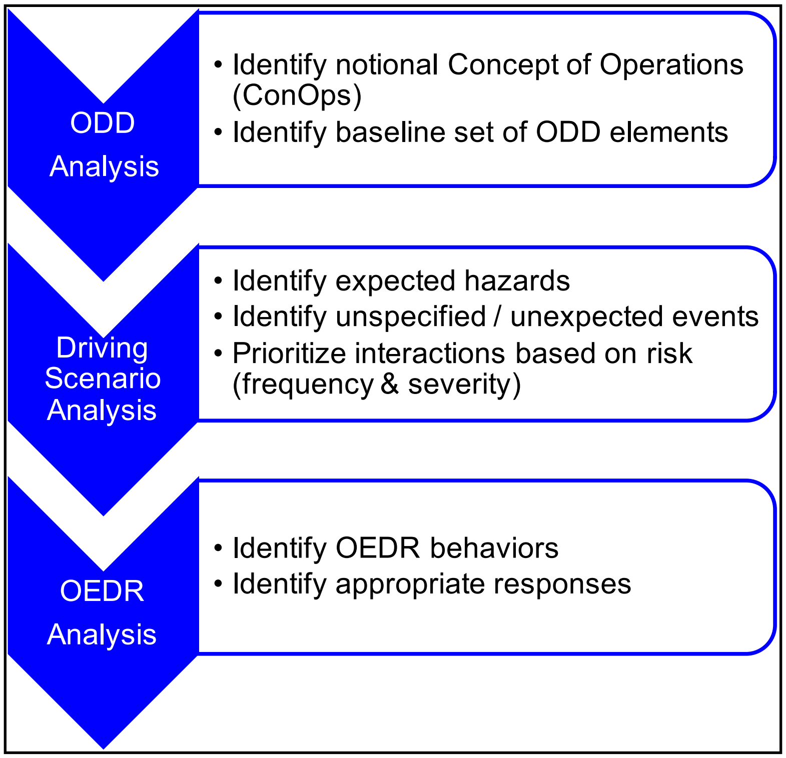

Figure 19. OEDR Capability Identification Process

The development of a notional, representative ConOps supported the identification of normal driving scenarios for each ADS feature. The operations descriptions explain the intended use of each feature and the circumstances in which it may be used. The operations descriptions are launching points for identifying the operational needs of each feature, including its OEDR capabilities.

Following the evaluation of the operational needs of the selected ADS features, a focusing exercise established baseline ODDs for each feature to further refine the analysis to identify OEDR capabilities for the three selected features. This exercise served to frame the OEDR analysis to account for the potential variability of certain ODD elements, as well as the substantial number of combinations and permutations of ODD elements. It is reasonable to expect that different organizations developing similar ADS features will generate unique designs and implementations, and thus will ultimately define different ODDs for their respective systems. For example, Vendor A designs and develops an L3 Traffic Jam Drive feature that can only operate on limited access highways where there are no pedestrians or pedalcyclists; while Vendor B designs an L3 Traffic Jam Drive feature with similar control capabilities but that also works on arterials and urban streets where pedestrians and pedalcyclists may be present. Similarly, there can be great diversity of abilities within specific categories of the ODD. For example, Vendor A's Traffic Jam Drive feature may be capable of operating only in light rain, while Vendor B's Traffic Jam Drive feature can operate in both light and heavy rain (light and heavy rain are treated purely qualitatively for the purposes of this example). A well-defined ODD helps to determine the OEDR capabilities that may be necessary and, as such, these baseline ODDs delineate the attributes of the ODD for each selected feature for the purposes of identifying OEDR capabilities. It should also be noted again that the developing OEMs and entities ultimately define the ODD for their respective features and, as such, these baseline ODDs are intended to be notional and descriptive, rather than normative. The baseline ODDs also serve to support the development of sample test scenarios and procedures described in Chapter 5.

With the ODD baselines established for each feature, a survey and analysis of the driving scenarios that fall out of the operations descriptions led to the identification of relevant objects and interactions that the ADS could encounter. These objects and events are derived from an evaluation of normal driving scenarios for a given ADS feature operating in its ODD, including:

- Expected hazards (e.g., vehicles, pedestrians, etc.);
- Unspecified/unexpected events (e.g., construction zones, emergency vehicles, etc.); and
- Key infrastructure elements (e.g., traffic signs and signals, road markings, etc.).

Prior work conducted by California PATH to define behavioral competencies (Nowakowski, Shladover, Chan, & Tan, 2015) informed this evaluation of driving scenarios. Table 12 reproduces a working list of critical driving maneuvers identified by PATH across a variety of driving environments. The driving environments correspond to certain attributes of the ODD at a high level. This list produced by PATH served as a starting point that was extended and refined based on the hierarchical ODD taxonomy developed in Chapter 3.

Table 12. California PATH Minimum Behavioral Competencies (Nowakowski, Shladover, Chan, & Tan, 2015)

Critical Driving Maneuvers	Freeway	Rural Highway	City Streets	Valet Parking	Low-Speed Shuttles
Detect System Engagement/Disengagement Conditions Including Limitations by Location, Operating Condition, or Component Malfunction	✓	✓	✓	✓	✓
Detect & Respond to Speed Limit Changes (Including Advisory Speed Zones)	✓	✓	✓		✓
Detect Passing and No Passing Zones					
Detect Work Zones, Temporary Lane Shifts, or Safety Officials Manually Directing Traffic	✓	✓	✓		
Detect and Respond to Traffic Control Devices		✓	✓		
Detect and Respond to Access Restrictions such as One-Way Streets, No-Turn Locations, Bicycle Lanes, Transit Lanes, and Pedestrian Ways			✓	✓	✓

Critical Driving Maneuvers	Freeway	Rural Highway	City Streets	Valet Parking	Low-Speed Shuttles
Perform High Speed Freeway Merge					
Perform a Lane Change or Lower Speed Merge			✓		
Park on the Shoulder or Transition the Vehicle to a Minimal Risk State (Not Required for SAE L3)					
Navigate Intersections & Perform Turns			✓		✓
Navigate a Parking Lot & Locate Open Spaces				✓	
Perform Car Following Including Stop & Go and Emergency Braking	✓	✓	✓	✓	
Detect & Respond to Stopped Vehicles	✓	✓	✓	✓	✓
Detect & Respond to Intended Lane Changes/Cut-Ins	✓	✓	✓		
Detect & Respond to Encroaching Oncoming Vehicles		✓	✓	✓	
Detect & Respond to Static Obstacles in Roadway	✓	✓	✓	✓	✓
Detect & Respond to Bicycles, Pedestrians, Animals, or Other Moving Objects		✓	✓	✓	✓
Detect Emergency Vehicles	✓	✓	✓		

Next, the evaluation of driving scenarios estimated the risk associated with the various objects and events. This risk analysis helps to prioritize scenarios for testing and evaluation. Risk is qualitatively estimated by considering the likelihood of an event or interaction occurring, and the resulting severity of the ADS incorrectly responding to the interaction (e.g., a response that results in a collision with the object). This analysis also used NHTSA pre-crash data for prioritizing scenarios. The prioritization was based on frequency of occurrence and severity (number resulting in injuries or fatalities) (Najm, Smith, & Yanagisawa, 2007). Table 13 shows pre-crash data for two-vehicle light-vehicle crashes involving manually driven vehicles. Following the development of the working list of tactical maneuver behaviors in Chapter 2, the list of objects and events was refined into a working list of OEDR behaviors that notionally represent a set of testable perception-related scenarios.

Control actions were then identified to support safe responses to the identified combinations of objects and events. These actions are seated in the tactical maneuver behaviors identified in Chapter 2 and PATH behavioral competencies reproduced in Table 12 above. The control action options are further informed by a task decomposition exercise. This decomposition, in some cases, breaks the behaviors down into their more specific control-related actions. The National

Institute of Standards and Technology 4D/RCS Reference Model Architecture for Unmanned Vehicle Systems was leveraged (Barbera, Horst, Schlenoff, & Aha, 2004) for this analysis.

Table 13. Pre-Crash Scenarios of Two-Vehicle Light-Vehicle Crashes (Najm, Smith, & Yanagisawa, 2007)

No.	Scenario	Frequency	Rel. Freq.
1	Lead Vehicle Stopped	792,000	20.46%
2	Vehicles Turning at Non-Signalized Junctions	419,000	10.83%
3	Lead Vehicle Decelerating	347,000	8.96%
4	Vehicles Changing Lanes - Same Direction	295,000	7.62%
5	Straight Crossing Paths at Non-Signalized Junctions	252,000	6.52%
6	Running Red Light	233,000	6.02%
7	Vehicles Turning - Same Direction	220,000	5.68%
8	LTAP/OD[4] at Signalized Junctions	205,000	5.29%
9	Lead Vehicle Moving at Lower Constant Speed	186,000	4.82%
10	LTAP/OD at Non-Signalized Junctions	181,000	4.68%
11	Backing Up Into Another Vehicle	131,000	3.38%
12	Vehicles Not Making a Maneuver - Opposite Direction	94,000	2.43%
13	Vehicles Drifting - Same Direction	91,000	2.35%
14	Following Vehicle Making a Maneuver	74,000	1.92%
15	Control Loss Without Prior Vehicle Action	52,000	1.33%
16	Vehicles Parking - Same Direction	47,000	1.21%
17	Running Stop Sign	43,000	1.12%
18	Evasive Action Without Prior Vehicle Maneuver	37,000	0.95%
19	Vehicle Turning Right at Signalized Junctions	34,000	0.89%
20	Control Loss With Prior Vehicle Action	26,000	0.68%
21	Non-Collision Incident	25,000	0.64%
22	Lead Vehicle Accelerating	16,000	0.41%
23	Vehicles Making a Maneuver - Opposite Direction	13,000	0.33%
24	Evasive Action With Prior Vehicle Maneuver	8,000	0.21%
25	Vehicle Failure	8,000	0.20%
26	Animal Crash Without Prior Vehicle Maneuver	6,000	0.14%
27	Road Edge Departure Without Prior Vehicle Maneuver	3,000	0.08%
28	Pedestrian Crash Without Prior Vehicle Maneuver	2,000	0.05%
29	Road Edge Departure With Prior Vehicle Maneuver	2,000	0.04%
30	Pedestrian Crash With Prior Vehicle Maneuver	1,000	0.02%
31	Pedalcyclist Crash Without Prior Vehicle Maneuver	1,000	0.02%
32	Other	28,000	0.73%

[4] *Left Turn Across Path/Opposite Direction

FINDINGS

Baseline ODDs

The ODD checklists referenced in Chapter 3 and the samples presented in Appendix A notionally represent the ODDs for ADS features based on available data. The baseline ODDs are similarly summarized here for the selected ADS features.

L3 Conditional Automated Traffic Jam Drive Feature

For the L3 Conditional Automated Traffic Jam Drive feature, a notional operational use case of a driver on a limited-access highway or urban arterial road encountering slow, stop-and-go traffic that is expected to persist for a period of time was considered. As described in Chapter 2, this feature implements lateral and longitudinal control to maintain the current lane of travel and a safe following distance behind an immediate lead vehicle. This will likely rely on a combination of cameras for lane tracking and radar for lead vehicle ranging.

Table 14. L3 TJD Baseline ODD – Physical Infrastructure

ODD Elements	Examples
Roadway Types	Interstates, freeways, divided highways undivided highways, arterials, urban, bridges, multi-lane, single-lane, one-way, tunnels
Roadway Surfaces	Asphalt, concrete, mixed
Roadway Edges and Markings	Lane markers, temporary lane markers, concrete barriers, curbs, cones
Roadway Geometry	Straight, curves, hills

Table 15. L3 TJD Baseline ODD – Operational Constraints

ODD Elements	Examples
Minimum Speed Limit	0 kph (0 mph)
Maximum Speed Limit	59 kph (37 mph) (notionally)
Traffic Density	Immediate lead vehicle

Table 16. L3 TJD Baseline ODD – Environmental Conditions

ODD Elements	Examples
Weather	Clear, calm
Weather-induced Roadway Conditions	Dry
Illumination	Day, dawn/dusk

Table 17. L3 TJD Baseline ODD - Connectivity

ODD Elements	Examples
Digital Infrastructure	Optional to determine if inside or outside of zone (e.g., geofence, infrastructure zone)

Table 18. L3 TJD Baseline ODD - Zones

ODD Elements	Examples
Regions/States	Adhere to State/local laws
School/Construction	Construction zones

L3 Conditional Automated Highway Drive Feature

For the L3 Conditional Automated Highway Drive feature, a notional use case of a driver on a limited access highway encountering nominal, free-flow traffic conditions allowing for high-speed driving was considered. The feature implements lateral and longitudinal control to maintain the current lane of travel, achieve the specified speed, and if necessary alter that speed to follow an immediate lead vehicle at a safe following distance. This feature may also implement automatic lane changing, potentially initiated by the occupant activating a turn signal or automatically to maintain the target speed if it is safe and prudent to do so.

Table 19. L3 HWD Baseline ODD – Physical Infrastructure

ODD Elements	Examples
Roadway Types	Interstates, freeways, divided highways undivided highways, arterials, urban, bridges, multi-lane, single-lane, one-way, tunnels
Roadway Surfaces	Asphalt, concrete, mixed
Roadway Edges and Markings	Lane markers, temporary lane markers, concrete barriers, curbs, cones
Roadway Geometry	Straight, curves, hills

Table 20. L3 HWD Baseline ODD – Operational Constraints

ODD Elements	Examples
Minimum Speed Limit	72 kph (45 mph) (notionally)
Maximum Speed Limit	112 kph (70 mph) (notionally)
Traffic Density	Minimal, normal

Table 21. L3 HWD Baseline ODD – Environmental Conditions

ODD Elements	Examples
Weather	Clear, calm
Weather-induced Roadway Conditions	Dry
Illumination	Day, dawn/dusk

Table 22. L3 HWD Baseline ODD - Connectivity

ODD Elements	Examples
Digital Infrastructure	Optional to determine if inside or outside of zone

Table 23. L3 HWD Baseline ODD - Zones

ODD Elements	Examples
Regions/States	Adhere to State/local laws
School/Construction	Construction zones
Interference	Urban canyons

L4 Highly Automated Vehicle/TNC Feature

For the L4 Highly Automated Vehicle/TNC feature, a use case of an unmanned TNC vehicle being hailed by a passenger in a dense urban area was considered.

Table 24. L4 HAV/TNC Baseline ODD – Physical Infrastructure

ODD Elements	Examples
Roadway Types	Arterials, urban, bridges, multi-lane, single-lane, one-way, turn-only, rail crossings, bridges, bicycle lanes, crosswalks, tunnels
Roadway Surfaces	Asphalt, concrete, mixed
Roadway Edges and Markings	Lane markers, temporary lane markers, concrete barriers, curbs, cones
Roadway Geometry	Straight, curves, hills, varying lane widths

Table 25. L4 HAV/TNC Baseline ODD – Operational Constraints

ODD Elements	Examples
Minimum Speed Limit	0 kph (0 mph)
Maximum Speed Limit	72 kph (45 mph) (notionally)
Traffic Density	Minimal, normal, heavy

Table 26. L4 HAV/TNC Baseline ODD – Environmental Conditions

ODD Elements	Examples
Weather	Clear, calm
Weather-induced Roadway Conditions	Dry
Illumination	Day, dawn/dusk

Table 27. L4 HAV/TNC Baseline ODD - Connectivity

ODD Elements	Examples
Digital Infrastructure	Optional digital map, optional GPS

Table 28. L4 HAV/TNC Baseline ODD - Zones

ODD Elements	Examples
Geofencing	CBDs, school campuses, communities, fixed routes
Traffic Management Zones	Temporary road/lane closures, dynamic traffic signs, human-directed traffic, loading/unloading zones, temporary lane markers
Regions/States	Adhere to State/local laws
School/Construction	School/construction zones
Interference	Urban canyons, tunnels, foliage

Baseline OEDR Behaviors

The developed baseline ODDs were used to identify important objects and events that ADS could feasibly encounter within those ODDs. Those relevant objects and events are presented for the selected ADS features. The events of interest are based on some manner of interaction between the subject ADS and an identified object. Figure 20 shows a notional depiction of how some events were categorized in the vicinity immediately around the ADS. Interactions with obstacles were indicated as occurring in a frontal, side, or rear zone. The tables presented below include a notional set of objects and events that an ADS could encounter in a baseline ODD. The events in bold type represent interactions that were used for test development in Chapter 5. Some of the events were considered lower priority for testing for safety assessment, as they did not fall within the immediate collision zone around the subject vehicle (SV). Potential maneuver and control actions that the ADS could implement in response to the objects and events were also identified.

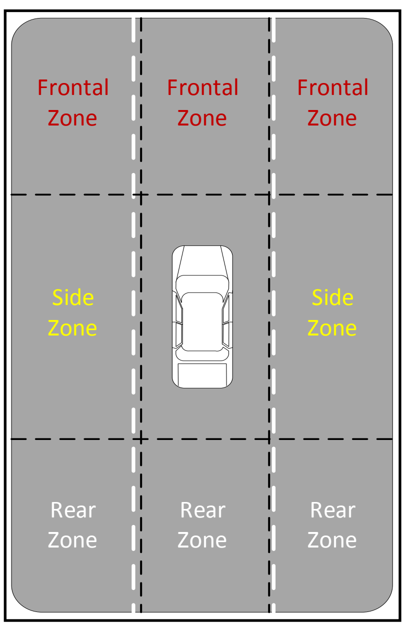

Figure 20. Notional Crash-Relevant Zones

L3 Conditional Automated Traffic Jam Drive Feature

Table 29. L3 TJD Summary of Roadway User Events

Objects	Events/Interactions
Vehicles (e.g., cars, light trucks, heavy trucks, buses, motorcycles)	**Lead vehicle decelerating (frontal), lead vehicle stopped (frontal), lead vehicle accelerating (frontal), changing lanes (frontal/side), cutting in (adjacent), turning (frontal), encroaching opposing vehicle (frontal/side), encroaching adjacent vehicle (frontal/side), entering roadway (frontal/side), cutting out (frontal)**
Pedestrians	**Crossing road – inside crosswalk (frontal), crossing road – outside crosswalk (frontal)**, walking on sidewalk/shoulder
Pedalcyclists	**Riding in lane (frontal)**, riding in adjacent lane (frontal/side), riding in dedicated lane (frontal/side), riding on sidewalk/shoulder, **crossing road – inside crosswalk (frontal/side), crossing road – outside crosswalk (frontal/side)**

Table 30. L3 TJD Summary of Non-Roadway User Events

Objects	Events/Interactions
Animals[5]	Static in lane (frontal), moving into/out of lane (frontal/side), static/moving in adjacent lane (frontal), static/moving on shoulder
Debris[6]	**Static in lane (frontal)**
Other dynamic objects (e.g., shopping carts)	**Static in lane (frontal/side)**, **moving into/out of lane (frontal/side)**

Table 31. L3 TJD Summary of Signs and Signals Events

Objects	Events/Interactions
Traffic signs[7]	Stop, yield, speed limit, crosswalk, railroad crossing, school zone
Traffic signals[7]	Intersection, railroad crossing, school zone
Vehicle signals	Turn signals

[5] Animals that may have safety impacts, such as causing physical damage to ADS or harm to its occupants (e.g., deer, moose)
[6] Debris that may have safety impacts, such as causing physical damage to ADS or harm to its occupants (e.g., large tires)
[7] Compliant with the *Manual on Uniform Traffic Control Devices*

Table 32. L3 TJD Summary of Other Objects of Interest

Objects	Events/Interactions
Emergency vehicles	Lights and sirens activated (frontal/side), passing on shoulder (side/rear), encroaching, driving wrong direction (frontal/side), violating precedence/right-of-way (frontal/side/rear)
School buses	Lights and signs activated (frontal), stopped in lane or adjacent lane (frontal/side), stopped in opposing/undivided lane (frontal/side)

L3 Conditional Automated Highway Drive Feature

Table 33. L3 HWD Summary of Roadway User Events

Objects	Events/Interactions
Vehicles (e.g., cars, light trucks, heavy trucks, buses, motorcycles)	**Lead vehicle decelerating (frontal), lead vehicle stopped (frontal), lead vehicle accelerating (frontal), changing lanes (frontal/side), cutting in (adjacent), turning (frontal), encroaching opposing vehicle (frontal/side), encroaching adjacent vehicle (frontal/side), entering roadway (frontal/side), cutting out (frontal)**
Pedestrians	**Crossing road (frontal)**, walking on shoulder
Pedalcyclists	Riding in lane (frontal), riding in adjacent lane (frontal/side), riding in dedicated lane (frontal/side), riding on shoulder, crossing road (frontal/side)

Table 34. L3 HWD Summary of Non-Roadway User Events

Objects	Events/Interactions
Animals[5]	**Static in lane (frontal)**, **moving into/out of lane (frontal/side)**, static/moving in adjacent lane (frontal), static/moving on shoulder
Debris[6]	**Static in lane (frontal)**
Other dynamic objects (e.g., shopping carts)	**Static in lane (frontal/side)**, **moving into/out of lane (frontal/side)**

Table 35. L3 HWD Summary of Signs and Signals Events

Objects	Events/Interactions
Traffic signs[7]	Stop, yield, **speed limit**, railroad crossing, school zone
Traffic signals[7]	Intersection (at grade), railroad crossing, school zone
Vehicle signals	Turn signals

Table 36. L3 HWD Summary of Other Objects of Interest

Objects	Events/Interactions
Emergency vehicles	Lights and sirens activated (frontal/side), passing on shoulder (side/rear), encroaching, driving wrong direction (frontal/side), violating precedence/right-of-way (frontal/side/rear)
School buses	Lights and signs activated (frontal), stopped in lane or adjacent lane (frontal/side), stopped in opposing/undivided lane (frontal/side)

L4 Highly Automated Vehicle/TNC Feature

Table 37. L4 HAV/TNC Summary of Roadway User Events

Objects	Events/Interactions
Vehicles (e.g., cars, light trucks, heavy trucks, buses, motorcycles)	**Lead vehicle decelerating (frontal), lead vehicle stopped (frontal), lead vehicle accelerating (frontal), changing lanes (frontal/side), cutting in (adjacent), turning (frontal), encroaching opposing vehicle (frontal/side), encroaching adjacent vehicle (frontal/side), parking (frontal/side), entering roadway (frontal/side), cutting out (frontal)**
Pedestrians	**Crossing road – inside crosswalk (frontal), crossing road – outside crosswalk (frontal)**, walking on sidewalk/shoulder
Pedalcyclists	**Riding in lane (frontal)**, **riding in adjacent lane (frontal/side)**, **riding in dedicated lane (frontal/side)**, riding on sidewalk/shoulder, **crossing road – inside crosswalk (frontal), crossing road – outside crosswalk (frontal)**

Table 38. L4 HAV/TNC Summary of Non-Roadway User Events

Non-roadway Users	
Animals[5]	**Static in lane (frontal)**, **moving into/out of lane (frontal/side)**, static/moving in adjacent lane (frontal), static/moving on shoulder
Debris[6]	**Static in lane (frontal)**
Other dynamic objects (e.g., shopping carts)	**Static in lane (frontal/side)**, **moving into/out of lane (frontal/side)**

Table 39. L4 HAV/TNC Summary of Signs and Signals Events

Signs and Signals	
Traffic signs[7]	**Stop, yield, speed limit, crosswalk, railroad crossing, school zone, access restriction (e.g., one-way), work zone**
Traffic signals[7]	**Intersection, railroad crossing, school zone**
Vehicle signals	Turn signals

Table 40. L4 HAV/TNC Summary of Other Objects and Events of Interest

Other Objects of Interest	
Emergency vehicles	**Lights and sirens activated (frontal/side/rear), passing on shoulder (side/rear), encroaching (frontal/side/rear), driving wrong direction (frontal/side/rear), violating precedence/right-of-way (frontal/side/rear)**
School buses	**Lights and signs activated (frontal/side), stopped in lane or adjacent lane (frontal/side), stopped in opposing/undivided lane (frontal/side)**
Other traffic control devices[7]	**Cones, barrels, safety officials (e.g., handheld signs, flags, or hand signals)**

Table 41 shows a summary of the objects and events highlighted in bold from the preceding tables, generalized into a working list of OEDR behavior capabilities. While not directly related to a specific object, operating outside of the defined ODD was also identified as an important event for OEDR, and is relevant to all of the selected features. These OEDR behaviors are intended to be a companion to the list of tactical maneuver behaviors identified and presented in Chapter 2. These OEDR behaviors provided the basis for the development of preliminary tests in Chapter 5. As previously mentioned, several other attempts have been made to develop similar sets of behaviors and conditions that are important, including the California PATH program behavioral competency analysis (Nowakowski, Shladover, Chan, & Tan, 2015) and NHTSA pre-crash scenario analysis (Najm, Smith, & Yanagisawa, 2007). Waymo also recently released a voluntary safety self-assessment that included a list of behavioral competencies above and beyond those included in the PATH analysis (Waymo, 2017b). A comparison of the behavior combined list of OEDR behaviors and tactical maneuver behaviors from Chapter 2 with those from the PATH, NHTSA, and Waymo analyses is provided in Appendix D.

Table 41. OEDR Behavior Capabilities

Detect & Respond to Speed Limit Changes	Detect & Respond to Relevant School Buses
Detect & Respond to Encroaching, Oncoming Vehicles	Detect & Respond to Relevant Emergency Vehicles
Perform Vehicle Following	Detect & Respond to Relevant Pedestrians
Detect & Respond to Relevant Stopped Vehicles	Detect & Respond to Relevant Pedalcyclists
Detect & Respond to Relevant Lane Changes/Cut-ins	Detect & Respond to Relevant Animals
Detect & Respond to Relevant Static Obstacles in Lane	Detect & Respond to Relevant Vehicle Cut-out/Reveal
Detect & Navigate Work Zones	Detect & Respond to Relevant Vehicle Roadway Entry
Detect & Respond to Relevant Safety Officials	Detect & Respond to Relevant Adjacent Vehicles
Detect & Respond to Relevant Access Restrictions	Detect & Respond to ODD Boundary Transition
Detect & Respond to Relevant Dynamic Traffic Signs	

The detection of objects and events may occur in multiple ways. ADS will likely employ a suite of perception sensors—potentially to include some combination of radar, lidar, cameras, and ultrasonic sensors—that can support detection and recognition of many of these objects and events. This path relies on supporting algorithms to parse and interpret the data provided by those sensors. V2V and V2I communications capability, via DSRC or other technology, can also support detection and recognition in some capacity. If available, SAE J2735 Basic Safety Messages include information on vehicle position, speed, and heading that could supplement or augment measurements taken by an ADS's onboard perception sensors. Other data, such as intersection signal, phase, and timing data could be broadcast through digital infrastructure to provide information on the state of a traffic signal. Furthermore, many prototype ADS under development rely on onboard, high-fidelity digital maps that have been collected and optimized *a priori*. These maps may include three-dimensional information about static objects and infrastructure, including the roadway itself. Maps may also include important navigation metadata, such as the number of lanes on a road segment and other important lane characteristics (e.g., directionality, left turn, bus-only), speed limits, and presence of traffic control devices or markings (e.g., stop signs, traffic signals, crosswalks). This map information can similarly be used to supplement or augment an ADS's onboard sensor data (or vice versa) or could be used independently to support the detection of certain objects and events. No assumptions regarding the mechanism for implementing detection were made when compiling the list of objects and events.

