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An Approach for the Selection and Description Of Elements Used to Define Driving Scenarios

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16. Abstract

This report reviews existing pre-crash scenario typologies and various proposed behavioral competencies in literature that may be relevant to automated driving systems (ADSs) and selects five example scenarios to facilitate exploration of elements that may be helpful in characterizing them. The selected scenarios were: rear-end scenario, lead vehicle lane change scenario, vulnerable road user scenario, crossing path scenario, and a merge scenario. From these five sample scenarios, scenario descriptions were created by first leveraging existing test track procedures when available and then modifying them such that they can be executed with ADSs. These scenario descriptions were broken down into five categories: initialization, environment, principal other vehicle, traffic, and subject vehicle status. For each one of these categories, the study targets identifying a preliminary list of elements necessary to describe the ground truth scenario information.

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GLOSSARY

AASHTO	American Association of State Highway and Transportation Officials
ABS	antilock brake system
ADAS	advanced driver assistance system
ADS	automated driving system
AEB	automatic emergency braking
API	Application program interface
CIB	crash imminent braking
DBS	dynamic brake support
ESC	electronic stability control
FARS	Fatality Analysis Reporting System
GES	General Estimates System
LTAP/LD	left turn across path, lateral direction
LTAP/OD	left turn across path, opposite direction
LTIP	left turn into path
LVA	lead vehicle accelerating
LVD	lead vehicle decelerating
LVLCB	lead vehicle lane change with braking
LVM	lead vehicle moving
LVS	lead vehicle stopped
NCAP	New Car Assessment Program
NASS	National Automotive Sampling System
ODD	operational design domain
OEDR	object and event detection and response
OEM	original equipment manufacturer
PAEB	pedestrian automatic emergency braking
PATH	(University of California) Partners for Advanced Transportation Technology
POV	principal other vehicle
RTAP	right turn across path
RTIP	right turn into path
SCP	straight crossing path
SOV	secondary other vehicle
SV	subject vehicle
TJA	traffic jam assist
VRU	vulnerable road user

EXECUTIVE SUMMARY

The primary goal of this research report is to consider the elements that may be needed to describe driving scenarios and facilitate reproducible and repeatable representation. To achieve this goal, this report characterizes a preliminary list of elements that describe driving scenarios and applies it to five sample scenarios commonly encountered in the real-world. In selecting the sample scenarios, pre-crash scenarios from human driving data and various proposed behavioral competencies for ADSs from literature were reviewed. The following scenarios were chosen based on their diversity in containing various scenario elements: rear-end scenario, lead vehicle lane change scenario, vulnerable road user scenario, crossing path scenario, and a merge scenario.

A preliminary set of elements to uniquely describe these five scenarios were documented and explained. For purposes of this report, the selected elements and their properties are focused on the ground truth scenario information. These elements aim to describe driving scenarios and facilitate reproducible and repeatable representation. These elements are grouped into five categories: initialization, environment, principal other vehicle, traffic, and subject vehicle status. For each scenario type, a range of parameters for each element can be varied to generate a broader list of possible scenarios. The work presented in this document leverages the work presented in the report titled *Review of Simulation Frameworks and Standards Related to Driving Scenarios* (Schnelle et al., 2019).

1 Introduction

ADS development, validation, and path to deployment may use simulation, closed course, and on-road tests to evaluate performance. Figure 1.1 illustrates an example of a generic simulation framework and how it may fit within a holistic ADS testing and evaluation process prior to, and in conjunction with closed course and public road testing. In the figure, the output data from the simulator is shown as “unknown framework” and may be considered in future research efforts.

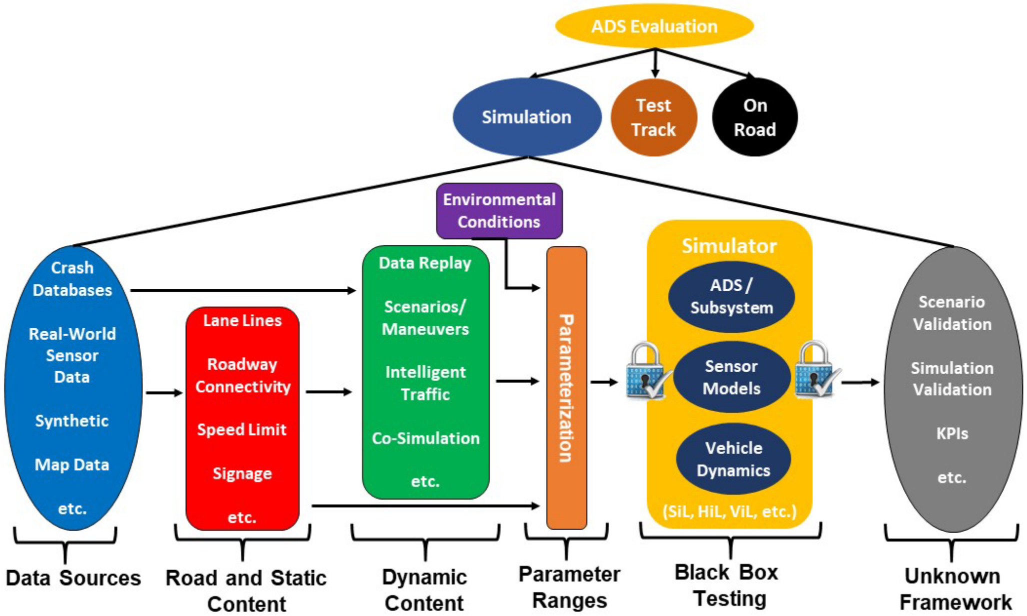

Figure 1.1. Generic ADS Testing Process

The work presented in this document is a continuation of the work presented in the report titled *Review of Simulation Frameworks and Standards Related to Driving Scenarios* (Schnelle et al., 2019). That report explained the basics of ADSs, methodologies for ADS testing, types of available simulation tools to test ADSs, existing simulation frameworks and their use within the industry, and the benefit of scenario description standards within the industry that could facilitate easier data translations and scenario exchanges.

This document builds on the prior work by examining the preliminary set of elements needed to describe sample driving scenarios in the United States. Five example scenarios were used to assess what elements may be necessary to describe scenarios that may be encountered in the real world. The performance of systems in these driving scenarios could then be evaluated in simulation frameworks, on a closed course, or on public roads. The primary goal of this research report is to consider the elements that may be needed to describe driving scenarios and facilitate reproducible and repeatable representation, i.e., to help ensure scenarios can be tested in the same manner to test performance across the industry. To reach this goal, the following steps were followed.

1. Literature review of pre-crash scenarios for human drivers and behavioral competencies for ADSs.
2. Selection of five example scenarios from the literature that contain diverse scenario elements.

3. Identifying preliminary elements of driving scenarios for the five scenarios chosen.
4. Parameterization of the elements and their properties to encompass many driving conditions and scenarios that could be encountered.
5. Consolidation of scenario elements deemed necessary to characterize all five chosen scenarios.

This document focusses on the ground truth scenario information. As described in the previous report (Schnelle et al., 2019), a generic ADS may be considered to operate using four main subsystems as shown in Figure 1.2: sensing, perception, planning, and control. In general, sensing and perception subsystems translate raw sensor data into objects. This study focuses on the scenario information necessary for the planning and control subsystems in the classified object world, downstream of the sensing/perception functions. The sensing and perception subsystems are out of scope for this study. This exclusion does not limit the ability to incorporate, with a few modifications, the sensing and perception scenario information, which can be generated from the ground truth information. This limited scope is because the complexities involved with defining and classifying all the sensory and aesthetic details of a scenario are significant and may be addressed in the future. What material properties (sensory and aesthetic details) are necessary, such as color, reflectivity, permeability, and how to describe them is still an ongoing area of research. Also, regarding ADSs, the sensing and perception subsystems may be developed and tested independently of the planning and control systems.

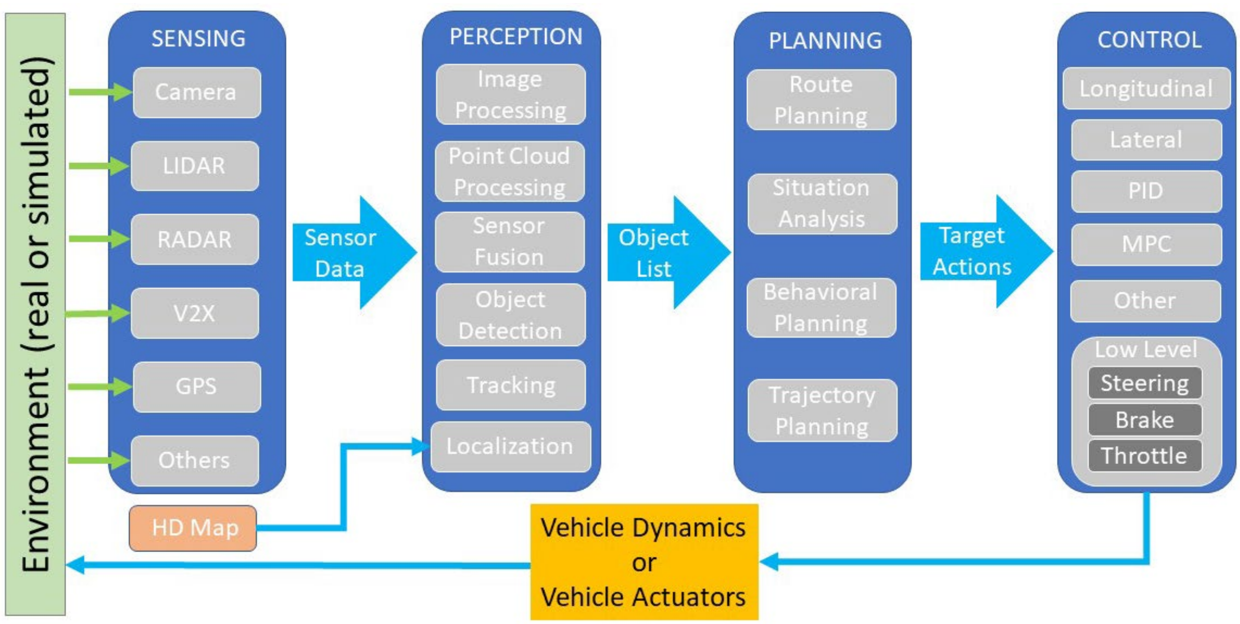

Figure 1.2. A Generic ADS Overview With Subsystems

1.1 Definitions

Clear definitions and consistent use of terminology are critical to advancing the discussion around automation, including scenario description. The term "scenario" could have different connotations and levels of detail depending on the phase of development. Common driving scenario description terms that are widely used in literature are also used in this report (Wood et al., 2019; Pegasus, n.d., SAKURA, n.d.). To this end, a few terms for this document are defined on the following page.

Driving Scenario

A driving scenario, or just scenario, describes the generic act of controlled operation and movement of a motor vehicle, including cars, motorcycles, trucks, and buses and contains no contextual information as more formally described in the scenario definitions below.

Functional Scenario

A functional scenario is described in plain language to facilitate conversations around scenario development and testing. Therefore, a functional scenario describes the basic function being tested and the broad interaction between the SV and other necessary actors of the scenario. The functional scenario describes the primary interaction in the scenario and leaves open the specifics like weather conditions, specific road geometry, timing, speeds, etc. An example of a functional scenario is a highway merge from an on-ramp into traffic.

Logical Scenario

The next step in further defining a functional scenario is adding variables and parameter ranges to form a logical scenario. By iterating over these variables and parameter ranges, all logical combinations of a functional scenario may be covered. To extend the previous example, the highway merge scenario coupled with various merge lane geometries, SV speed range, traffic speed ranges, gap for merging and timing forms a logical scenario.

Concrete Scenario

A concrete scenario refers to a specific instance of the logical scenario, where exact values/conditions are set for the various scenario parameters. This would include exact weather conditions, a specific road geometry, POV/SOV speeds, timing of the interaction, etc. Hence a concrete scenario is a specific, repeatable scenario with a unique set of values for the various parameters in the logical scenario.

Elements and Properties

Elements of a scenario refer to all actors, objects, and environmental aspects of a scenario. Each of the elements have their own set of properties required to define them in a repeatable and reproducible manner.

For example, a scenario element could be a pedestrian, and one of its properties is dimension (height, width, length). Another element could be weather, with precipitation as a property.

Dynamic Actor

A dynamic actor refers to any scenario element that is physically capable of moving. For most scenarios, these refer to vehicles, pedestrians, animals and other road users. Some common dynamic actors are defined below:

Subject Vehicle

The SV refers to the vehicle of interest or the vehicle under test in the scenario.

Principal Other Vehicle

The POV refers to the principal actor/actors in the scenario that are intended to influence the behavior of the SV, due to their interaction with the SV.

Secondary Other Vehicle

The SOV refers to the secondary actors that may be necessary to facilitate the interaction between the SV and POV.

Traffic

Traffic elements are part of the scenario that interact with the SV and influence its decision-making process within the scenario.

Ground Truth Scenario Information

Ground truth scenario information is produced by direct observation and not derived by inference. In the context of ADSs, ground truth refers to information about scenario elements and their properties (real or simulated) without the uncertainties of the sensing and perception subsystems. This information can be presented to an ADS in a repeatable and reproducible manner, irrespective of the way the ADS would perceive it. This information includes a list of static and dynamic actors in the scenario, their positions, bounding boxes, velocities, heading information etc.

For environment parameters, the ground truth information is provided, e.g. if it is raining or not, if lane lines exist or not, and type of lane markers if they do exist etc. Though information such as the intensity of the rain or the condition of lane markers (faded, degraded etc.) is not covered, researchers and developers can add this information on top of the ground truth information provided.

2 Literature Review

This chapter examines sources for selecting sample scenarios and the preliminary list of elements necessary to define them. The goal is to choose five functional scenarios from literature that have a diverse set of scenario elements. Various published reports in the public domain were reviewed to compile lists of environmental conditions, scenario information, and behavioral competencies that are necessary to describe a scenario. This section briefly describes the reports reviewed and the insights gained that helped in the selection of the scenarios that this report examines further.

2.1 Pre-Crash Scenario Typology for Crash Avoidance Research

This NHTSA report (Wassim et al., 2007) defines and statistically describes a pre-crash scenario typology for light vehicles based on the 2004 GES crash database. This typology consists of pre-crash scenarios that depict vehicle movements and dynamics as well as the critical event occurring immediately prior to a crash. The report also quantifies the severity of each scenario in terms of frequency of occurrence, economic cost, and functional years lost.

2.2 Statistics of Light-Vehicle Pre-Crash Scenarios Based on 2011-2015 National Crash Data

This NHTSA report (Swanson et al., 2019) is a follow-up to Wassim et al. (2007) that considers newer crash data. This report defines a set of 36 distinct pre-crash scenarios that represent the crash population involving light vehicles from the 2011-2015 FARS and NASS GES crash databases.