Assuming an ADS has correctly detected a safety-critical object or event, it then implements an appropriate response. The response will ideally be a stable control action or maneuver that allows the ADS to maintain a safe avoidance distance from all relevant obstacles in the immediate crash vicinity, and that continues to follow the applicable rules and etiquette of the road, to the best extent possible. The identified responses that notionally fit these criteria include:

- Follow Vehicle – Implement lateral and/or longitudinal control actions to maintain a safe[8] following distance from an immediate lead vehicle, while continuing to follow the current lane of travel.
- Accelerate – Implement longitudinal control actions to increase speed, as appropriate and lawful.
- Decelerate – Implement longitudinal control actions to decrease speed, as appropriate.
- Stop – Implement longitudinal control actions to decelerate in a safe and stable manner to a complete stop.
- Yield – Relinquish right-of-way to another road user.
- Change Lane – Implement longitudinal and/or lateral control actions to shift into an adjacent lane.
    - Abort Lane Change – Cancel the maneuver to shift into an adjacent lane (remain in or return to original lane).
- Pass – Implement longitudinal and/or lateral control actions to shift into an adjacent lane to accelerate to desired speed.
    - Abort Pass – Cancel maneuver to shift into an adjacent lane (remain in or return to original lane).
- Turn – Implement lateral and longitudinal control actions to transition from current road/lane to connecting road/lane.
- Shift Within Lane – Implement lateral and/or longitudinal control actions such that the ADS does not follow the center (or near-center) of the current lane but remains fully within the current lane.
- Shift Outside of Lane – Implement lateral and/or longitudinal control actions such that the ADS partially or fully moves outside of the current lane of travel (i.e., one or more wheels cross the lane boundary).
- Move Out of Travel Lane/Park – Implement lateral and longitudinal control actions such that the ADS fully exits the current active lane of travel onto a shoulder or parking lane and stops.
- Transition to MRC:
    - Return Control to Fallback-ready User – Return longitudinal and lateral control to human occupant/driver (while providing sufficient warning).
    - ADS Implements Minimal Risk Maneuver – Implement lateral and/or longitudinal control actions to achieve a minimal risk condition (see Chapter 6).

These control actions and maneuvers represent a variety of options for an ADS to respond to objects and events of interest. Table 42 through Table 53 show mappings of these responses to the objects and events identified in Table 29 through Table 40. Again, these mappings are intended to be notional rather than normative. It should also be noted again that, as an ADS's ODD will be specified by the OEM or developer, some of these objects and events may fall outside the final ODD. These cases may be captured by the event representing operation outside of the ODD, for which the appropriate response may likely be to transition to an MRC.

[8] Could be defined by State or local regulations, but notionally should ensure vehicle can decelerate safely to avoid a collision.

L3 Conditional Automated Traffic Jam Drive Feature

Table 42. L3 TJD Response Mapping - Roadway Users

Event	Response
Lead vehicle decelerating	Follow vehicle, decelerate, stop
Lead vehicle stopped	Decelerate, stop
Lead vehicle accelerating	Accelerate, follow vehicle
Lead vehicle turning	Decelerate, stop
Vehicle changing lanes	Yield, decelerate, follow vehicle
Vehicle cutting in	Yield, decelerate, stop, follow vehicle
Vehicle entering roadway	Follow vehicle, decelerate, stop
Opposing vehicle encroaching	Decelerate, stop, shift within lane, shift outside of lane
Adjacent vehicle encroaching	Yield, decelerate, stop
Lead vehicle cutting out	Accelerate, decelerate, stop
Pedestrian crossing road – inside crosswalk	Yield, decelerate, stop
Pedestrian crossing road – outside of crosswalk	Yield, decelerate, stop
Pedalcyclist riding in lane	Yield, follow
Pedalcyclist riding in dedicated lane	Shift within lane[9]
Pedalcyclist crossing road – inside crosswalk	Yield, decelerate, stop
Pedalcyclist crossing road – outside crosswalk	Yield, decelerate, stop
Lead vehicle decelerating	Follow vehicle, decelerate, stop
Lead vehicle stopped	Decelerate, stop
Lead vehicle accelerating	Accelerate, follow vehicle

Table 43. L3 TJD Response Mapping - Non-Roadway Users

Event	Response
Debris static in lane	Decelerate, stop
Dynamic object in lane	Decelerate, stop
Dynamic object moving into/out of lane	Decelerate, stop

Table 44. L3 TJD Response Mapping - Other Events of Interest

Event	Response
Operating outside of ODD	Transition to MRC (fallback-ready user)

[9] Could be informed by State or local regulations.

L3 Conditional Automated Highway Drive Feature

Table 45. L3 HWD Response Mapping - Roadway Users

Event	Response
Lead vehicle decelerating	Follow vehicle, decelerate, stop, change lane, pass
Lead vehicle stopped	Decelerate, stop, change lane, pass
Lead vehicle accelerating	Accelerate, follow vehicle
Lead vehicle turning	Decelerate, stop, change lane, pass
Vehicle changing lanes	Yield, decelerate, follow vehicle
Vehicle cutting in	Yield, decelerate, stop, follow vehicle, change lane
Vehicle entering roadway	Follow vehicle, decelerate, stop, change lane, pass
Opposing vehicle encroaching	Decelerate, stop, shift within lane, shift outside of lane, change lane
Adjacent vehicle encroaching	Yield, decelerate, stop, shift within lane, shift outside of lane, change lane
Lead vehicle cutting out	Accelerate, decelerate, stop
Pedestrian crossing road – inside crosswalk	Yield, decelerate, stop
Pedestrian crossing road – outside of crosswalk	Yield, decelerate, stop
Pedalcyclist riding in lane	Yield, follow, change lane, pass
Pedalcyclist riding in dedicated lane	Shift within lane[10], change lane
Pedalcyclist crossing road – inside crosswalk	Yield, decelerate, stop
Pedalcyclist crossing road – outside crosswalk	Yield, decelerate, stop

Table 46. L3 HWD Response Mapping - Non-Roadway Users

Event	Response
Animal static in lane	Decelerate, stop, change lane, pass, shift within lane, shift outside of lane
Animal moving into/out of lane	Decelerate, stop, change lane, pass, shift within lane, shift outside of lane
Debris static in lane	Decelerate, stop, change lane, pass, shift within lane, shift outside of lane
Dynamic object in lane	Decelerate, stop, change lane, pass, shift within lane, shift outside of lane
Dynamic object moving into/out of lane	Decelerate, stop, change lane, pass, shift within lane, shift outside of lane

Table 47. L3 HWD Response Mapping - Signs and Signals

Event	Response
Speed limit change	Accelerate, decelerate

[10] Could be informed by State or local regulations.

Table 48. L3 HWD Response Mapping - Other Events of Interest

Event	Response
Operating outside of ODD	Transition to MRC (fallback-ready user)

L4 Highly Automated Vehicle/TNC Feature

Table 49. L4 HAV/TNC Response Mapping - Roadway Users

Event	Response
Lead vehicle decelerating	Follow vehicle, decelerate, stop, change lane, pass
Lead vehicle stopped	Decelerate, stop, change lane, pass
Lead vehicle accelerating	Accelerate, follow vehicle
Lead vehicle turning	Decelerate, stop, change lane, pass
Vehicle changing lanes	Yield, decelerate, follow vehicle
Vehicle cutting in	Yield, decelerate, stop, follow vehicle, change lane
Vehicle entering roadway	Yield, decelerate, stop, change lane, pass
Vehicle cutting out	Accelerate, decelerate, stop, change lane, pass
Opposing vehicle encroaching	Decelerate, stop, shift within lane, shift outside of lane, change lane
Adjacent vehicle encroaching	Yield, decelerate, stop, shift within lane, shift outside of lane, change lane
Lead vehicle cutting out	Accelerate, decelerate, stop
Lead vehicle parking	Decelerate, stop, change lane, pass
Pedestrian crossing road – inside crosswalk	Yield, decelerate, stop
Pedestrian crossing road – outside of crosswalk	Yield, decelerate, stop
Pedalcyclist riding in lane	Yield, follow, change lane, pass
Pedalcyclist riding in adjacent lane	Yield, shift within lane
Pedalcyclist riding in dedicated lane	Shift within lane[11], change lane
Pedalcyclist crossing road – inside crosswalk	Yield, decelerate, stop
Pedalcyclist crossing road – outside crosswalk	Yield, decelerate, stop

Table 50. L4 HAV/TNC Response Mapping - Non-Roadway Users

Event	Response
Animal static in lane	Decelerate, stop, change lane, pass, shift within lane, shift outside of lane
Animal moving into/out of lane	Decelerate, stop, change lane, pass, shift within lane, shift outside of lane
Debris static in lane	Decelerate, stop, change lane, pass, shift within lane, shift outside of lane
Dynamic object in lane	Decelerate, stop, change lane, pass, shift within lane, shift outside of lane
Dynamic object moving into/out of lane	Decelerate, stop, change lane, pass, shift within lane, shift outside of lane

[11] Could be informed by State or local regulations.

Table 51. L4 HAV/TNC Response Mapping - Signs and Signals

Event	Response
Stop sign	Decelerate, stop
Yield sign	Decelerate, yield, stop
Speed limit sign	Accelerate, decelerate
Crosswalk sign	Decelerate, yield, stop
Railroad crossing	Decelerate, yield, stop
School zone	Decelerate, yield, stop
Access restriction	Stop, turn, change lane, transition to MRC (ADS), move out of travel lane/park
Work zone	Decelerate, yield, change lane, shift within lane, shift outside of lane
Intersection signals	Decelerate, stop, accelerate, yield, turn
Railroad crossing signal	Decelerate, stop
School zone signal	Decelerate, yield, stop

Table 52. L4 HAV/TNC Response Mapping - Other Objects of Interest

Event	Response
Emergency vehicle (active) static	Decelerate, yield, stop, change lane, pass, shift within lane, shift outside of lane
Emergency vehicle (active) passing	Decelerate, yield, stop, change lane, shift within lane, shift outside of lane
Emergency vehicle (active) encroaching	Decelerate, yield, stop, change lane, shift within lane, shift outside of lane
Emergency vehicle (active) driving wrong direction	Decelerate, yield, stop, change lane, shift within lane, shift outside of lane
Emergency vehicle (active) violating precedence	Decelerate, yield, stop
School bus (active) stopped in lane	Yield, stop
School bus (active) stopped in adjacent lane	Yield, stop
School bus stopped in opposing/undivided lane	Yield, stop
Other traffic control devices	Dependent on scenario configuration[12]

Table 53. L4 HAV/TNC Response Mapping for Other Events of Interest

Event	Response
Operating outside of ODD	Transition to MRC (fallback-ready user or ADS)

SUMMARY

This chapter identified a set of baseline ODDs for the selected ADS features to frame the analysis of driving scenarios and the identification of OEDR capabilities. Relevant objects and events that an ADS could reasonably be expected to encounter within its ODD were then

[12] Any of the listed responses could be appropriate for temporary or alternative traffic control devices (e.g., hand signals, flags), depending on the situation and context.

identified. These objects and events were generalized into a set of 19 OEDR-related behaviors for further evaluation. A number of the potential control-related actions an ADS could implement in response to the objects and events were also identified. The responses were then mapped to the identified key objects and interactions. While ADS features brought to market may inevitably have specified ODDs that differ from the baselines, the OEDR capabilities identified using these baselines capture a significant cross-section of potential OEDR-related behaviors. The baseline ODDs and OEDR capabilities will serve to inform and drive the construction of a flexible testing framework, and specific tests that can be performed within that framework in Chapter 5.

CHAPTER 5. PRELIMINARY TESTS AND EVALUATION METHODS

OVERVIEW

This chapter describes the development of preliminary tests and evaluation methods to support the assessment of ADS for safe deployment. This builds on findings reported in Chapter 2, Chapter 3, and Chapter 4. The test methods and procedures were developed using engineering judgments, previous test procedure development experience, functional requirements, and use cases. The test framework and procedures developed gave special consideration to achieving repeatability, reliability, and practicality. Lastly, many challenges associated with testing ADS and further research needed to help address these challenges were identified. Challenges included those related to the technology itself as well as test execution. While this task did not involve any actual testing, the findings may inform future physical and virtual tests.

The current automotive certification landscape in the United States involves OEMs and suppliers to self-certify that each piece of regulated equipment and each regulated vehicle is compliant with relevant Federal Motor Vehicle Safety Standards. NHTSA's authority includes the ability to select vehicles and equipment to verify compliance with these standards, and to pursue enforcement actions when it finds a noncompliance or defect posing a safety risk. To support this, NHTSA's Office of Vehicle Safety Compliance audits and verifies compliance, and its Office of Defects Investigation explores safety issues to determine if a safety-related defect exists. No assumptions about the structure of the future automotive certification landscape that includes ADS were made. Rather, the aim was to develop an example of a flexible evaluation framework and common test scenarios. The resulting framework focuses on common test scenarios that can be leveraged and applied across multiple testing techniques.

A goal was to develop the framework such that it could be used for testing in a variety of ways, including:

- Black-box testing – The functionality of the system is tested, while the internal design and implementation of the system are largely unknown or unexposed to the tester.
- White-box testing –The internal structure or workings of a system are tested as opposed to its overall functionality.

An example of black-box testing in the context of an ADS assessment would be to evaluate its obstacle avoidance capabilities. In this example, the test may involve positioning a large static obstacle along an ADS's intended route and observing its ability to avoid a collision with the object while continuing to navigate to its desired destination. In this case, only the resulting navigation outcome is evaluated to answer one primary question:

- Did the ADS avoid the obstacles in a safe and stable manner?

An example of white-box testing in the same context would involve measuring the outputs of one or more of the ADS's perception and navigation algorithms to answer a multitude of questions, potentially including:

- At what range did the ADS detect the obstacle?
- Did the ADS correctly classify the type of obstacle?
- Did the ADS correctly estimate the location of the obstacle?
- Did the ADS correctly estimate the size of the obstacle?
- How quickly did the ADS decide to react?
- How stable was the control response?

In some cases, black-box testing may be sufficient for safety verifications of ADS or other systems; however, there is significant value in answering the questions associated with white-box testing. Answering these questions supports a deeper understanding of the performance bounds of a system. A goal was to establish a testing framework that could benefit and support government and industry with both black-box and white-box testing, as ADS are developed and deployed.

APPROACH

To identify appropriate methods to evaluate ADS, a review and assessment of existing testing methods and tools was performed. This evaluation served to develop an understanding of how testing is currently being executed for vehicles capable of various levels of automation. It also served to identify potential gaps in this existing testing framework, which led to the identification of additional and modified tools and methods to fill those gaps and helped create a testing framework. This assessment included a meeting with crash avoidance test engineers at NHTSA's Vehicle Research and Testing Center in Ohio to discuss their current testing of vehicles capable of SAE International L1 and L2 driving automation. Findings from the previous tasks were presented and initial thoughts on the steps to develop a useful set of test methods and actual tests were provided.

A common test scenario framework that could be used broadly across the various testing methods and tools was then established. This framework built upon the findings of the previous tasks to include the principal elements of ADS operation (tactical maneuver, ODD, and OEDR) that have a direct impact on their overall safety. Each of these elements can be viewed as an input or integrated component in the overall test scenario. The framework was developed in such a way that it could be used for both black-box and white-box testing. Each of the core scenario components can be applied similarly for both black-box and white-box analyses; the differences come in the ability to inject inputs and take output measurements at various levels within the system under test. As part of this analysis, key interfaces where this injection and measurement could take place were identified.

With this scenario framework established, notional test procedures for a subset of the important scenarios were developed. The structure of the procedures was based on prior tests related to connected-vehicle technology (Howe, Xu, Hoover, Elsasser, & Barickman, 2016). Aspects of these procedures include the following.

- Test subject and purpose
- Test personnel, facilities, and equipment
- Test scenario
  - Inputs
  - Initial conditions
  - Execution
  - Data measurement and metrics

Several guiding principles were identified to support the development of the testing framework and the test procedures themselves.

- Testing variables should be isolated, not integrated
- Test environments should be characterized or controlled for test repeatability
- Test metrics should not contain inherent thresholds
- Test methods should allow for sufficient dynamic range
- Tests should be conducted at the lowest level of integration possible
- Low-level tests should help create boundary conditions for high-level integrated system tests
- Parameterization of testing variables and conditions should focus on a "reasonable worst case"

Finally, challenges associated with testing ADS were identified. ADS add a significant level of complexity to a base vehicle platform that can make their assessment more difficult in many ways. These challenges were broken down into two main categories: (1) challenges associated with developing tests and metrics, and (2) challenges associated with test execution.

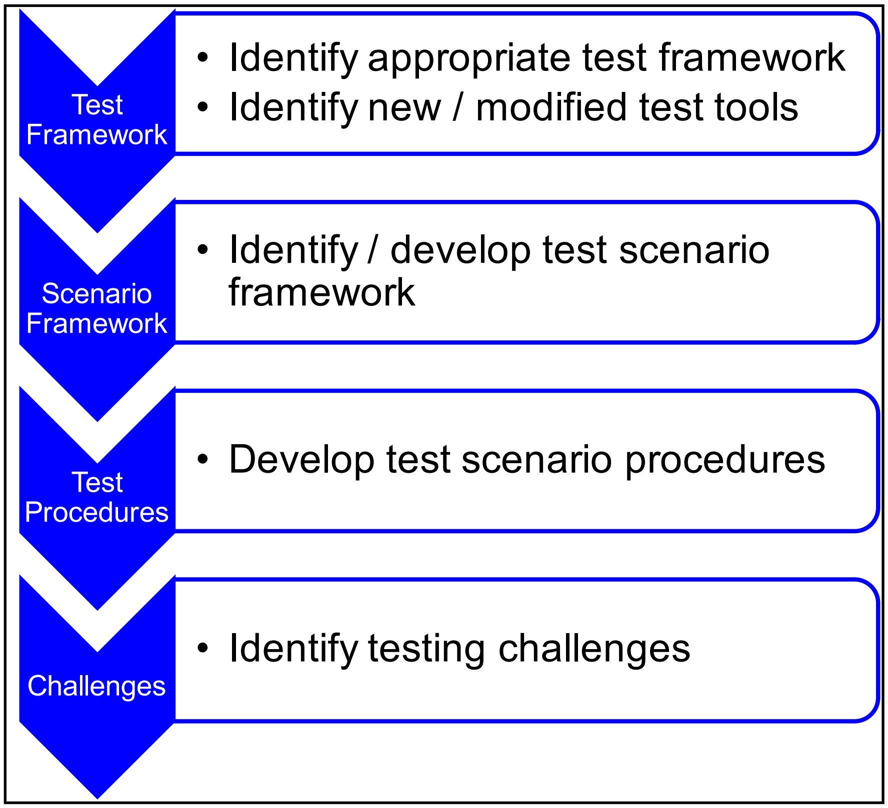

Figure 21. ADS Test and Evaluation Method Development Process

FINDINGS

Testing Architecture

Available literature and reports on current ADS testing activities conducted by both government and industry were reviewed. The review identified several ways that these tests are primarily being conducted.

- Modeling and simulation (M&S)
- Closed-track testing
- Open-road testing

These three techniques offer a multifaceted testing architecture with varying degrees of test control, and varying degrees of fidelity in the test environment. In many cases, two or more of these techniques can be used in parallel or in an iterative fashion to progressively evaluate a complex system such as an ADS.

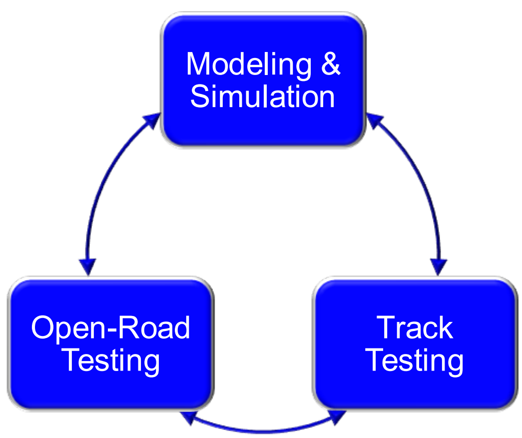

Figure 22. Primary Testing Methods

Modeling and Simulation

M&S rely on a virtual environment with virtual agents to generate knowledge about an ADS's behavior without the need for a physical vehicle and actual testing in the real world. The base vehicle platform and the underlying ADS components need to be modeled physically and/or mathematically to the extent that the behavior of the virtual system can mimic that of the real system to the desired degree of fidelity. Similarly, the virtual environment in which the ADS will be operating is modeled to the desired degree of fidelity. The higher the fidelity of these models, the more closely they represent the actual nature of the vehicle or environment, which results in more substantive data for analysis.

Simulation testing provides several advantages:

- **Controllability** – Simulation affords an unmatched ability to control many aspects of a test.
- **Predictability** – Simulation is designed to run as specified, so there is little uncertainty as to how the test will run.
- **Repeatability** – Simulation allows a test to be run many times in the same fashion, with the same inputs and initial conditions.
- **Scalability** – Simulation allows for generation of a large number and type of scenarios.
- **Efficiency** – Simulation includes a temporal component, which allows it to be sped up faster than real time so that many tests can be run in a relatively short amount of time.

These features are important for the testing of complex systems. Simulation may also serve as a relatively cheaper option for initial testing, as opposed to building up one or more fully functional test vehicles. Simulation environments are also faster to implement and deploy and may be able to test a broader range of conditions.

There are several approaches to M&S that may be applied to support the validation and verification of ADS with existing tools. Examples of the applications are discussed in this section and described more expansively in Appendix B. Appendix B also includes a breakdown of tools by functional area.

Several subfields within the field of M&S that could be used for ADS testing were identified.

- Software-in-the-loop (SIL) simulation
- Hardware-in-the-loop (HIL) simulation
- Vehicle-in-the-loop (VIL) simulation

SIL simulation might be viewed as a traditional simulation system where a subset or all of the underlying ADS software is incorporated into the modeled vehicle to drive the physical response to stimuli. This could include processing modeled sensor data that then feed into world-modeling, decision-making, and motion-planning algorithms. The output of the motion-planning algorithm could be fed into the vehicle model to then induce the virtual vehicle's motion.

HIL simulation incorporates some level of physical hardware and equipment into the simulation environment to provide real data inputs and processing for some parts of the system. For example, an actual radar may be tied into the simulation to provide live range data for the virtual ADS to process and enact a response to, or an actual electronic control unit could be tied into the virtual system to study how the physical production-intent hardware functions. Alternatively, a real heavy-duty vehicle pneumatic brake actuation system could be installed on a static stand and tied into the simulator (Salaani, Mikesell, Boday, & Elsasser, 2016). The brake signals generated by the virtual ADS model could be sent to the brake system to collect data to understand the actual dynamic response to certain conditions and stimuli.

Finally, VIL simulation can allow for a somewhat more integrated test and analysis by leveraging the production-intent vehicle and subsystems. The ADS platform could be placed on a roller test bench, such as a chassis-dynamometer, to allow physical actuation of the steering, throttle, and brake systems to get the wheels rolling and turning, while the vehicle remains in place. The simulation system could be tied into both the roller bench and the vehicle itself. The interface with the vehicle could allow for injection of sensor data to simulate terrain and objects and injection of map data to support routing and decision-making, among other things. The interface with the roller bench could facilitate simulation of road surface conditions (e.g., roughness, traction loss). Alternatively, virtual scenarios and objects could be injected into a real-world test environment, with the actual ADS running on a track and reacting to the virtual scenarios (Kallweit, Prescher, & Butenuth, 2017). Communications infrastructure, such as DSRC, could be integrated into the simulation to provide V2V or V2I data exchange to inject these virtual objects or scenarios.

Figure 23 shows a generalized ADS simulation architecture diagram. The diagram calls out external inputs that could be simulated and injected into a test, inputs that can otherwise be controlled or measured, as well as outputs that can be measured. The nature of the simulation (e.g., white-box versus black-box) could allow for other interfaces for data injection and measurement.

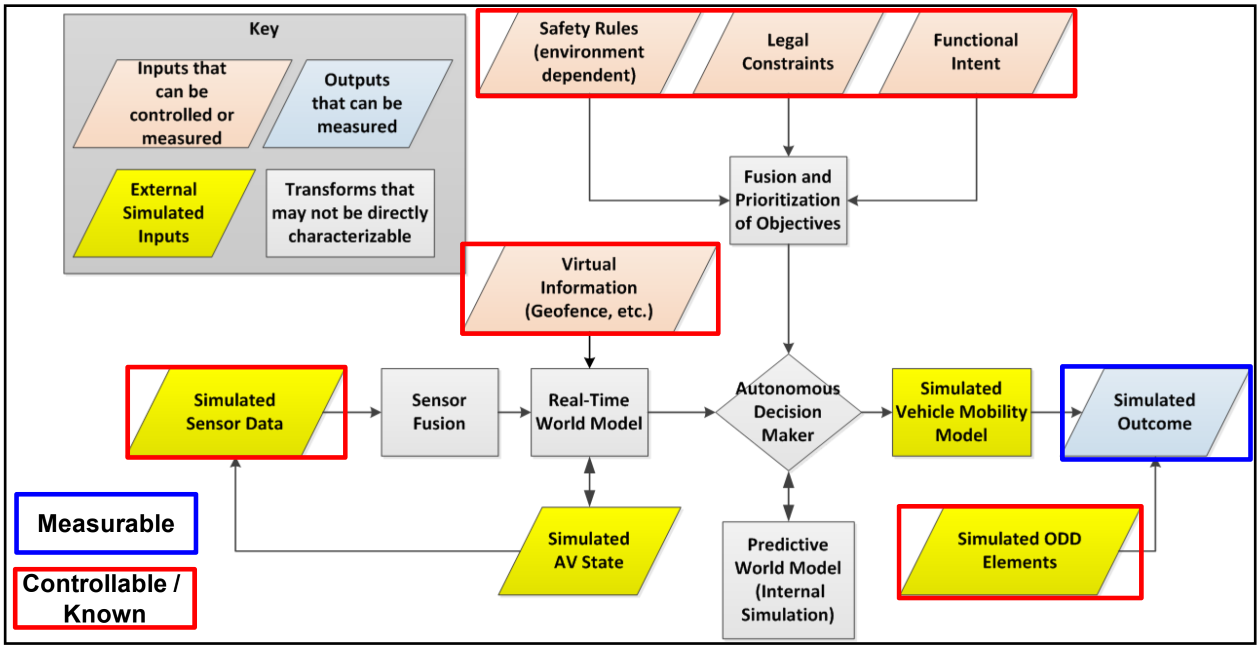

Figure 23. Notional ADS Simulation Architecture

M&S testing offers several additional benefits to address some of the challenges associated with testing ADS. The magnitude of the number of scenarios an ADS could encounter, along with the magnitude and variability of the components that make up a scenario (e.g., ODD, OEDR), likely present an impractical set of test cases. M&S can be leveraged to inform testing requirements and prioritize test scenarios for additional testing using the other techniques of the proposed testing architecture. Simulation can be used as a tool to assess the impact of the sensitivity of ODD and OEDR to the accuracy of ADS. The wide variety of test case parameters (e.g., sensor errors, types of intersections, types of objects) can be varied efficiently to estimate the potential associated risk. This can inform the development of risk profiles that can help prioritize those parameters and scenarios. Additionally, simulation can easily allow for fault injection to test failure modes and the ADS's responses to those failures.

Several disadvantages also exist to the use of M&S. It is difficult to model systems and physical properties with full-fidelity, which may impact how well the simulation environment mimics the real world. There is also a wide variety of commercially available simulation tools, as well as vendor-developed tools, with distinctive features and capabilities. This presents challenges to perform comparisons of results across the different tools.

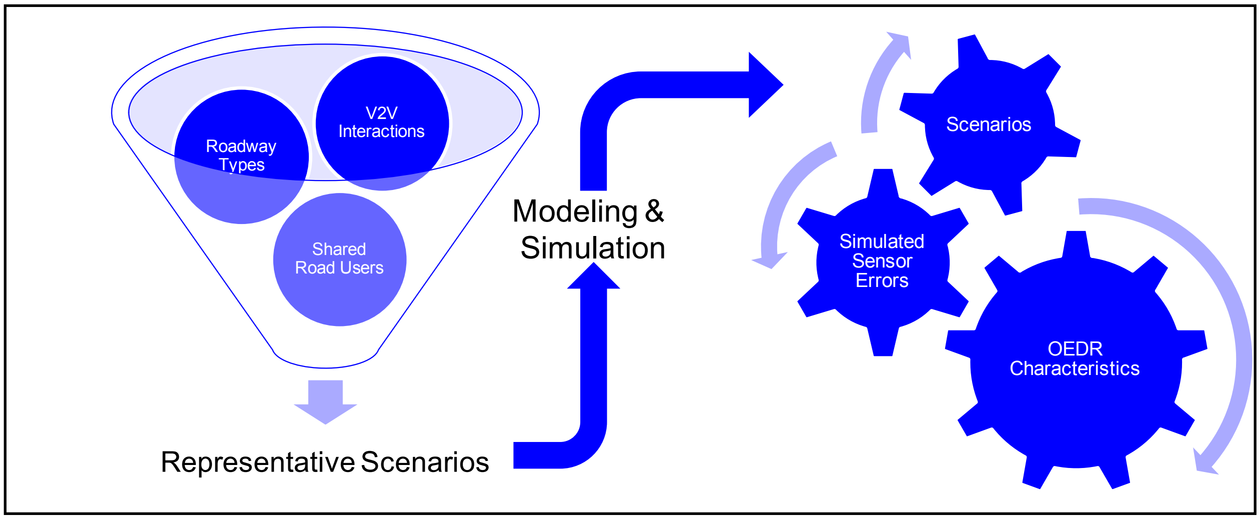

Figure 24. Modeling and Simulation Used to Inform Test Requirements and Prioritize Test Scenarios

Closed-Track Testing

Running tests in a real-world environment is an important component of assessing ADS. Putting physical vehicles through a gamut of lifelike scenarios allows for an evaluation of full system performance that may not be practical using M&S techniques. Rather than presenting virtual objects and environments to a vehicle that is modeled with potentially limited fidelity, as is the case in simulation, physical testing presents real obstacles or obstacle surrogates to a production-level vehicle using actual sensors and software running on target platforms. Testing in a closed-track or road-course setting is one way to achieve such lifelike testing conditions.

Many organizations developing ADS technology either have their own closed-access proving grounds or have access to similar proving grounds through partnerships. Independent proving grounds also exist. Additionally, USDOT recently designated 10 proving ground pilot sites to encourage ADS testing and data sharing (USDOT, 2017). Teams with expertise in CV and ADS technology and with available test facilities to support evaluation of those technologies, including closed test tracks, have organized these proving ground pilot sites across the country to meet those goals.

Track testing provides a few advantages compared to M&S or open-road testing.

- **Controllability** – Track testing allows for control over many of the test variables, including certain aspects of ODD and OEDR.
- **Improved fidelity** – Track testing involves functional, physical ADS and lifelike obstacles and environmental conditions.
- **Transferability** – Track testing scenarios can be replicated in different locations.
- **Repeatability** – Track testing allows for multiple iterations of tests to be run in the same fashion, with the same inputs and initial conditions.

Conversely, closed-track testing also suffers from several drawbacks that present challenges to its utility in assessing and evaluating ADS.

- **Prolonged and costly** –Track testing can take a significant amount of time to set up and execute, resulting in elevated costs.
- **Limited variability** – Track testing facility infrastructure and conditions may be difficult to modify to account for a wide variety of test variables (e.g., ODD conditions).
- **Personnel and equipment needs** – Track testing may need specialized test equipment (e.g., obstacle objects, measurement devices, safety driver).
- **Potentially hazardous** – Track testing with physical vehicles and real obstacles presents a potentially uncertain and hazardous environment to the test participants (e.g., safety driver and experiment observers).

Figure 25 shows a generalized ADS track testing architecture diagram. The diagram calls out external inputs and conditions that could be controlled or measured during a test, as well as outputs that could be measured. The nature of the test (e.g., white-box versus black-box) could allow for different interfaces for data injection and measurement. In a black-box testing scenario, the primary measured output is the navigation outcome, which could include an OEDR-related response as described in Chapter 4. Alternatively, a white-box testing scenario could incorporate measurement at a number of other points within the architecture, including the outputs of sensor-fusion, decision-making, and motion-planning stages. This proposed white-box scenario presents additional challenges, such as gaining access to necessary subsystem interfaces for relevant data collection. It should be noted that elements of the real-world environment, including environmental conditions (e.g., road geometry, road surface, and infrastructure) and tempo-spatial motions of objects, can largely be controlled in track settings. Other conditions, such as weather and ambient lighting, cannot necessarily be controlled. It should also be noted that, regardless of whether some of those conditions can be controlled and replicated or not, the sheer variability of some ODD and OEDR-related conditions (e.g., quality of lane markers, amount of rain or snow, roughness of road, orientation of objects and infrastructure) may make testing completeness intractable. Prioritization of testing scenarios based on risk profiles was identified as a key factor in test scenario selection.

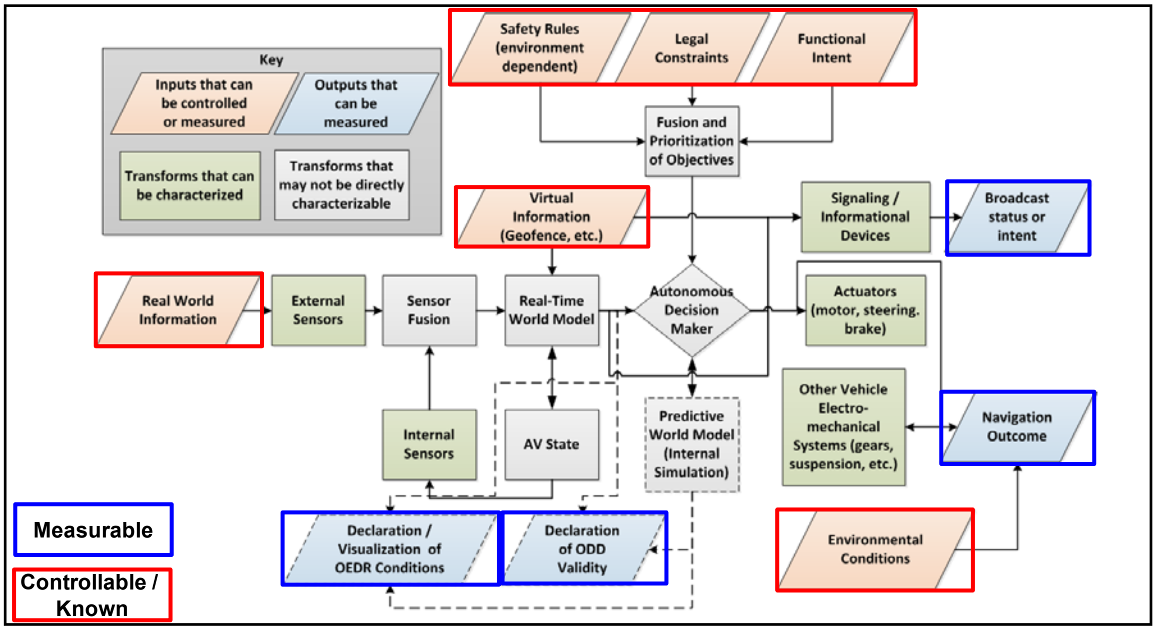

Figure 25. Notional ADS Track Testing Architecture

Open-Road Testing

Public roads offer a "real-world laboratory" to support testing and evaluation of ADS. Several entities are actively testing prototype ADS in public, open-road settings to support ongoing development and refinement (General Motors, 2016), (Krok, 2017), (Guardian, 2015), (Lomas, 2017). In addition to allowing a full performance assessment of the prototype systems, public roads expose the systems to an extremely wide variety of real-world conditions related to ODD and OEDR that would not be feasible with established closed test tracks.

However, open-road testing for ADS also has several drawbacks.

- **Lack of controllability** – Public-road scenarios do not afford much, if any, control over ODD and OEDR conditions.
- **Lack of replicability** – Public-road scenarios are difficult to replicate exactly in different locations.
- **Lack of repeatability** – Public-road scenarios are difficult to repeat exactly over multiple iterations.
- **Limited scalability** – Public-road scenarios may not scale up well, as ADS may require additional data, such as *a priori* digital maps.

Figure 26 represents a notional ADS test architecture for open-road testing. It is important to note that very few of the system inputs are controllable or known. Little to no control exists over the primary system inputs (e.g., environmental conditions and real-world information). This testing technique may present a reasonable and critical "final step" for evaluating systems further along in the development process.

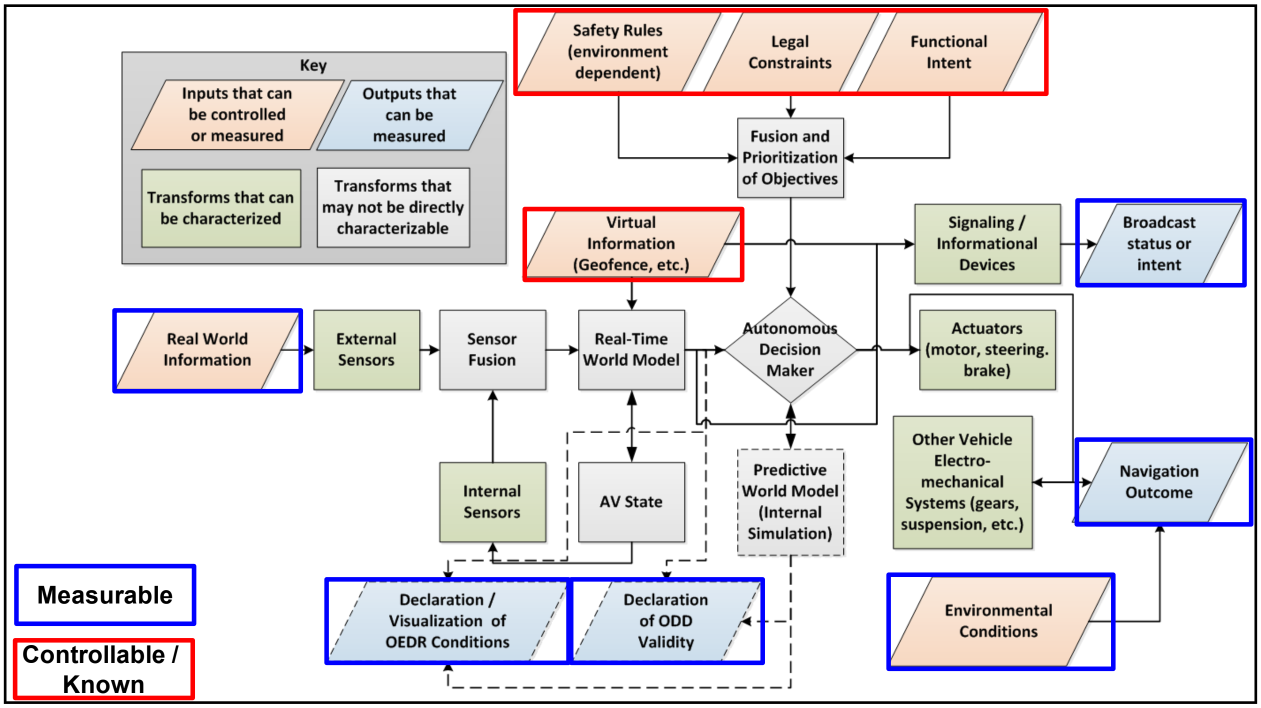

Figure 26. Notional ADS Open-Road Testing Architecture

Efforts have been, and currently are, underway to provide guidance to developing organizations on the safe testing and validation of ADS, including in public-road settings (SAE International, 2015; NHTSA, 2016a). Some States have investigated similar guidance or, in some cases, legislation that governs the testing and deployment of ADS on public roads within their State boundaries (Nowakowski, Shladover, Chan, & Tan, 2015). Since 2012, 41 States and districts have considered such legislation (National Conference of State Legislatures, 2017), although the degree to which this legislation addresses some of the primary concerns is uncertain and/or varied. In California, which has a considerable number of companies testing ADS on public roads, the California Department of Motor Vehicles requires those companies to submit annual disengagement reports that detail the number of autonomous miles driven, and the number and nature of safety driver interventions per test vehicle (State of California Department of Motor Vehicles, 2017).

Test Scenarios

The previous chapters summarized several important functional components that drive the safe deployment of ADS, and the next chapter will summarize a final important component. The following components were identified as collectively making up the core aspects of a common ADS test scenario.

- Tactical maneuver behaviors
- ODD elements
- OEDR capabilities
- Failure mode behaviors

Tactical maneuver behaviors relate to the immediate control-related tasks the ADS is executing as part of the test (e.g., lane following, lane change, turning). The relevant ODD elements generally define the operating environment in which the ADS is navigating during the test (e.g., roadway type, traffic conditions, or environmental conditions). OEDR capabilities relate directly to the objects and events the ADS encounters during the test (e.g., vehicles, pedestrians, traffic signals). Finally, some tests may include injection or simulation of errors or faults that induce failures at various stages within the ADS's functional architecture. Failure modes will be discussed in more detail in Chapter 6.

Test scenarios can be composed of one or more elements of each of these core components, visualized as the individual dimensions of the multidimensional test matrix in Figure 27. Each of these components may be included in a checklist identifying the aspects of each category that are incorporated in a given test.

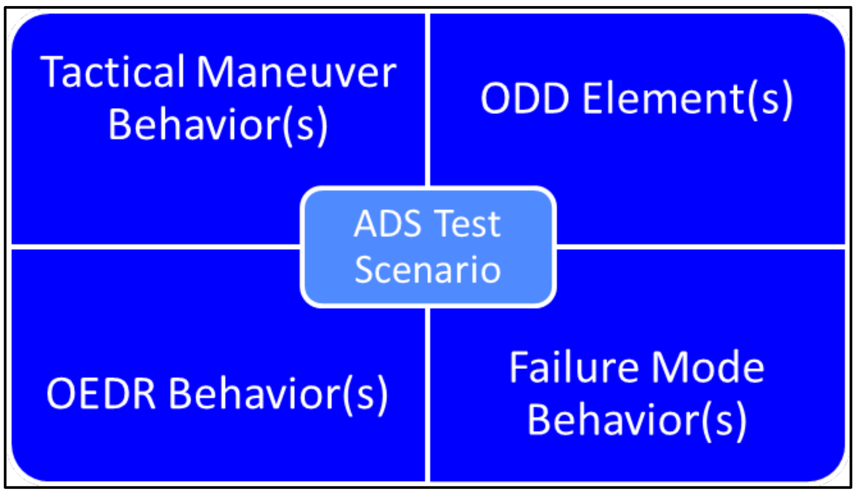

Figure 27. ADS Test Scenario Matrix

For example, a sample ADS test scenario for the L4 Highly Automated Vehicle/TNC feature may be notionally described by the items indicated in Table 54. In this scenario, the primary tactical maneuver behavior is the ADS performing a low-speed merge into an adjacent lane. The primary OEDR behavior under test is detecting and responding to other vehicles in the target adjacent lane. The nominal ODD conditions place the test on a straight, flat arterial road with non-degraded lane markers, nominal traffic, and a maximum speed limit of 72 kph (45 mph). The test occurs during the day with clear and dry conditions, and the ADS is functioning as designed.

This method of specifying a scenario descriptor could be established as a series of checklists: one checklist for each dimension of the scenario test matrix shown in Figure 27. This multidimensional checklist approach would provide the high-level structure of the scenario test.

Table 54. Sample ADS Scenario Test Descriptor

Scenario Elements	Example
Tactical Maneuver Behaviors	Perform lane change/low-speed merge
ODD Elements	Arterial roadway type
	Asphalt roadway surface
	Lane markers
	Straight, flat
	72 kph (45 mph) speed limit
	Nominal traffic
	Clear, dry weather
	Daylight
	…
OEDR Behaviors	Detect and respond to relevant adjacent vehicles (frontal, side, rear)
Failure Mode Behaviors	N/A

The underlying components of each category are then further defined and quantified to fully develop an actionable set of scenario test procedures. For example, the tactical maneuver behavior could be further specified to indicate the direction of the lane change and how it will be induced (e.g., shift to adjacent left lane due to upcoming left turn). The ODD elements could be further specified to indicate radius of curvature and pitch for the test road, time of day and sun position at which the test will be conducted, and presence of surrounding infrastructure, if any. The OEDR behaviors could be further specified to indicate the number of obstacle vehicles and their initial conditions (e.g., positions, speeds, orientations) and trajectories during the test. Failure mode components could be further specified to indicate the exact failure that will be induced (e.g., GPS receiver failure), as well as how and when it will be induced (e.g., unplugging coaxial cable between GPS antenna and receiver after ADS has begun moving and before it begins changing lanes).

Additional information is necessary to further set the stage for the actual execution of the tests, including vehicles (subject and object vehicles) and their roles. General test procedures were modeled on prior tests conducted by NHTSA for CV technology, specifically a test for an FCW system for commercial vehicles (Howe, Xu, Hoover, Elsasser, & Barickman, 2016). Aspects of those test procedures include the following.

- Ambient conditions
- Sample test personnel
- Sample test facilities
- Sample test equipment
- Sample test scenario
  - Description
  - Purpose
  - Sample initial conditions
  - Sample metrics

- Sample execution of procedure
- Sample trial validity
- Sample evaluation criteria

A more detailed sample set of test scenarios and procedures for the selected generic features, including performing low-speed lane changes or merges, are outlined in Appendix C. Each of these scenarios was generated for one of the selected generic features by identifying the elements of the proposed test matrix in Figure 27. The procedures define a test for a single scenario. There are numerous relevant scenarios related to an ADS performing a low-speed merge, some of which are shown in Figure 28, as well as most of the other behaviors. In these scenario visualizations, the ADS is highlighted in green. These scenarios show a hypothetical progression of testing, starting with a simple case with no vehicles in the adjacent lane and iteratively getting more complex to a situation where the vehicles in the adjacent lane are spaced such that there is insufficient room for the ADS to safely merge.

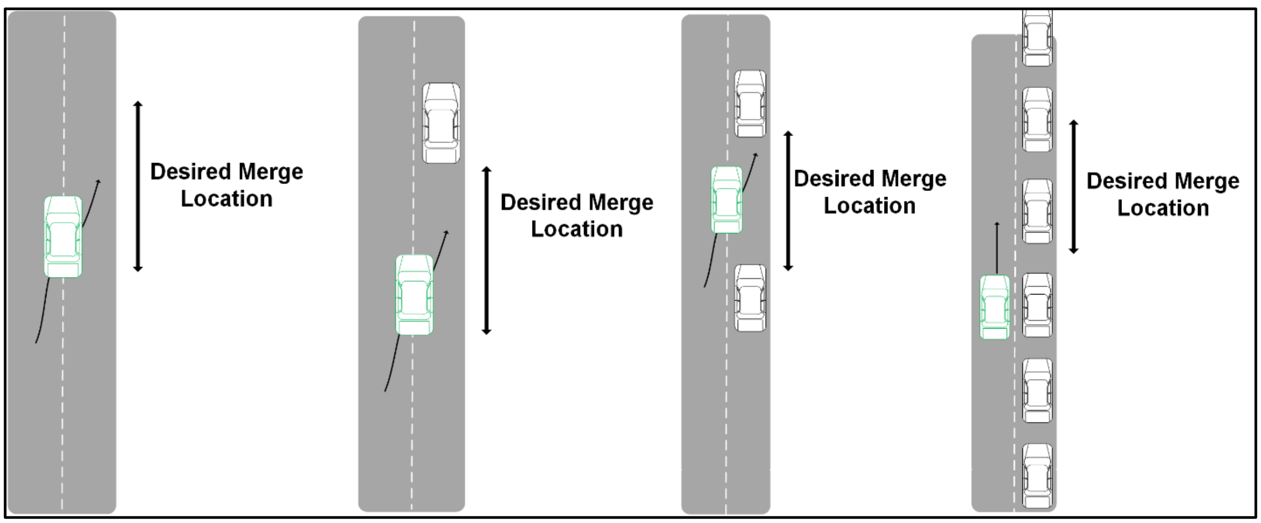

Figure 28. Sample Low-Speed Merge Test Scenarios

The scenario framework described here is flexible enough to support the definition of test scenarios that can apply to simulation, closed-track, and open-road testing. Some elements of the test procedures described above are more relevant to closed-track or open-road testing; however, those elements can likely be modified or ignored for simulation-based testing (e.g., test personnel, test facilities). The core components of the scenarios (tactical maneuver behaviors, ODD, OEDR behaviors, failure mode behaviors) lend themselves well to configuration for all legs of the testing architecture. They also lend themselves well to defining scenarios for both black-box and white-box testing. One of the significant differences for white-box testing will be identifying key interfaces for data measurement to support performance metrics for evaluation that may otherwise be unavailable for black-box testing techniques.

The framework can be leveraged to facilitate a progression of testing, where certain conditions are modified to increase complexity (e.g., speeds and trajectories of the subject vehicle and obstacles). This type of test progression supports identification of behavior and performance boundaries and limits. Furthermore, the scenario framework lends itself well to constructing combinations or sequences of scenarios to extend an ADS evaluation to include more comprehensive operational tests. Testing of specific scenarios or behaviors, while important, may have limited utility in assessing the safe operation of an ADS. Combining scenarios into operational tests provides a means to evaluate the system and assess the test space.

Testing Challenges

The previous sections in this chapter have identified a framework to develop ADS scenario tests, and the methods to execute those tests. While this framework provides a flexible means to conduct ADS evaluation, the challenges associated with these evaluations are numerous. This section builds off prior work to identify several key challenges associated with testing ADS (Koopman & Wagner, 2016). The list of challenges presented is not comprehensive but is rather intended to provide an initial working list.

Two primary categories of challenges to consider when developing and conducting tests were identified: (1) challenges associated with ADS technology, and (2) challenges associated with test execution.

Challenges associated with ADS technology focus on some of the characteristics of the technology and the underlying implementations of the integrated hardware and software systems:

- **Probabilistic and non-deterministic algorithms** – To meet some of the temporal needs related to ADS decision-making, many developers are leveraging algorithms that rely on heuristics or probability to provide a "best guess" relatively quickly. This leaves the system open to making incorrect decisions or decisions that vary from one iteration to the next, even when presented with identical or near-identical conditions. This lack of a repeatable system output emphasizes that new testing methodologies may be needed. Probabilistic and non-deterministic algorithms are often used when the State space is extremely large or even unbounded, making complete testing of all conditions virtually impossible.
- **Machine learning algorithms** – Many developers are also leveraging algorithms, such as convolutional neural networks, that allow the system to learn from experience as it is exposed to new conditions and scenarios. This similarly could result in the ADS responding differently in tests with similar or identical situations.
- **Digital mapping needs** – Some prototype ADS (typically L4 or L5 systems) use *a priori* digital map information for localization and obstacle mapping. This effectively limits the geographic areas in which the ADS can function, and subsequently be tested.
- **Regression testing** – The advent of over-the-air updates to software and firmware will allow ADS developers to push out new features and fix defects rapidly. These updates could potentially have significant impacts on overall system performance that may augment or even invalidate prior test results.

The challenges associated with the execution of tests on ADS highlight the expansiveness of the conditions that vehicles may encounter and handle with minimal, if any, input or guidance from a human. These challenges, among others, include:

- **Testing completeness** – The number of tests or miles driven (Kalra & Paddock , 2016) required to achieve statistical significance to claim safe operation could be staggering.
- **Testing execution controllability** – Without a driver to direct the vehicle, new tools or methods may be needed to direct the ADS to conduct the test in the desired manner (e.g., follow desired route/trajectory, force encounters with objects).
- **Testing scalability** – It will be difficult to achieve significant coverage of the variety and combination of conceivable test conditions, particularly related to ODD and OEDR.
- **Unknown or unclear constraints/operating conditions** – There are a substantial number of real-world corner cases (e.g., missing lane markers, missing signage) that may present the ADS with a situation in which it does not have all the necessary information. The appropriate response may be clear (e.g., transition to MRC); however, identifying and testing against all those corner cases may be intractable.
- **Degraded testing** – Testing against ideal conditions provides a good starting point but establishing tests against even "reasonable worst case" scenarios (e.g., degraded lane markers, rain, snow, shadows) will be cumbersome.
- **Infrastructure considerations** – Changes to key infrastructure elements (e.g., road surface, lane markings, signs) may have substantial impacts on ADS performance.
- **Laws and regulations** – Driving laws vary within and across State lines, can change, and in some cases and to a certain extent are open to interpretation. Successful tests against certain laws and regulations may not be transferable.
- **Assumptions** – Establishing tests with certain assumptions or expectations (e.g., other vehicles obey rules of road and follow driving etiquette) may oversimplify the scenarios such that they are unrealistic or lose value from an assessment standpoint.

International ADS Testing Programs

A few international programs related to ADS testing that may be relevant or complement the goals of this research were identified.

AdaptIVe

The AdaptIVe Automated Driving project, which recently concluded, involved 28 partners from eight different countries in Europe to further applications for automated driving through collaborative development and testing (AdaptIVe, 2017). The program addressed SAE International L1 through L4 systems, and evaluated other aspects of automated driving, including human factors and legal issues. The AdaptIVe project evaluated several scenarios that were categorized as the following.

- Close-distance scenarios – garage parking (L3), stop-and-go traffic (L3), safe stop (L4)
- Urban scenarios – city chauffeur (L3), safe stop (L4)
- Highway scenarios – lane change (L3), lane/vehicle following (L3), safe stop (L4)

The program also addressed evaluation methods for ADS for four key areas.

- Technical assessment – performance of ADS features
- User-related assessment – interaction between user and ADS features
- In-traffic assessment – effects of ADS on surrounding traffic and non-users
- Impact assessment – effects of ADS features on safety and environmental aspects

PEGASUS

Previously referenced in Chapter 3, the PEGASUS Project has goals of:

- Defining standardized procedures for ADS testing and experimentation in simulation, on test stands, and in real environments;
- Developing a continuous and flexible tool chain to safeguard automated driving;
- Integrating tests in the development process at an early stage; and
- Creating a cross-manufacturer method for safeguarding highly automated driving functions.

The program involves 17 partners, including OEMs, Tier 1 suppliers, test labs, and scientific institutes. An important aspect of the program is the identification and generation of scenarios at various levels of abstraction. Furthermore, the program seeks to implement some of these scenario tests using simulation, closed-track testing, and open-road testing, and seeks to identify formal performance metrics for those test techniques. Similar to this work, a subset of available ADS features was selected for analysis and testing.

SUMMARY

This task identified and developed an example of a flexible testing framework for ADS, as well as preliminary tests and procedures. The framework leverages existing testing techniques, namely M&S, closed-track testing, and open-road testing. Each of these techniques has advantages and disadvantages for assessing the performance of ADS features, but when used together in a potentially iterative process, they can provide a comprehensive evaluation framework. M&S can provide significant coverage of a wide variety of test conditions in an efficient manner. M&S can be used to perform test variable sensitivity analyses and can help to prioritize scenarios for further evaluation. Closed-track testing uses physical systems and objects to set up lifelike scenarios in a controlled setting. Open-road testing affords an opportunity to assess full system performance in a real-world, unpredictable, and uncontrollable environment.

This chapter established a flexible ADS test scenario framework that built on the other key testing components identified in this research—tactical maneuver behaviors, ODD elements, OEDR behaviors, and failure mode behaviors. This framework identified a multidimensional approach to specifying the key test scenario data inputs, based on those four test components. This framework is flexible enough to add or modify specific items within those components, as new maneuvers or OEDR behaviors are identified, and allows for the efficient design of new tests. The flexibility of the framework is also manifest in that it can be used for all the testing techniques mentioned above. High-level test procedures are proposed for a set of sample scenarios to further define how tests could be executed and what data to collect to measure performance.

Several challenges were identified with the assessment of ADS that could be categorized as challenges associated with the ADS technology itself and challenges associated with executing tests on ADS. To a certain extent, the testing architecture and scenario framework can be leveraged to address some of those challenges. The chapter also described international research programs that share the common goal of finding ways to assess the performance of ADS.

CHAPTER 6. FAIL-OPERATIONAL AND FAIL-SAFE MECHANISMS

OVERVIEW

This chapter describes an assessment approach to FO and FS mechanisms for an ADS. ADSs will use FO and FS mechanisms when the system does not function as intended. These mechanisms enable an ADS to attain an MRC that removes the vehicle and its occupants from harm's way, to the best extent possible. Defining, testing, and validating FO and FS strategies for achieving an MRC are important steps in ensuring the safe operation and deployment of ADS.

MRC is defined in SAE J3016 as:

> A condition to which a *user* or an ADS may bring a *vehicle* after performing the DDT *fallback* in order to reduce the risk of a crash when a given *trip* cannot or should not be completed.

SAE J3016 further states:

> At level 3, given a DDT *performance-relevant system failure* in the *ADS* or *vehicle*, the DDT *fallback-ready user* is expected to achieve a *minimal risk condition* when s/he determines that it is necessary
>
> At levels 4 and 5, the *ADS* is capable of automatically achieving a *minimal risk condition* when necessary (i.e., due to *ODD* exit, if applicable, or a DDT *performance-relevant system failure* in the *ADS* or *vehicle*). The characteristics of automated achievement of a *minimal risk condition* at levels 4 and 5 will vary according to the type and extent of the *system failure*, the *ODD* (if any) for the *ADS feature* in question, and the particular *operating* conditions when the *system failure* or *ODD* exit occurs. It may entail automatically bringing the *vehicle* to a stop within its current travel path, or it may entail a more extensive maneuver designed to remove the *vehicle* from an active lane of traffic and/or to automatically return the *vehicle* to a *dispatching* facility.