The 36 pre-crash scenarios are arranged into nine groups, which account for 94 percent of all fatal crashes and 89 percent of all police-reported crashes where light vehicles made the critical actions, based on the 2011-2015 FARS and GES crash databases.

Though the data presented in Wassimet al. (2007) and Swanson et al. (2019) are exclusively from human drivers, it gives important insights regarding types of light vehicle pre-crash scenarios that are frequently encountered and what elements may be used to define them. The ability of any vehicle, whether driven solely by a human driver, or ADS-operated, to mitigate or avoid such crashes will be important to study.

2.3 Target Crash Populations for Crash Avoidance Technologies in Passenger Vehicles

This report (Wang, 2019) describes the methods used to establish crash populations for five groups of ADAS technologies in passenger vehicles: forward collision prevention, lane keeping, blind spot detection, forward pedestrian AEB, and backing collision avoidance. This study followed the pre-crash typology concept to categorize real-world crashes into pre-crash scenarios that are defined by vehicle movements and critical events occurring immediately prior to a crash.

The applicable pre-crash scenarios were mapped to the five groupings of ADAS technologies to derive addressable target crash populations. In summary, the author found that, collectively, the five groups of technologies can affect 62% of all crashes annually. As mentioned, the ability of any vehicle, whether driven solely by a human driver, driven by a human and assisted by some level of automation, or operated by an ADS, to negotiate the known pre-crash scenarios is important to study.

2.4 University of California Partners for Advanced Transportation Technology Behavioral Competencies

The University of California PATH program published a list of behavioral competency requirements (Nowakowski et al., 2015) for ADSs. This set of 24 requirements details a list of behaviors that PATH believed ADSs need to possess to operate safely in the traffic conditions that they will regularly encounter. The report states that these minimum behavioral competencies for ADSs are necessary but are by no means sufficient capabilities for public operation.

2.5 A Framework for ADS Testable Cases and Scenarios

This NHTSA report (Thorn et al., 2018) describes a framework for establishing sample preliminary tests for ADSs. The focus is on light-duty vehicles exhibiting higher levels of automation, where the system is required to perform the complete dynamic driving task, including lateral and longitudinal control, as well as object and event detections and responses. Regarding scenario specification, the report identifies the attributes that define the ODD and its taxonomy. Scenario specification is broken down into a hierarchy of categories and subcategories, each with definitions and, where appropriate, gradations. This hierarchical taxonomy includes the following top-level categories.

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

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

2.6 Waymo Safety Report – On the Road to Fully Self-Driving

As part of the Voluntary Safety Self-Assessment outlined by NHTSA (NHTSA, 2016), Waymo released its safety report (Waymo, 2018) in 2018. Waymo expanded on PATH's list of 28 behavioral competencies and published an additional 19 behavioral competency requirements that it uses to test its vehicles.

2.7 Identifying and Assessing Key Weather-Related Parameters and Their Impacts on Traffic Operations Using Simulation

The Federal Highway Administration published research (Zhang et al., 2004) detailing the impact of weather phenomenon on traffic operations. The research employed simulation to conduct sensitivity analysis of weather-related parameters that affect traffic operations the most. These weather-related parameters could be important for determining how to test ADS operation in adverse environmental conditions.

3 Scenario Selection Methodology and Selected Scenarios

This chapter briefly presents the scenario selection criteria and the reasoning behind these criteria. The behavioral competencies and pre-crash scenarios considered are then presented followed by grouping of the scenarios into categories based on functional interactions. This is followed by the list of selected scenario categories. Additional details of the selected scenario categories such as frequency of occurrence in the 2011 – 2015 GES crash database, behavioral competencies covered, and relevant test procedures are explained in detail in **Appendix A**.

3.1 Scenario Selection Considerations

First, scenarios that may involve multiple actors are considered as these may be more complex to define, meaning they generally require more elements and properties to be presented to an ADS. For this research, scenario elements and descriptions for ADSs do not include vehicle inputs or prescribe test conditions contingent on vehicle actions. This is due to the fact that, while in operation, these ADSs are responsible for the complete driving task; telling the ADS what to do or how to respond does not test the ADS's driving capabilities, but instead its ability to follow commands. Hence scenarios that may require prescribed inputs to the vehicle, such as SV steering wheel inputs that may take the vehicle off the road or destabilize a vehicle to create a loss of control event, are not considered. On the other hand, scenarios involving interaction with other vehicles/actors can be presented to the ADS in the normal course of operation. During the normal course of operation, it is possible that the ADS may respond to any presented scenario with control actions that result in road edge departure or control loss event, as examples. Additionally, scenarios with multiple actors offer complexities that enable selection of diverse scenario elements and their parameters, which aid in the goals of this report.

Second, scenarios are selected depending on their relative frequency of occurrence to cover the most frequent pre-crash scenarios and select the elements to describe them. These crash statistics are from human driving data. The distributions/frequency of human crash scenarios may not be representative of ADS crash distributions, but testing the ADS is these scenarios that are challenging to humans may be of interest.

Third, behavioral competencies are considered since these competencies represent scenarios that are frequently encountered in the real world. Testing behavioral competencies might reveal ADS crashes that are not prevalent in human driving statistics. The ability of an ADS to navigate these scenarios may be of interest.

Finally, consideration is given to NHTSA's previous research on ADAS and ADS technology and test procedure development. These test procedures define in detail scenario elements and their corresponding parameter ranges for the given scenario being tested. Therefore, these existing test procedures will be leveraged to develop scenarios for ADSs in this report.

3.2 Scenario Grouping and Behavioral Competencies Considered

Based on the literature review presented in Section 2, the list of the pre-crash scenarios classified in the NHTSA report (Swanson et al., 2019) is presented in Table 3.1. From the report, the list shown in Table 3.1 classifies the light vehicle crash population into a list of pre-crash scenarios based on vehicle dynamics and movements. Each crash is represented by just one scenario. The scenarios in Table 3.1 are not in order of frequency or priority, but reproduced in the same order as in the Swanson report. For this research, Table 3.1, combined with the information presented in this chapter, is used to help support the rationale for the selection of scenarios to consider for describing the elements of a driving scenario.

From the pre-crash scenarios report, 27 of the 36 pre-crash scenarios were further categorized into 9 scenario groups depending on the critical action performed by the light-vehicle involved in the crash. These are presented in Table 3.2. NOTE: Scenarios 1, 6, 13, 31, 32, 33, 34, 35, and "other" are not included in the "Scenario group" categories. These scenarios represent crash frequencies that are either very low, the vehicle is stationary, or the scenarios are not adequately defined because of missing information.

Table 3.1. Thirty-Six Pre-Crash Scenario Typology

No	Scenario	No	Scenario
1	Vehicle failure	20	Rear-end/striking maneuver
2	Control loss with prior vehicle action	21	Rear-end/lead vehicle accelerating
3	Control loss without prior vehicle action	22	Rear-end/lead vehicle maintaining speed
4	Road edge departure with prior vehicle maneuver	23	Rear-end/lead vehicle decelerating
5	Road edge departure without prior vehicle maneuver	24	Rear-end/lead vehicle decelerating
6	Road edge departure while backing up	25	Right turn into path
7	Animal crash with prior vehicle maneuver	26	Right turn across path
8	Animal crash without prior vehicle maneuver	27	Straight crossing path
9	Pedestrian crash with prior vehicle maneuver	28	Left turn across path, lateral direction
10	Pedestrian crash without prior vehicle maneuver	29	Left turn into path
11	Pedalcyclist crash with prior vehicle maneuver	30	Left turn across path, opposite direction
12	Pedalcyclist crash without prior vehicle maneuver	31	Evasive maneuver with prior vehicle maneuver
13	Backing into vehicle	32	Evasive maneuver without prior vehicle maneuver
14	Vehicles turning – same direction	33	Noncollision incident – no impact
15	Vehicle(s) parking – same direction	34	Object crash with prior vehicle maneuver
16	Vehicles changing lanes – same direction	35	Object crash without prior vehicle maneuver
17	Vehicle(s) drifting – same direction	36	Other: Rollover (untripped), hit-and-run, Other rear-end, Other sideswipe, Other turn into path, Other straight paths, Other turn across path, Other opposite direction, Other
18	Vehicle(s) making a maneuver – opposite direction		
19	Vehicle(s) not making a maneuver – opposite direction		

Table 3.2. Light-Vehicle Role and Scenario Grouping

Scenario No.	Scenario Group	Pre-Crash Scenario
2	**Control Loss**	Control loss/vehicle action
3		Control loss/no vehicle action
4	**Road Departure**	Road edge departure/maneuver
5		Road edge departure/no maneuver
7	**Animal**	Animal/maneuver
8		Animal/no maneuver
9	**Pedestrian**	Pedestrian/maneuver
10		Pedestrian/no maneuver
11	**Pedalcyclist**	Pedalcyclist/maneuver
12		Pedalcyclist/no maneuver
14	**Lane Change**	Turning/same direction
15		Parking/same direction
16		Changing lanes/same direction
17		Drifting/same direction
18	**Opposite Direction**	Opposite direction/maneuver
19		Opposite direction/no maneuver
20	**Rear-End**	Rear-end/striking maneuver
21		Rear-end/lead vehicle accelerating
22		Rear-end/lead vehicle moving
23		Rear-end/lead vehicle decelerating
24		Rear-end/lead vehicle stopped
25	**Crossing Paths**	Right turn into path
26		Right turn across path
27		Straight crossing paths
28		Left turn across path, lateral direction
29		Left turn into path
30		Left turn across path, opposite direction

In addition to the pre-crash scenarios, the combined behavioral competencies from PATH (Nowakowski et al., 2015), and Waymo (Waymo, 2018) are listed in Table 3.3.

Table 3.3. PATH and Waymo Behavioral Competencies

No	Behavioral Competency	No.	Behavioral Competency
1	Detect operating envelope	25	Make appropriate right-of-way decisions
2	Detect vehicle, system, and sensor fault and failures	26	Follow local and state driving laws
3	Move out of travel lane and park	27	Follow law enforcement officer/first responder controlling traffic (overriding or acting as traffic control device)
4	Detect and respond to speed limit changes	28	Respond to citizens directing traffic after a crash
5	Perform high-speed merge	29	Detect and respond to temporary traffic control devices
6	Perform lane change/ lower speed merge	30	Yield to pedestrians and pedalcyclist at intersections and crosswalks
7	Detect and respond to encroaching oncoming vehicle	31	Provide safe distance from vehicles, pedestrians, pedalcyclist on side of the road
8	Detect and perform passing and no passing zones	32	Detect/respond to detours and/or other temporary changes in traffic patterns
9	Perform car following (including stop & go)	33	Detect and respond to a merging vehicle
10	Detect & respond to stopped vehicles	34	Detect and respond to pedestrians in road (not walking through intersection or crosswalk)
11	Detect & respond to lane changes	35	Provide safe distance from pedalcyclist traveling on road (with or without bike lane)
12	Detect & respond to static obstacles in road	36	Detect and respond to animals
13	Detect bikes, pedestrians, animals, etc.	37	Detect and respond to motorcyclists
14	Respond to bikes, pedestrians, animals, etc.	38	Detect and respond to school buses
15	Detect traffic signals & stop/yield signs	39	Navigate around unexpected road closures (e.g. Lane, intersection, etc.)
16	Respond to traffic signals & stop/yield signs	40	Navigate railroad crossings
17	Navigate intersections & perform turns	41	Make appropriate reversing maneuvers
18	Navigate a parking lot & locate spaces opt	42	Detect and respond to vehicle control loss (e.g. Reduced road friction)
19	Detect & respond to access restrictions	43	Detect and respond to unanticipated weather or lighting conditions outside of vehicle's capability (e.g. Rainstorm)

No	Behavioral Competency	No.	Behavioral Competency
20	Detect work zones and/or safety officials	44	Detect and respond to unanticipated lighting conditions (e.g. Power outages)
21	Navigate work zones and/or safety officials	45	Detect and respond to non-collision safety situations (e.g. Vehicle doors ajar)
22	Detect emergency vehicles	46	Detect and respond to faded or missing roadway markings or signage
23	Respond to emergency vehicles	47	Detect and respond to vehicles parking in the roadway
24	Navigate roundabouts		

Of the nine scenario groupings in Table 3.2, control loss and road departure groups were not explicitly included in this research. As stated earlier in this section, single vehicle crashes are not considered. This is because control loss or road departure cannot be included as an input to an ADS as part of a scenario. Though not explicitly considered, control loss and road departure can still be part of the any other scenario groups where it could occur during the normal operation of the ADS. For example, let us consider a rear-end/stopped lead vehicle scenario from Table 3.2. It is possible that as the ADS encounters a stopped lead vehicle on a curved section of a wet road, it loses control and departs the road. The scenario under test was a rear-end scenario, but a loss of control or road edge departure could occur and may still be studied. This can be done with the caveat that the absence of control loss/road edge departure in any of the scenarios tested does not necessarily prove safety but can be indicative/informative about performance.

For the purpose of scenario selection, the remaining seven groups can be distilled into five categories of functional interactions: vulnerable road users, which includes the pedestrian, animal, and pedalcyclist groups; lane change; opposite direction; rear-end; and crossing paths. The mapping of these 4 categories to the pre-crash scenarios and the scenario groups is shown in Table 3.4.

Table 3.4. Scenario Description Categories From Pre-Crash Scenarios and Groups

Scenario No.	Scenario Description Category	Pre-Crash Scenario Group	Pre-Crash Scenario
7	**Vulnerable Road User Interaction**	**Struck animal**	Animal/maneuver
8			Animal/no maneuver
9		**Struck pedestrian**	Pedestrian/maneuver
10			Pedestrian/no maneuver
11		**Struck pedalcyclist**	Pedalcyclist/maneuver
12			Pedalcyclist/no maneuver
14	**Lane Change**		Turning/same direction
15			Parking/same direction
16			Changing lanes/same direction
17			Drifting/same direction
18	**Opposite Direction**		Opposite direction/maneuver
19			Opposite direction/no maneuver
20	**Rear-End**		Rear-end/striking maneuver
21			Rear-end/lead vehicle accelerating
22			Rear-end/lead vehicle moving
23			Rear-end/lead vehicle decelerating
24			Rear-end/lead vehicle stopped
25	**Crossing Paths**		Right turn into path
26			Right turn across path
27			Straight crossing paths
28			Left turn across path, lateral direction
29			Left turn into path
30			Left turn across path, opposite direction

3.3 Selected Scenario Categories

Following the selection criteria listed in Section 3.1, crash statistics and behavioral competencies were used to select five scenarios. The first four were selected from the pre-crash scenario categories while a fifth scenario, a highway merge, was selected based on the behavioral competency requirements in Table 3.3. The highway merge is covered by 3 separate competencies, and is discussed as potentially challenging to ADSs in (Thorn et al, 2018).

Table 3.5 lists the selected scenario categories, their relative frequency of occurrence, behavioral competencies covered, and the applicable NHTSA test procedures. Explanations of the specific pre-crash scenarios that make up each scenario category, their frequencies of occurrence, and the specific behavioral competencies covered are detailed in **Appendix A**.

Table 3.5. Selected Scenario Categories, Their Relative Frequency of Occurrence, Behavioral Competencies Covered, and Applicable NHTSA Test Procedures

Pre-Crash Scenario Category	Relative Frequency of Occurrence [1]	No. of Behavioral Competencies Covered	Applicable NHTSA Test Procedure
Rear-End Scenario	31%	4	CIB and DBS NCAP Test Procedures
Lead Vehicle Lane Change Scenario	12%	3	TJA System Confirmation Test - LVLCB Test
Vulnerable Road Users Interaction	7%	8	Pedestrian Cross Path Test (with various road users)
Crossing Path Scenario	20%	4	ISA System Confirmation Test – LTAP Scenario
Merge Scenario	Not applicable	6	Not applicable

3.3.1 Scenario Adaptation and Selection Methodology

It is important to emphasize that all scenarios considered and the five scenarios that have been chosen in this study are all based exclusively on human-driving crash data. Though it is unknown if these scenarios will occur at a similar frequency with ADS-operated vehicles, these types of pre-crash scenarios are currently most prevalent in the crash data, and the ability of ADSs to navigate such scenarios is important to study. As more ADS crash/near-miss cases occur, new scenarios modeled from such cases could also be examined and, if necessary, any additional elements or properties not previously covered could be added. The five scenarios studied primarily serve a purpose to facilitate variety for the parametrization objective and do not imply necessity or sufficiency of scenarios for safety assessment of ADSs.

3.4 Summary

These five scenario categories each add unique characteristics leading to an expanded set of elements to define the collection of scenarios. The pre-crash scenarios and behavioral competencies not explicitly

[1] From 2011 – 2015 GES Crash Statistics

covered by the five scenarios are presented in Table 3.6 and Table 3.7, respectively. Though not covered by the five scenarios selected in this report, these remain relevant and of interest to investigate in the future. It is important to reiterate that though vehicle failure, control loss, and road departure events (Scenario numbers 1 to 6) are not explicitly studied with specific scenarios, such events can still be studied if they occur during other scenarios, and hence are not completely overlooked by efforts detailed in this report.

Table 3.6. Pre-Crash Scenarios Not Covered

Sc. No.	Pre-Crash Scenario Description
1	Vehicle failure
2	Control loss without prior vehicle action
3	Control loss with prior vehicle action
4	Road edge departure with prior vehicle maneuver
5	Road edge departure without prior vehicle maneuver
6	Road edge departure while backing up
13	Backing into another vehicle
18	Vehicle(s) making a maneuver – opposite direction
19	Vehicle(s) not making a maneuver – opposite direction
31	Evasive maneuver with prior vehicle maneuver
32	Evasive maneuver without prior vehicle maneuver
33	Non-collision incident – no impact
34	Object crash with prior vehicle maneuver
35	Object crash without prior vehicle maneuver
36	Other

Table 3.7. Behavioral Competencies Not Covered

Competency No.	Behavioral Competency Description
3	Move out of travel lane and park
7	Detect and respond to encroaching oncoming vehicle
18	Navigate a parking lot and locate spaces
20	Detect work zones and/or safety officials
21	Navigate work zones and/or safety officials
24	Navigate roundabouts
27	Follow law enforcement officer/first responder controlling traffic (overriding or acting as traffic control device)
28	Respond to citizens directing traffic after a crash
29	Detect and respond to temporary traffic control devices
32	Detect and respond to detours and/or other temporary changes in traffic patterns
37	Detect and respond to motorcyclists
38	Detect and respond to school buses
39	Navigate around unexpected road closures (e.g. lane, intersection, etc.)
40	Navigate railroad crossings
41	Make appropriate reversing maneuvers

4 Scenario Description

This section summarizes the scenario description for each of the scenarios chosen in the previous chapter. As mentioned, for this research, scenario descriptions for ADSs do not include vehicle inputs or prescribe test conditions contingent on vehicle actions. This is due to the fact that, while in operation, these ADSs are responsible for the complete driving task; telling the ADS what to do or how to respond does not test the ADS's driving capabilities, but instead its ability to follow commands. The ADSs are assigned a starting location and a goal destination, and while navigating between them a scenario is presented to the vehicle to see how it responds. This research is focused on describing the elements and properties necessary to test ADS performance only and does not take into consideration any handoffs with human drivers or consider human machine interfaces.

The complexities involved in testing ADSs and the various ODD and other requirements for the ADSs' continued operation are recognized. These factors may preclude testing of certain conditions due to violation of ODD, but the ability of the ADS to attain a minimum risk fallback condition may still be worthwhile to verify. Since the ADSs are expected to handle a wide range of situations, a large set of scenario variants generated by varying parameters of a logical scenario could also be tested.

4.1 Logical Scenario Elements

In this chapter, each functional scenario is described, followed by the various elements and their properties that make up the corresponding logical scenarios. These properties could then be varied to generate a large set of concrete scenarios.[2] The elements and properties to be varied are broadly divided into the following categories:

1. **Initialization:** It is recognized that various ADSs target different ODDs and require certain conditions for system initialization and continued operation. The study intends these maneuvers to be modified to meet these conditions for each specific vehicle as long as the essence of the maneuver is maintained. If the ODD of the vehicle precludes certain conditions, those conditions could be used to demonstrate minimum risk fallback operation of the vehicle. The initialization includes:
    - Initial positions, velocities, and orientation of SV, POV, SOV, and traffic.
    - Initialization period:
        - Time based event triggering to allow for maneuver initialization time.
    - Define scenario end conditions:
        - Time or duration of maneuver conditions.
        - Collision / no collision, road edge departure, illegal actions, control loss.
        - End goal position: absolute or relative.
        - Etc.

[2] ODD factors, computational capabilities, and time are to be considered. A finer parameter increment may be required when challenging parameter ranges are encountered. This may require optimization techniques to determine parameter ranges and values.

2. **Environment:** This includes the aspects of physical environment and encompasses the following elements:
    - Scenario speed (influenced by road speed limits).
    - Road layout.
        - Curvature.
        - Grade.
        - Road Type (Highway, Rural, Urban, etc.).
        - Number of lanes.
        - Lane width.
        - Lane direction of travel.
        - Lane markings (type, color, location, dimension).
        - Intersection layout.
        - Etc.
    - Signage:
        - Signalized/4-way stop/2-way stop.
        - Pedestrian crossing.
        - Speed limit signs.
        - Construction zone.
        - Etc.
    - Weather conditions:
        - Precipitation:
            - None.
            - Rain.
            - Snow.
            - Etc.
        - Wind.
        - Temperature.
        - Etc.
    - Lighting:
        - Illuminance
    - Date/Time
        - Time of Day
        - Sun Angle/Orientation
    - Roadway surface conditions:

- Dry.
- Wet.
- Snow covered.
- Ice.
- Coefficient of friction.[3]
- Etc.

3. **POV/ SOV/ VRU:** Detailed information regarding the actors for the scenario, including:
    - Position, speed, orientation, and acceleration of actor
    - Headway/timing to trigger actor event
    - Ability to define behavior:
        - Relative to SV position.
        - Relative to SV speed.
        - Relative to other actor speed or position.
        - Open loop definition.
        - Transition behavior from one type to other.
    - Ability to trigger behavior (e.g. lane change, deceleration) on:
        - SV or other actor position.
        - In series at end of another behavior/event of another actor.
        - In parallel with another behavior/event of another actor.
    - Ability to define dimensions and type of the POV/SOV.
    - Dimensions and type of VRU:
        - Adult/child.
        - Male/female.
        - Animal.
        - Pedalcyclist.
4. **Traffic:** The other dynamic actors are included in this section. The presence of dynamic actors may prevent certain actions by the SV and permit other actions. Traffic elements and properties include:
    - Number and types of surrounding actors.
    - Relative distance to the SV/POV.
    - Behavior/purpose.

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[3] Friction coefficients and ranges can be controlled and influenced by multiple parameters and variables such as time, surface, and weather conditions.

5. **ADS Status:** Another factor that can affect the SV's response is the status of the ADS. These properties could include:
    - Normal operation.
    - ESC/ABS activation.
    - Fault codes/warnings.
        - Engine temperature.
        - Engine fault code.
        - Etc.
    - Low fuel/low battery charge.
    - ADS sensor fault.
    - Mechanical failure.

For each scenario, element property ranges can be determined based on ODD, with values falling within and outside the ODD to test nominal operating conditions and minimum risk fallback operations.

It is important to reiterate that this report, as stated in Section 1, focuses on supplying ground truth scenario information, in the object world downstream of sensing and perception layers. Though elements such as speed limit signs and weather are listed in the environment category, the information for these elements may be passed directly to the planning and control systems of the ADS in the form of an object list downstream of the sensing and perception layers. For example, ground truth information about changing weather and road conditions such as rainfall in combination with a corresponding reduction in roadway friction may be used to demonstrate how an ADS's path planning and control systems adapt its speed for the given environment. In this example, if the change in conditions exceed the ODD thresholds, then the ADS may perform a minimum risk fallback maneuver, giving a useful demonstration of behavior adaptation and competency, design intent, and may show risk reduction. The authors encourage developers to integrate perception and sensing information to the scenario description, if possible.

4.2 Rear-End Scenario

The rear-end pre-crash scenario described in Section A.1 included various lead vehicle behaviors, traffic conditions, and environmental conditions that caused the SV to encounter the lead vehicle. The functional scenario, along with its elements and properties of the logical scenario, are described in the following sub-sections.

4.2.1 Functional Scenario Description

The CIB[4] test track procedures in (NHTSA, 2014a) and (NHTSA, 2014b) are specific concrete scenarios of the rear-end scenario. These are used as a starting point for the initial development of the functional scenario description. Table 4.5 details the three concrete scenarios from the NHTSA CIB test procedure.

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[4] AEB systems, specifically CIB and DBS, are ADASs which can use information from forward looking sensors to enhance the driver's ability to avoid or mitigate rear-end crashes. CIB systems provide automatic braking when forward-looking sensors indicate that a crash is imminent and the human driver is not braking. DBS systems provide supplemental braking when sensors determine that human driver-applied braking is insufficient to avoid an imminent crash.

These tests are all performed on an idealized, straight road with no traffic other than the POV, as shown in Figure 4.1.

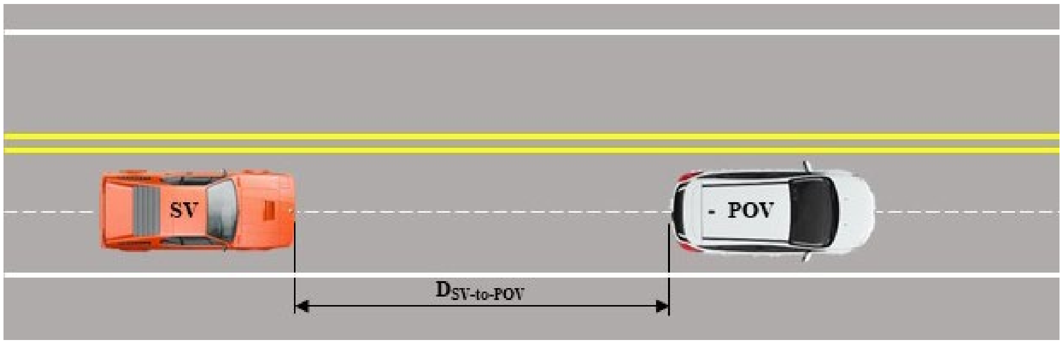

Figure 4.1. Rear-End Test Functional Scenario

The test parameters in terms of speed and deceleration listed in Table 4.5 are a very limited set of rear-end concrete scenarios designed to describe only CIB scenarios. To be able to describe a more generic scenario, a wider range of parameters can be used. The following subsections list the elements and some possible ranges that could be used for scenario description.

4.2.2 Logical Scenario Elements

Initialization

The authors recognize that various subject vehicles require different conditions for system initialization and continued operation. The authors intend these maneuvers to be modified to meet these conditions for each specific subject vehicle as long as the essence of the maneuver is maintained.

- The maneuver is initiated at any time after the POV is in the same lane as the SV.
- A start position and end goal position for the SV should be specified. The end goal position could be a global position or relative to the POV.
- The test ends when either the SV reaches the end/goal position, or when the SV comes in contact with the POV, or when any other end condition is met (e.g. scenario duration).

Environmental Elements and Properties

The environment surrounding the SV has the potential to greatly affect its response to a specific scenario. For example, while encountering a slower moving lead vehicle, the availability of an adjacent lane may allow the SV to perform a lane change. Even opposing travel lanes, when allowed by traffic laws, may be used to overtake the slower moving vehicle. The presence of adverse weather conditions may affect the performance and may even require the ADS to perform a minimum risk fallback maneuver if it violates its ODD requirements. These elements may be varied and included in a scenario description. The environment elements and an initial set of ranges for their properties are listed in Table 4.1. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.1. Environment Parameters for Rear-End Interaction

Element/Property	Range
Speed Limit	15 to 70 mph (24 to 113 km/h)
Road Curvature	Straight, curved (maximum specified by AASHTO standard for speed limit or as allowed by ODD)
Grade	Level, not level maximum specified by AASHTO standard for speed limit or as allowed by ODD)
Super Elevation	All applicable
Road Type	All applicable
Number of Lanes	1 to 3
Lane Width	8 to 14 feet (2.4 to 4.2 m)
Lane Direction of Travel	Same, opposing
Lane Marking (As pertaining to traffic laws)	White and yellow dashed, solid, double solid (passing/no passing or lane change allowed/not allowed etc.)
Intersection Layout	All applicable
Signage	All applicable
Weather	All conditions listed in Section 4.1
Time of Day	All applicable
Lighting	All applicable illuminance values
Sun Angle/Orientation	All applicable
Roadway Surface Condition	All applicable
Road Surface Obscurants	All applicable
Friction of Drivable Surfaces	0.1 to 1

POV/SOV/VRU Elements and Properties

The POV may be stopped, decelerating, accelerating, or moving at a slower constant speed when the SV encounters it. These speed and acceleration properties can be varied, and relevant permutations included in a scenario description. The elements and an initial set of ranges are shown in Table 4.2. These ranges are a suggested starting point and can be modified, as deemed appropriate.