As described in Chapter 5, the sample test framework includes failure mode behavior as one important high-level dimension in defining test scenarios and procedures. The efforts undertaken in this task help to frame how failure mode behavior plays into that larger testing architecture, with the goal of evaluating an ADS feature's ability to achieve an MRC.

APPROACH

As stated previously, the appropriate failure mitigation strategy and resulting MRC is largely dependent on the type and nature of failures the ADS experiences. To this end, an understanding of potential ADS failure modes is necessary. As such, a high-level failure analysis was performed. The results of this analysis informed the assessment of FO and FS mechanisms. A variety of failure and hazard analysis techniques exist, including fault tree analysis, system FMEA, FMECA, system-theoretic process analysis, and HazOp. System FMEA was identified and selected as an initial approach to develop the high-level analysis needed to identify potential failures in each subsystem of the representative functional architecture, as well as their causes and impacts.

FMEA analyses typically occur early in the design phase of a system, or potentially iteratively throughout the design, development, and testing phases. The general goal is to attempt to identify and correct or address potential malfunctions before the system is available to customers. An FMEA can generally be broken down into the following steps.

1. Identify potential failure modes
2. Identify potential causes and effects of those failure modes
3. Prioritize the failure modes based upon risk
4. Identify an appropriate corrective action or mitigation strategy

In this process, existing reports and literature on ADS failures, including from the Defense Advanced Research Projects Agency Grand and Urban Challenges (DARPA, 2008), as well as engineering judgments and prior experience in ADS development and testing were leveraged and considered. It was assumed that a detailed failure analysis employing a range of techniques noted above has been performed on the base vehicle platform, and therefore efforts were focused on components specifically related to the ADS. This allowed for a deeper dive into the ADS functional architecture presented in Figure 3. A more detailed architecture diagram, which is a working diagram from the SAE International ORAD committee, provided the basis for the high-level FMEA and is shown in Figure 2. Furthermore, failures that could have safety implications, as opposed to failures that are merely an inconvenience, were prioritized.

A notional FMEA worksheet was used to perform the analysis, a summary of which is shown in Table 55. The components of that worksheet are described as follows.

- **Architecture Elements** – System/subsystem from ADS functional architecture (e.g., sensors – radar)
- **Function** – Purpose the element serves (e.g., acquire range data to obstacles)
- **Failure Modes** – Possible ways the element can fail (e.g., hardware failure – loss of power)
- **Potential Causes** – Potential reasons failure occurred (e.g., power cable disconnected)
- **Potential Effects** – Potential downstream implications of failure (e.g., object segmentation algorithm fails to identify lead vehicle, resulting in collision with lead vehicle)
- **Occurrence (O)** – Measure of the likelihood the failure will occur
- **Severity s** – Measure of the severity of the effects if the failure did occur
- **Detectability (D)** – Measure of the ability of the system to detect the failure
- **Risk Priority Number (RPN)** – Overall measure of risk associated with failure, composed of *occurrence* (O), *severity* (S), and *detectability* (D): ($RPN = {O \cdot S}/{D}$)
- **Process Controls** – Methods or actions to eliminate or mitigate failure

Table 55. Notional Worksheet for ADS FMEA

Architecture Elements		Function	Failure Modes	Potential Causes	Potential Effects	Occurrence	Severity	Detectability	RPN
Sensors	Lidar								
	Radar								
	…								

This worksheet includes quantitative measures of occurrence, severity, and detectability to ultimately prioritize the failure modes according to their significance and risk. For this analysis, the types of failures and their impacts were of more interest than their overall risk; however, the team completed the exercise for completeness. The three metrics were evaluated on a notional 0-10 scale, with larger values indicating failures occurring more frequently, with higher severity, and with higher detectability. Values for each were assigned based on research team discussion and insight.

The failure modes and their implications in relation to the ADS tactical maneuver behaviors identified in Chapter 2 and the OEDR behaviors identified in Chapter 5 were highlighted and summarized. As these behaviors are common across many of the ADS features, this then provided a similar mapping between failure modes and those features.

The last step outlined in the FMEA procedure above was completed to identify conceptual FO and FS mechanisms to mitigate identified failures. FS mechanisms are employed when the ADS cannot continue to operate due to a significant failure. When this type of failure occurs, the system should fail in a predictable, controlled manner to the MRC. FO mechanisms are employed when a failure occurs, but the ADS is still able to operate, albeit potentially with reduced capabilities or only for a limited duration. A variety of potential FS and FO options for ADS, as well as advantages, disadvantages, and potential limitations for each were identified and described.

The test architecture and framework from Chapter 5 was revisited to incorporate testing and validating failure mode behavior. The comprehensive testing architecture presented includes options for M&S, closed-track testing, and open-road testing. Inducing failures to evaluate an ADS's response adds a level of complexity and risk that may necessitate modified approaches or procedures to execute tests.

Several other programs and ongoing activities related to failure mitigation techniques for ADS were identified. USDOT's Functional Safety Analysis of Automated Lane Centering Controls (Brewer & Najm, 2015) program also includes analysis of failure modes, and the SAE International ORAD committee is currently discussing failure strategies for ADS.

FINDINGS

Failure Modes and Effects

The FMEA was broken down by architecture subsystems to identify potential key failures at each step through the ADS "pipeline."

- Sensing and communication
- Perception
- Navigation and control
- HMI

Sensing and Communication

Failures related to sensing and communication focus on hardware and software related to exteroception, proprioception, and communication. Sensors related to exteroception acquire data about the external environment around the vehicle. Some examples of exteroceptive sensors include radar, lidar, cameras, and ultrasonics. Sensors related to proprioception acquire data about the internal state of the vehicle, most commonly to support localization. Some examples of proprioceptive sensors include GPS, inertial measurement units, gyroscopes, wheel speed sensors, compasses, steering wheel sensors, and brake pedal sensors. Communication equipment, such as DSRC, cellular technology (3G/4G/LTE/5G), Wi-Fi, and Bluetooth, provides wireless one-way or two-way transmission of data with other roadway users or with infrastructure. The data acquired through communication could include information on other vehicles or roadway users (individual roadway users or larger traffic volumes and patterns), as well as information on relevant incidents, warnings, or infrastructure changes/updates (e.g., traffic accidents, emergency vehicles, and temporary construction zones).

Failure modes associated with exteroceptive sensors include loss of power, loss of data connection, internal hardware failures, and emitter/receiver fouling (e.g., mud, dirt). Failure modes associated with proprioceptive sensors similarly include loss of power, loss of data connection, internal hardware failures, and poor calibration/alignment. Failure modes associated with communication equipment similarly include loss of power, loss of data connection, internal hardware failure, and loss of external signal. Additionally, many of these sensors need software drivers that process the raw data coming from each sensor into data that are more ADS-friendly. These software drivers may fail, or may fail to produce the data at the desired rate, although this may similarly be caused by an internal fault or failure of the equipment itself.

The downstream effects of exteroceptive sensor failures could lead to the ADS failing to detect and track relevant obstacles (e.g., fails to segment or classify another vehicle), or the ADS inaccurately characterizing relevant obstacles (e.g., incorrectly estimates position or shape of object). The effects of proprioceptive sensor failures could lead to the ADS failing to accurately estimate its internal state (e.g., relative and/or absolute position, orientation, speed). The effects of communication equipment failures could lead to the ADS failing to account for or act on relevant warnings or updates (e.g., fails to detect and react to lane closure). These failures ultimately lead to the ADS being unable to perceive and model the surrounding environment accurately.

Perception

Failures associated with perception focus primarily on software algorithms related to sensor processing, localization, and world modeling. Sensor processing involves algorithms to support perception field segmentation (near-field/mid-field/far-field), roadway/terrain segmentation and classification, and object segmentation and classification. Localization involves algorithms for absolute and relative state estimation. World modeling involves algorithms to aggregate information from digital maps and other static and dynamic obstacle maps into a common coordinate frame, as well as incorporating known traffic rules and other virtual information (e.g., geo-fencing).

Failure modes associated with sensor processing include failing to model or detect the information for which the sensor was designed or providing suboptimal results. Failure modes associated with localization include failing to estimate the state of the ADS, or more likely providing an inaccurate estimate. Failure modes associated with world modeling include failing to appropriately combine and register the disparate data into a cohesive model or map, or more likely providing a suboptimal model or map. Failure modes for these perception tasks also include typical software failures, such as memory corruption, control flow errors, or calculation errors. Similarly, these algorithms will be running on computing hardware, which could experience any of a number of failures, including internal hardware failures, loss of power, or loss of data connection.

The downstream effects of failures associated with sensor processing could lead to the ADS ignoring undetected objects or roadway features or misinterpreting them. The effects of failures associated with localization include the ADS losing track of its position and/or orientation and being unable to safely navigate. The failures associated with world modeling lead to the system misrepresenting the environment in which the ADS is operating. This could also include the ADS failing to recognize that it is crossing an ODD or OEDR operational boundary. In general, these failures could lead to the ADS making suboptimal or unsafe navigation decisions.

Navigation and Control

Failures associated with navigation focus primarily on software algorithms related to mission planning, maneuver/trajectory planning, and steering and speed control. Mission planning involves algorithms to derive a high-level route for the ADS to follow from its initial location to a desired destination, potentially to include roads to follow and turns to take, and potentially considering travel time or distance. Maneuver and trajectory planning involve algorithms to iteratively determine appropriate and safe motions that allow the ADS to make progress along its high-level route. This includes determining the appropriate tactical maneuver behaviors identified in Chapter 2, such as lane following, lane switching, merging, navigating intersections, and executing U-turns, as well as the optimal paths for the vehicle to follow to execute those behaviors and the appropriate and safe speeds at which to follow the prescribed path. Steering control involves algorithms to convert the initial, near-field segments of those paths into control inputs to the steering actuator. Speed control involves algorithms to convert the target speed along the desired trajectory into control inputs to the ADS throttle and brake actuators.

Failure modes associated with mission planning include algorithm failures where the high-level route is not generated (e.g., missing connection in digital map), or an inefficient or suboptimal route is generated (e.g., route is not the shortest distance or duration possible). Failures associated with maneuver planning include algorithm failures where a necessary maneuver is not planned (e.g., turn not recognized) or an incorrect or inappropriate maneuver is planned (e.g., incorrect lane change planned before upcoming turn). Failures associated with trajectory planning include algorithm failures where a feasible trajectory is not found to implement a maneuver (e.g., path to execute lane change not generated, even if a feasible one exists, and vehicle continues in current lane), or the trajectory generated is incorrect or suboptimal. Failures associated with steering and speed control include algorithm failures where control inputs are not generated or are incorrect or suboptimal in relation to the planned trajectory.

The effects of failures associated with mission planning may include the ADS being unable to reach its desired destination or following an inefficient route to get there. Effects of failures associated with maneuver planning include the ADS getting stuck or needing to recalculate its mission route, or potentially executing unsafe maneuvers. Effects of failures associated with trajectory planning include the ADS getting stuck, or potentially following unsafe paths. Effects of failures associated with steering or speed control include the ADS not accurately following its planned path, or not safely and stably maintaining the target speed. These lower-level navigation failures could have dire consequences in cases where the vehicle is navigating in complex environments around many dynamic obstacles, ultimately leading to collisions.

Human-Machine Interface

Failures associated with the vehicle interface focus on hardware and software failures related to visual displays or audible or tactile warnings that may otherwise be necessary to facilitate an operator takeover. The HMI is crucial for occupied ADS where the occupant may need to perform the functions of a fallback-ready user in the event of a major failure. The HMI provides information about the state of the environment, as well as the internal state of the system and its ability to function as intended. If any of this information is not provided, or the information provided is incorrect, the operator may either fail to retake control of the vehicle when necessary or may lack vital information or context to facilitate a safe takeover.

Failure modes associated with the HMI include internal hardware failures such as a display, speaker, or tactile mechanism not functioning as intended (e.g., display screen dies, steering wheels fails to vibrate). They also include software failures related to the presentation of relevant data or warnings for the operator (e.g., misrepresenting automation status, not issuing an audible warning of imminent collision).

Downstream effects of these failures include a delay in an operator retaking control of the vehicle when requested, or the operator being uninformed that a takeover is necessary. Alternatively, the operator could successfully retake control, but could make poor decisions based on the misrepresentation or lack of data provided. These types of failures may be mitigated in L4 systems, as the ADS achieves the MRC; however, for a L3 system, these types of failures could be pertinent to safety.

Summary

In general, many of the ADS failure modes described above could be attributed to failures of information. These were summarized into three primary categories as failures attributed to:

- No data – Information is absent altogether
- Inadequate quality data – Information is of poor or degraded quality
- Latent data – Information is delayed or old

For each of these three categories, the temporal nature of the failure is also a key component to the resolution. Information failures can be transient/intermittent or persistent. Intermittent or transient data failures may be mitigated by filtering or the recursive nature of many of the elements of the functional architecture. They may also be more difficult to detect. Persistent data failures may be more severe but are also likely to manifest themselves relatively quickly and be easier to detect. Many ADS architectures will provide robustness to some of these failures by fusing and filtering data from multiple sources (e.g., fusing data from a suite of perception sensors, filtering data from multiple relative and absolute localization sensors, extended Kalman filters). This robustness may still have a limited functional time horizon in the event of persistent errors or failures (e.g., state estimation drift accumulation).

The progression or propagation of failures through the ADS architecture also presents a challenge. Small errors or faults that occur early in the pipeline (e.g., sensing failures) may ultimately develop into more significant errors or faults at the end of the pipeline (e.g., the perception system does not identify an adjacent vehicle, resulting in the navigation subsystem generating a trajectory that leads to a collision). Similarly, small simultaneous errors in disparate subsystems could potentially lead to unintended or undesired emergent behavior. Providing confidence or other measures of quality for output data at each step along the pipeline could support identification of faults or failures early and allow for mitigation.

The effects of these failures were summarized into four primary categories, although each may build off the others.

- Suboptimal performance (e.g., hugging one side of a lane, driving slower than allowed, taking an inefficient route or trajectory)

- Unexpected/unpredictable behavior (e.g., sudden acceleration/deceleration, erratic steering oscillation)
- Unsafe behavior (e.g., driving out of desired lane, not reacting to relevant obstacles)
- Collisions

Failures that result in suboptimal performance may mostly be benign and be more of an inconvenience than a safety concern, although it may still be beneficial to identify and quantify them. Failures that result in unexpected or unsafe behavior or collisions are certainly a safety concern and need to receive careful consideration when developing a failure response strategy.

Like the vastness of potential ODDs presented in Chapter 3, a wide variety of failure modes are possible at each stage of the ADS functional architecture. Coupling this with the extensive combination and propagation space of failures presents a significant challenge to deploying ADS safely. The nature and extent of a single failure or sequence of failures plays a key role in determining the appropriate failure response.

ADS Behavior Mapping

After completing the FMEA for the ADS architecture, the various failure modes and effects were summarized and mapped to the relevant tactical maneuver and OEDR behaviors for the three down-sampled ADS features (L3 Traffic Jam Drive, L3 Highway Drive, and L4 Highly Automated Vehicle/TNC). This notionally provides a mapping from the specific failures identified in the FMEA, to the generalized failures summarized in the previous section, to the behaviors implemented by various ADS features.

This exercise could be extended to the other features identified in Chapter 2. A more thorough analysis and mapping could eventually provide a means to identify potential failure effects that are manifested in the testing architecture outlined in Chapter 5. For example, if an ADS under test could not safely and continuously maintain its specified lane, the test team could follow the detailed mapping back to identify possible root causes (e.g., relative localization solution instability caused by intermittent power failure in camera tasked with detecting and tracking lane markers).

Table 56. L3 Traffic Jam Drive Failure Mode/Effects Summary

Behavior Failure	Effects
Fail to maintain lane	Impact adjacent vehicle or infrastructure
Fail to maintain safe following distance	Impact lead vehicle
Fail to detect and respond to maneuvers by other vehicles	Impact lead or adjacent vehicles
Fail to detect relevant obstacles in or near lane	Impact obstacles
Fail to identify ODD/OEDR boundary	Operate outside of ODD/OEDR capabilities

Table 57. L3 Highway Drive Failure Mode/Effects Summary

Behavior Failure	Effects
Fail to maintain lane	Impact adjacent vehicle or infrastructure
Fail to maintain safe following distance	Impact lead vehicle
Fail to maintain appropriate/safe speed	Exceed speed limit, lose stability, impact lead vehicle
Fail to detect and respond to maneuvers by other vehicles	Impact lead or adjacent vehicles
Fail to detect relevant obstacles in or near lane	Impact obstacles
Fail to identify ODD/OEDR boundary	Operate outside of ODD/OEDR capabilities

Table 58. L4 Highly Automated Vehicle/TNC Failure Mode/Effects Summary

Behavior Failure	Effects
Fail to maintain lane	Impact adjacent vehicle or infrastructure
Fail to maintain safe following distance	Impact lead vehicle
Fail to maintain appropriate/safe speed	Exceed speed limit, lose stability, impact lead vehicle
Fail to maneuver appropriately/safely (e.g., lane change, intersection)	Impact vehicles or infrastructure
Fail to detect and respond to maneuvers by other vehicles	Impact lead or adjacent vehicles
Fail to detect relevant obstacles in or near lane	Impact obstacles
Fail to obey traffic rules and etiquette	Impact vehicles
Fail to recognize and respond to nonstandard hazards (e.g., work zones, emergency vehicles)	Navigate unsafely, impact obstacles
Fail to identify ODD/OEDR boundary	Operate outside of ODD/OEDR capabilities

Failure Mitigation Strategies

Based on the general failure modes identified, potential failure mode responses and strategies were identified. This effort focused on FS strategies for cases where the ADS cannot continue to operate due to a significant failure, and FO strategies for cases where the ADS could continue to operate even in the face of a failure.

Fail-Safe Mechanisms

The primary goal of an FS strategy is to rapidly achieve an MRC where the vehicle and occupants are safe. Three candidate FS mechanisms were considered for further evaluation.

- Transition to fallback-ready user control
- Safely stop in lane of travel
- Safely move out of travel lane and stop

For L3 systems, requesting intervention by a fallback-ready user may be the primary FS strategy. This assumes that an operator is present and attentive to the HMI. Furthermore, there is an assumption that the information being provided by the ADS through the HMI is appropriate to reengage the operator. A challenge with this strategy is providing sufficient warning to the operator before an intervention is needed. Prior studies have shown that the timing of this warning in L2 and L3 systems can be substantial, depending on the nature of the event and the alert provided (Blanco et al., 2015). Furthermore, the ADS feature needs to continue to function until that transition occurs. Additional questions and challenges arise if the user is not fallback-ready (e.g., asleep and does not notice intervention request). This intervention request may also be a feasible FS strategy for a L4 system, again assuming a fallback-ready user is present, and the necessary information is available; however, L4 systems can achieve the MRC in the event an operator is unavailable or fails to act.

The strategy of stopping in the current lane of travel is a debated approach with the technical and policy community. In this case, the ADS may rapidly but safely decelerate to a stop while maintaining its current lane. The actions and time needed are minimal; however, there is considerable disagreement as to whether this is a safe state for the vehicle, its occupants, and other road users. The ODD and driving conditions play a role in answering this question. For example, stopping in an active lane of travel on a lower-speed urban road with good visibility may be a relatively safe condition, whereas stopping in an active lane of travel on a higher-speed rural highway after a blind curve may not fit the intent of a safe state. The frequency, nature, and extent of the failure also play into answering that question. For example, if one or more of the ADS's primary sensors fails and it cannot detect adjacent obstacles, stopping in an active lane of travel may be safer than attempting to maneuver out of the travel lanes to stop. Remote fleet management integration could further support this strategy if a remote operator could be hailed to assist in maneuvering the vehicle to a safe state.

Finally, an ADS maneuvering safely out of the active roadway and stopping/parking presents an appealing FS mechanism. The frequency, nature, and extent of the failures, as well as the initial driving conditions, again play a role in determining if this is a viable strategy. For example, if the vehicle is in a middle lane of a large freeway, a complicated set of maneuvers conducted over a substantial period of time may be necessary to shift one or more lanes around adjacent traffic to be able to merge onto a shoulder or safe area to achieve the MRC. If one or more of its primary sensors has failed or if no shoulder or safe harbor is available, then this strategy may be impractical.

Fail-Operational Mechanisms

FO strategies allow the ADS to continue to function, even in the event of one or more failures. It is important to note that this operation may only be supported for a limited duration, or potentially with a reduced set of capabilities. Three primary FO mechanisms were considered for further analysis.

- Hardware/software redundancy
- Adaptive compensation
- Degraded operations
  - Reduced top speed
  - Reduced level of automation
  - Reduced ODD
  - Reduced maneuver capabilities
  - Reduced OEDR capabilities

Integrating redundant hardware or software, which is more of a design strategy, provides backups for critical pieces of equipment or logical processes. For example, multiple identical ECUs running a steering control application could be installed on an ADS. In the event the primary ECU experienced a hardware failure, a logic mechanism could trigger the system to begin responding to outputs from the secondary ECU. This strategy may improve reliability and robustness from an operational standpoint so as to allow the ADS to continue to function. However, this strategy increases cost, complexity, and potentially the "footprint" of the ADS feature (e.g., needs additional power and cabling, takes up additional space).

Adaptive compensation allows an ADS subsystem to compensate for a failure in one or more components by relying more on other complementary components or processes, if available. For example, if a GPS receiver suffers a hardware failure and is providing noisy or intermittent data, the state estimation system could potentially reduce the weight of the GPS data and increase the weight on other available sensors (e.g., IMU, wheel-speed sensors) to continue to provide a robust, filtered solution. This strategy may work particularly well for subsystems that already fuse data from multiple sources (e.g., perception and localization), although possibly not for others. It is also possible that this compensation technique is only effective for a limited amount of time (e.g., state estimator drift could cause vehicle to lose track of its absolute position over time if GPS or other absolute data are not acquired). This strategy may become less practical as developers seek to minimize components on their ADS to move to market.

Finally, a variety of degraded modes of operation exist that could allow an ADS to continue to function after a failure. Operating at a reduced speed is a useful tool for mitigating faults or failures that are associated with constrained resources (e.g., network bandwidth, processing power, processing latency/lag). This strategy provides the ADS additional time to evaluate a scenario and make navigation decisions; however, it may be impractical or unsafe in some driving scenarios (e.g., freeway, HOV lane). Operating at a reduced level of automation is another option, albeit one that may shift responsibility of one or more aspects of the DDT or fallback performance (e.g., reduction from L4 to L3 implies a fallback-ready user is available). This strategy may include emphasis on driver state monitoring, if applicable, to ensure that the operator is attentive and aware of the circumstances. It may therefore be impractical for ADS features without a defined driver (e.g., L4 or L5 Highly Automated Vehicle/TNC feature, automated delivery vehicle). Operating with a reduced ODD further limits the conditions and domains in which the ADS can function (e.g., daytime only, low-speed only).

SUMMARY

This task considered and analyzed potential failure modes for a generic ADS, and possible failure mitigation strategies. A high-level system FMEA was performed to identify failure modes and their implications for the primary subsystems within the ADS functional architecture. Failures were primarily related to failures of information resulting from both physical and logical faults and errors. The failure modes were generalized according to the severity of their effects, and mapped to the tactical maneuver behaviors and OEDR behaviors identified in Chapter 2 and Chapter 4, respectively, as well as to the down-selected ADS features.

Potential mechanisms that allow ADS to either fail safely when a critical failure occurs such that the vehicle cannot continue to function as designed, or fail operationally when a failure occurs such that the vehicle can continue to function, were identified and evaluated. FS strategies generally attempt to achieve an MRC as efficiently as possible, while FO strategies generally attempt to continue to perform the primary elements of the DDT, albeit potentially for a limited duration or with a reduced set of capabilities. The identified FS and FO strategies each have advantages and disadvantages. A hierarchy of these mechanisms may be necessary, as the appropriate failure mitigation strategy will largely depend on the nature and extent of the failures, as well as the initial conditions present when the failure occurs.

The test scenario framework and testing architecture were revisited to incorporate evaluation of failure response into the proposed architecture, as described in Chapter 5. Failure mode behavior lends itself to being included as a fourth dimension in the test scenario framework (shown in Figure 27). M&S may be well-suited to efficiently and effectively evaluate the wide variety of potential failure modes an ADS could experience, as well as the wide variety of initial conditions in which it could fail. Common root causes of some failure modes, including noise and latency, can be modeled for virtual testing. Fault injection and failure analysis can occur safely in a virtual environment, but they present hazards when using real systems during closed-track or open-road testing. Furthermore, M&S can support failure mode analysis early and iteratively through the ADS design and development process, long before prototype test vehicles or systems are available.

CHAPTER 7. SUMMARY AND CONCLUSIONS

A functional testing architecture and framework is an approach to support the safe deployment of ADS and evaluate and assess their performance. This report describes an example of a testing architecture and a scenario-based test framework. Efforts focused on the testing of ADS (SAE International L3–L5), where the ADS is fully capable of all aspects of the DDT. To facilitate the identification of the testing architecture and framework, common and relevant operational components for ADS were identified and evaluated, specifically these.

- ADS features
- ODD
- OEDR
- FO and FS strategies

Prototype ADS that have been conceived or that are currently under development were surveyed. A working list of 24 such proprietary systems were identified by performing a literature review and interacting with stakeholders and categorized into seven generic ADS features. Three of these generic features were down-selected to focus the remaining analyses. Potential ODDs for ADS were surveyed and identified, and a hierarchical ODD taxonomy was developed. An ADS's ODD is specified by the developing entity, but this taxonomy provides an early step in establishing an example of a common language that could be used. Important obstacles and events that ADS are likely to encounter within their ODD and potential response maneuvers and actions were surveyed and identified. The objects and events were derived from an evaluation of the expected normal driving scenarios for the given ADS features. Potential mitigation strategies that an ADS could employ in the event of a failure were also identified and evaluated. Both FO and FS strategies were identified and assessed for cases where the ADS can or cannot continue to function as intended.

The primary contribution of this report is the conceptual development of a test scenario framework that incorporates elements of each of these operational components. The framework uses a checklist-type approach to identify high-level scenario tests by specifying relevant tactical maneuvers, ODD, OEDR, and potential failures. Each of these components are then further specified to develop a comprehensive set of procedures for a given scenario test. The scenario framework lends itself well to being applied across the three testing techniques identified for the testing architecture (M&S, closed-track testing, and open-road testing), although specific test procedures and implementations will vary, depending on the technique and tools used. This test scenario framework and the sample test procedures developed can provide a launching point to more comprehensive ADS test development and ultimately, test execution. Figure 29 shows a sample ADS test scenario visualization, with the principal elements notionally specified. (In this figure, POV stands for principal other vehicle.)