Table 4.2. POV Parameters for Rear-End Interaction

Element/Property	Range
Position (Absolute/Relative)	SV controls relative distance
Speed (Absolute/Relative)	0 to 80 mph (0 to 129 km/h) absolute
Deceleration	0 to 1.5g
Time-to-Trigger or Headway to Trigger Deceleration	0 seconds to as required or 3 to 328 ft (1 to 100 m)
Lane Identification Number	1 to 3 (same as SV)
Lateral Lane Position	0 to lane width
Type	All applicable
Length	All applicable
Width	All applicable

Traffic Elements and Properties

The presence of traffic actors, or lack thereof, may interfere with the SV's response. For example, the traffic rules may allow for the SV to change lanes into the oncoming traffic lane and overtake the POV, but the presence of an oncoming traffic vehicle may prevent the SV from executing such a maneuver. Such elements and an initial set of ranges are shown in Table 4.3. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.3. Traffic Vehicle Parameters for Rear-End Interaction

Element/Property	Range
Number of Traffic Actors	0 to as required
Relative X Position to SV/POV	All applicable
Relative Y Position to SV/POV	All applicable
Speed (Absolute/Relative)	All applicable
Width	All applicable
Length	All applicable

ADS Status:

Another factor that can affect the SV's response is the status of the ADS. A few of these elements are listed in Table 4.4. In simulation, these status messages could be supplied to the simulated vehicle to study the minimum risk fallback operation when a fault exists. This category is applicable to all the maneuvers discussed in this chapter.

Table 4.4. ADS Status Parameters for Rear-End Interaction

Element/Property	Range
Engine/Motor Fault Codes	Various
Fuel Level/Battery Charge	Prevent overtake, block lane change, occlude view, etc.
ADS Sensor Fault	Sensor type, fault code
ADS Software Failure	
Mechanical Failure	Component
Emergency Subsystem Activations	ESC/ABS activation, lane keeping, AEB etc.

If an element or its property is not explicitly stated, it was determined to be outside the requirements for the logical scenario description. If an element is to be included, a reasonable range of properties for that variable should be used. Additional possible logical scenarios from element and property permutations are represented graphically in Figure 4.2 below:

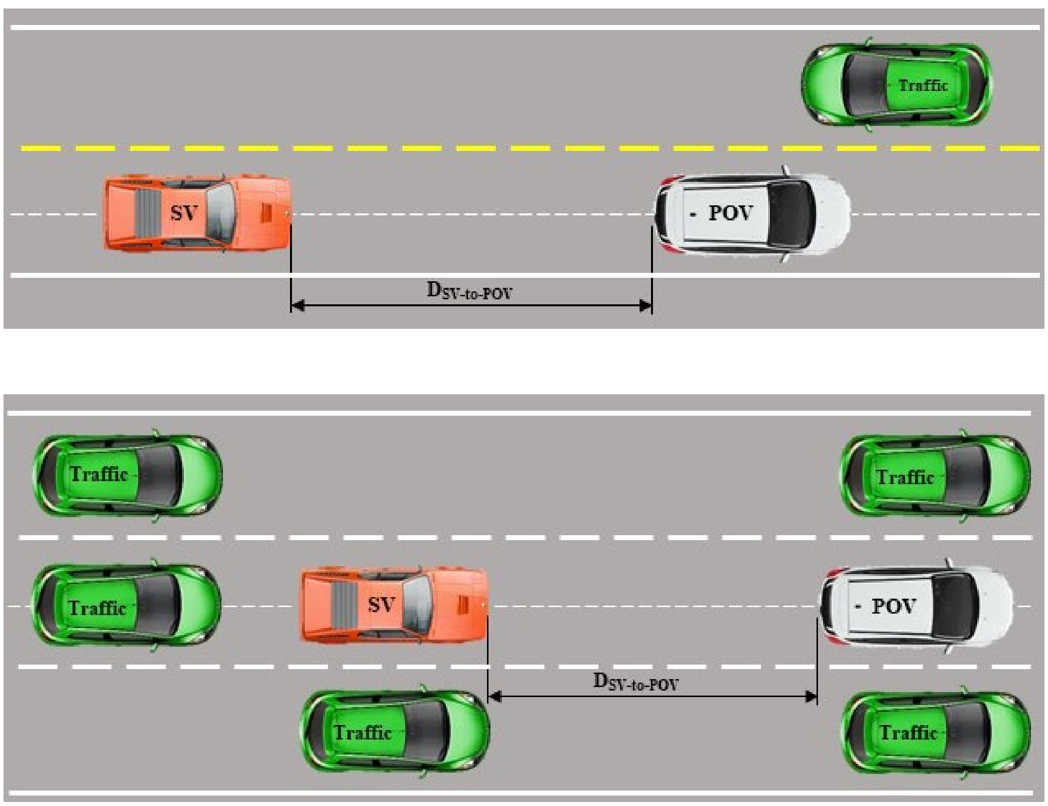

Figure 4.2. Possible Permutations of Rear-End Interactions

4.2.3 Concrete Scenario Examples

Figure 4.1 and Table 4.5 details the three concrete scenarios from the NHTSA CIB test procedure.

Table 4.5. CIB Concrete Scenarios

Test Type	Speed Limit	POV Speed	POV Deceleration	Test End Condition
SV approaches stopped POV	25 mph (40.2 km/h)	0 mph (0 km/h)	NA	- SV comes in contact with POV OR - 1 second after velocity of SV becomes less than or equal to velocity of POV
SV approaches slower moving POV	25 mph (40.2 km/h)	10 mph (16.1 km/h)		
	45 mph (72.4 km/h)	20 mph (32.2 km/h)		
SV approaches decelerating POV	35 mph (56.3 km/h)	35 mph (56.3 km/h)	-0.3 g triggered at 13.8 m headway	- SV comes in contact with POV OR - 1 second after minimum longitudinal SV-POV range occurs

4.3 Lane Change Scenario

The lane change scenario described in Section A.2 involves lead vehicles drifting and changing lanes into the SV travel lane. This broad scenario involves a lot of different parameters. The functional scenario, along with its elements and parameters for the logical scenario are described in the following sub-sections.

4.3.1 Functional Scenario Description

A similar scenario, called the LVLCB, has been studied by NHTSA in the TJA draft test procedure (NHTSA, 2018). The objective of this test is to evaluate the subject vehicle's ability to detect and respond to a moving POV that brakes during and/or after performing a lane change into a space between the SV and SOV. The SV and SOV remain in the same lane for the duration of each test trial. The POV begins in a lane adjacent to the SV and SOV, but performs a single lane change into the space between the SV and SOV. For repeatability, an explicit lane change path is given in the test procedure as shown in Figure 4.5. Although this exact lane change geometry need not be followed, it does show the need for repeatable, reproducible actor behaviors, such as lane changes, in a concrete scenario description. Any ambiguities in the actor behaviors and actions could lead to different results. During and/or after the lane change, the POV decelerates depending on the test conditions. The initial and final positions of the POV with respect to the SV and SOV are illustrated in Figure 4.3.

These LVLCB tests are used as a starting point for the initial development of the scenario descriptions. These tests can be part of the subset to be included in testing to allow comparable results between on road, closed course, and simulation. Table 4.9 details the concrete scenarios from the NHTSA TJA LVLCB test procedure. These test procedure scenarios are all performed on an idealized, straight road with no traffic other than the POV and SOV.

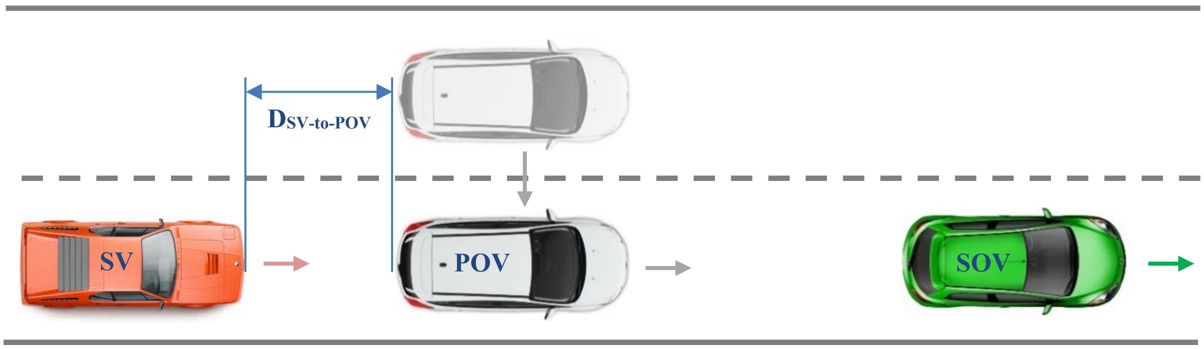

Figure 4.3. Lead Vehicle Lane Change With Braking Scenario

4.3.2 Logical Scenario Elements

Initialization

The authors recognize that various SVs require different conditions for system initialization and continued operation. The authors intend these maneuvers to be modified to meet these conditions for each specific SV as long as the essence of the maneuver is maintained.

- The maneuver is initiated when the SOV enters the SV's lane, oriented in the same direction.
- The SV encounters the SOV and adapts its speed to the SOV's. The SV is forced to follow the SOV. This can be achieved by using blocking vehicles, road design, or other means.
- A start position and an end/goal position for the SV should be specified. The end goal position could be a global position or relative to the POV.
- The test ends when either the SV stops/reaches the end/goal position, when the SV comes in contact with the POV, or when any other end condition is met.

Environment Elements and Properties

For this scenario, the number of lanes may help limit the ability of the SV to change lanes to avoid the POV that is cutting in. The speed limit, road curvature, and lane line markings can also be varied. These parameters and some possible ranges that could be tested are listed in Table 4.6. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.6. Environment Parameters for Lane Change Interaction

Element/Property	Range
Speed Limit	15 to 70 mph (24 to 113 km/h)
Road Curvature	Straight, curved (maximum specified by AASHTO standard for speed limit or as allowed by ODD)
Grade	Level, not level (max specified by AASHTO standard for speed limit or as allowed by ODD)
Super Elevation	All applicable
Road Type	All applicable
Number of Lanes	2 to 3
Lane Width	8 to 14 feet (2.4 to 4.2 m)
Lane Direction of Travel	Same, opposing
Lane Marking (pertaining to traffic laws)	White and yellow dashed, solid, double solid (passing/no passing or lane change allowed/not allowed etc.)
Intersection Layout	All applicable
Signage	All applicable
Weather	All conditions listed in Section 4 introduction
Time of Day	All applicable
Lighting	All applicable illuminance values
Sun Angle/Orientation	All applicable
Roadway Surface Condition	All applicable
Road Surface Obscurants	All applicable
Friction of Drivable Surface	0.1 to 1

POV/SOV/VRU Elements and Properties

The POV has the ability to decelerate while changing lanes and continue to decelerate. The longitudinal distance ($D_{SV\text{-}POV}$) at which the lane change is triggered as well as the aggressiveness of the lane change (D_{lane_change}) could also be varied to control the severity of this maneuver. These parameters relating to the POV are listed in Table 4.7, along with possible parameter value ranges. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.7. POV Parameters for Lane Change Interaction

Element/Property	Range
SOV Position (Absolute/Relative)	SV sets relative distance
SOV Speed (Absolute/Relative)	5 to 80 mph (8 to 129 km/h) absolute
POV Speed (Relative) POV Speed (Absolute)	-40 to 20 mph (-64 to 32 km/h) relative 5 to 80 mph (8 to 129 km/h) absolute
Lane Change Deceleration	0 to 0.3g
Deceleration After Lane Change	0.1 to 1.5g
$D_{SV\text{-}POV}$	0 to 66 ft (0 to 20 m)
D_{lane_change}	17 to 148 ft (5 to 45 m)
Direction of Lane Change	Left/right
Lane Identification Number	1 to 3 (adjacent to SV lane)
Lateral Lane Position	0 to lane width
Type	All applicable
Length	All applicable
Width	All applicable

Traffic Elements and Properties

The presence of a traffic vehicle in the adjacent lane may limit the ability of the SV to perform a lane change to avoid the POV. The traffic parameters are listed in Table 4.8.

Table 4.8. Traffic Parameters for Lane Change Interaction

Element/Property	Range
Number of Traffic Actors	0 to as required
Relative X Position to SV/POV	All applicable
Relative Y Position to SV/POV	All applicable
Speed (Absolute/Relative)	All applicable
Width	All applicable
Length	All applicable

ADS Status:

Refer to ADS status section in Section 4.2.2.

If an element or its property range is not explicitly stated, it was determined to be outside the requirements for the logical scenario description. If an element is to be included, a reasonable range of properties for that variable should be used. Additional possible logical scenarios from parameter permutations are represented graphically in Figure 4.4 below:

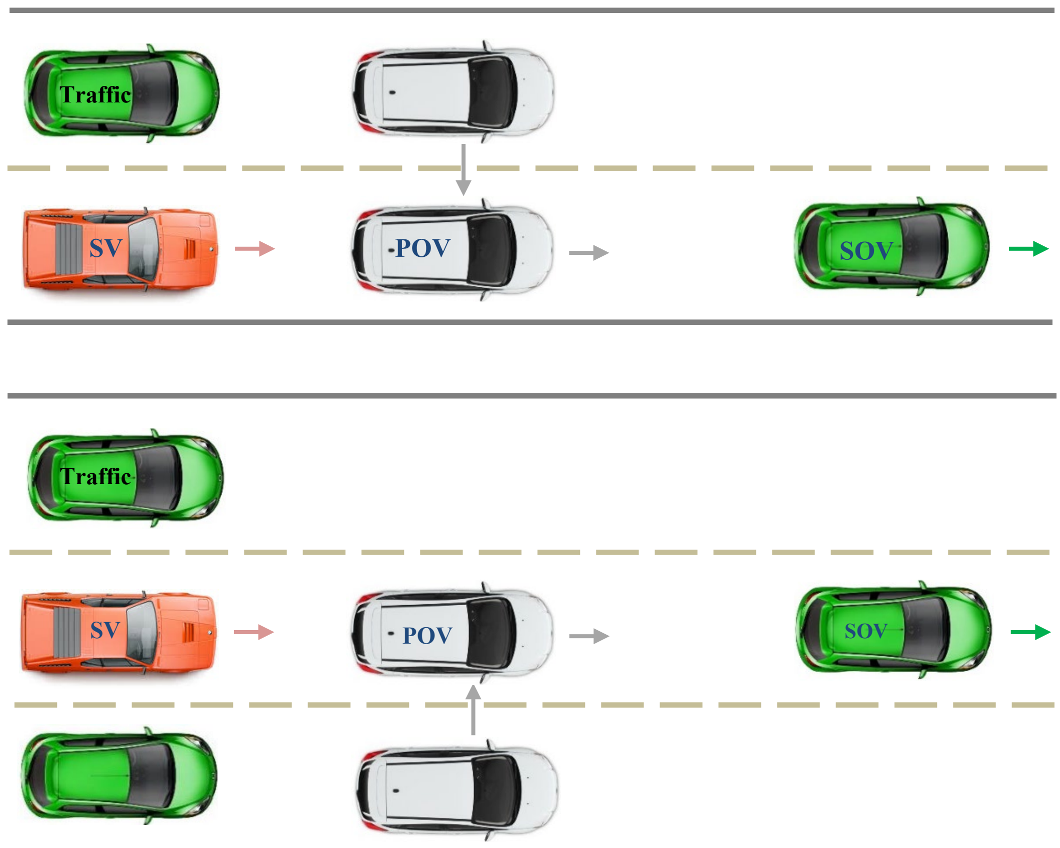

Figure 4.4. Possible Permutations of Lane Change Interactions

4.3.3 Concrete Scenario Examples

Figure 4.3 and 4.5. and Table 4.9 details the concrete scenarios from the NHTSA TJA LVLCB test procedure.