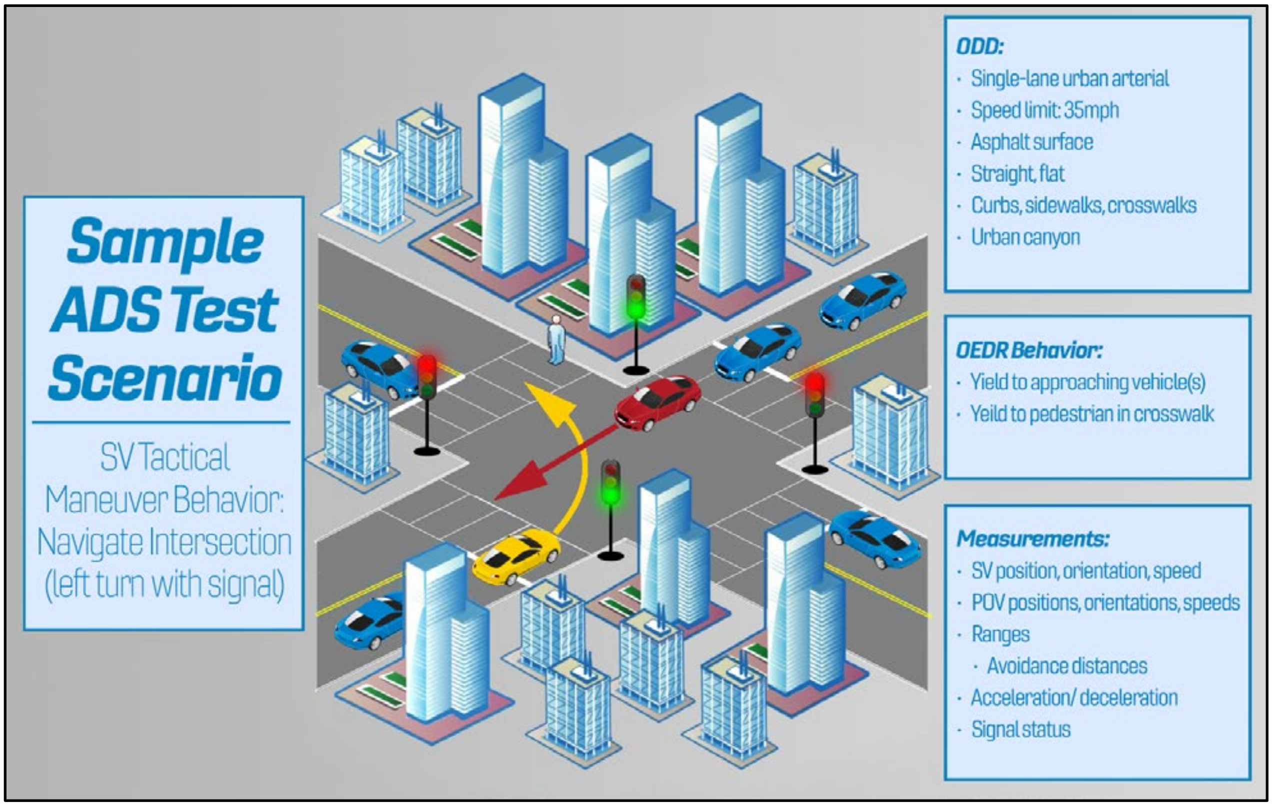

Figure 29. Sample ADS Test Scenario

The expansiveness of conceivable ODD, OEDR, and failure conditions presents a significant challenge to achieving comprehensive testing, even considering the test scenario framework identified during this project and described in this report. The concept of risk associated with driving scenarios, notionally based on probability and severity of occurrence, has helped focus the analyses of ODD, OEDR, and failure modes to identify an appropriate testing process. A "reasonable worst case" approach may prove sufficient for general safety assessments; however, it is necessary to extend testing beyond the reasonable cases to understand the performance boundaries and limitations of ADS. This report also identifies M&S capabilities and tools as a potential approach to addressing the expansiveness of these test components, as well as their potential combinations. M&S provide a number of features and advantages that make it suitable to play a role in this type of testing.

- Highly repeatable and reliable
- Rapid and inexpensive compared to other testing techniques
- Able to cover a wide range of scenarios and conditions efficiently
- Allow for assessment of impact of the sensitivity of those scenarios and conditions on ADS performance
- Allow for variance of test parameters to support estimation of risk
- Able to establish integrity of ADS subsystems to reduce overall system testing requirements
- Well-suited for certain types of fault injection

APPENDIX A. OPERATIONAL DESIGN DOMAIN SAMPLES

L3 CONDITIONAL TRAFFIC JAM DRIVE

ODD CHECKLIST: L3 Conditional Traffic Jam Drive	
PHYSICAL INFRASTRUCTURE	
Roadway Types	
Divided highway	Y
Undivided highway	N
Arterial	
Urban	
Rural	
Parking (surface lots, structures, private/public)	
Bridges	
Multi-lane/single lane	Multi-lane
Managed lanes (HOV, HOT,[13] etc.)	Y
On-off ramps	N
Emergency evacuation routes	
One way	If barriers present
Private roads	
Reversible lanes	
Intersection Types - signaled - U-turns - 4-way vs. 3-way vs. 2-way - stop sign - roundabout - merge lanes - left turn across traffic, one-way to one-way - right turn - multiple turn lane - crosswalk - toll plaza - railroad crossing	Signaled (4-way, 3-way), toll plaza
Other	
Roadway Surfaces	
Asphalt	Y
Concrete	
Mixed	
Grating	n/a
Brick	
Dirt	

[13] HOT- high occupancy toll

Gravel	
Scraped road	
Partially occluded	
Speed bumps	
Potholes	
Grass	
Other	
Roadway Edges & Markings	
Lane markers	Clear markers
Temporary lane markers	N
Shoulder (paved or gravel)	Limited to divided highway
Shoulder (grass)	Limited to divided highway
Lane barriers	Barrier, concrete or metal
Grating	Y
Rails	Barrier, concrete or metal
Curb	N
Cones	N
Other	
Roadway Geometry	
Straightaways	Y
Curves	n/a
Hills	
Lateral crests	
Corners (Regular, Blind)	
Negative obstacles	
Lane width	
Other	
OPERATION CONSTRAINTS	
Speed Limits	
Minimum Speed Limit	0 mph
Maximum Speed Limit	< 37 mph
Relative to Surrounding Traffic	n/a
Other	
Traffic Conditions	
Traffic density	Only heavy traffic with preceding vehicle to follow and convoy in adjacent lane
Altered (Accident Emergency vehicle, Construction, Closed road, Special event)	n/a
Other	

OBJECTS	
Signage	
Signs (e.g., stop, yield, pedestrian, railroad, school zone, etc.)	N
Traffic Signals (regular, flashing, school zone, fire dept. zone)	
Crosswalks	
Railroad crossing	
Stopped buses	
Construction signage	
First responder signals	
Distress signals	
Roadway user signals	
Hand signals	
Other	
Roadway Users	
Vehicle types (cars, light trucks, large trucks, buses, motorcycles, wide-load, emergency vehicles, construction or farming equipment, horse-drawn carriages/buggies)	Cars, trucks
Stopped vehicles	N
Other automated vehicles	Y
Pedestrians	N
Cyclists	N
Other	
Non-Roadway Users Obstacles	
Animals (e.g., dogs, deer, etc.)	N
Shopping carts	
Debris (e.g., pieces of tire, trash, ladders)	
Other	
ENVIRONMENTAL CONDITIONS	
Weather	
Wind	No information available at this time, but potentially may include mild rain and typical temperatures
Rain	
Snow	
Sleet	
Temperature	
Other	
Weather-Induced Roadway Conditions	
Standing Water	No information available at this time
Flooded Roadways	
Icy Roads	
Snow on Road	

Other	
Particulate Matter	
Fog	No information available at this time
Smoke	
Smog	
Dust/Dirt	
Mud	
Other	
Illumination	
Day (sun: Overhead, Back-lighting and Front-lighting)	No information available at this time
Dawn	
Dusk	
Night	
Street lights	
Headlights (Regular & High-Beam)	
Oncoming vehicle lights (Overhead Lighting, Back-lighting & Front-lighting)	
Other	
CONNECTIVITY	
Vehicles	
V2I and V2V communications	May have V2I to warn if driver incapacitated
Emergency vehicles	N
Other	
Remote Fleet Management System	
Does the system require an operations center?	N
Does remote operation expand ODD or support fault handling?	
Other	
Infrastructure Sensors	
Work zone alerts	N
Vulnerable road user	
Routing and incident management	
Other	
Digital Infrastructure	
GPS	Y
3-D Maps	Y
Pothole Locations	No information available at this time
Weather Data	
Infrastructure Data	
Other	

ZONES	
Geofencing	
CBDs	No information available at this time
School Campuses	
Retirement Communities	
Fixed Route	
Other	
Traffic Management Zones	
Temporary Closures	No information available at this time
Dynamic Traffic Signs	
Variable Speed Limits	
Temporary or Non-Existent Lane Marking	
Human-Directed Traffic	
Loading and Unloading Zones	
Other	
School/construction zones	
Dynamic speed limit	No information available at this time
Erratic pedestrian	
Vehicular behaviors	
Other	
Regions/States	
Legal/Regulatory	No information available at this time
Enforcement Considerations	
Tort	
Other	
Interference Zones	
Tunnels	No information available at this time
Parking Garage	
Dense Foliage	
Limited GPS	
Atmospheric Conditions	
Other	

L3 CONDITIONAL HIGHWAY DRIVE

ODD CHECKLIST: L3 Conditional Highway Drive	
PHYSICAL INFRASTRUCTURE	
Roadway Types	
Divided highway	Y
Undivided highway	N
Arterial	
Urban	
Rural	
Parking (surface lots, structures, private/public)	
Bridges	
Multi-lane/single lane	Multi-lane/ single lane
Managed lanes (HOV, HOT, etc.)	Y
On-off ramps	Y
Emergency evacuation routes	Y
One way	If barriers present
Private roads	
Reversible lanes	
Intersection Types - signaled - U-turns - 4-way vs. 3-way vs. 2-way - stop sign - roundabout - merge lanes - left turn across traffic, one-way to one-way - right turn - multiple turn lane - crosswalk - toll plaza - railroad crossing	Merge lanes, no intersections, limited information on other elements
Other	
Roadway Surfaces	
Asphalt	Y
Concrete	
Mixed	
Grating	n/a
Brick	
Dirt	
Gravel	
Scraped road	
Partially occluded	

Speed bumps	
Potholes	
Grass	
Other	
Roadway Edges & Markings	
Lane markers	Clear markers
Temporarily lane markers	N
Shoulder (paved or gravel)	Limited to divided highway
Shoulder (grass)	Limited to divided highway
Lane barriers	Y
Grating	Y
Rails	Y
Curb	N
Cones	N
Other	
Roadway Geometry	
Straightaways	Y
Curves	n/a
Hills	
Lateral crests	
Corners (Regular, Blind)	
Negative obstacles	
Lane width	
Other	
OPERATION CONSTRAINTS	
Speed Limits	
Minimum Speed Limit	0 mph
Maximum Speed Limit	Speed limit (55-70 mph)
Relative to Surrounding Traffic	n/a
Other	
Traffic Conditions	
Traffic density	No traffic restrictions
Altered (Accident Emergency vehicle, Construction, Closed road, Special event)	n/a
Other	
OBJECTS	
Signage	
Signs (e.g., stop, yield, pedestrian, railroad, school zone, etc.)	N
Traffic Signals (regular, flashing, school zone, fire dept. zone)	
Crosswalks	
Railroad crossing	

Stopped buses	
Construction signage	
First responder signals	
Distress signals	
Roadway user signals	
Hand signals	
Other	
Roadway Users	
Vehicle types (cars, light trucks, large trucks, buses, motorcycles, wide-load, emergency vehicles, construction or farming equipment, horse-drawn carriages/buggies)	Cars, trucks
Stopped vehicles	N
Other automated vehicles	Y
Pedestrians	N
Cyclists	N
Other	
Non-Roadway Users Obstacles	
Animals (e.g., dogs, deer, etc.)	Y
Shopping carts	
Debris (e.g., pieces of tire, trash, ladders)	
Other	
ENVIRONMENTAL CONDITIONS	
Weather	
Wind	No information available at this time, but potentially may include mild rain and typical temperatures
Rain	
Snow	
Sleet	
Temperature	
Other	
Weather-Induced Roadway Conditions	
Standing Water	No information available at this time
Flooded Roadways	
Icy Roads	
Snow on Road	
Other	
Particulate Matter	
Fog	No information available at this time
Smoke	
Smog	
Dust/Dirt	
Mud	

Other	
Illumination	
Day (sun: Overhead, Back-lighting and Front-lighting)	No information available at this time
Dawn	
Dusk	
Night	
Street lights	
Headlights (Regular & High-Beam)	
Oncoming vehicle lights (Overhead Lighting, Back-lighting & Front-lighting)	
Other	
CONNECTIVITY	
Vehicles	
V2I and V2V communications	May have V2I to warn if driver incapacitated
Emergency vehicles	N
Other	
Remote Fleet Management System	
Does the system require an operations center?	N
Does remote operation expand ODD or support fault handling?	
Other	
Infrastructure Sensors	
Work zone alerts	N
Vulnerable road user	
Routing and incident management	
Other	
Digital Infrastructure	
GPS	Y
3-D Maps	Y
Pothole Locations	No information available at this time
Weather Data	
Infrastructure Data	
Other	
ZONES	
Geofencing	
CBDs	No information available at this time
School Campuses	
Retirement Communities	
Fixed Route	
Other	

Traffic Management Zones	
Temporary Closures	No information available at this time
Dynamic Traffic Signs	
Variable Speed Limits	
Temporary or Non-Existent Lane Marking	
Human-Directed Traffic	
Loading and Unloading Zones	
Other	
School/construction zones	
Dynamic speed limit	No information available at this time
Erratic pedestrian	
Vehicular behaviors	
Other	
Regions/States	
Legal/Regulatory	No information available at this time
Enforcement Considerations	
Tort	
Other	
Interference Zones	
Tunnels	No information available at this time
Parking Garage	
Dense Foliage	
Limited GPS	
Atmospheric Conditions	
Other	

L4 HIGHLY AUTOMATED TNC

ODD CHECKLIST: L4 Highly Automated TNC	
PHYSICAL INFRASTRUCTURE	
Roadway Types	
Divided highway	Y
Undivided highway	
Arterial	
Urban	
Rural	
Parking (surface lots, structures, private/public)	
Bridges	
Multi-lane/single lane	
Managed lanes (HOV, HOT, etc.)	No information available at this time
On-off ramps	
Emergency evacuation routes	
One way	
Private roads	
Reversible lanes	
Intersection Types - signaled - U-turns - 4-way vs. 3-way vs. 2-way - stop sign - roundabout - merge lanes - left turn across traffic, one-way to one-way - right turn - multiple turn lane - crosswalk - toll plaza - railroad crossing	Yes to signalized intersections, 4-way, 3-way, and 2-way intersections, stop signs, left turn across traffic, right turn. No information on roundabout, merge, multiple turn lane, toll plaza and railroad crossings
Other	
Roadway Surfaces	
Asphalt	Y
Concrete	
Mixed	
Grating	No information is available
Brick	
Dirt	
Gravel	
Scraped road	
Partially occluded	

Speed bumps	
Potholes	
Grass	
Other	
Roadway Edges & Markings	
Lane markers	Clear markers
Temporarily lane markers	No information available, but several of these are likely to be needed to enable travel across a city, including concrete barrier, grating, rail, curb
Shoulder (paved or gravel)	
Shoulder (grass)	
Concrete barriers	
Grating	
Rails	
Curb	
Cones	
Other	
Roadway Geometry	
Straightaways	Y
Curves	
Hills	
Lateral crests	
Corners (Regular, Blind)	
Negative obstacles	
Lane width	
Other	
OPERATION CONSTRAINTS	
Speed Limits	
Minimum Speed Limit	At least 35 mph is likely to be needed to traverse a city
Maximum Speed Limit	
Relative to Surrounding Traffic	n/a
Other	
Traffic Conditions	
Traffic density	All conditions
Altered (Accident Emergency vehicle, Construction, Closed road, Special event)	Y
Other	
OBJECTS	
Signage	
Signs (e.g., stop, yield, pedestrian, railroad, school zone, etc.)	Yes, most if not all of these will be necessary to operate across a city
Traffic Signals (regular, flashing, school zone, fire dept. zone)	
Crosswalks	
Railroad crossing	

Stopped buses	
Construction signage	
First responder signals	
Distress signals	
Roadway user signals	
Hand signals	
Other	
Roadway Users	
Vehicle types (cars, light trucks, large trucks, buses, motorcycles, wide-load, emergency vehicles, construction or farming equipment, horse-drawn carriages/buggies)	Y
Stopped vehicles	
Other automated vehicles	
Pedestrians	
Cyclists	
Other	
Non-Roadway Users Obstacles	
Animals (e.g., dogs, deer, etc.)	Y
Shopping carts	
Debris (e.g., pieces of tire, trash, ladders)	
Other	
ENVIRONMENTAL CONDITIONS	
Weather	
Wind	Likely limited capability
Rain	
Snow	
Sleet	No information available at this time
Temperature	
Other	
Weather-Induced Roadway Conditions	
Standing Water	No information available at this time
Flooded Roadways	
Icy Roads	
Snow on Road	
Other	
Particulate Matter	
Fog	Limited capability
Smoke	
Smog	
Dust/Dirt	
Mud	
Other	

Illumination	
Day (sun: Overhead, Back-lighting and Front-lighting)	Y
Dawn	
Dusk	
Night	
Street lights	
Headlights (Regular & High-Beam)	
Oncoming vehicle lights (Overhead Lighting, Back-lighting & Front-lighting)	No information available at this time
Other	
CONNECTIVITY	
Vehicles	
V2I and V2V communications	No definitive information; connectivity is being tested by many potential implementers
Emergency vehicles	No information available
Other	
Remote Fleet Management System	
Does the system require an operations center?	No information available at this time
Does remote operation expand ODD or support fault handling?	
Other	
Infrastructure Sensors	
Work zone alerts	No information available at this time
Vulnerable road user	
Routing and incident management	
Other	
Digital Infrastructure	
GPS	No information available at this time
3-D Maps	
Pothole Locations	
Weather Data	
Infrastructure Data	
Other	
ZONES	
Geofencing	
CBDs	Y
School Campuses	No information available at this time
Retirement Communities	
Fixed Route	
Other	

Traffic Management Zones	
Temporary Closures	No information available at this time
Dynamic Traffic Signs	
Variable Speed Limits	
Temporary or Non-Existent Lane Marking	
Human-Directed Traffic	
Loading and Unloading Zones	N
Other	
School/construction zones	
Dynamic speed limit	No information available at this time
Erratic pedestrian	
Vehicular behaviors	
Other	
Regions/States	
Legal/Regulatory	No information available at this time
Enforcement Considerations	
Tort	
Other	
Interference Zones	
Tunnels	No information
Parking Garage	Y
Dense Foliage	No information
Limited GPS	
Atmospheric Conditions	
Other	

APPENDIX B. MODELING AND SIMULATION FOR SCENARIO TESTING

As described in Chapter 5, M&S could offer a good basis for scenario testing of ADS. Simulation-based tests feature highly repeatable and reliable testing platforms due to the controlled environments established by the models. Additionally, software-based simulation provides a rapid and inexpensive testing platform. In addition, certain types of M&S enable controlled testing of micro- to macro-scale models (e.g., vehicle subsystems or a large-scale transportation network, respectively). The modular nature of M&S tools makes them suitable for the testing of systems or subsystems or both.

ADSs are complex, with multiple subsystems interacting with each other. Modeling transportation networks enables the testing of ADS in their entirety and individual subsystems under different operational environments. Such M&S-based methods are increasingly becoming the industry method of choice for certain types of testing of ADS and ADS subsystems before they go into the field for controlled-environment and open-road field tests.[14]

Consider the functional diagram of an ADS. As shown in Figure 30 below, a typical ADS consists of five modules/processes which are active as an iterative list that is enacted at a high frequency.

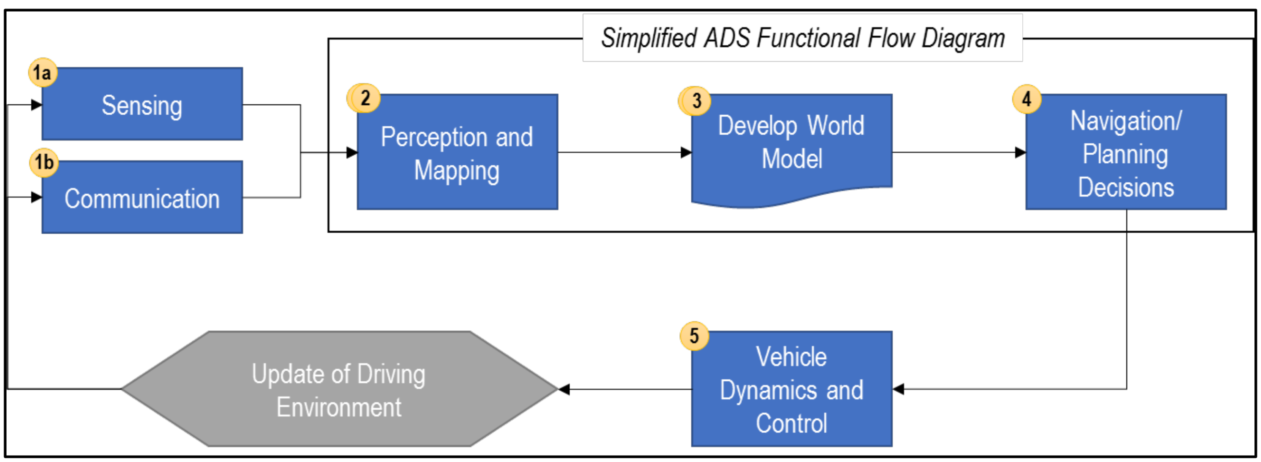

Figure 30. Simplified ADS Functional Flow Diagram

The modules/processes are:

1. Sensing – A variety of sensors, such as radar, lidar, etc., detect external stimuli and communicate with external agents, such as other vehicles, the cloud environment, and infrastructure.
2. Perception and Mapping – High-accuracy localization and output from sensing and communication are used to understand the externalities that the vehicle is subject to.

[14] For example, Alphabet's Waymo has been using a custom-designed simulation system named "Carcraft," to test its self-driving vehicle software under different operational characteristics and detection parameters. Similarly, automated driving OEMs use software such as Cognata to conduct "virtual tests" of its systems prior to deploying the code for on-road tests.

3. Develop World Model – A world model is developed based on the perception and mapping that defines the persistent and transient state of the vehicle.
4. Navigation/Planning Decisions – Navigation and planning are performed based on the path-planning algorithms defined within the ADS.
5. Vehicle Dynamics and Control – Vehicle dynamic and control processes take place as a consequence of navigation and planning decisions and trajectory calculations.

Please note that this set of iterative processes represents a simplified ADS and that each of the processes consists of smaller processes and subsystems. M&S may be a suitable method to test the entire system or individual subsystems and is being used effectively by industry to continuously improve driving algorithms. Applications of M&S in testing of ADS are numerous and are supported by different types of simulation:

1. Parameter characterization – By simulating a range of operational parameters such as visibility, sensing, communication delay, and world model completeness, this kind of testing will help evaluate the parameters that form the ODD of the ADS.
2. Subsystem testing – Based on the functional diagram, M&S can be used to test different subsystems. For example, a sensor fusion simulation tool can be used to assess how noises in the provided sensor data transform to the developed world model and associated ADS actions.
3. Decision modules – M&S can also be used to perform system testing under different operational conditions to allow testing of the entire ADS based on its navigation decisions under each event.
4. Fault detection – M&S can also be used to evaluate a system or subsystem's ability to recognize and respond to faults or failures.

Some of these use cases are described further below.

Parameter Characterization

To support the validation and verification of ADS, it is vital to understand the range of operational parameters that form the system's ODD. Full-range parameter testing will help to determine that range and is conducted through Monte Carlo simulations of different parameters that define an ODD. For example, the range of visibility under which the machine-vision algorithm can confidently parse the sensor data can be assessed by providing sensor cloud data that emulates different levels of lighting.

Subsystem Testing

As discussed in Chapter 5, the modular nature of simulations allows SIL and HIL simulations. These are excellent options when conducting subsystem testing, where components of a fully known simulation setup are replaced with testable subsystems. For example, to test the navigation and path-planning algorithms, an SIL system can be configured where the path-planning algorithms interact with a variety of world models and provide output to the vehicle dynamics models. By assessing the stability of the models to deal with different situations, subsystem testing can be done to support overall performance assessment.

HIL tests can be performed, for example, to assess how sensors react to identifying objects (such as sign boards and pedestrians under different lighting conditions) by how they translate to the development of world models. Conducting subsystem testing involves emulating an ADS as a modular system that is representative of the feature. Several simulation programs exist that can be used to emulate components of a typical ADS. Some examples are provided in the following table.

Table 59. Simulation Software Examples

Simulated ADS Process	Simulation Type	Description	Example Software Applications
1a, 2	Sensor Fusion	Represents applications that emulate sensor data when an environment is presented to them. The sensor data could be developed either in the form of vector graphics or as a sensor point cloud.	MATLAB ADS Toolbox
1b	V2V/V2I Communication	Represents applications that emulate communications interaction between vehicles and other infrastructure elements so that parameters such as latency and error rates can be incorporated into data packets.	Riverside Modeler, OMNET, etc.
3	Simulate World Models	Represents applications that emulate the world model, either based on sensor data or from a known environment.	Cognata, MATLAB ADS
5	Vehicle Dynamics	Represents applications that emulate the physical characteristics of a vehicle when subject to path-planning and navigation decisions.	Simulink, CarSim, etc.
Process	Transportation Network Modeling	Represents applications that can emulate V2V, V2I, and vehicle-to-pedestrian interaction with respect to the navigation of each of the elements in a transportation network.	Vissim, Aimsun, TransModeler, etc.

Fault Detection

As discussed in Chapter 6, ADS may be prone to a wide variety of faults that could lead to the system not performing as expected or intended. Many types of errors can be modeled and incorporated into a virtual environment to induce faults or failures (e.g., sensor noise, hardware failure). M&S can be used to efficiently and safely replicate a significant amount of the potential faults and failures, and therefore allow for analysis of the ADS's implemented failure mitigation strategies. Critical failures can be induced to elicit an FS response, while non-critical failures can be induced to elicit an FO response.

APPENDIX C. SAMPLE TEST PROCEDURES

PERFORM LANE CHANGE/LOW-SPEED MERGE

ODD Characteristics

- Multi-lane divided highway (or similar)
- Asphalt or concrete
- Straight, flat
- Clear lane markers
- Clear sky, dry, daylight

OEDR Characteristics

- Optional object vehicles

Failure Behaviors

- None

Test Protocol

Vehicle Platforms

Subject Vehicle– The vehicle equipped with the ADS feature being tested.

Principal Other Vehicles– The primary object vehicles for which the detection and response of the subject vehicle are being tested.

Vehicle Roles

The SV is a light-duty vehicle equipped with an ADS feature that is being evaluated.

The POVs are other fully functional (operational brake lights, etc.) light-duty vehicles (e.g., sedan, SUVs, pickup trucks, etc.) or vehicle surrogates. If a vehicle surrogate is used, it would ideally be frangible and should possess similar mobility and detection characteristics as a regular light-duty vehicle.

- Ability to be towed or remotely controlled to follow the test course
- Ability to achieve test speeds
- Similar visual appearance
- Similar radar and/or lidar reflectivity

Test Scenarios

Table 60. Perform Lane Change Test Scenarios

Maneuver	SV Speed kph (mph)	POV[15] Speed kph (mph)	Location of POV_1	Location of POV_2	Location of POV_3
Baseline 15 PLC_B_15	24 (15)	N/A	N/A	N/A	N/A
Baseline 25 PLC_B_25	40 (25)	N/A	N/A	N/A	N/A
Baseline 35 PLC_B_35	56 (35)	N/A	N/A	N/A	N/A
Simple Positive 15 PLC_SP_15	24 (15)	24 (15)	Rear bumper 6 m (20 ft) in front of SV front bumper	N/A	N/A
Simple Positive 25 PLC_SP_25	40 (25)	40 (25)	Rear bumper 6 m (20 ft) in front of SV front bumper	N/A	N/A
Simple Positive 35 PLC_SP_35	56 (35)	56 (35)	Rear bumper 6 m (20 ft) in front of SV front bumper	N/A	N/A
Complex Positive 15 PLC_CP_15	24 (15)	24 (15)	Rear bumper 8 m (25 ft) in front of SV front bumper	Front bumper 25 ft (8 m) behind SV rear bumper	N/A
Complex Positive 25 PLC_CP_25	40 (25)	40 (25)	Rear bumper 8 m (25 ft) in front of SV front bumper	Front bumper 25 ft (8 m) behind SV rear bumper	N/A
Complex Positive 35 PLC_CP_35	56 (35)	56 (35)	Rear bumper 8 m (25 ft) in front of SV front bumper	Front bumper 25 ft (8 m) behind SV rear bumper	N/A
Simple Negative 15 PLC_SN_15	24 (15)	24 (15)	Rear bumper ≤ 5 m (15 ft) in front of SV front bumper	Front bumper even with SV front bumper	Front bumper ≤ 15 ft (5 m) behind SV rear bumper
Simple Negative 25 PLC_SN_25	40 (25)	40 (25)	Rear bumper ≤ 6 m (20 ft) in front of SV front bumper	Front bumper even with SV front bumper	Front bumper ≤ 20 ft (6 m) behind SV rear bumper
Simple Negative 35 PLC_SN_35	56 (35)	56 (35)	Rear bumper ≤ 8 m (25 ft) in front of SV front bumper	Front bumper even with SV front bumper	Front bumper ≤ 25 ft (8 m) behind SV rear bumper

[15] Principal other vehicle

Test Scenario Sample Visualizations

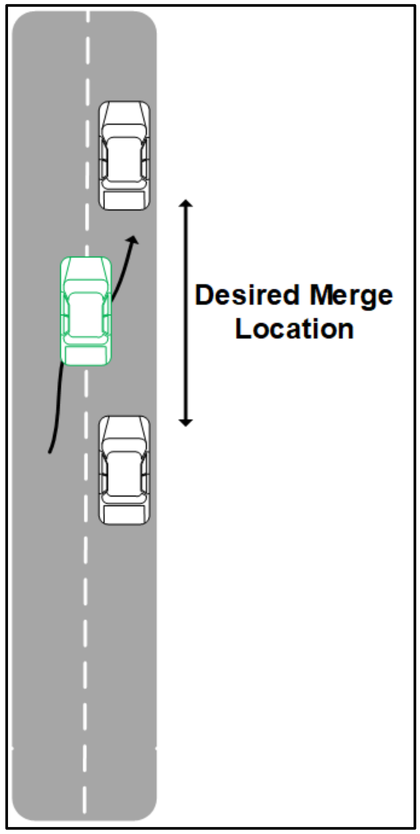

Figure 31. Merge Test Scenario

General Procedures

Ambient Conditions

- The ambient temperature shall be between 0 ˚C (32 ˚F) and 38 ˚C (100 ˚F).
- The maximum wind speed shall be no greater than 10 m/s (22 mph).
- Tests should not be performed during periods of inclement weather. This includes, but is not limited to, rain, snow, hail, fog, smoke, or ash.
- Unless specified otherwise, the tests shall be conducted during daylight hours with good atmospheric visibility (defined as an absence of fog and the ability to see clearly for more than 5,000 m). The test shall not be conducted with the vehicle oriented into the sun during very low sun angle conditions (the sun is oriented 15 degrees or less from horizontal), where low sun angles degrade forward visibility for the test vehicle operators.
- Unless stated otherwise, all tests shall be conducted such that there are no overhead signs, bridges, or other significant structures over, or near, the testing site. Each trial shall be conducted with no vehicles, obstructions, or stationary objects within one lane width of either side the vehicle path.