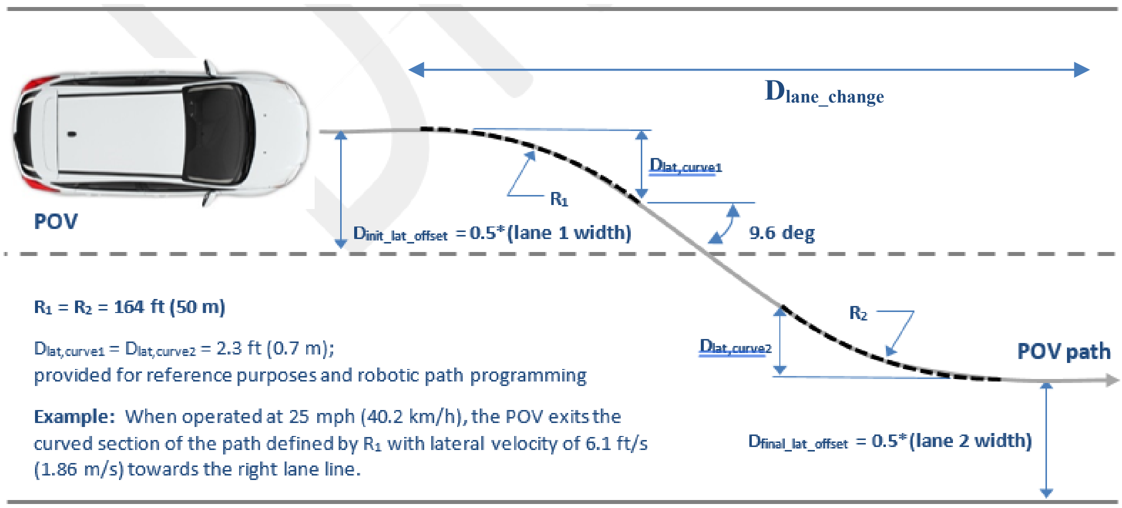

Figure 4.5. NHTSA TJA LVLCB POV Lane Change Path

Table 4.9. TJA LVLCB test types and parameters

Initial Speed			POV Braking During Lane Change		POV Braking After Lane Change	
SV Speed	POV	SOV	Timing	Magnitude	Timing	Magnitude
15 mph (24.1 km/h)	15 ± 1 mph (24.1 ± 1.6 km/h)	15 ± 1 mph (24.1 ± 1.6 km/h)	N/A	0	Applied within 100 ms of lane change completion; magnitude realized within 0.5s of braking onset	0.3g ± 0.05g
						0.5g ± 0.05g
25 mph (40.2 km/h)	25 ± 1 mph (40.2 ± 1.6 km/h)	25 ± 1 mph (40.2 ± 1.6 km/h)	N/A	0	Applied within 100 ms of lane change completion; magnitude realized within 0.5s of braking onset	0.3g ± 0.05g
						0.5g ± 0.05g
			Applied within 100 ms of lane change onset; magnitude realized within 0.5s of braking onset	0.1 ± 0.05g	Applied within 100 ms of lane change completion; magnitude realized within 0.5s of braking onset	0.3g ± 0.05g
						0.5g ± 0.05g

4.4 Vulnerable Road User Interaction

The VRU interactions discussed in Section A.3 include various configurations with different vulnerable road users. A subset of these interactions has been investigated by NHTSA for PAEB tests (Albrecht, 2017). These tests are used for scenario description and presented in this section.

4.4.1 Functional Scenario Description

Some of the concrete scenarios described in the NHTSA PAEB test procedure (Albrecht, 2017) involve a pedestrian walking into the path of a vehicle travelling perpendicular to the path of the pedestrian (Figure 4.6). The pedestrian types, pedestrian speeds, and impact overlaps described in the test procedure are listed in Table 4.13.

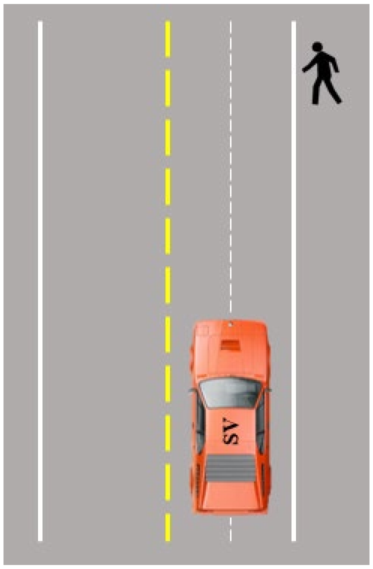

Figure 4.6. Pedestrian Crash Avoidance Test

4.4.2 Logical Scenario Elements and Properties

The test parameters listed in Table 4.13 are a very limited set. For ADS testing, a wider range of parameters could be used. The following subsections list the parameters and some possible ranges that could be used for describing a vulnerable road user scenario.

Initialization

The authors recognize that various SVs require different conditions for system initialization and continued operation. The authors intend these maneuvers to be modified to meet these conditions for each specific SV as long as the essence of the maneuver is maintained.

- The VRU is oriented as shown in Figure 4.6 with respect to the path of the SV.
- A start position and end goal position for the SV and VRU should be specified. The end goal position could be a global position or relative to the VRU.
- The test ends when either the SV reaches the end/goal position, when the SV comes in contact with the VRU, or when any other end condition is met.

Environment Elements and Properties

The environment surrounding the SV has the potential to greatly affect its response to a specific scenario. For example, while encountering a VRU, the availability of an adjacent lane may allow the SV to perform an evasive maneuver. The presence of adverse weather conditions may affect the performance and may even require the ADS to perform a minimum risk fallback maneuver if it violates its ODD requirements. These parameters need to be defined for comprehensive scenario description. The environment parameters and some initial ranges are listed in Table 4.10. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.10. Environment Parameters for VRU Interaction

Element/Property	Range
Speed Limit	5 to 55 mph (8 to 89 km/h) or ODD specific
Road Curvature	Straight, curved (maximum specified by AASHTO standard for speed limit or as allowed by ODD)
Grade	Level, not level (maximum specified by AASHTO standard for speed limit or as allowed by ODD)
Super Elevation	All applicable
Road Type	Rural, urban
Number of Lanes	1 to 3
Lane Width	8 to 14ft (2.4 to 4.2m)
Lane Direction of Travel	Same, opposing
Lane Marking (pertaining to traffic laws)	White and yellow dashed, solid, double solid (passing/no passing or lane change allowed/not allowed etc.)
Intersection Layout	All applicable
Pedestrian Crossing	Yes/No
Signage	All applicable
Weather	All conditions listed in Section 4 introduction.
Time of Day	All applicable
Lighting	All applicable illuminance values
Sun Angle/Orientation	All applicable
Roadway Surface Condition	All applicable
Road Surface Obscurants	All applicable
Friction of Drivable Surfaces	0.1 to 1

POV/SOV/VRU Elements and Properties

The VRU speed and road encroachment timing may be varied such that the impact may occur at different portion of the track of the SV. The VRU may approach the vehicle from the near side or the far side. These VRU parameters can be varied for a comprehensive scenario description. The parameters and some initial ranges are shown in Table 4.11. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.11. VRU Parameters for VRU Interaction

Element/Property	Range
VRU Predicted Impact Overlap or, VRU Predicted Impact Lane Position	-25 to 125 % of SV trackwidth -23 to 23 ft (-7 to 7m)
Speed (Absolute/Relative)	0 to 20mph absolute
Deceleration	0 to 1.5g
SV Headway to Trigger VRU Motion	16 to 328ft (5 to 100m)
Initial Lateral Position w.r.t SV	-23 to 23ft (-7 to 7m)
Type	Adult, child, animal, pedalcyclist, etc.
Side of Approach	Near/far side
Length	All applicable
Width	All applicable
Height	All applicable

Traffic Elements and Properties

The presence of traffic vehicles, or lack thereof, may interfere with the SV's response. For example, the presence of a parked vehicle may delay when the VRU can be detected, as a result, reduce the reaction time available. Such properties and some initial ranges are shown in Table 4.12. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.12. Traffic Vehicle Parameters for VRU Interaction

Element/Property	Range
Number of Traffic Actors	0 to as required
Relative X Position to SV/POV	All applicable
Relative Y Position to SV/POV	All applicable
Speed (Absolute/Relative)	All applicable
Width	All applicable
Length	All applicable

ADS Status:

Refer to ADS status section in Section 4.2.2.

If an element or its property range is not explicitly stated, it was determined to be outside the requirements for the logical scenario description. If an element is to be included, a reasonable range of properties for that variable should be used. Additional possible logical scenarios from parameter permutations are represented graphically in Figure 4.7.

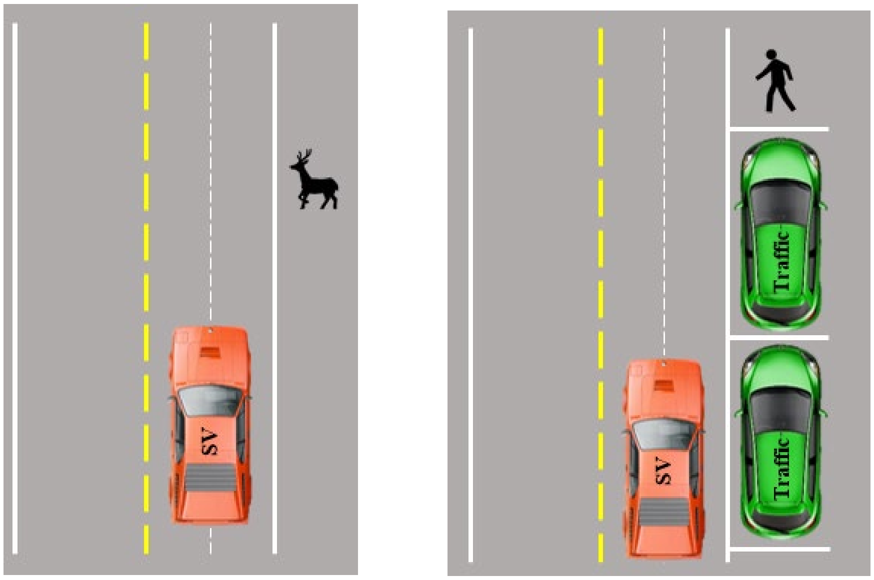

Figure 4.7. Possible permutations of VRU interactions

4.4.3 Concrete Scenario Examples

Figure 4.6 and Table 4.13 details the concrete scenarios from the NHTSA PAEB test procedure.

Table 4.13. PAEB System Tests

Test	Pedestrian Start Side	Adult/ Child	Target Lateral Distance From SV Centerline	Overlap at Collision	Target Speed	Target Acceleration Distance	Test End Condition
S1a, b, c, f, g	Nearside	Adult	11.5ft (3.5m)	25%, 50%, 75%, Stops-short, Clears vehicle path	3.1 mph (5 km/h)	1.6ft (0.5m)	
					4.9 mph (8 km/h)	3.2ft (1.0m)	
S1d	Behind Parked Vehicle (Nearside)	Child	11.5ft (3.5m)	50%	3.1 mph (5 km/h)	1.6ft (0.5m)	
					4.9 mph (8 km/h)	3.2ft (1.0m)	

Test	Pedestrian Start Side	Adult/ Child	Target Lateral Distance From SV Centerline	Overlap at Collision	Target Speed	Target Acceleration Distance	Test End Condition
S1e	Offside	Adult	18ft (5.5m)	50%	3.1 mph (5 km/h)	1.6ft (0.5m)	- The SV comes in contact with the mannequin OR, - The SV comes to a stop before making contact with the mannequin OR, - The mannequin clears the direct path of the SV.
					4.9 mph (8 km/h)	3.2ft (1.0m)	

4.5 Crossing Path Scenario

The crossing path scenario described in Section A.4 includes various interactions at intersections including straight cross path, turning at non-signalized intersections, POV failing to stop at stop signs, etc. However, only the LTAP intersection scenario has been chosen for scenario description below for brevity. The complexities in describing the LTAP scenario would cover the elements required to describe many other types of crossing path scenarios.

4.5.1 Functional Scenario Description

In this scenario, the SV attempts to go through an intersection as an oncoming vehicle attempts to turn left across the SV's path. A similar maneuver has been studied by NHTSA as part of intersection safety assist draft test procedure (NHTSA, 2019). This scenario is shown in Figure 4.8. The various test speeds of the SV and POV used in the draft test procedure are listed in Table 4.17. The draft test procedure is used as a starting point for the scenario description. The ability of the SV to detect and respond to the POV is of interest. The specific SV and POV speed combination and triggers used may result in a near crash or crash if the SV continues. The specific details of how a given intersection-based scenario is performed depends on the SV-to-POV speed combination and timing.

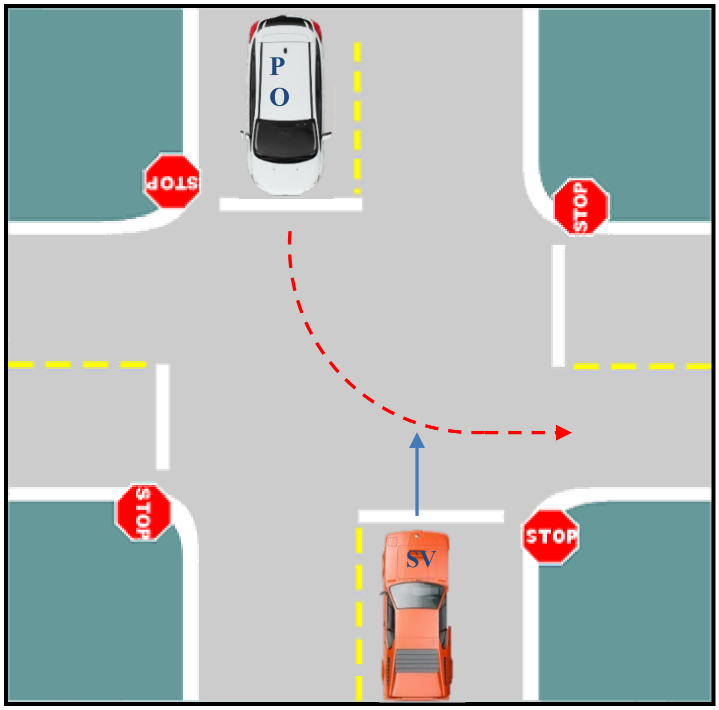

Figure 4.8. Intersection-Based Scenario Setup

4.5.2 Logical Scenario Elements

A wide range of parameters could be used to describe intersection-based crossing path scenarios. The following subsections list the parameters and some possible ranges that could be used for scenario description.