Personnel

A test execution team would include an SV safety driver, an experimenter, and one or more POV operators, and potentially external observers. The team would typically coordinate using person-to-person radios for communication.

The SV safety driver would be skilled in the operation of the ADS feature under test. This skill and knowledge would include familiarity with the ADS feature user interface, activation and deactivation procedures, and potential failure modes. The safety driver must be capable of disengaging the ADS feature under test and bringing the vehicle to a minimal risk state, if the experiment approaches or reaches an unsafe state.

The experimenter observes and directs execution of each test trial and would typically be in the SV as the test is executed. The experimenter would also be knowledgeable of the operation of the ADS feature under test to determine if it is functioning properly. The experimenter records test conditions and test trial notes, and judges apparent test trial validity. The experimenter might also operate the data acquisition system and other test equipment.

The POV operator would hold a valid driver's license and be comfortable operating the POVs. The POV operator would be responsible for positioning the POVs for each trial. If the POV is a vehicle surrogate, the POV operator would be knowledgeable of its construction and mobility and be able to position and control the surrogate for the prescribed trials.

The other observers may be responsible for operating external data collection equipment (e.g., video recording of test execution, etc.).

Test Data and Equipment

Relevant data listed below should be collected to support the metrics identified for each test scenario/trial. Options for equipment to collect the individual data elements are also provided.

- Vehicle Positions (SV and POVs): GPS/inertial navigation system (< X cm RMS, 95% confidence interval)
- Vehicle Speeds (SV and POVs): GPS/INS, estimated from position information
- Ranges (closest points between SV and POV): lidar, radar, estimated from position information
- Turn signal status
- Ambient Conditions:
  - Temperature: thermometer (˚C, ˚F)
  - Wind Speed: anemometer (mph, kph)
  - Precipitation: range gauge (in/h, cm/h)
  - Time: clock
  - Sun position: manual observation
- Test Documentation: camera
- Experimenter Notes

Test Facility

For performing lane change competency tests, the test facility is a straight, flat, and level roadway that includes one driving lane, whose surface is constructed of asphalt or concrete, and whose driving lane is at least 12 ft wide and delineated by lane markings visible to the vehicle operators. The only exceptions to this may be for tests where the roadway is curved instead of straight. The length of the roadway will be sufficient to allow the ADS feature under test to establish and maintain a specified lane and speed, and to allow the SV to stop or exit the course, if applicable. The length of the test course is at least greater than the maximum SV perception range, or 105 m, whichever is greater.

Scenario Test: PLC_Comp_15 – Straight Road, Complex, 15 mph

Scenario Description

A vehicle equipped with an ADS feature is driving along a straight urban street with multiple lanes. It is approaching a necessary turn and needs to change lanes to position itself in the appropriate lane to make the turn.

Test Subject and Purpose

The subject of this test is an ADS feature whose specified ODD includes operation on improved urban roads with other traffic vehicles. The test determines the ability of the ADS feature to change lanes in the presence of other traffic vehicles.

Initial Conditions

The SV will initially be static in the prescribed positions and orientations.

The POVs will initially be static in the prescribed positions ahead of the SV in an adjacent lane. The leading edge of POV_2 will be approximately 3 m behind the trailing edge of POV_1.

Test Velocities

The steady state velocities of the SV and POV are specified for each trial or set of trials.

Metrics

Disengagements

A disengagement is defined as the SV safety driver deactivating the ADS feature being evaluated and taking manual control of the SV. The location and manner of the disengagement should be included in the experimenter’s notes.

Separation Distances
The separation distances are the distances between the SV and each of the POVs. The minimum separation distances (closest approach) should be identified, as well as the separation distances being observed as a continuum.

Signal Status
Signal status is the activation state of the SV turn signal, to be measured at a periodic rate to determine when the signal is activated and deactivated.

Execution of Procedure

1. The POVs are positioned in the center of the right lane of the test road at their specified locations.
2. The SV is positioned in the center of a left lane of the test road immediately adjacent to POV_2.
3. The SV is given a target destination in the right lane at the end of the test course.
4. The SV's navigation system is activated to begin traversing the course.
5. As the SV begins moving, the POVs simultaneously begin accelerating to the specified steady state velocity while maintaining the approximate separation distance.
6. Each trial ends when the SV successfully changes lanes to merge between POV_1 and POV_2 and stops at the target destination, or the SV driver must intervene.
7. After the end of the trial, the SV driver disengages the ADS feature (if it is not already disengaged).

Trial Validity

An individual trial is valid if during the trial:

1. The velocity of the POVs did not exceed ±X kph from the specified steady state velocities.
2. The separation distance between the POVs did not exceed ±X m from the specified separation distance.
3. The POVs did not deviate from the specified lane.

NOTE: Other trial validity requirements might include GPS coverage requirements.

Evaluation Metrics

A trial is successful if the SV:

- Successfully accelerates and merges between the two POVs with a minimum separation distance of ≥X m with each POV.
- Successfully decelerates and merges behind POV_2 with a minimum separation distance of ≥X m with POV_2.
- Successfully accelerates and merges ahead of POV_1 with a minimum separation distance of ≥X m with POV_1 and does not exceed Y kph of the specified speed limit.

PERFORM VEHICLE FOLLOWING

ODD Characteristics

- Multi-lane divided highway (or similar)
- Asphalt or concrete
- Straight/curved, flat
- Clear lane markers
- Clear sky, dry, daylight

OEDR Characteristics

- Lead object vehicle

Failure Behaviors

- None

Test Protocol

Vehicle Platforms

Subject Vehicle– The vehicle equipped with the ADS feature being tested.

Principal Other Vehicle– The primary object vehicle for which the detection and response of the SV are being tested.

Vehicle Roles

The SV is a light-duty vehicle equipped with an ADS feature that is being evaluated.

The POV is another fully functional (operational brake lights, etc.) light-duty vehicle (e.g., sedan, SUV, pickup truck, etc.) or vehicle surrogate. If a vehicle surrogate is used, it would ideally be frangible and should possess similar mobility and detection characteristics as a regular light-duty vehicle.

- Able to be towed or remotely controlled to follow the test course
- Able to achieve test speeds
- Similar visual appearance
- Similar radar and/or lidar reflectivity

Test Scenarios

Table 61. Vehicle Following Test Scenarios

Maneuver	SV Speed kph (mph)	POV Speed kph (mph)	Initial Headway; m (ft)[1]
Straight 25, slower speed VF_S_25_Slow	40 (25)	32 (20)	> 30 (> 100)
Straight 45, slower speed VF_S_45_Slow	72 (45)	64 (40)	> 68 (> 225)
Straight 65, slower speed VF_S_55_Slow	105 (65)	96 (60)	> 105 (> 345)
Curve 25, slower speed VF_C_25_Slow	40 (25)	32 (20)	> 30 (> 100)
Curve 45, slower speed VF_C_45_Slow	72 (45)	64 (40)	> 68 (> 225)
Curve 65, slower speed VF_C_65_Slow	105 (65)	96 (60)	> 105 (> 345)

Test Scenario Sample Visualizations

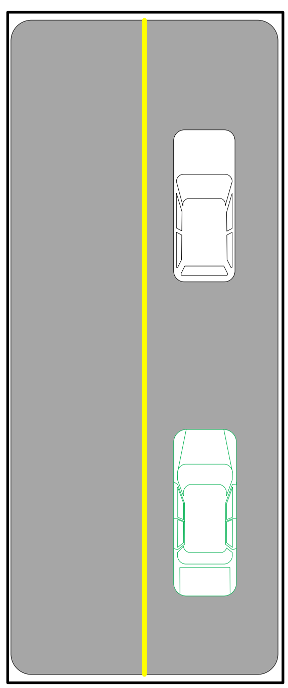

Figure 32. Vehicle Following Test Scenario

General Procedures

Ambient Conditions

- The ambient temperature shall be between 0 ˚C (32 ˚F) and 38 ˚C (100 ˚F).
- The maximum wind speed shall be no greater than 10 m/s (22 mph).
- Tests should not be performed during periods of inclement weather. This includes, but is not limited to, rain, snow, hail, fog, smoke, or ash.
- Unless specified otherwise, the tests shall be conducted during daylight hours with good atmospheric visibility (defined as an absence of fog and the ability to see clearly for more than 5,000 m). The test shall not be conducted with the vehicle oriented into the sun during very low sun angle conditions (the sun is oriented 15 degrees or less from horizontal), where low sun angles degrade forward visibility for the test vehicle operators.
- Unless stated otherwise, all tests shall be conducted such that there are no overhead signs, bridges, or other significant structures over, or near, the testing site. Each trial shall be conducted with no vehicles, obstructions, or stationary objects within one lane width of either side the vehicle path.

Personnel

A test execution team would include an SV safety driver, an experimenter, a POV operator, and potentially external observers. The team would typically coordinate using person-to-person radios for communication.

The SV safety driver would be skilled in the operation of the ADS feature under test. This skill and knowledge would include familiarity with the ADS feature user interface, activation and deactivation procedures, and potential failure modes. The safety driver must be capable of disengaging the ADS feature under test and bringing the vehicle to a minimal risk state, if the experiment approaches or reaches an unsafe state.

The experimenter observes and directs execution of each test trial and would typically be in the SV as the test is executed. The experimenter would also be knowledgeable of the operation of the ADS feature under test to determine if it is functioning properly. The experimenter records test conditions and test trial notes and judges apparent test trial validity. The experimenter might also operate the data acquisition system and other test equipment.

The POV operator would hold a valid driver’s license and be comfortable operating the POV. The POV operator would be responsible for following the prescribed lane at the prescribed speed for each trial. If the POV is a vehicle surrogate, the POV operator would be knowledgeable of its construction and mobility and be able to position and control the surrogate for the prescribed trials.

The other observers may be responsible for operating external data collection equipment (e.g., video recording of test execution, etc.).

Test Data and Equipment

Relevant data listed below should be collected to support the metrics identified for each test scenario/trial. Options for equipment to collect the individual data elements are also provided:

- Vehicle Positions (SV and POV): GPS/INS (< X cm root mean square (RMS) error, 95% confidence interval)
- Vehicle Speeds (SV and POV): GPS/INS, estimated from position information
- Ranges (following distance between SV and POV): lidar, radar, estimated from position information
- Ambient Conditions:
  - Temperature: thermometer (˚C, ˚F)
  - Wind Speed: anemometer (mph, kph)
  - Precipitation: range gauge (in/h, cm/h)
  - Time: clock
  - Sun position: manual observation
- Test Documentation: camera
- Experimenter Notes

Test Facility

For vehicle-following competency tests, the test facility is a straight, flat, and level roadway that includes one driving lane, whose surface is constructed of asphalt or concrete, and whose driving lane is at least 12 ft wide and delineated by lane markings visible to the vehicle operators. The only exceptions to this may be for tests where the roadway is curved instead of straight. The length of the roadway will be sufficient to allow the ADS feature under test to establish and maintain a specified lane and speed before encountering the POV, and to allow the SV to stop or exit the course, if applicable. The length of the test course is at least greater than the maximum SV perception range, or 105 m, whichever is greater. The test course should be a single lane so as not to allow the SV to change lanes to maneuver around the POV (if that is a capability of the ADS feature.)

Scenario Tests: VF_S_25_Slow – Straight Road, POV Slower than SV

Scenario Description

A vehicle equipped with an ADS feature is driving along a straight highway or urban road with one or more lanes. It approaches a slower moving lead vehicle in the same lane from behind.

Test Subject and Purpose

The subject of this test is an ADS feature whose specified ODD includes operation on improved roads with other traffic vehicles. The test determines the ability of the ADS feature to maintain a safe following distance behind another traffic vehicle.

Initial Conditions

The SV will initially be static in the prescribed positions and orientations.

The POV will initially be static in the prescribed positions ahead of the SV.

Test Velocities

The steady state velocities of the SV and POV are specified for each trial or set of trials.

Metrics

Disengagements

A disengagement is defined as the SV safety driver deactivating the ADS feature being evaluated and taking manual control of the SV. The location and manner of the disengagement should be included in the experimenter's notes.

Following Distance

The following distance is the distance between the leading edge (front bumper) of the SV and the trailing edge (rear bumper) of the POV. The minimum following distance (closest approach) should be identified, as well as the following distance being observed as a continuum.

Deceleration Rate

The deceleration rate is the rate of change of speed of the vehicle (presuming that the vehicle slows down in this case). Ideally, the rate of change would be smooth, as opposed to an abrupt deceleration as the SV approaches the POV.

Execution of Procedure

1. The POV is positioned in the center of a lane of the test road at the specified starting location.
2. The SV is positioned in the center of a lane of the test road at the specified initial headway.
3. The SV is given a target destination at the end of the test course such that it will remain in the lane as it traverses the course and reaches the specified speed.
4. The SV's navigation system is activated to begin traversing the course.
5. The POV accelerates to and maintains the specified speed while maintaining the specified lane.
6. The SV approaches the POV at the specified speed (higher than the POV speed) in the specified lane.
7. Each trial ends when the SV successfully stops at the target destination, or the SV driver must intervene.
8. After the end of the trial, the SV driver disengages the ADS feature (if it is not already disengaged).

Trial Validity

An individual trial is valid if during the trial:

1. The velocity of the SV did not exceed ±X kph from the specified steady state velocity before the POV came within its perception horizon.
2. The velocity of the POV did not exceed ±X kph from the specified steady state velocity.
3. The POV did not deviate from the specified lane.
4. The yaw rate of the POV did not exceed ±X degrees/s.

   NOTE: Other trial validity requirements might include GPS coverage requirements.

Evaluation Metrics

A trial is successful if the SV remains within its prescribed lane and reduces its speed to maintain a safe, speed-dependent following distance behind the POV for the remaining length and duration of the trial.

MOVE OUT OF TRAVEL LANE/PARK

ODD Characteristics

- Multi-lane arterial street (or similar)
- Asphalt or concrete
- Straight, flat
- Clear lane markers
- Clear sky, dry, daylight

OEDR Characteristics

- Optional object vehicles

Failure Behaviors

- None

Test Protocol

Vehicle Platforms

Subject Vehicle– The vehicle equipped with the ADS feature being tested.

Principal Other Vehicles– The primary object vehicles for which the detection and response of the SV are being tested.

Vehicle Roles

The SV is a light-duty vehicle equipped with an ADS feature that is being evaluated.

The POVs are other fully functional (operational brake lights, etc.) light-duty vehicles (e.g., sedan, SUV, pickup truck, etc.) or vehicle surrogates. If a vehicle surrogate is used, it would ideally be frangible and should possess similar mobility and detection characteristics as a regular light-duty vehicle:

- Ability to be towed or remotely controlled to follow the test course
- Ability to achieve test speeds
- Similar visual appearance
- Similar radar and/or lidar reflectivity

Test Scenarios

Table 62. Move Out of Travel Lane Test Scenarios

Maneuver	SV Speed kph (mph)	POV Speed kph (mph)	# of POVs	Location of POV_1	Location of POV_n	Length of "Parking" Zone m (ft)
Simple Positive 15 MOTL_Simp_15	24 (15)	0 (0)	1	Rear bump. 12 m (40 ft) beyond Int_1	Front bump. ≥24 m (80 ft) before Int_2	24 (80)
Simple Positive 25 MOTL_Simp_15	40 (25)	0 (0)	1	Rear bump. 12 m (40 ft) beyond Int_1	Front bump. ≥24 m (80 ft) before Int_2	24 (80)
Complex Positive 15 MOTL_Comp_15	24 (15)	0 (0)	≥ 2	Rear bump. 11 m (35 ft) beyond Int_1	Front bump. 6 m (20 ft) before Int_2	24 (80)
Complex Positive 25 MOTL_Comp_25	40 (25)	0 (0)	≥ 2	Rear bump. 11 m (35 ft) beyond Int_1	Front bump. 6 m (20 ft) before Int_2	24 (80)
Negative 15 MOTL_Neg_15	24 (15)	0 (0)	≥ 2	Rear bump. 6 m (20 ft) beyond Int_1	Front bump. 6 m (20 ft) before Int_2	≤ 3 (10)
Negative 25 MOTL_Neg_25	40 (25)	0 (0)	≥ 2	Rear bump. 6 m (20 ft) beyond Int_1	Front bump. 6 m (20 ft) before Int_2	≤ 3 (10)
*Int = Intersection, bump. = bumper						

Test Scenario Sample Visualizations

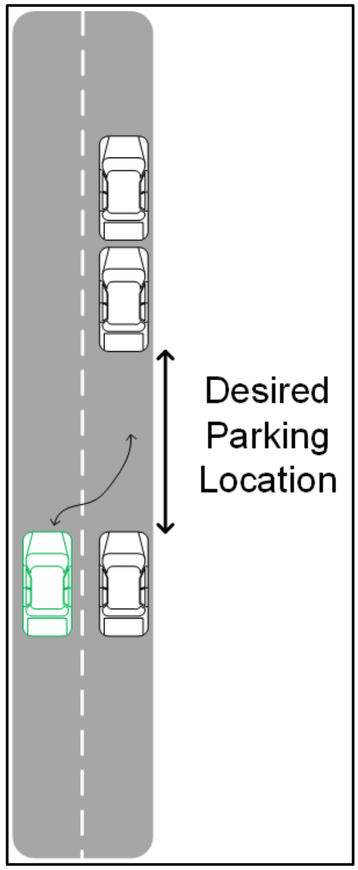

Figure 33. Move Out of Travel Lane/Park Test Scenario

General Procedures

Ambient Conditions

- The ambient temperature shall be between 0 ˚C (32 ˚F) and 38 ˚C (100 ˚F).
- The maximum wind speed shall be no greater than 10 m/s (22 mph).
- Tests should not be performed during periods of inclement weather. This includes, but is not limited to, rain, snow, hail, fog, smoke, or ash.
- Unless specified otherwise, the tests shall be conducted during daylight hours with good atmospheric visibility (defined as an absence of fog and the ability to see clearly for more than 5,000 m). The test shall not be conducted with the vehicle oriented into the sun during very low sun angle conditions (the sun is oriented 15 degrees or less from horizontal), where low sun angles degrade forward visibility for the test vehicle operators.
- Unless stated otherwise, all tests shall be conducted such that there are no overhead signs, bridges, or other significant structures over, or near, the testing site. Each trial shall be conducted with no vehicles, obstructions, or stationary objects within one lane width of either side the vehicle path.

Personnel

A test execution team would include an SV safety driver, an experimenter, a POV operator, and potentially external observers. The team would typically coordinate using person-to-person radios for communication.

The SV safety driver would be skilled in the operation of the ADS feature under test. This skill and knowledge would include familiarity with the ADS feature user interface, activation and deactivation procedures, and potential failure modes. The safety driver must be capable of disengaging the ADS feature under test and bringing the vehicle to a minimal risk state, if the experiment approaches or reaches an unsafe state.

The experimenter observes and directs execution of each test trial and would typically be in the SV as the test is executed. The experimenter would also be knowledgeable of the operation of the ADS feature under test to determine if it is functioning properly. The experimenter records test conditions and test trial notes, and judges apparent test trial validity. The experimenter might also operate the data acquisition system and other test equipment.

The POV operator would hold a valid driver's license and be comfortable operating the POVs. The POV operator would be responsible for positioning the POVs for each trial. If the POV is a vehicle surrogate, the POV operator would be knowledgeable of its construction and mobility and be able to position and control the surrogate for the prescribed trials.

The other observers may be responsible for operating external data collection equipment (e.g., video recording of test execution).

Test Data and Equipment

Relevant data listed below should be collected to support the metrics identified for each test scenario/trial. Options for equipment to collect the individual data elements are also provided:

- Vehicle Positions (SV and POVs): GPS/INS (< X cm root mean square error, 95% confidence interval)
- Vehicle Speeds (SV and POVs): GPS/INS, estimated from position information
- Ranges (closest points between SV and POV): lidar, radar, estimated from position information
- Turn signal status
- Ambient Conditions:
  - Temperature: thermometer (˚C, ˚F)
  - Wind Speed: anemometer (mph, kph)
  - Precipitation: range gauge (in/h, cm/h)
  - Time: clock
  - Sun position: manual observation
- Test Documentation: camera
- Experimenter Notes

Test Facility

For moving out of travel lane competency tests, the test facility is a straight, flat, and level roadway that includes one driving lane, whose surface is constructed of asphalt or concrete, and whose driving lane is at least 3.6 m (12 ft) wide and delineated by lane markings visible to the vehicle operators. The only exceptions to this may be for tests where the roadway is curved instead of straight. A curb of standard height 0.09 to 0.18 m (4 to 8 in) shall be located on the right edge of the right lane of the test road. The length of the roadway will be sufficient to allow the ADS feature under test to establish and maintain a specified lane and speed before encountering the parking area, and to allow the SV to stop or exit the course, if applicable. The length of the test course is at least greater than the maximum SV perception range, or 105 m, whichever is greater.

Scenario Tests: MOTL_Comp_15 – Straight Road, Complex, 15 mph

Scenario Description

A vehicle equipped with an ADS feature is driving along a straight urban street with one or more lanes. It needs to move out of the active travel lanes to a parking area to allow passengers to embark or disembark.

Test Subject and Purpose

The subject of this test is an ADS feature whose specified ODD includes operation on improved urban roads with other vehicle traffic. The test determines the ability of the ADS feature to move out of active travel lanes to park in a safe and timely manner.

Initial Conditions

The SV will initially be static in the prescribed positions and orientations.

The POVs will initially be static in the prescribed positions ahead of the SV. The leading edge of POV_2 will be approximately 80 ft behind the trailing edge of POV_1, allowing sufficient space for the SV to maneuver and park.

Test Velocities

The steady state velocities of the SV and POV are specified for each trial or set of trials.

Metrics

Disengagements

A disengagement is defined as the SV safety driver deactivating the ADS feature being evaluated and taking manual control of the SV. The location and manner of the disengagement should be included in the experimenter's notes.

Separation Distances
The separation distances are the distances between the SV and each of the POVs. The minimum separation distances (closest approach) should be identified, as well as the separation distances being observed as a continuum.

The separation distance at stop is also measured and represents the distance between the SV and each of the POVs when the SV has come to a complete stop in its parking position.

Deceleration Rate
The deceleration rate is the rate of change of speed of the vehicle (presumed that the vehicle slows down in this case). Ideally the rate of change would be smooth, as opposed to an abrupt deceleration as the SV reaches the parking location.

Execution of Procedure

1. The POVs are positioned in the center of the parking lane (right lane) of the test road at their specified locations.
2. The POVs' engines are turned off and are placed in park with their emergency brakes activated.
3. The SV is positioned in the center of a lane of the test road at the specified initial headway.
4. The SV is given a target "park" destination between the leading edge of POV_1 and the trailing edge of POV_2.
5. The SV's navigation system is activated to begin traversing the course.
6. The SV approaches the POVs at the specified speed (higher than the POV speed) in the specified lane.
7. Each trial ends when the SV successfully stops at or near the target destination (between the POVs) and shifts to park, or the SV driver must intervene.
8. After the end of the trial, the SV driver disengages the ADS feature (if it is not already disengaged).

Trial Validity

An individual trial is valid if during the trial:

1. The velocity of the SV did not exceed ±X kph from the specified steady state velocity before the POV came within its perception horizon.
2. The velocity of the POVs did not exceed ±X kph from the specified steady state velocities.

   NOTE: Other trial validity requirements might include GPS coverage requirements.

Evaluation Metrics

A trial is successful if the SV:

- Remains within its prescribed lane before reaching the parking area.
- Enters the parking lane with a moving separation distance of ≥X m with each POV.
- Stops with separation distance at stop of ≥X m with each POV.
- Shifts to park upon stopping in the parking lane.

DETECT AND RESPOND TO SCHOOL BUSES

ODD Characteristics

- Multi-lane divided highway (or similar)
- Asphalt or concrete
- Straight, flat
- Clear lane markers
- Clear sky, dry, daylight

OEDR Characteristics

- Object school bus

Failure Behaviors

- None

Test Protocol

Vehicle Platforms

Subject Vehicle– The vehicle equipped with ADS feature being tested.

Principal Other Vehicle– The primary object vehicle for which the detection and response of the SV are being tested.

Vehicle Roles

The SV is a light-duty vehicle equipped with an ADS feature that is being evaluated.

The POV is a “Type C” school bus, also known as a “conventional” school bus, with a gross vehicle weight rating of more than 4,535 kg (10,000 pounds), designed to carry more than ten persons. The bus has functioning onboard traffic control devices, including warning lights and articulating stop signs. Alternatively, a school bus surrogate can be used. If a bus surrogate is used, it would ideally be frangible and should possess similar mobility and detection characteristics as a regular light-duty vehicle.