Initialization

The authors recognize that various SVs require different conditions for system initialization and continued operation. The authors intend these maneuvers to be modified to meet these conditions for each specific SV as long as the essence of the maneuver is maintained.

- The POV is initialized and oriented either in the oncoming direction (as shown in Figure 4.8) or on the road to the right of the SV, facing the intersection.
- A start position and end goal position for the SV and POV should be specified. The end goal position could be a global position or relative to the POV.
- The test ends when either the SV reaches the end/goal position, when the SV comes in contact with the POV, or when any other end condition is met.

Environment Elements and Properties

The intersection design could greatly affect the SV's response to a POV cutting across its path. For example, an SV approaching an intersection with a green light will likely maintain its speed, whereas if the intersection was a 4-way stop, the SV would be required to come to a stop. In addition, the presence of adverse weather conditions may affect the performance and may even require the ADS to perform a minimum risk fallback maneuver if it violates its ODD requirements. These parameters can be varied for a comprehensive scenario description. The environment parameters and some initial ranges are listed in Table 4.14. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.14. Environment Parameters for Intersection-Based Scenario

Element/Property	Range
Speed Limit	5 to 55 mph (8 to 89 km/h)
Road Curvature	Straight, curved (maximum specified by AASHTO standard for speed limit or as allowed by ODD)
Grade	Level, not level (maximum specified by AASHTO standard for speed limit or as allowed by ODD)
Super Elevation	All applicable
Road Type	Rural, urban
Number of Lanes	1 to 3
Lane Width	8 to 14ft (2.4 to 4.2m)
Lane Direction of Travel	Same, opposing
Lane Marking	White and yellow dashed, solid, double solid
Intersection Layout	No. of roads, lanes, lane width, intersection angles, design etc.
Pedestrian Crossing	Yes/no
Signage	All applicable
Weather	All applicable
Time of Day	All applicable
Lighting	All applicable
Sun Angle/Orientation	All applicable
Roadway Surface Condition	All applicable
Road Surface Obscurants	All applicable
Friction of Drivable Surfaces	0.1 to 1

POV/SOV/VRU Elements and Properties

The POV speed and LTAP timing may be varied such that the impact may occur at different points along the POV's path, or miss the POV altogether. The length of the POV may be a critical variable as a car cutting across would clear the SV's path much quicker than a bus or a truck would. These parameters can be varied within a scenario description. The parameters and some initial ranges are shown in Table 4.15. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.15. POV Parameters for Intersection-Based Scenario

Element/Property	Range
POV Approach Direction	On-coming, crossing, near/far side
POV Predicted Impact Overlap or, POV Predicted Impact Lane Position	-25 to 125 % of SV trackwidth -23 to 23ft (-7 to 7m)
Speed (Absolute/Relative)	5 to 55 mph (8 to 88 km/h) absolute
Lane Identification	All applicable
Initial Lateral Lane Position	All applicable
Type	All applicable
Length	All applicable
Width	All applicable

Traffic Elements and Properties

The presence of traffic vehicles, or lack thereof, may interfere with the SV's response. For example, the presence of a stopped vehicle in a left-turn-only lane may delay when the POV can be detected and as a result reduce the reaction time available. Such parameters and some initial ranges are shown in Table 4.16. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.16. Traffic Vehicle Parameters for Intersection-Based Scenario

Element/Property	Range
Number of Traffic Actors	0 to as required
Relative X Position to SV/POV	All applicable
Relative Y Position to SV/POV	All applicable
Speed (Absolute/Relative)	All applicable
Width	All applicable
Length	All applicable

ADS Status:

Refer to ADS status section in Section 4.2.2.

If an element or its property range is not explicitly stated, it was determined to be outside the requirements for the logical scenario description. If an element is to be included, a reasonable range of properties for that variable should be used. Additional possible logical scenarios from parameter permutations are represented graphically in Figure 4.9.

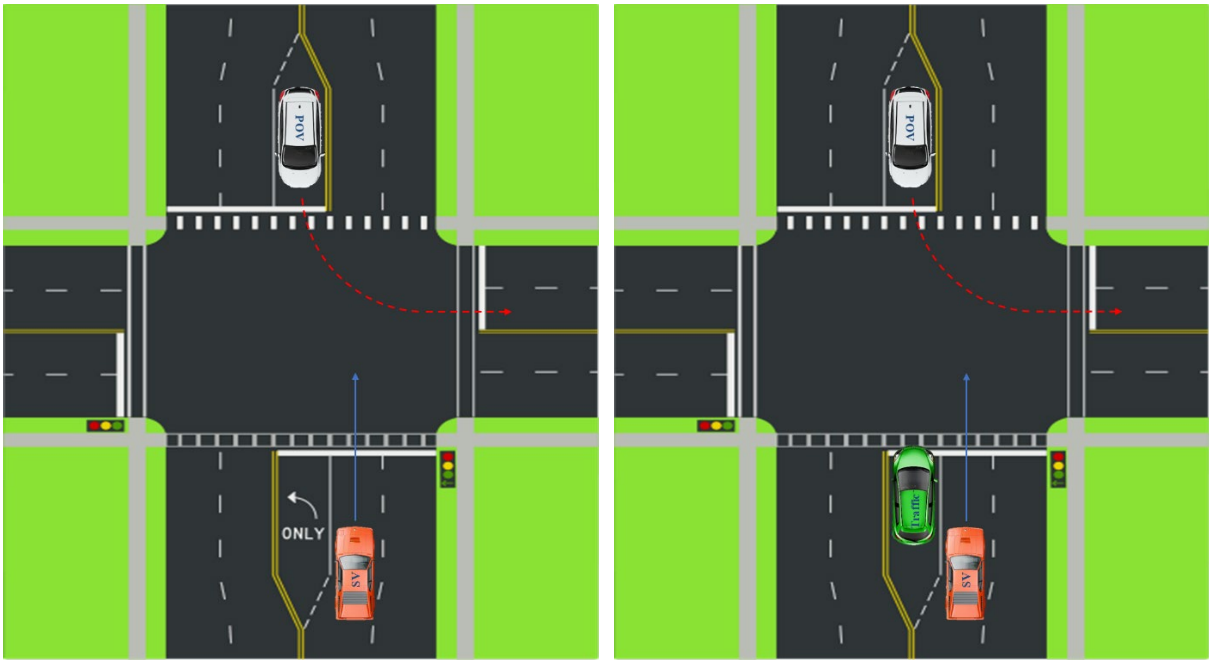

Figure 4.9. Possible Permutations of LTAP Intersection Scenario

4.5.3 Concrete Scenario Examples

Figure 4.8 and Table 4.17 details the concrete scenarios from the NHTSA intersection safety assist draft test procedure.

Table 4.17. LTAP Draft Test Procedure SV and POV Speeds

ISA Scenario	**Vehicle Speeds**	
	SV	**POV**
S2-A	25 mph (40.2 km/h)	25 ⇨15 mph (40.2 ⇨24.1 km/h)
S2-B	25 mph (40.2 km/h)	0 ⇨25 mph (0 ⇨40.2 km/h)
S2-C	0 ⇨25 mph (0 ⇨40.2 km/h)	25 ⇨15 mph (40.2 ⇨24.1 km/h)

4.6 Merge Scenario

The merge scenario is the typical highway on-ramp scenario where the SV attempts to merge with highway traffic. The pre-crash categories covered by the merge scenario are a combination of the rear-end and lane change scenario categories. This type of scenario also tests the higher-level path planning and control abilities of the SV.

4.6.1 Functional Scenario Description

A merge scenario is shown in Figure 4.10. In this case the SV can speed up and merge ahead of the POV, or slow down and merge behind the traffic vehicle. Various parameters can influence the choice the SV makes in such a scenario. These parameters are listed in the following subsection.

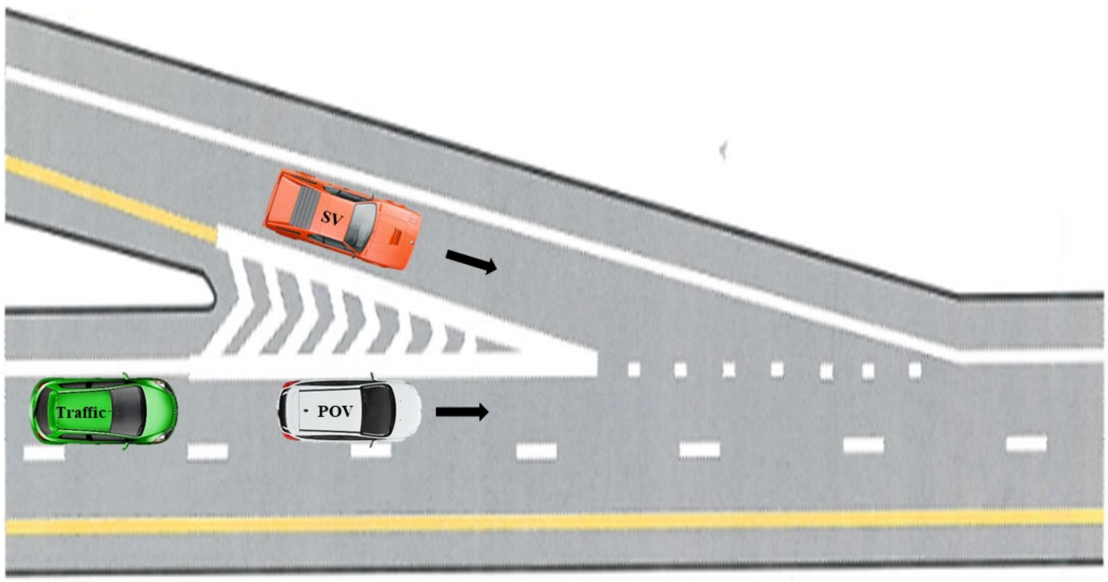

Figure 4.10. Example Merge Scenario

4.6.2 Logical Scenario Elements

Initialization

The authors recognize that various SVs require different conditions for system initialization and continued operation. The authors intend these maneuvers to be modified to meet these conditions for each specific SV as long as the essence of the maneuver is maintained.

- The POV and traffic vehicles are initialized and oriented in the direction of travel of the lane to be merged into.
- A start position and end goal position for the SV and POV should be specified. The end goal position could be a global position or relative to the POV.
- The test ends when either the SV reaches the end/goal position, when the SV comes in contact with the POV or other traffic actors, or when another end condition is met.

Environment Elements and Properties

The merge ramp design could greatly affect the SV's response. For example, the SV might have to merge directly with the flowing traffic lane as shown in Figure 4.10, or the merge might add an extra lane to the highway. In addition, the presence of adverse weather conditions may affect the performance and may even require the ADS to perform a minimum risk fallback maneuver if it violates its ODD requirements. These parameters could be varied within the scenario description. The environment parameters and some possible ranges are listed in Table 4.18. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.18. Environment Elements and Properties for Merge Scenario

Element/Property	Range
Speed Limit	25 to 70 mph (40 to 113 km/h)
Road Curvature	Straight, curved (maximum specified by AASHTO standard for speed limit or as allowed by ODD)
Grade	Level, not level (maximum specified by AASHTO standard for speed limit or as allowed by ODD)
Super Elevation	All applicable
Merge Ramp Design/Layout	Cloverleaf ramps, parallel acceleration lane, tapered acceleration lane, etc.
Number of Lanes	1 to 3
Lane Width	10 to 14 ft (3 to 4.2m)
Lane Direction of Travel	Same, opposing
Lane Marking (pertaining to traffic laws)	White and yellow dashed, solid, double solid (passing/no passing or lane change allowed/not allowed etc.)
Signage	All applicable
Weather	All conditions listed in Section 4 introduction
Time of Day	All applicable
Lighting	All applicable illuminance values
Sun Angle/Orientation	All applicable
Roadway Surface Condition	All applicable
Road Surface Obscurants	All applicable
Friction of Drivable Surfaces	0.1 to 1

POV/SOV/VRU Elements and Properties

The POV speed and timing may be varied such that it may interfere with the SV's merge maneuver. The length of the POV may be a critical variable as a truck would take a longer time to clear the merge point than a car. These POV parameters could be varied for a comprehensive scenario description. The parameters and some possible ranges are shown in Table 4.19. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.19. POV Elements and Properties for Merge Scenario

Element/Property	Range
Position (Absolute/Relative)	SV sets relative distance
Speed (Absolute/Relative)	0 to 85 mph (0 to 137 km/h) Absolute
Type	All applicable
Length	All applicable
Width	All applicable

Traffic Elements and Properties

The presence of traffic vehicles, or lack thereof, may interfere with the SV's response. For example, the presence of a traffic vehicle behind the POV may predispose the SV to speed up and merge ahead of the POV rather than slowdown. Such traffic parameters and possible ranges are shown in Table 4.20. These ranges are a suggested starting point and can be modified as deemed appropriate.

Table 4.20. Traffic Elements and Properties for Merge Scenario

Element/Property	Range
Number of Traffic Actors	0 to as required
Relative X Position to SV/POV	All applicable
Relative Y Position to SV/POV	All applicable
Speed (Absolute/Relative)	All applicable
Width	All applicable
Length	All applicable

ADS Status:

Refer to ADS status section in Section 4.2.2.

If an element or its property range is not explicitly stated, it was determined to be outside the requirements for the logical scenario description. If an element is to be included, a reasonable range of properties for that variable should be used. Possible logical scenarios from parameter permutations are represented graphically in Figure 4.11.

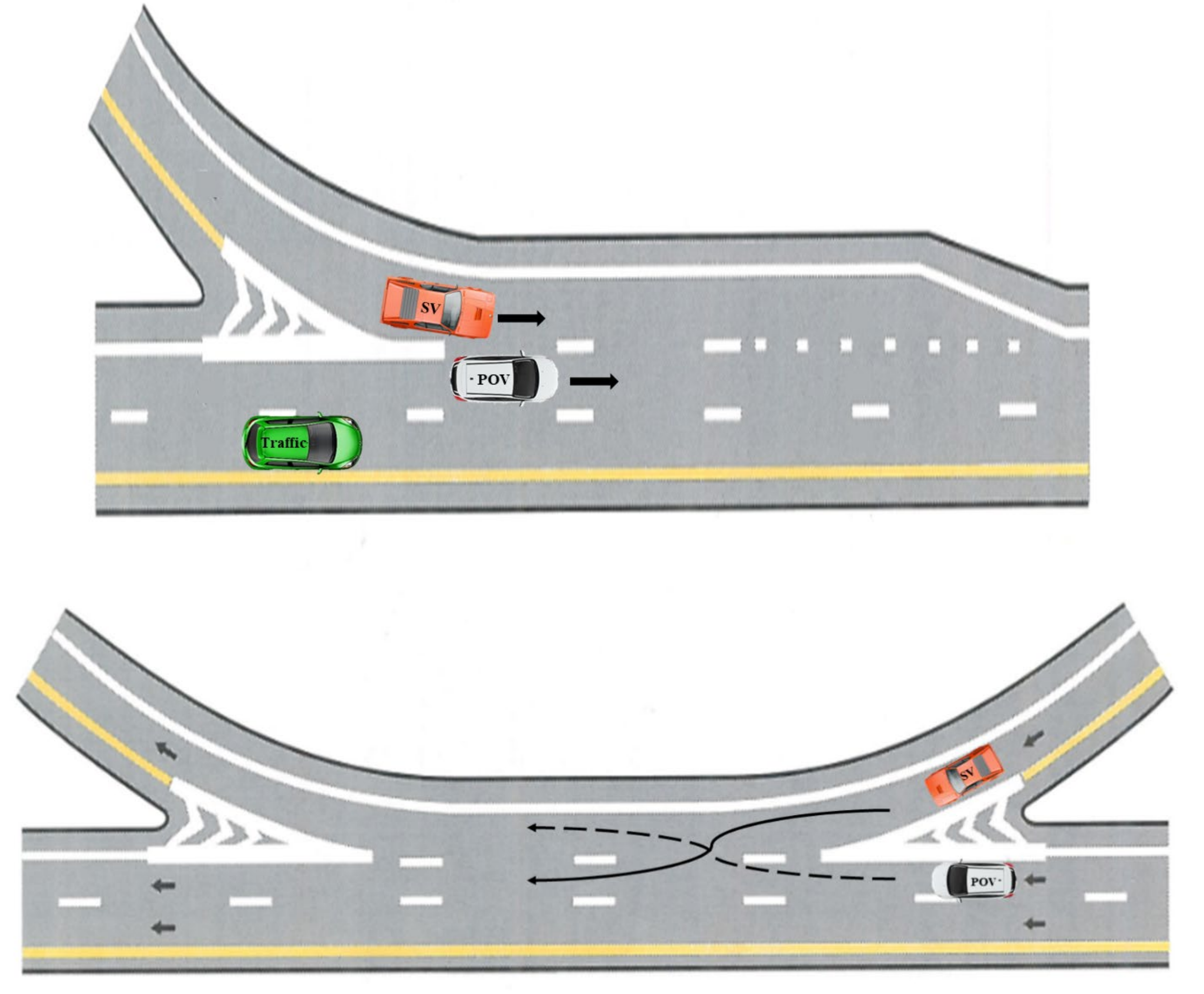

Figure 4.11. Possible Permutations of Merge Scenario

5 Preliminary Set of Elements and Their Properties for Scenario Description

This section describes the elements and their properties needed to be able to adequately describe various aspects of the driving scenarios included in Section 4. These elements and properties are pertinent to human drivers, ADAS-equipped vehicles, and ADS path-planning and control subsystems. If the scenario description scope and fidelity are expanded to include sensing and aesthetic information, the requirements for describing the driving scenarios will likely need to be expanded.

The objects, actors, and elements of the driving scenarios have varying property sets as described in Section 4. A consolidated list of elements and their properties required to describe the scenarios presented in the prior chapter is compiled in this chapter. Specific systems may require a more detailed list of properties.

5.1 Scenario Initialization Elements and Properties

There are several scenario-specific inputs that need to be provided to a subject vehicle for it to be able to operate for a given scenario. These include the SV and dynamic actors' starting positions and orientations, along with desired destinations, to name a few. The minimum scenario specific properties considered are listed in Table 5.1. These properties provide enough elements to set the initial conditions of a driving scenario to be presented to an ADS in simulation, and in concrete form, can be executed on a closed course track or public road.

Table 5.1. Scenario Initialization Properties Considered

Element	Property Level 1
Initial State	Position
	Orientation
	Velocity
Destination/Goal	Absolute
	Relative
End Conditions	Goal Reached
	Scenario time limit exceeded
	Collision
	Loss of control
	Illegal maneuver
	Etc.

5.2 Environment Elements and Properties

Defining environmental conditions is an important but complex aspect of any driving scenario description, whether implemented on the public road, closed course, or in simulation architectures. Environment includes weather, time-of-day/year, visibility, road properties, road network definitions, road-side signage and traffic control devices. These aspects are discussed in more detail in the following subsections.

5.2.1 Weather and Time

Weather conditions involve complex interactions with sensing systems and require further research to determine the fidelity required to accurately and sufficiently describe a certain weather condition, such as snow, as it pertains to scenario description. However, weather fundamentally affects driving (Zhang et al., 2004), human or otherwise, and a rudimentary, ground truth definition of environmental conditions can be included in a scenario, with allowances made for future improvement. In scope with this research, the weather and time conditions for driving scenarios can be used to demonstrate changes in driving behavior and the approach to the minimum risk fallback condition as the environmental conditions deteriorate. The high-level ground truth definition of the weather could be used in the scenario description to increase the uncertainty of the information fed into the planning subsystem for an ADS. The condition of "heavy rain," for example, is subject to interpretation, and it is unknown how it may influence sensing and perception systems. However, the weather condition can be used to define driving scenarios where the adverse weather may force the ADS to reach a minimum risk fall back state. Hence, at least a rudimentary weather model is required even at this stage.

Table 5.2, as an example, lists some of the weather phenomena of interest and the properties these phenomena may affect. The properties may be used for sensing and aesthetics but are primarily used for a more complete scenario description and to help demonstrate behavioral competency, and ADS operational, and minimum risk fallback performance.

Table 5.2. Weather Phenomena and Associated Scenario Properties

Element	Property Level 1	Property Level 2
Weather Phenomenon	Precipitation/conditions	None, rain, snow, sleet, hail, fog, cloud cover
	Wind	Speed, direction
	Temperature	
	Other	Flooding, tornado, hurricane etc.
Scenario Properties Affected by Weather	Visibility	
	Road friction	
Date/Time	Time of day	
	Sun angle & direction	
Lighting	Illuminance	

The effects weather phenomena might have on the SV and the scenario are listed in Table 5.3.

Table 5.3. Potential Impacts of Test Scenario Weather Phenomena on ADS Performance

Weather Events	Impact on Scenario
Fog, dust, rain, snow, sleet, hail, cloud cover	Reduced sensing visibility ODD violations
Ice, rain, snow, sleet, hail, flooding	Blocked lanes or covered signs and pavement markings Reduced pavement friction (note that reducing pavement friction leads to a reduction in vehicle maneuverability) ODD violations
Wind	Reduced vehicle maneuverability and stability
Extreme weather	Failed traffic control devices and communications

5.2.2 Road Properties

Part of the scenario description is a complete definition of the road layout. This includes the layout of the lanes, speed limits, lane widths, direction of travel, the lane boundaries, etc. that define the law and legal maneuvers allowed on the road. These properties are not constant for a road but change throughout the length of the road. Hence, for every road-center/lanelet coordinate (x, y, z) in the global reference frame, it was determined that the scenario description needs to be able to specify the following properties as shown in Table 5.4.

Table 5.4. Properties for Road Element

Elements	Property Level 1	Property Level 2
Road Type	Highway, rural, urban, etc.	
Road Surface	Asphalt, concrete, cobble stone, etc.	
	Condition	Rutted
		Potholes, etc.
	Surface obscurants[5]	Dust, debris
		Snow, etc.
Lanes	Number of lanes	
	Lane width	
	Direction of travel	
	Lane type (shoulder, turn only, bike, etc.)	
	lane marking/barrier type (dashed, yellow, barrier, curb, etc., and more properties)	Left
		Right

[5] Automated Vehicle Safety Consortium, 2020

Elements	Property Level 1	Property Level 2
	Intersection layout	
	Curvature	
	Grade	
	Super elevation (banking)	
	Sub-lanes (split lanes further if necessary)	Friction (split mu)

5.2.3 Road Network Definition

Once the roads are defined, the road networks, which include how roads meet and intersect, need to be defined. An accurate description of the intersection geometry, lane mapping, and layout are important in defining the scenario and for the SV to navigate the intersection in an efficient and safe manner. This includes the permissible maneuvers from each lane at an intersection connecting multiple roads. The driving scenario requirements considered to define road networks are shown in Table 5.5.

Table 5.5. Road Network Definition Considerations

Elements	Property Level 1	Property Level 2
Road Section Connectivity	Predecessor and successor	
Junction	No. of roads at junction and their IDs	Lane to lane mapping for intersection navigation
	Junction type	Signaled
		Un-signaled
		U-turns
		4-way stop
		2-way stop
		Roundabout
		Traffic circle
		Railroad crossing
	Detailed geometry	

5.2.4 Static Objects

The scenario description needs to include the various static objects found in a scenario. These static objects include traffic lights, road signs, streetlamps, barrels, cones, etc. It is also useful to know if this static content was part of the existing base map (e.g., pole or sign) or is a new static object (e.g., traffic cones). Depending on the type of object, certain properties may not be applicable. The minimum considered properties for the static objects are shown in Table 5.6. These properties enable the rudimentary representation of static objects in scenarios. If required, experimenters can add to this list to facilitate better representation of static objects in their test scenarios.

Table 5.6. Static Objects Properties Considered

Elements	Property Level 1	Property Level 2
Position of Centroid	Global/local coordinates	
Orientation	Roll, yaw, pitch (r, y, p)	
Bounding box	Length, width, height (l, w, h)	
Category Label	Car, pole, sign, etc.	
Traffic Control Device (Sign, Pole, Traffic Light, etc.)	Traffic light	Light status
		Time to change
	Sign	Sign information
	Interactive sign	Sign status
		Sign information
	Barrels/cones	
Light Sources	Luminosity	

5.3 Dynamic Actors Elements and Properties

Dynamic actors include all objects capable of movement during the scenario and include the POV, SOV, VRU, and other traffic vehicles described in the scenario definitions in Chapter 4. These could be pedestrians, pedalcyclists, animals, or various other types of vehicles. Depending on the scenario design, it might be required that the motion of these actors depends on a triggering event or the motion of the ADS vehicle or another actor. The scenario description should allow for such scenario design. Moreover, the option to use various kinematics/dynamics models to govern the motion of these actors is important. The complexity of these motion models contributes to the overall fidelity and accuracy of the simulation. At minimum, models should exhibit reasonable capabilities such as being mathematically continuous and within the physical capabilities of the actor modeled. The minimum considered properties for a dynamic actor are shown in Table 5.7. These properties enable the rudimentary representation of dynamic actors in scenarios. If required, experimenters can add to this list to facilitate better representation of dynamic actors in their test scenarios.

Table 5.7. Dynamic Actor Properties Considered

<table>
<tr><th>Element</th><th>Property Level 1</th><th colspan="2">Property Level 2</th></tr>
<tr><td>Category label</td><td>Pedestrian, Pedalcyclist, Motorcyclist, light vehicle, etc.</td><td colspan="2">Corresponding behaviors</td></tr>
<tr><td>Bounding box</td><td>Length, width, height</td><td colspan="2"></td></tr>
<tr><td rowspan="7">Motion model</td><td>Intelligent (automated traffic)</td><td colspan="2" rowspan="3">Corresponding properties</td></tr>
<tr><td>Kinematic model</td></tr>
<tr><td>Dynamics model</td></tr>
<tr><td rowspan="4">User defined motion</td><td>Position</td><td rowspan="4">These could be functions of time, relative to state of another actor, or dependent on other conditions</td></tr>
<tr><td>Orientation</td></tr>
<tr><td>Linear velocity, Angular rates</td></tr>
<tr><td>Linear acceleration, Angular acc.</td></tr>
</table>

5.4 ADS Status

Another factor that can affect the SV's response is the status of the ADS. A few of these factors are listed in Table 4.4. In simulation, these status messages could be supplied to the simulated vehicle to study the minimum risk fallback operation when a fault exists. This category is applicable to all the maneuvers discussed in the chapter.

Table 5.8. ADS Status Properties Considered

<table>
<tr><th>Elements</th><th>Property Level 1</th></tr>
<tr><td>Engine/Motor Fault Codes</td><td rowspan="2">Fault information (sensor fault, software failure, etc.)</td></tr>
<tr><td>ADS Sensor Fault</td></tr>
<tr><td>ADS Software Bug</td><td></td></tr>
<tr><td>Fuel Level/Battery Charge</td><td>Status</td></tr>
<tr><td>Mechanical Failure</td><td>Component</td></tr>
<tr><td>ESC/ABS Activation</td><td>Duration</td></tr>
</table>

5.5 Other Features and Considerations

In addition to specific scenario elements and properties discussed above, the scenario description needs to have other capabilities to handle complex scenarios and its variations. This section discusses a few such features that the authors deem necessary.

5.5.1 Encoding Language, Syntax, and Conventions

The authors recognize that the programming language syntax, units and conventions are important details that affect the usability of the scenario description language for robotic test equipment and in simulation, as well as for human readability. Hence, it is crucial that a scenario description language be well-documented with examples for ease of use. In particular, the language syntax must be well-defined, with appropriate naming conventions detailed.

The various units and the coordinate reference frames used natively within the language also need to be clearly defined for accurate coding of scenarios in the language. This information can also be included in the file header.

5.5.2 Triggers

Complex scenario choreographies require the triggering of specific actions/maneuvers of traffic and other scenario elements based on a variety of different conditions being satisfied. The software and scenario description language need to support these complex triggers, to simulate complex choreographed scenarios. Table 5.9 on the following page lists some of the triggers considered.

Table 5.9. Trigger Types

Trigger Type	Sub Type	Description
Distance	Magnitude	Compares the relative distance (magnitude/lateral/longitudinal) between the defined objects, and triggers an event based on the outcome of the comparison.
	Lateral	
	Longitudinal	
Speed	Same as distance	Same as distance
Acceleration	Same as distance	Same as distance
Position		Triggers an event when a certain actor reaches a defined position
Time		Triggers an event after a pre-defined period of time has passed
Sequential		Triggers an event after the completion of another event
Parallel		Triggers multiple events when a certain condition or a combination of conditions are met.

Note: It is also necessary that the scenario description support logical combinations (and, or, xor, etc.) of the above triggers to make custom trigger conditions.

5.5.3 Design of Experiments

A large number of concrete scenarios may be created and tested. It becomes important to make the process of selecting scenario parameters more efficient. The design of experiments involves selecting relevant parameter ranges and combinations to form concrete scenarios. After the experiments are run, it is necessary to check whether the designed interactions occurred and measure various other performance metrics. The parametrization and confirmation metrics are discussed further in the following subsections.