- Similar visual appearance
- Similar radar and/or lidar reflectivity
- Similar traffic control devices

Test Scenarios

Table 63. School Bus Test Scenarios

Maneuver	SV Speed kph (mph)	POV Speed kph (mph)	Initial Headway; m (ft)[1]
Same Direction 25 SB_SD_25	40 (25)	0	> 30 (> 100)
Same Direction 45 SB_SD_45	72 (45)	0	> 68 (> 225)
Same Direction 65 SB_SD_55	105 (65)	0	> 105 (> 345)
Opposing Direction 25 SB_OD_25	40 (25)	0	> 30 (> 100)
Opposing Direction 45 SB_OD_45	72 (45)	0	> 68 (> 225)
Opposing Direction 65 SB_OD_65	105 (65)	0	> 105 (> 345)

Test Scenario Sample Visualizations

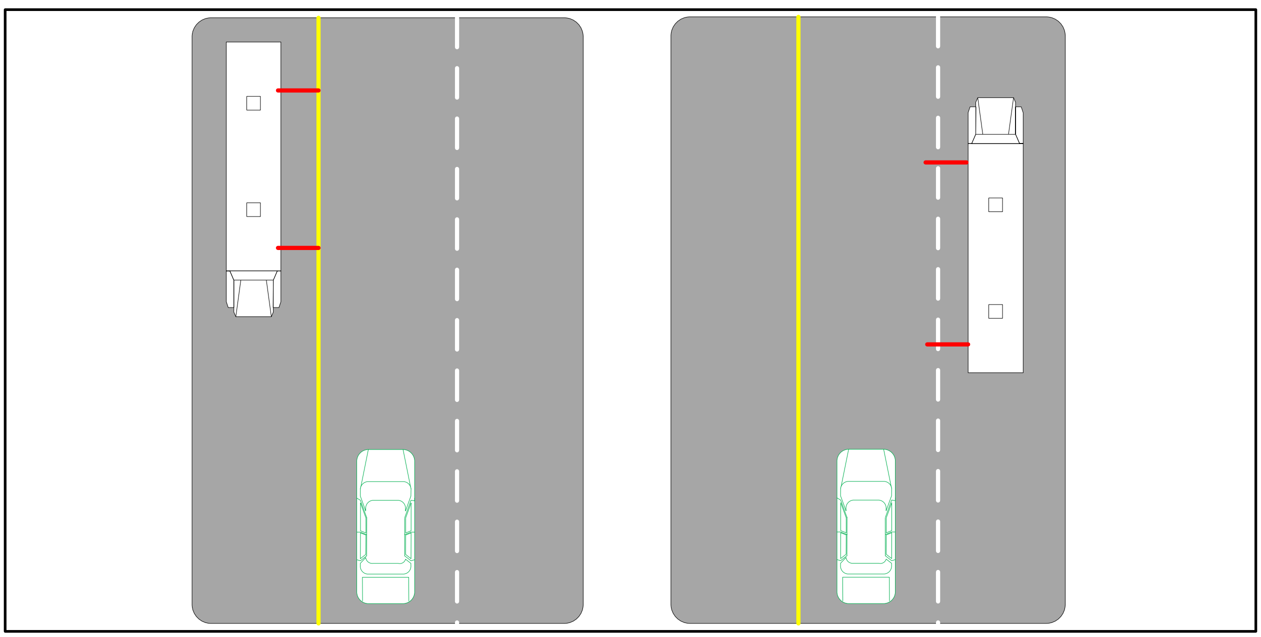

Figure 34. School Bus Test Scenarios

General Procedures

Ambient Conditions

- The ambient temperature shall be between 0 ˚C (32 ˚F) and 38 ˚C (100 ˚F).

- The maximum wind speed shall be no greater than 10 m/s (22 mph).
- Tests should not be performed during periods of inclement weather. This includes, but is not limited to, rain, snow, hail, fog, smoke, or ash.
- Unless specified otherwise, the tests shall be conducted during daylight hours with good atmospheric visibility (defined as an absence of fog and the ability to see clearly for more than 5,000 m). The test shall not be conducted with the vehicle oriented into the sun during very low sun angle conditions (the sun is oriented 15 degrees or less from horizontal), where low sun angles degrade forward visibility for the test vehicle operators.
- Unless stated otherwise, all tests shall be conducted such that there are no overhead signs, bridges, or other significant structures over, or near, the testing site. Each trial shall be conducted with no vehicles, obstructions, or stationary objects within one lane width of either side the vehicle path.

Personnel

A test execution team would include an SV safety driver, an experimenter, and a POV operator. The team would typically coordinate using person-to-person radios for communication.

The SV safety driver would be skilled in the operation of the ADS feature under test. This skill and knowledge would include familiarity with the ADS feature user interface, activation and deactivation procedures, and potential failure modes. The safety driver must be capable of disengaging the ADS feature under test and bringing the vehicle to a minimal risk state, if the experiment approaches or reaches an unsafe state.

The experimenter observes and directs execution of each test trial and would typically be in the SV as the test is executed. The experimenter would also be knowledgeable of the operation of the ADS feature under test to determine if it is functioning properly. The experimenter records test conditions and test trial notes, and judges apparent test trial validity. The experimenter might also operate the data acquisition system and other test equipment.

The POV operator would be skilled in the operation of the other object vehicles, in this case a Class C school bus. The POV operator would position the POV for each trial and would activate and deactivate the necessary POV features (bus lights and signs). If the POV is a vehicle surrogate, the POV operator would be knowledgeable of its construction and mobility and be able to position the surrogate and operate its traffic control devices for the prescribed trials.

Test Data and Equipment

Relevant data listed below should be collected to support the metrics identified for each test scenario/trial. Options for equipment to collect the individual data elements are also provided.

- Vehicle Positions (SV and POV): GPS/INS (< X cm root mean square error, 95% confidence interval)
- Ranges (closest points between SV and POVs): lidar, radar

- Ambient Conditions:
  - Temperature: thermometer (˚C, ˚F)
  - Wind Speed: anemometer (mph, kph)
  - Precipitation: range gauge (in/h, cm/h)
  - Time: clock
  - Sun position: manual observation
- Test Documentation: camera
- Experimenter Notes

Test Facility

For school bus competency tests, the test facility is a straight, flat, and level roadway that includes two or more adjacent driving lanes and one or more opposing driving lanes, whose surface is constructed of asphalt or concrete, and whose driving lanes are at least 3.6 m (12 ft) wide and delineated by lane markings visible to the vehicle operators. The only exceptions to this may be for tests where the roadway is curved instead of straight. The length of the roadway will be sufficient to allow the ADS feature under test to establish and maintain a specified lane and speed before interaction with the POV and to allow the SV to stop or exit the course after passing the POV, if applicable. The length of the test course is at least greater than the maximum SV perception range, or 105 m, whichever is greater.

SCENARIO TESTS: SB_OD_25_Straight – Opposing Direction in Adjacent Lanes, Straight Road

Scenario Description

A vehicle equipped with an ADS feature is driving along a straight, undivided, multilane highway. It approaches a school bus that is stopped in an opposing lane, with lights and signs activated, to allow students to disembark.

Test Subject and Purpose

The subject of this test is an ADS feature whose specified ODD includes operation in areas where interaction with a school bus with activated traffic control devices is reasonably expected. The test determines the ability of the ADS feature to respond to the bus's traffic control devices by stopping in a safe and timely manner.

Initial Conditions

The SV and POV will initially be static in the prescribed positions and orientations.

Test Velocities

The steady state velocities of the SV and POV are specified for each trial or set of trials.

Metrics

Disengagements

A disengagement is defined as the SV safety driver deactivating the ADS feature being evaluated and taking manual control of the SV. The location and manner of the disengagement should be included in the experimenter's notes.

Separation Distance at Stop

Separation distance at stop is defined as the distance between the leading edge of the SV and a plane extending from the leading edge of the POV when the SV has come to a complete stop.

Execution of Procedure

1. The POV is positioned in the center of the opposing lane of test road.
2. The POV's engine remains running and the POV is placed in park with the emergency brake activated.
3. The POV's traffic control devices are activated (lights on and signs extended).
4. The SV is positioned in the center of the left lane of the test road at the specified initial headway distance behind the POV.
5. The SV is given a target destination at the end of the test course such that it will remain in the left lane as it traverses the course and reaches the specified speed.
6. The SV's navigation system is activated to begin traversing the course.
7. Each trial ends when the SV successfully stops, or the SV driver must intervene.
8. After the end of the trial, the SV driver disengages the ADS feature (if it is not already disengaged).

Trial Validity

An individual trial is valid if during the trial:

1. The SV did not deviate from its specified lane (wheels crossing lane boundaries).
2. The velocity of the SV did not exceed ±X kph from the specified velocity.
3. The yaw rate of the SV did not exceed ±X degrees/s.
4. The POV did not deviate from the specified velocity by more than 0.1 kph.
5. The POV's traffic control devices remained active for the entirety of the trial.

NOTE: Other trial validity requirements might include GPS coverage requirements.

Evaluation Metrics (Performance Metrics – Pass/Fail Criteria)

A trial is successful if the SV stops before its leading edge (front bumper) crosses a hypothetical plan extending horizontally from the leading edge (front bumper) of the POV.

DETECT AND RESPOND TO ENCROACHING ONCOMING VEHICLES

Test Protocol

Vehicle Platforms

Subject Vehicle– The vehicle equipped with ADS feature being tested.

Principal Other Vehicle– The primary object vehicle for which the detection and response of the SV are being tested.

Vehicle Roles

The SV is a light-duty vehicle equipped with an ADS feature that is being evaluated.

The POV is another fully functional (operational brake lights, etc.) light-duty vehicle (e.g., sedan, SUV, pickup truck, etc.) or vehicle surrogate. If a vehicle surrogate is used, it would ideally be frangible and should possess similar mobility and detection characteristics as a regular light-duty vehicle:

- Ability to be towed or remotely controlled to follow the test course
- Ability to achieve test speeds
- Similar visual appearance
- Similar radar and/or lidar reflectivity

Test Scenarios

Table 64. Encroaching Opposing Vehicle Test Scenarios

Maneuver	SV Speed kph (mph)	POV Speed kph (mph)	Initial Headway; m (ft)[1]
Straight 25/20 EOV_S_25_20	40 (25)	32 (20)	> 30 (> 100)
Straight 45/40 EOV_S_45_40	72 (45)	64 (40)	> 68 (> 225)
Straight 65/60 EOV_S_65_60	105 (65)	96 (60)	> 105 (> 345)
Curve 25/20 EOV_C_25_20	40 (25)	32 (20)	> 30 (> 100)
Curve 45/40 EOV_C_45_40	72 (45)	64 (40)	> 68 (> 225)
Curve 65/60 EOV_C_65_60	105 (65)	96 (60)	> 105 (> 345)

Test Scenario Sample Visualizations

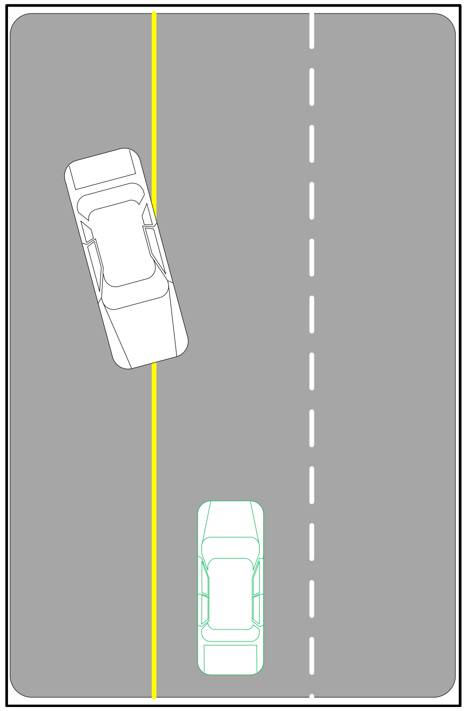

Figure 35. Encroaching, Oncoming Vehicle Test Scenario

General Procedures

Ambient Conditions

- The ambient temperature shall be between 0 ˚C (32 ˚F) and 38 ˚C (100 ˚F).
- The maximum wind speed shall be no greater than 10 m/s (22 mph).
- Tests should not be performed during periods of inclement weather. This includes, but is not limited to, rain, snow, hail, fog, smoke, or ash.
- Unless specified otherwise, the tests shall be conducted during daylight hours with good atmospheric visibility (defined as an absence of fog and the ability to see clearly for more than 5,000 m). The test shall not be conducted with the vehicle oriented into the sun during very low sun angle conditions (the sun is oriented 15 degrees or less from horizontal), where low sun angles degrade forward visibility for the test vehicle operators.
- Unless stated otherwise, all tests shall be conducted such that there are no overhead signs, bridges, or other significant structures over, or near, the testing site. Each trial shall be conducted with no vehicles, obstructions, or stationary objects within one lane width of either side the vehicle path.

Personnel

A test execution team would include an SV safety driver, an experimenter, a POV operator, and potentially external observers. The team would typically coordinate using person-to-person radios for communication.

The SV safety driver would be skilled in the operation of the ADS feature under test. This skill and knowledge would include familiarity with the ADS feature user interface, activation and deactivation procedures, and potential failure modes. The safety driver must be capable of disengaging the ADS feature under test and bringing the vehicle to a minimal risk state, if the experiment approaches or reaches an unsafe state.

The experimenter observes and directs execution of each test trial and would typically be in the SV as the test is executed. The experimenter would also be knowledgeable of the operation of the ADS feature under test to determine if it is functioning properly. The experimenter records test conditions and test trial notes, and judges apparent test trial validity. The experimenter might also operate the data acquisition system and other test equipment.

The POV operator would hold a valid driver's license and be comfortable operating the POV. The POV operator would be responsible for following the prescribed lane at the prescribed speed for each trial. If the POV is a vehicle surrogate, the POV operator would be knowledgeable of its construction and mobility and be able to position and operate the surrogate for the prescribed trials.

The other observers may be responsible for operating external data collection equipment (e.g., video recording of test execution).

Test Data and Equipment

Relevant data listed below should be collected to support the metrics identified for each test scenario/trial. Options for equipment to collect the individual data elements are also provided.

- Vehicle Positions (SV and POV): GPS/INS (< X cm root mean square error, 95% confidence interval)
- Vehicle Speeds (SV and POV): GPS/INS, estimated from position information
- Ranges (following distance between SV and POV): lidar, radar, estimated from position information
- Ambient Conditions:
  - Temperature: thermometer (˚C, ˚F)
  - Wind Speed: anemometer (mph, kph)
  - Precipitation: range gauge (in/h, cm/h)
  - Time: clock
  - Sun position: manual observation
- Test Documentation: camera
- Experimenter Notes

Test Facility

For vehicle-following competency tests, the test facility is a straight, flat, and level roadway that includes one or more driving lanes and one opposing lane, whose surface is constructed of asphalt or concrete, and whose driving lanes are at least 3.6 m (12 ft) wide and delineated by lane markings visible to the vehicle operators. The only exceptions to this may be for tests where the roadway is curved instead of straight. The length of the roadway will be sufficient to allow the ADS feature under test to establish and maintain a specified lane and speed before encountering the POV, and to allow the SV to stop or exit the course, if applicable. The length of the test course is at least greater than the maximum SV perception range, or 105 m, whichever is greater.

SCENARIO TESTS: EOV_S_45_40 – Straight Road, 45 mph, 40 mph Opposing Vehicle

Scenario Description

A vehicle equipped with an ADS feature is driving along a straight highway with one or more lanes. Another moving vehicle is approaching in an opposing lane of travel and begins to drift into the SV's lane of travel such that a collision would occur if the SV did not react.

Test Subject and Purpose

The subject of this test is an ADS feature whose specified operational design domain includes operation on multidirectional, undivided, improved roads with other vehicle traffic. The test determines the ability of the ADS feature to detect an opposing vehicle that is encroaching into its lane to the extent that a collision would occur if the SV did not implement an avoidance maneuver.

Initial Conditions

The SV will initially be static in the prescribed positions and orientations.

The POV will be static in the prescribed positions and orientations.

Test Velocities

The steady state velocities of the SV and POV are specified for each trial or set of trials.

Metrics

Disengagements
A disengagement is defined as the SV safety driver deactivating the ADS feature being evaluated and taking manual control of the SV. The location and manner of the disengagement should be included in the experimenter's notes.

Avoidance Distance
The avoidance distance is the minimum distance between the SV and POV.

Deceleration Rate
The deceleration rate is the rate of change of speed of the vehicle (presumed that the vehicle slows down in this case).

Yaw Rate
The yaw rate is defined as the rate of change of the heading of the vehicle.

Execution of Procedure

1. The POV is positioned in the opposing lane of the test road with its left (driver's side) tires entirely over the center dividing lane markers in the SV's lane.
2. The SV is positioned in the center of a lane of the test road at the specified initial headway.
3. The SV is given a target destination at the end of the test course such that it will remain in the lane as it traverses the course and reaches the specified speed.
4. The SV's navigation system is activated to begin traversing the course.
5. The POV begins driving in the opposing direction and maintains a trajectory parallel to the center of the opposing lane, with its left (driver's side) entirely over the center dividing lane markers, in the SV's lane.
6. The SV and POV approach each other in opposing directions at the specified speeds.
7. Each trial ends when a collision occurs or is avoided, or if the SV driver disengages the ADS Feature.
8. After the end of the trial, the SV driver disengages the ADS Feature (if it is not already disengaged).

Trial Validity

An individual trial is valid if during the trial:

1. The velocity of the SV did not exceed ±X kph from the specified steady state velocity before the POV came within its perception horizon.
2. The velocity of the POV did not exceed ±X kph from the specified velocity for the duration of the trial.
3. The left (driver's side) wheels of the POV remained fully in the SV's lane for the duration of the trial.

   NOTE: Other trial validity requirements might include GPS coverage requirements.

Evaluation Metrics

A trial is successful if the SV either:

- Maneuvers fully into an available adjacent lane and avoids a collision with the POV.
- Maneuvers fully onto an available shoulder and avoids a collision with the POV.
- Maneuvers to shift within its lane (potentially partially entering an available adjacent lane or shoulder) and avoids a collision with the POV.
- Decelerates rapidly to mitigate an imminent collision with the POV.

DETECT AND RESPOND TO PEDESTRIANS

Test Protocol

Vehicle Platforms

Subject Vehicle– The vehicle equipped with ADS feature being tested.

Vehicle Roles

The SV is a light-duty vehicle equipped with an ADS feature that is being evaluated.

Other Definitions

Pedestrian Surrogate– A human surrogate that is attached to a self-propelled or freewheeling mobile base. The surrogate would ideally be frangible and with similar mobility and detection characteristics.

- Ability to be towed or remotely controlled to follow prescribed course
- Similar articulation of joints (if applicable)
- Similar visual appearance
- Similar radar and/or lidar reflectivity

Test Scenarios

Table 65. Pedestrian Test Scenarios

Maneuver	SV Speed kph (mph)	PS Speed kph (mph)	Initial Headway; ft (m)[1]
In Crosswalk Straight 25 Ped_Crosswalk_S_25	40 (25)	5 (3)	> 30 (> 100)
In Crosswalk Straight 45 Ped_Crosswalk _S_45	72 (45)	5 (3)	> 68 (> 225)
In Crosswalk/Sign Straight 25 Ped_Crosswalk_Sign_S_25	40 (25)	5 (3)	> 30 (> 100)
In Crosswalk/Sign Straight 45 Ped_Crosswalk_Sign _S_45	72 (45)	5 (3)	> 68 (> 225)
In No Crosswalk Straight 25 Ped_NoCrosswalk _S_65	40 (25)	5 (3)	> 30 (> 100)
In No Crosswalk Straight 45 Ped_NoCrosswalk _S_25	72 (45)	5 (3)	> 68 (> 225)
Entering Crosswalk Straight 25 Ped_Crosswalk_S_25	40 (25)	5 (3)	> 30 (> 100)
Entering Crosswalk Straight 45 Ped_Crosswalk _S_45	72 (45)	5 (3)	> 68 (> 225)
Entering Crosswalk/Sign Straight 25 Ped_Crosswalk_Sign_S_25	40 (25)	5 (3)	> 30 (> 100)
Entering Crosswalk/Sign Straight 45 Ped_Crosswalk_Sign _S_45	72 (45)	5 (3)	> 68 (> 225)

NOTE: Further iterations of tests could have pedestrians coming from different directions.

Test Scenario Sample Visualizations

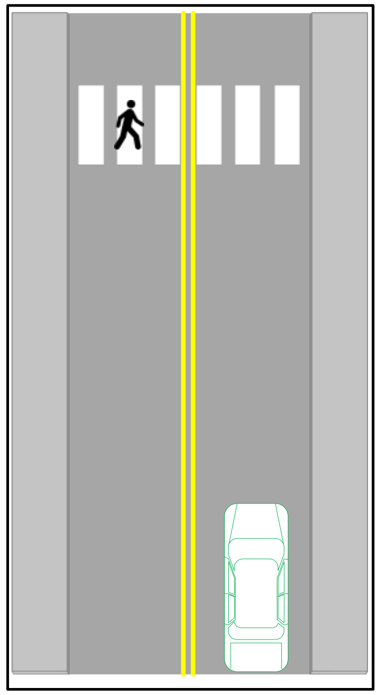

Figure 36. Pedestrian Test Scenario

General Procedures

Ambient Conditions

- The ambient temperature shall be between 0 ˚C (32 ˚F) and 38 ˚C (100 ˚F).
- The maximum wind speed shall be no greater than 10 m/s (22 mph).
- Tests should not be performed during periods of inclement weather. This includes, but is not limited to, rain, snow, hail, fog, smoke, or ash.
- Unless specified otherwise, the tests shall be conducted during daylight hours with good atmospheric visibility (defined as an absence of fog and the ability to see clearly for more than 5,000 m). The test shall not be conducted with the vehicle oriented into the sun during very low sun angle conditions (the sun is oriented 15 degrees or less from horizontal), where low sun angles degrade forward visibility for the test vehicle operators.
- Unless stated otherwise, all tests shall be conducted such that there are no overhead signs, bridges, or other significant structures over, or near, the testing site. Each trial shall be conducted with no vehicles, obstructions, or stationary objects within one lane width of either side the vehicle path.

Personnel

A test execution team would include an SV safety driver, an experimenter, a PS operator, and potentially external observers. The team would typically coordinate using person-to-person radios for communication.

The SV safety driver would be skilled in the operation of the ADS feature under test. This skill and knowledge would include familiarity with the ADS feature user interface, activation and deactivation procedures, and potential failure modes. The safety driver must be capable of disengaging the ADS feature under test and bringing the vehicle to a minimal risk state, if the experiment approaches or reaches an unsafe state.

The experimenter observes and directs execution of each test trial, and would typically be in the SV as the test is executed. The experimenter would also be knowledgeable of the operation of the ADS feature under test to determine if it is functioning properly. The experimenter records test conditions and test trial notes, and judges apparent test trial validity. The experimenter might also operate the data acquisition system and other test equipment.

The PS operator would be responsible for positioning and controlling the pedestrian surrogate. The PS operator would be knowledgeable of its construction and mobility, and be able to position and operate the surrogate for the prescribed trials.

The other observers may be responsible for operating external data collection equipment (e.g., video recording of test execution, etc.).

Test Data and Equipment

Relevant data listed below should be collected to support the metrics identified for each test scenario/trial. Options for equipment to collect the individual data elements are also provided:

- Vehicle Positions (SV): GPS/INS (< X cm root mean square error, 95% confidence interval)
- Pedestrian Surrogate Position: GPS/INS (< X cm root mean square error, 95% confidence interval)
- Vehicle Speeds (SV): GPS/INS, estimated from position information
- Pedestrian Surrogate Speed: GPS/INS, estimated from position information
- Ranges (between SV and PS): lidar, radar, estimated from position information
- Ambient Conditions:
    - Temperature: thermometer (˚C, ˚F)
    - Wind Speed: anemometer (mph, kph)
    - Precipitation: range gauge (in/h, cm/h)
    - Time: clock
    - Sun position: manual observation
- Test Documentation: camera
- Experimenter Notes

Test Facility

For pedestrian competency tests, the test facility is a straight, flat, and level roadway that includes one or more driving lanes, whose surface is constructed of asphalt or concrete, and whose driving lanes are at least 12 ft wide and delineated by lane markings visible to the vehicle operators. The only exceptions to this may be for tests where the roadway is curved instead of straight. The length of the roadway will be sufficient to allow the ADS feature under test to establish and maintain a specified lane and speed before encountering the PS, and to allow the SV to stop or exit the course, if applicable. The length of the test course is at least greater than the maximum SV perception range, or 105 m, whichever is greater.

For some of the tests, crosswalk markings and pedestrian crossing signs will be present. The crosswalk markings will fully traverse the test road perpendicularly to the travel lanes. The signs will be installed outside of the travel lanes, on the shoulder or similar area. Signs and markings will adhere to the *Manual on Uniform Traffic Control Devices* (MUTCD.)

SCENARIO TESTS: Ped_Crosswalk_Sign_S_25 – Crosswalk Markings and Signs, Straight, 25 mph

Scenario Description

A vehicle equipped with an ADS feature is driving along a straight urban road with one or more lanes. The vehicle approaches a crosswalk in which a pedestrian is crossing the road.

Test Subject and Purpose

The subject of this test is an ADS feature whose specified ODD includes operation on roadways where it may reasonably be expected that pedestrians could enter the roadway. The test determines the ability of the ADS feature to detect and yield to the pedestrian in the roadway (leveraging markings and signs, if available).

Initial Conditions

The SV will initially be static in the prescribed positions and orientations.

The PS will be static in the prescribed positions and orientations.

Test Velocities

The steady state velocities of the SV and PS are specified for each trial or set of trials.

Metrics

Disengagements

A disengagement is defined as the SV safety driver deactivating the ADS feature being evaluated and taking manual control of the SV. The location and manner of the disengagement should be included in the experimenter’s notes.

Separation Distance
The separation distances are the distances between the SV and the PS. The minimum separation distance (closest approach) should be identified, as well as the separation distance being observed as a continuum.

Deceleration Rate
The deceleration rate is the rate of change of speed of the vehicle (presumed that the vehicle slows down in this case).

Execution of Procedure

1. The PS is positioned outside of the test course travel lanes, adjacent to the marked crosswalk.
2. The SV is positioned in the center of a lane of the test road at the specified initial headway.
3. The SV is given a target destination at the end of the test course such that it will remain in the lane as it traverses the course and reaches the specified speed.
4. The SV's navigation system is activated to begin traversing the course.
5. When the SV approaches within X meters of the crosswalk, the PS is set into motion to traverse the crosswalk, such that it is fully in the crosswalk.
6. Each trial ends when a collision occurs or is avoided by the SV slowing down and/or stopping, or if the SV driver disengages the ADS feature.
7. After the end of the trial, the SV driver disengages the ADS feature (if it is not already disengaged).

Trial Validity

An individual trial is valid if during the course of the trial:

1. The velocity of the SV did not exceed ±X kph from the specified steady state velocity before the PS came within its perception horizon.
2. The velocity of the PS did not exceed ±X kph from the specified velocity for the duration of the trial.
3. The PS was actively moving through the lanes of travel in the direction of the SV's course (e.g., the PS was not still approaching the active travel lanes and had not already exited the relevant side of the road).
4. The PS remained inside of the crosswalk bounds for the duration of its traversal.

   NOTE: Other trial validity requirements might include GPS coverage requirements.

Evaluation Metrics

A trial is successful if the SV slows down and/or stops to yield to the PS until it has exited the active travel lanes. If multiple lanes are available, the SV should not attempt a lane change to go around the PS (neither in front of, nor behind).

APPENDIX D. BEHAVIOR COMPETENCY COMPARISON

This section describes an analysis conducted after the main body of research for this project had been completed. This addendum seeks to clarify the concept of ADS Behavioral Competencies, due to the existence of several embodiments of this concept found in the literature.

Several pieces of research have sought to define and catalogue the behavioral competencies of ADS. In this document, we provide a framework for ADS behavioral competencies in the context of developing ADS test scenarios. Furthermore, this document provides a notional condensed list of ADS behavioral competencies that represents findings from research by the NHTSA testable cases and scenarios for ADS research project, Waymo's Voluntary Safety Self-Assessment, California PATH at the Institute of Transportation Studies at University of California, Berkeley, and NHTSA pre-crash scenarios.

In this work, it was helpful to think of a test case in four dimensions.

- Tactical Maneuver Behaviors
- ODD Elements
- OEDR Behaviors
- Failure Mode Behaviors

This summary uses the three categories for behaviors (tactical maneuvers, OEDR, and failure mode) as a means of summarizing research findings. It should be noted that each behavioral competency can be necessary in multiple ODDs. For example, lane changes may take place on highways or low speed urban environments. The development of a test scenario will depend both on the behavioral competency being tested, as well as the ODD in which that competency is expected to perform.

It should also be noted that the SAE International ORAD Committee has an active task force on behaviors and maneuvers that is seeking to harmonize the terms and definitions for behavioral competencies. The work of this task force is intended to support the definition of ADS test scenarios, which will benefit from a harmonized approach to cataloguing behavioral competencies, and providing an ontology of OEDR, tactical maneuver, and failure mode behaviors, as well as ODD for each behavior.

The multiple behavioral competencies based on the literature and analysis from this project were condensed into a single list. This list may not be complete, but does attempt to incorporate all behavioral competencies from the four major literature sources that were reviewed. The behavioral competencies listed here provide a high-level description, but the development of a test scenario will require significant additional definition of ODD, narrative and purpose, trajectory information, traffic control devices, and other aspects described in the full report.

Table 66. Summary List of Behavioral Competencies

Categories of Behavioral Competencies	Specific Behavioral Competencies
Tactical Maneuvers	
Parking (Note: ODD may include parking garages, surface lots, parallel parking)	• Navigate a parking lot, locate spaces, make appropriate forward and reverse parking maneuvers
Lane Maintenance & Car Following (Note: ODD may include high and low speed roads)	• Car following, including stop and go, lead vehicle changing lanes, and responding to emergency braking • Speed maintenance, including detecting changes in speed limits and speed advisories • Lane centering • Detect and respond to encroaching vehicles • Enhancing conspicuity (e.g., headlights) • Detect and respond to vehicles turning at non-signalized junctions
Lane Change (Note: ODD may include high and low speed roads)	• Lane switching, including overtaking or to achieve a minimal risk condition • Merge for high and low speed • Detect and respond to encroaching vehicles • Enhancing conspicuity (e.g., blinkers) • Detect and respond to vehicles turning at non-signalized junctions • Detect and respond to no passing zones
Navigate Intersection (Note: ODD may include signalized and non-signalized junctions)	• Navigate on/off ramps • Navigate roundabouts • Navigate signalized intersection • Detect and respond to traffic control devices • Navigate crosswalk • U-Turn • Car following through intersections, including stop and go, lead vehicle changing lanes, and responding to emergency braking • Navigate rail crossings • Detect and respond to vehicle running red light or stop sign • Vehicles turning - same direction • LTAP/OD at signalized junction and non-signalized junction • Navigate right turn at signalized and non-signalized junctions
Navigate Temporary or A-Typical Condition	• Detect and respond to work zone or temporary traffic patterns, including construction workers directing traffic

	• Detect and respond to relevant safety officials that are over-riding traffic control devices • Detect and respond to citizens directing traffic after an incident • N-point turn
OEDR Capabilities	
OEDR: Vehicles	• Detect and respond to encroaching, oncoming vehicles • Vehicle following • Detect and respond to relevant stopped vehicle, including in lane or on the side of the road • Detect and respond to lane changes, including unexpected cut-ins • Detect and respond to cut-outs, including unexpected reveals • Detect and respond to school buses • Detect and respond to emergency vehicles, including at intersections • Detect and respond to vehicle roadway entry • Detect and respond to relevant adjacent vehicles • Detect and respond to relevant vehicles when in forward and reverse
OEDR: Traffic Control Devices and Infrastructure	• Follow driving laws • Detect and respond to speed limit changes or advisories • Detect and respond to relevant access restrictions, including one-way streets, no-turn locations, bicycle lanes, transit lanes, and pedestrian ways (See MUTCD for more complete list)) • Detect and respond to relevant traffic control devices, including signalized intersections, stop signs, yield signs, crosswalks, and lane markings (potentially including faded markings) (See MUTCD for more complete list) • Detect and respond to infrastructure elements, including curves, roadway edges, and guard rails (See AASHTO Green Book for more complete list)
OEDR: Vulnerable Road Users, Objects, Animals	• Detect and respond to relevant static obstacles in lane • Detect and respond to pedestrians, pedalcyclists, animals in lane or on side of road
Failure Modes	
ODD Boundary	• Detect and respond to ODD boundary transition, including unanticipated weather or lighting conditions outside of vehicle's capability
Degraded Performance/ Health Monitoring, Including Achieving Minimal Risk Condition	• Detect degraded performance and respond with appropriate fail-safe/fail-operational mechanisms, including detect and respond to conditions involving vehicle, system, or component-level failures or faults (e.g., power failure, sensing

	failure, sensing obstruction, computing failure, fault handling or response) • Detect and respond to vehicle control loss (e.g., reduced road friction) • Detect and respond to vehicle road departure • Detect and respond to vehicle being involved in incident with another vehicle, pedestrian, or animal • Non-collision safety situations, including vehicle doors ajar, fuel level, engine overheating
Failure Mitigation Strategy	• Detect and respond to catastrophic event, for example flooding or debilitating cyber attack

Based on the four literature sources reviewed, the research team developed a side by side comparison of the behavioral competencies identified in each. Table 67 is divided into categories that help compare similar competencies.

Table 67. Comparison of Behavior Competency Analyses

Categories of Behavioral Competencies	NHTSA Testable Cases	Waymo Voluntary Safety Self-Assessment	California PATH Behavior Competencies	NHTSA Pre-Crash Scenarios
Tactical Maneuvers				
Parking	• Parking	• Navigate a Parking Lot and Locate Spaces • Make Appropriate Reversing Maneuvers	• Navigate a Parking Lot and Locate Open Spaces	• Vehicles Parking
Lane Maintenance & Car Following	• Car Following • Speed Maintenance • Lane Centering • Enhancing Conspicuity (headlights)	• Detect and Respond to Speed Limit Changes and Speed Advisories • Detect and Respond to Encroaching Oncoming Vehicles • Perform Car Following (Including Stop and Go)	• Perform Car Following Including Stop & Go and Emergency Braking • Detect & Respond to Speed Limit Changes (Including Advisory Speed Zones)	• Lead Vehicle Stopped • Vehicles Turning at Non-Signalized Junctions • Lead Vehicle Decelerating • Vehicles Changing Lanes • Straight Crossing paths at Non-Signalized Junctions

Lane Change (e.g., overtake, merge)	• Lane Switching/ Overtaking • Enhancing Conspicuity (e.g., blinkers) • Merge (high & low speed)	• Perform High-Speed Merge (e.g., Freeway) • Perform Low-Speed Merge • Move Out of the Travel Lane and Park (e.g., to the Shoulder for Minimal Risk) • Detect and Respond to Encroaching Oncoming Vehicles • Detect Passing and No Passing Zones and Perform Passing Maneuvers • Perform Lane Changes	• Detect Passing and No Passing Zones • Perform High Speed Freeway Merge • Perform a Lane Change or Lower Speed Merge • Park on the Shoulder or Transition the Vehicle to a Minimal Risk State (Not Required for SAE L3)	• Vehicles Turning at Non-Signalized Junctions • Vehicles Changing Lanes • Straight Crossing paths at Non-Signalized Junctions
Navigate Intersection: • Type: Signalized, Non-signalized, Roundabout, Rail Crossing • Turn: Left/ Right/ Straight	• Navigate On/Off Ramps • Roundabouts • Intersection (left, right, straight) • Crosswalk • U-Turn	• Perform Car Following (Including Stop and Go) • Navigate Intersections and Perform Turns • Navigate Roundabouts • Navigate Railroad Crossings	• Navigate Intersections & Perform Turns • Detect and Respond to Traffic Control Devices • Navigate Intersections & Perform Turns	• Running Red Light • Vehicles Turning - Same Direction • LTAP/OD at Signalized Junction • LTAP/OD at Non-Signalized Junction • Running Stop Sign • Vehicle Turning Right at Signalized Intersection
Navigate Temporary or A-Typical Condition	• Detect and Respond to Workzone • N-Point Turn • Detect and Respond to Relevant Safety Officials	• Detect and Respond to Work Zones and People Directing Traffic in Unplanned or Planned Events • Follow Police/First Responder Controlling Traffic (Overriding or Acting as Traffic Control Device) • Follow Construction Zone Workers Controlling Traffic Patterns (Slow/Stop Sign Holders) • Respond to Citizens Directing Traffic After a Crash • Detect/Respond to Detours and/or Other	• Detect Work Zones, Temporary Lane Shifts, or Safety Officials Manually Directing Traffic	

		Temporary Changes in Traffic Patterns • Navigate Around Unexpected Road Closures (e.g., Lane, Intersection, etc.)		
OEDR Capabilities				
OEDR: Vehicles	• Detect and Respond to Encroaching, Oncoming Vehicles • Vehicle Following • Detect and Respond to Relevant Stopped Vehicle • Detect and Respond to Lane Changes/ Cut-ins • Detect and Respond to Cut-outs/ Reveals • Detect and Respond to School Buses • Detect and Respond to Emergency Vehicles • Detect and Respond to Vehicle Roadway Entry • Detect and Respond to Relevant Adjacent Vehicles	• Detect and Respond to Encroaching Oncoming Vehicles • Detect and Respond to Stopped Vehicles • Detect and Respond to Lane Changes • Detect and Respond to Emergency Vehicles • Yield for Law Enforcement, EMT, Fire, and Other Emergency Vehicles at Intersections, Junctions, and Other Traffic Controlled Situations • Provide Safe Distance From Vehicles, Pedestrians, Bicyclists on Side of the Road • Detect and Respond to Lead Vehicle • Detect and Respond to a Merging Vehicle • Detect and Respond to Motorcyclists • Detect and Respond to School Buses • Detect and Respond to Vehicles Parking in the Roadway	• Detect Emergency Vehicles • Detect & Respond to Stopped Vehicles • Detect & Respond to Intended Lane Changes/Cut-Ins • Detect & Respond to Encroaching Oncoming Vehicles	• Running Red Light • Lead Vehicle Moving at Lower Constant Speed • Backing Up Into Another Vehicle • Vehicless Not Making A Maneuver - Opposite Direction • Vehicles Drifting - Same Direction • Following Vehicle Making Maneuver • Running Stop Sign • Lead Vehicle Accelerating • Vehicles Making a Maneuver - Opposite Direction

OEDR: Traffic Control Devices & Infrastructure	• Follow Driving Laws • Detect and Respond to Speed Limit Changes • Detect and Respond to Relevant Access Restrictions • Detect and Respond to Relevant Dynamic Traffic Signs	• Detect Traffic Signals and Stop/Yield Signs • Respond to Traffic Signals and Stop/Yield Signs • Detect and Respond to Access Restrictions (One-Way, No Turn, Ramps, etc.) • Make Appropriate Right-of-Way Decisions • Follow Local and State Driving Laws • Detect and Respond to Temporary Traffic Control Devices • Detect/Respond to Detours and/or Other Temporary Changes in Traffic Patterns • Detect and Respond to Faded or Missing Roadway Markings or Signage	• Detect and Respond to Access Restrictions such as One-Way Streets, No-Turn Locations, Bicycle Lanes, Transit Lanes, and Pedestrian Ways • Detect and Respond to Traffic Control Devices	
OEDR: Vulnerable Road Users (VRU), Objects, Animals	• Detect and Respond to Relevant Static Obstacles in Lane • Detect and Respond to Pedestrians, Pedalcyclists, Animals	• Detect and Respond to Static Obstacles in the Path of the Vehicle • Yield to Pedestrians and Bicyclists at Intersections and Crosswalks • Provide Safe Distance From Vehicles, Pedestrians, Bicyclists on Side of the Road • Detect and Respond to Pedestrians in Road (Not Walking Through Intersection or Crosswalk) • Provide Safe Distance from Bicyclists Traveling on Road (With or Without Bike Lane) • Detect and Respond to Animals	• Detect & Respond to Static Obstacles in Roadway • Detect & Respond to Bicycles, Pedestrians, Animals, or Other Moving Objects	

Failure Modes				
ODD Boundary	• Detect and Respond to ODD Boundary Transition	• Detect and Respond to Unanticipated Weather or Lighting Conditions Outside of Vehicle's Capability (e.g., rainstorm)	• Detect System Engagement/Disengagement Conditions Including Limitations by Location, Operating Condition, or Component Malfunction	•
Degraded Performance/ Health Monitoring	• Fail-Safe/Fail-Operational Mechanisms	• Detect and Respond to Non-Collision Safety Situations (e.g., vehicle doors ajar) • Detect and Respond to Conditions Involving Vehicle, System, or Component-Level Failures or Faults (e.g., power failure, sensing failure, sensing obstruction, computing failure, fault handling or response) • Detect and Respond to Vehicle Control Loss (e.g., reduced road friction) • Moving to a Minimum Risk Condition When Exiting the Travel Lane is Not Possible	• Park on the Shoulder or Transition the Vehicle to a Minimal Risk State (Not Required for SAE L3)	• Control Loss Without Prior Vehicle Action • Evasive Action Without Prior Vehicle Maneuver • Control Loss With Prior Vehicle Action • Non-Collision Incident • Evasive Action With Prior Vehicle Maneuver • Vehicle Failure • Animal Crash Without Prior Vehicle Maneuver • Road Edge Departure Without Prior Vehicle Maneuver • Pedestrian Crash Without Prior Vehicle Maneuver • Road Edge Departure With Prior Vehicle Maneuver • Pedestrian Crash With Prior Vehicle Maneuver • Pedalcyclist Crash Without Prior Vehicle Maneuver

REFERENCES

AdaptIVe. (2017). *AdaptIVe Automated Driving*. Retrieved from The Project - Objectives: www.adaptive-ip.eu/index.php/objectives.html

Aljaafreh, A., Khalel, M., Al-Fraheed, I., Almarahleh, K., Al-Shwaabkeh, R., Al-Etawi, S., & Shaqareen, W. (2011). Vehicular data acquisition system for fleet management automation. *2011 IEEE International Conference on Vehicular Electronics and Safety*, (pp. 130-133).

Audi. (2015). *Audi Q7 traffic jam assist*. Retrieved from Audi Technology Portal: www.audi-technology-portal.de/en/electrics-electronics/driver-assistant-systems/audi-q7-traffic-jam-assist

Austin, T. R. (2016, February). *Letter to Dr. Steven E. Shladover.* Retrieved from NSPE: www.nspe.org/sites/default/files/resources/pdfs/Shladover%20Ltr-2016-Feb5-FINAL.pdf

Barber, M. (2016). *A self-driving truck just delivered beer in Colorado*. Retrieved from Curbed: www.curbed.com/2016/10/26/13413992/self-driving-truck-anheuser-busch

Barbera, T., Horst, J., Schlenoff, C., & Aha, D. (2004). Task Analysis of Autonomous On-road Driving. *Proceedings of SPIE Mobile Robots 2004* (pp. 61-72). Bellingham, WA: SPIE.

Blanco, M., Atwood, J., Vasquez, H. M., Trimble, T. E., Fitchett, V. L., Radlbeck, J., ... & Morgan, J. F. (2015, August). *Human factors evaluation of level 2 and level 3 automated driving concepts* (Report No. DOT HS 812 182). Washington, DC: National Highway Available at www.nhtsa.gov/sites/nhtsa.dot.gov/files/812182_humanfactorseval-l2l3-automdrivingconcepts.pdf

Bojarski, M., Del Testa, D., Dworakowski, D., Firner, B., Flepp, B., Goyal, P., . . . Zhao, J. (2016, April). *End to End Learning for Self-Driving Cars.* Retrieved from arXiv.org: https://arxiv.org/abs/1604.07316

Bomey, N., & Zambito, T. (2017, June). *Regulators scramble to stay ahead of self-driving cars*. Retrieved from USA Today: www.usatoday.com/story/money/cars/2017/06/25/regulators-scramble-stay-ahead-self-driving-cars/100963150/

Bosch. (2017). *Connected and Automated Parking*. Retrieved from Bosch Mobility Solutions: www.bosch-mobility-solutions.de/en/highlights/connected-mobility/connected-and-automated-parking/

Brewer, J., & Najm, W. (2015). Functional Safety Analysis of Automated Vehicle Lane Centering Control Systems. *Automated Vehicles Symposium.* San Fransisco, CA.

California Department of Motor Vehicles. (2017, November). *Deployment of Autonomous Vehicles for Public Operation.* Retrieved from State of California Department of Motor Vehicles: www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/auto

California Department of Motor Vehicles. (2016). *Autonomous Vehicle Disengagement Reports 2016*. Retrieved from dmv.ca.gov: www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/disengagement_report_2016

Caliper. (2017). *TransModeler Traffic Simulation Software*. Retrieved from Caliper: www.caliper.com/transmodeler/Simulation.htm

Christensen, A., Cunningham, A., Engelman, J., Green, C., Kawashima, C., Kiger, S., . . . Barickman, F. (2015). Key Considerations in the Development of Driving Automation Systems. *Enhanced Safety Vehicles Conference.* Gothenberg, Sweden.

CityMobil2. (2013, December). *CityMobil2 Newsletter.* Retrieved from CityMobil2: www.citymobil2.eu/en/upload/public-docs/Citymobil2%20Newsletter%20No2.pdf

CityMobil2. (2017). *Cities Demonstrating Automated Road Passenger Transport*. Retrieved from CityMobil2: www.citymobil2.eu/en/

DARPA. (2008). *Urban Challenge*. Retrieved from DARPA: http://archive.darpa.mil/grandchallenge/

EasyMile. (2017). *Shared Driveless Vehicles*. Retrieved from EasyMile: http://easymile.com/

Ellichipuram, U. (2016, October). *HERE and Iowa DOT to develop automated vehicle technologies on I-380 corridor*. Retrieved from Road Traffic Technology: www.roadtraffic-technology.com/uncategorised/newshere-and-iowa-dot-to-develop-automated-vehicle-technologies-on-i-380-corridor-5029332/

Elpern-Waxman, J. (2016, December). *How Fast Should Autonomous Vehicles Be Allowed to Drive?* Retrieved from Medium: https://medium.com/jordan-writes-about-cities/how-fast-should-autonomous-vehicles-be-allowed-to-drive-1ee710063975

Erdman, J. (2015, March). *Fog: Deadlier Driving Danger Than You Think*. Retrieved from Weather.com: https://weather.com/news/news/fog-driving-travel-danger-20121127

Federal Highway Administration. (2008). *Managed Lanes: A Primer.* Washington, DC: Author. Available at https://ops.fhwa.dot.gov/publications/managelanes_primer/managed_lanes_primer.pdf

FHWA. (2012). *Manual on Uniform Traffic Control Devices (MUTCD).* Washington, DC: Author.

FHWA. (2017, February). *Low Visibility - FHWA Road Weather Management*. Retrieved from FHWA: https://ops.fhwa.dot.gov/weather/weather_events/low_visibility.htm

FHWA. (2017a). *FHWA Road Weather Management Best Practices.* Retrieved from FHWA: https://ops.fhwa.dot.gov/weather/best_practices/1024x768/transform_param2.asp?xslname=pub.xsl&xmlname=publications.xml&keyname=453

FHWA. (2017b, February). *How Do Weather Events Impact Roads? - FHWA Road Weather Management*. Retrieved from FHWA: https://ops.fhwa.dot.gov/weather/q1_roadimpact.htm

Ford Motor Company. (2015, December). *New Ford Autonomous Tech Turns Traffic Jams into Chill Time and Parks Your Car by Remote Control*. Retrieved from Ford: https://media.ford.com/content/fordmedia/feu/en/news/2015/12/02/new-ford-autonomous-tech-turns-traffic-jams-into-chill-time-and-.html

General Motors. (2016, December). *GM Corporate Newsroom*. Retrieved from General Motors: http://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2016/dec/1215-autonomous.html

Gibbons, J. (1999). *Pavements and Surface Materials* (Technical Paper No. 8). Haddam, CT: University of Connecticut Cooperative Extension.

Goreham, J. (2017). *Tesla Autopilot Update Foreshadows Slower American Roads - No Speeding with Autonomous Vehicles*. Retrieved from BestRide.com: http://bestride.com/news/safety-and-recalls/tesla-autopilot-update-foreshadows-slower-american-roads-no-speeding-with-autonomous-vehicles

Guardian. (2015, May). *Self-driving Cars*. Retrieved from The Guardian: www.theguardian.com/technology/2015/may/15/google-testing-purpose-built-self-driving-cars-public-roads

Hayhurst, K. J., Maddalon, J. M., Miner, P. S., DeWalt, M. P., & McCormick, G. F. (2006). Unmanned aircraft hazards and their implications for regulation. *IEEE/AIAA Digital Avionics Systems Conference* (pp. 2-12). Portland, OR: IEEE.

Howe, G., Xu, G., Hoover, R., Elsasser, D., & Barickman, F. (2016, July). *Commercial connectedvehicle test procedure development and test results – Forward collision warning* (Report No. DOT HS 812 298). Washington, DC: National Highway Traffic Safety Administration. Available at www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/812298_connectedvehiclev2vreport.pdf

Huang, A. (2010). *Lane Estimation for Autonomous Vehicles using Vision adn LIDAR.* Cambridge, MA: Massachusetts Institute of Technology.

Hungar, H. (2017, June). *Test Specifications for Highly Automated Driving Functions: Highway Pilot.* Retrieved from PEGASUS Project: www.pegasusprojekt.de/en/lectures-publications

Inside EVs. (2015). Retrieved from Nissan to Offer "Piloted Drive 1.0 in Japan by teh End of 2016: https://insideevs.com/nissan-to-offer-piloted-drive-1-0-in-japan-by-the-end-of-2016/

Insurance Institute for Highway Safety. (2016, March). *Automakers agree to standard AEB by 2022*. Retrieved from IIHS HLDI: www.iihs.org/iihs/news/desktopnews/u-s-dot-and-iihs-announce-historic-commitment-of-20-automakers-to-make-automatic-emergency-braking-standard-on-new-vehicles

Jaynes, N. (2016, August). *Timeline: The future of driverless cars, from Audi to Volvo*. Retrieved from Mashable: http://mashable.com/2016/08/26/autonomous-car-timeline-and-tech/

Kallweit, R., Prescher, P., & Butenuth, M. (2017). Vehicle-in-the-Loop: Augmenting Real-World Driving Tests with Virtual Scenarios in Order to Enhance Validation of Active Safety Systems. *International Technical Conference on the Enhanced Safety of Vehicles (ESV).* Detroit, MI.

Kalra, N., & Paddock, S. M.. (2016). *Driving to Safety: How Many Miles of Driving Would It Take To Demonstrate Autonomous Vehicle Reliability.* Santa Monica, CA: RAND Corporation. Available at www.rand.org/content/dam/rand/pubs/research_reports/RR1400/RR1478/RAND_RR1478.pdf

Koopman, P., & Wagner, M. (2016). Challenges in Autonomous Vehicle Testing and Validation. *SAE International Journal of Transportation Safety*, (pp. 15-24).

Krok, A. (2017, February). *Roadshow*. Retrieved from CNET: www.cnet.com/roadshow/news/tesla-is-now-testing-autonomous-vehicles-on-public-california-roads/

Kyrouz, M. (2017). *Medium*. Retrieved from https://medium.com/smart-cars-a-podcast-about-autonomous-vehicles/industry-comments-to-nhtsas-Federal-automated-vehicles-policy-436e7e24911a

Local Motors. (2017). *Meet Olli*. Retrieved from Local Motors: https://localmotors.com/meet-olli/

Lomas, N. (2017, March). Retrieved from Tech Crunch: https://techcrunch.com/2017/03/27/ubers-autonomous-cars-return-to-the-road-in-san-francisco-today/

Marshall, A. (2017, February). *Why Self-Driving Cars *Can't Even* With Construction Zones*. Retrieved from Wired: www.wired.com/2017/02/self-driving-cars-cant-even-construction-zones/

Michel, P., Karbowski, D., & Rousseau, A. (2016). *Impact of Connectivity and Automation on Vehicle Energy Use.* Warrendale, PA: SAE International.

Najm, W. G., Smith, J. D., & Yanagisawa, M.. (2007). *Pre-crash scenario typology for crash avoidance research* (Report No. DOT HS 810 767). Washington, DC: Author. Available at www.nhtsa.gov/sites/nhtsa.dot.gov/files/pre-crash_scenario_typology-final_pdf_version_5-2-07.pdf

National Center for Statistics and Analysis. (2017, October). *2016 fatal motor vehicle crashes: Overview*. (Traffic Safety Facts Research Note. Report No. DOT HS 812 456). Washington, DC: National Highway Traffic Safety Administration. Available at https://crashstats.nhtsa.dot.gov/Api/Public/Publication/812456

National Conference of State Legislatures. (2017, September). *Autonomous Vehicles - Self-Driving Vehicles Enacted Legislation*. Retrieved from NCSL: www.ncsl.org/research/transportation/autonomous-vehicles-self-driving-vehicles-enacted-legislation.aspx

Navya. (2017). *Navya Arma: 100% autonomous and electric*. Retrieved from Navya.

National Highway Traffic Safety Administraion. (2016a, September). *Federal automated vehicles policy: Accelerating the next revolution in roadway safety.* Washington, DC: Author. Available at www.transportation.gov/sites/dot.gov/files/docs/AV%20policy%20guidance%20PDF.pdf

NHTSA. (2016b). *Budget Estimates - Fiscal Year 2017.* Washington, DC: Author. Available at www.transportation.gov/sites/dot.gov/files/docs/NHTSA-FY-2017-CJ.pdf

NHTSA. (2016c). *Automated Vehicle Research for Enhanced Safety - Final Report.* NHTSA. Washington, DC: Author.

NHTSA. (2017a). *Automated Drivings Systems 2.0 - A Vision for Safety.* Washington, DC: Author.

NHTSA. (2017b). *Traffic Safety Facts 2015: A compilation of motor vehicle crash data from the Fatality Analysis Reporting System and the General Estimates System* (Report No. DOT HS 812 384). Washington, DC: Author. Available at https://crashstats.nhtsa.dot.gov/Api/Public/Publication/812384

National Research Council. (2005). *Autonomous Vehicles in Support of Naval Operations.* Washington, DC: The National Academies Press. doi:https://doi.org/10.17226/11379

Nishimoto, A. (2016). *Volkswagen I.D. Concept Previews Autonomous Features Slated for 2025*. Retrieved from Motortrend: www.motortrend.com/news/volkswagen-i-d-concept-previews-autonomous-features-slated-for-2025/

Nissan. (2017). *Concept of Nissan's Autonomous Drive*. Retrieved from Nissan Global: www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/autonomous_drive.html

Nowakowski, C., Shladover, S., Chan, C.-Y., & Tan, H.-S. (2015). Development of California Regulations to Govern Testing and Operation of Automated Driving Systems. *Journal of the Transportation Research Board*, 137-144.

SAE International. (2015). *Guidelines for Safe On-Road Testing of SAE Level 3, 4, and 5 Prototype Automated Driving Systems (ADS).* Warrendale, PA: Author.

SAE International. (2016). *J3016: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles.* Warrendale, PA: Author.

Sage, A. (2016, March). *Where's the lane? Self-driving cars confused by shabby U.S. roadways*. Retrieved from Reuters: www.reuters.com/article/us-autos-autonomous-infrastructure-insig/wheres-the-lane-self-driving-cars-confused-by-shabby-u-s-roadways-idUSKCN0WX131

Salaani, M., Mikesell, D., Boday, C., & Elsasser, D. (2016). Heavy Vehicle Hardware-in-the-Loop Automatic Emergency Braking Simulation with Experimental Validation. *SAE International Journal of Commercial Vehicles*, 57-62.

Stoklosa, A. (2016, January). *Bosch Shows Off Haptic Touchscreen, Autonomous Vehicles, More at CES*. Retrieved from Car and Driver: http://blog.caranddriver.com/bosch-shows-off-haptic-touchscreen-autonomous-features-more-at-ces/

Tesla. (2017). Accelerating the world to sustainable energy. Retrieved from Tesla: www.tesla.com/presskit/autopilot

Underwood, S. (2016, January 8). On Road Automated Vehicle (ORAV) Committee (PowerPoint presentation) Warrendale, PA: SAE International. Available at https://pdfs.semanticscholar.org/presentation/0245/4487c3fb7121170f492b11b5fc9e09e198d8.pdf

University of California PATH Program. (2016, February). *Peer Reveiw of Behavioral Competencies for AVs.* Retrieved from NSPE: www.nspe.org/sites/default/files/resources/pdfs/Peer-Review-Report-IntgratedV2.pdf

U.S. Department of Transportation. (2017, January 19). *U.S. Department of Transportation Designates 10 Automated Vehicle Proving Grounds to Encourage Testing of New Technologies*. Retrieved from Transportation.gov: www.transportation.gov/briefing-room/dot1717

Volvo. (2017). *IntelliSafe Autopilot*. Retrieved from Volvo Cars: www.volvocars.com/us/about/our-innovations/intellisafe/intellisafe-autopilot

Wang, Y., & Hussein, I. (2012). *Search and classification using multiple autonomous vehicles: decision-making and sensor management.* London: Springer-Verlag .

Waymo. (2017a). *A new way forward for mobility* (Web page). Retrieved from Alphabet, Inc. [parent corporation of Google] at www.google.com/selfdrivingcar/

Waymo. (2017b). *Waymo Safety Report - On the Road to Fully Self-Driving.* Retrieved from Waymo: https://waymo.com/safetyreport/

Winner, H., Wachenfeld, W., & Junietz, P. (2016). Safety Assurance for Highly Automated Driving - The PEGASUS Approach. *Automated Vehicles Symposium 2016.* San Francisco, CA.

DOT HS 812 623
September 2018

U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

NHTSA

13882-092618-v1a