Parametrization

Describing just one concrete scenario is likely not sufficient to establish the performance capabilities of complex automated control systems. Since it is unknown how many scenarios are needed to understand the performance of ADSs, often increasingly severe iterations of the same logical scenario are tested to gain a better understanding. Creating a different concrete scenario from scratch for each of these iterations may be prohibitive and inefficient. For instance, simulation software may allow for the design of a functional scenario with various parametrizations of speeds, distances, and other conditions. This is an important feature for simulation to have, so that a large number of concrete scenarios can be automatically generated and simulated.

Another aspect of parametrization is the selection of parameter combinations to create concrete scenarios. Efficient selection can reduce the total number of scenarios tested by skipping combinations that may not result in the desired interaction. Efficient selection of parameter combinations would also result in finer resolution of parameter values when metrics indicate interesting interactions. There are various parameter interpolation techniques available and published in literature that can be used for optimization of this process. Further detail on parameter optimization in design of experiments is outside the scope of this report.

Confirmation

In addition to being able to describe a scenario, it is also necessary to verify if the parameter values were reproduced in the test. Moreover, it is necessary to confirm whether the interaction occurred and determine the various metrics for the test. This is necessary since certain parameter combinations may prevent the SV from encountering the interaction described in the functional scenario, and when a large number of tests are run, this process needs to be automated. Such a confirmation feature will also give the experimenter insights into the behavior of the SV, by exposing the parameter ranges that led to the desired interactions. As an example, a desired rear-end driving scenario with the lead vehicle triggered to decelerate once the SV's front bumper is 20 m from the POV's rear bumper may not be executed. This is because the SV ADS controls how close it follows a lead vehicle and may choose to maintain distances greater than the trigger value (20 m) and therefore the deceleration triggering distance of 20m is never met and the deceleration event never occurs.

5.5.4 Control System Implementation

Though this report focuses mainly on the elements and properties for specific scenario descriptions, when implemented in software, it is necessary that the software supports implementation of the ADS control system. The control system implementation can be supported either natively or externally in the form of co-simulation to be eventually useful to developers.

6 Summary

This research study considered pre-crash statistics and behavioral competencies to choose five scenarios that would be used to explore elements and properties needed to describe each driving scenario. The chosen scenarios and the pre-crash scenarios that were explicitly considered while designing the test procedure are listed in Table 6.1.

Table 6.1. Scenario Category Chosen and Their Constituent Pre-Crash Scenarios Considered in the Test Procedure Design

Scenario Category	**Pre-Crash Scenarios Included**	**Applicable NHTSA Test Procedure**
Rear-End Scenario Category	Rear-end/striking maneuver	AEB/CIB Confirmation Tests
	Rear-end/lead vehicle accelerating	
	Rear-end/lead vehicle moving	
	Rear-end/lead vehicle decelerating	
	Rear-end/lead vehicle stopped	
Lane Change Scenario Category	Changing lanes/same direction	TJA Confirmation Test
	Vehicle(s) drifting – same direction	
Vulnerable Road User Interaction Category	Animal crash without prior vehicle maneuver	Pedestrian Cross Path Test (with various road users)
	Pedestrian crash without prior vehicle maneuver	
	Pedalcyclist crash without prior vehicle maneuver	
Crossing Path Scenario Category	Left turn across path, lateral direction	ISA System Confirmation Test – LTAP Scenario
	Left turn across path, opposite direction	
Merge Scenario Category	Not applicable	Not applicable

Four of the five scenarios used existing test track procedures to help explore elements and properties needed to describe driving scenarios. These test track procedures were originally written for ADAS or lower level driving automation system testing and were adapted for potential use in research, development, and performance testing with ADSs. This adaptation included defining five broad categories of scenario elements: initialization, environmental, POV/SOV/VRU, traffic, and ADS status. Each scenario was then described, and a preliminary set of scenario elements and properties for each category were listed along with possible ranges. After this, the elements and properties of all five scenarios were consolidated, grouped, and presented in Section five.

This work selected and studied a set of five scenarios (Chapter 4) that cover a significant portion of 2011-2015 FARS and GES light vehicle crashes and behavioral competencies. These scenarios were used to understand the elements and properties that may be necessary for describing scenarios from a path planning and control perspective. These scenarios may be tested in simulation, on a closed course, or encountered in the real world and may aid in the development, validation, and deployment of ADSs.

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Appendix A Scenario Crash Statistics and Behavioral Competencies

A-1 Rear-End Scenario Category

The scenarios that belong to the rear-end category where the light vehicle made the critical action are shown in Table A.1, along with the 2011-2015 FARS and GES frequency of occurrence and overall relative frequency when compared to all 36 light vehicle pre-crash scenarios. The five scenarios in Table A.1 cover 31.1 percent of all crashes represented in the pre-crash scenarios identified in the report (Swanson et al., 2019) where a light vehicle made the critical action. The scenarios in the rear-end category also map to 4 of the 47 behavioral competencies from Table 3.3. These 4 behavioral competencies are listed in Table A.2.

The scenarios in the rear-end category are similar to NHTSA's CIB and DBS NCAP test procedures (NHTSA, 2014a) (NHTSA, 2014b); therefore, the CIB and DBS test procedures used by NHTSA's NCAP were selected in this study to help determine the necessary elements required to describe this category of scenarios. These test scenarios will be parametrized so various speeds, decelerations, and ranges of both lead vehicle and following vehicle will be described.

The CIB and DBS test procedures are only used as a starting point for the functional scenario descriptions. The scenario description framework needs to handle all forms of driving, including human and higher level ADSs. Since higher level ADSs may choose to avoid the lead vehicle by changing lanes and/or braking, the pass/fail criteria set in the CIB and DBS test procedures may not apply.

Table A.1. Rear-End Scenarios Involving Light Vehicles

Scenario No.	Scenario Description	Frequency[6]	Rel. Frequency
20	Rear-end/striking maneuver	57,224	1.0%
21	Rear-end/lead vehicle accelerating	22,008	0.4%
22	Rear-end/lead vehicle moving	214,001	3.8%
23	Rear-end/lead vehicle decelerating	412,536	7.3%
24	Rear-end/lead vehicle stopped	1,050,558	18.6%

Table A.2. Behavioral Competencies Mapped by Rear-End Scenarios

Competency No.	Behavioral Competency Description
9	Perform car following (including stop & go)
10	Detect & respond to stopped vehicles
12	Detect & respond to static obstacles in road
47	Detect and respond to vehicles parking in the roadway

[6] This is annual average frequency based on 2011 – 2015 GES crash statistics

A-2 Lane Change Scenario Category

The scenarios that belong to the lane change category are shown in Table A.3 along with the frequency of occurrence and overall relative frequency when compared to all 36 pre-crash scenarios. These two scenarios account for 12.3 percent of all crashes involving light vehicles from the 2011-2015 GES crash statistics (Swanson et al., 2019). The lead vehicle lane change scenarios map to 3 behavioral competencies, which are listed in Table A.4.

The lane change scenarios are similar to the draft TJA test called LVLCB (NHTSA, 2018). Moreover, the LVLCB test involves complex choreography between multiple actors, which is helpful because the ability of a scenario description framework to define such complex interactions needs to be evaluated. Hence the LVLCB test was chosen as a scenario for evaluation.

The LVLCB scenario will be used as a starting point for the lane change category, and scenario description and parametrization will be employed to describe various combinations of speeds, decelerations etc. to arrive at a large set of concrete scenarios. Again, when this scenario is applied to higher level ADSs, the pass/fail criteria set in the LVLCB test procedure may not apply since the ADSs may choose to avoid the intended interaction by changing lanes. The LVLCB will cover the scenarios highlighted in blue in Table A.3.

Table A.3. Lane Change Scenarios Involving Light Vehicles

Sc. No.	Scenario Description	Frequency[7]	Rel. Frequency
14	Vehicle(s) turning – same direction	194,303	3.4%
15	Vehicle(s) parking – same direction	34,898	0.6%
16	Vehicle(s) changing lanes – same direction	348,464	6.2%
17	Vehicle(s) drifting – same direction	120,223	2.1%

Table A.4. Behavioral Competencies Mapped by Lane Change Scenarios

Competency No.	Behavioral Competency Description
9	Perform car following (including stop & go)
11	Detect & respond to lane changes
33	Detect and respond to a merging vehicle

[7] Crash frequencies are based on annual averages of 2011-2015 GES crash statistics

A-3 Vulnerable Road User Interaction Scenario Category

The scenarios based on an interaction with a vulnerable road user are shown in Table A.5 along with the frequency of occurrence and overall relative frequency when compared to all 36 pre-crash scenarios. The pre-crash scenarios pertaining to vulnerable road users account for 7.4 percent of all crashes involving light vehicles from 2011-2015 GES crash statistics (Swanson et al., 2019) . The vulnerable road user scenarios map to 8 behavioral competencies, which are listed in Table A.6.

To address the elements required to sufficiently describe scenarios with vulnerable road users, pedestrian crash avoidance maneuvers previously published by NHTSA are adopted as a baseline. The cross-path maneuver discussed by Albrecht et al. (2017) is used and the pedestrian will be substituted with other road users (like cyclists, animals, etc.) to diversify the scenario. The speeds of the vehicle and the vulnerable road user will be parametrized, so a large combination of scenarios can be described. These maneuvers will cover the scenarios highlighted in blue in Table A.5.

Table A.5. Vulnerable Road Users Scenarios Involving Light Vehicles

Sc. No.	Pre-Crash Scenario Description	Frequency[8]	Rel. Frequency
8	Animal crash without prior vehicle maneuver	295,273	5.2%
10	Pedestrian crash without prior vehicle maneuver	41,094	0.7%
12	Pedalcyclist crash without prior vehicle maneuver	26,149	0.5%
7	Animal crash with prior vehicle maneuver	2,833	0.1%
9	Pedestrian crash with prior vehicle maneuver	28,018	0.5%
11	Pedalcyclist crash with prior vehicle maneuver	23,019	0.4%

Table A.6. Behavioral Competencies Mapped by Vulnerable Road Users Scenarios

Competency No.	Behavioral Competency Description
12	Detect & respond to static obstacles in road
13	Detect bikes, pedestrians, animals, etc.
14	Respond to bikes, pedestrians, animals, etc.
30	Yield to pedestrians and pedalcyclist at intersections and crosswalks
31	Provide safe distance from vehicles, pedestrians, pedalcyclist on side of the road
34	Detect and respond to pedestrians in road (not walking through intersection or crosswalk)
35	Provide safe distance from pedalcyclist traveling on road (with or without bike lane)
36	Detect and respond to animals

[8] Crash frequencies are based on annual averages of 2011-2015 GES crash statistics

A-4 Crossing Path Scenario Category

Another common setting for the pre-crash scenarios in Table 3.1 is intersections described by the crossing path group. Table A.7 lists the pre-crash scenarios that are explicitly based at intersections and involve other vehicles. These crashes total 20.3 percent of all crashes involving light vehicle from the 2011-2015 GES crash statistics (Swanson et al., 2019). The intersection scenarios map to 4 behavioral competencies shown in Table A.8. Hence, studying the ability of the vehicle to safely navigate intersections is also important.

To determine the elements required to define intersection-based crossing path scenarios, the LTAP pre-crash scenario has been chosen for scenario description. LTAP test track procedure previously published by NHTSA (NHTSA, 2019) are adopted as a baseline. The speeds of the SV and the POV will be parametrized, as well as the intersection geometry, existence of pedestrians, traffic vehicles, etc. so a large combination of scenarios can be described.

The two LTAP scenarios (highlighted in blue) account for a total of 9.2 percent of all crashes involving light vehicle crashes from the 2011-2015 GES crash statistics (Swanson et al., 2019).

Table A.7. Crossing Path Scenarios Involving Light Vehicles

Sc. No.	Pre-Crash Scenario Description	Frequency[9]	Rel. Frequency
25	Right turn into path	91,191	1.6%
26	Right turn across path	23,451	0.4%
27	Straight crossing paths	434,374	7.7%
28	Left turn across path, lateral direction	193,102	3.4%
29	Left turn into path	80,585	1.4%
30	Left turn across path, opposite direction	329,410	5.8%

[9] Crash frequencies are based on annual averages of 2011-2015 GES crash statistics

Table A.8. Behavioral Competencies Mapped by Crossing Path Scenarios

Com. No.	Behavioral Competency Description
15	Detect traffic signals & stop/yield signs
16	Respond to traffic signals & stop/yield signs
17	Navigate intersections & perform turns
25	Make appropriate right-of-way decisions

A-5 Merge Scenario Category

Another important behavior to be studied is the ability of the ADS to perform a merge into traffic, or plan to allow a vehicle to merge ahead of it. The pre-crash scenarios pertaining to such a scenario are a combination of the rear-end scenario and lane change scenario categories discussed in Table A.1 and Table A.3, respectively. For this work, a merge scenario was selected where a vehicle is forced to change lanes or merge with traffic based on road geometry (i.e. entry/exit ramp, lane end, etc.), similarly as described in Thorn et al. (2018).

Such a scenario could potentially map to the 6 behavioral competencies shown in Table A.9. Along with testing the ability to describe the roadway elements and properties associated with a merge scenario, the geometry of the merge may also test the ADS's path planning and control abilities in a complex interaction, as the interacting vehicles may be in front of, behind, and/or to the side of the SV.

Table A.9. Behavioral Competencies Mapped by Merge Scenario

Com. No.	Behavioral Competency Description
5	Perform high-speed merge
6	Perform lane change/ lower speed merge
11	Detect & respond to lane changes
19	Detect & respond to access restrictions
25	Make appropriate right-of-way decisions
33	Detect and respond to a merging vehicle

A-6 General Behavioral Competencies

Some of the behavioral competencies are very broad and may be incorporated into many of the scenarios chosen in this chapter, or they are obvious and apply to all the scenarios. It is conceivable that during any of the scenarios chosen in this chapter, the vehicle may encounter a system fault, an emergency vehicle, or any of the other situations described by the behavioral competencies listed in Table A.10. Instead of listing these behavioral competencies repeatedly for all the scenarios chosen in this chapter, they are consolidated and presented here.

Table A.10. General Behavioral Competencies

Competency No.	Behavioral Competency Description
1	Detect operating envelope on the basis of vehicle's ODD criteria for system engagement and disengagement
2	Detect vehicle, system, and sensor fault and failures
4	Detect and respond to speed limit changes
8	Detect and perform passing and no passing zones
22	Detect emergency vehicles
23	Respond to emergency vehicles
26	Follow local and state driving laws
42	Detect and respond to vehicle control loss (e.g. reduced road friction)
43	Detect and respond to unanticipated weather or lighting conditions outside of vehicle's capability (e.g. rainstorm)
44	Detect and respond to unanticipated lighting conditions (e.g. power outages)
45	Detect and respond to non-collision safety situations (e.g. vehicle doors ajar)
46	Detect and respond to faded or missing roadway markings or signage

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