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16. Abstract

The primary goal of this research report is to study the elements and properties that may be used to describe driving scenarios. This report builds on previous research in which five scenarios were chosen from human driving data and various proposed behavioral competencies for automated driving systems. A preliminary list of elements and properties that may be used to uniquely describe the five driving scenarios was developed to help facilitate reproducible, repeatable, and traceable representation. The selected elements and their properties were focused on the ground truth scenario information. In this report six scenarios were selected from available driving databases, crash databases, and the behavioral competencies not covered in the previous research. These six scenarios were analyzed to consider expansion of the preliminary list of elements and properties that can be used to facilitate more complete descriptions of driving scenarios.

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List of Acronyms

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
AM	autonomous mode
API	application program interface
ASRS	Aviation Safety Reporting System
CIB	crash imminent braking
CM	conventional mode
DDT	dynamic driving task
DMV	Department of Motor Vehicles
ESC	electronic stability control
FARS	Fatality Analysis Reporting System
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FMVSS	Federal Motor Vehicle Safety Standards
GES	General Estimates System
HOV	high-occupancy vehicle
IIHS	Insurance Institute for Highway Safety
LTAP/LD	left turn across path, lateral direction
LTAP/OD	left turn across path, opposite direction
LTIP	left turn into path
LV	lead vehicle
LVA	lead vehicle accelerating
LVD	lead vehicle decelerating
LVLCB	lead vehicle lane change with braking
LVM	lead vehicle moving
LVS	lead vehicle stopped
NASS	National Automotive Sampling System
NCAP	New Car Assessment Program
NTSB	National Traffic Safety Board
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
SAE	Society of Automotive Engineers (this organization changed its name to SAE International in 2006)
SCP	straight crossing path
SOV	secondary other vehicle
SRSV	suddenly revealed stopped vehicle
SV	subject vehicle
TJA	traffic jam assist
USFA	United States Fire Administration
VRU	vulnerable road user

Executive Summary

The primary goal of this research report is to establish the elements and properties that may be used to describe driving scenarios and facilitate reproducible, repeatable, and traceable representation. This report builds on the work described in *An Approach for the Selection and Description of Elements Used to Define Driving Scenarios* (Rao et al., 2021) in which 5 scenarios were chosen from human driving data and various proposed behavioral competencies for ADSs. A preliminary list of elements actors, weather, etc. and their properties (dimensions, color, etc.) that may be used to uniquely describe these 5 scenarios was compiled. The selected elements and their properties were focused on describing the ground truth scenario information. These elements were grouped into five categories: initialization, environmental factors, POV/SOV/VRU, traffic, and ADS status. For each scenario type, a range of parameters for each element's properties can be varied to generate a broader list of possible scenarios.

In this report, based on a review of additional data sources, 6 more scenarios were selected that, when added to the previous 5 selected in the 2020 report, provide a diverse set of driving scenarios that may be relevant to ADS vehicle testing in the future. The additional data sources used in this study included available driving databases, crash databases, and behavioral competencies not covered in the previous analysis. The 6 scenarios selected were: suddenly revealed stopped vehicle scenario, straight crossing path scenario, opposing traffic scenario, parking/reversing scenario, encountering construction zone scenario, encountering an emergency vehicle/school bus scenario. These 6 scenarios were analyzed using the framework set in Rao et al., (2021) to expand on the preliminary list of elements and properties compiled in it. As a result of this analysis, one new element (parking lot) was added to the road properties category, two new elements (special vehicle and special pedestrian) were added to the dynamic actors category and an additional element (ADS Mode) was added to the ADS status category. The new elements were accompanied with new, related properties for each of them, that expanded the previously established set of elements and properties to form a more complete list.

Introduction

The work presented in this document is a continuation of the work presented in the reports titled *Review of Simulation Frameworks and Standards Related to Driving Scenarios* (Schnelle et al., 2019) and *An Approach for the Selection and Description of Elements Used to Define Driving Scenarios* (Rao et al., 2021). The first 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. In the Rao group's report, pre-crash scenario typologies, behavioral competencies, and test track procedures were selected, analyzed, and reviewed to identify a preliminary list of elements and their properties that can be used to describe ground truth[1] scenario information.

In this document the authors present a detailed review of available SAE level 2[2] to level 5 (SAE International, 2021) driving automation system crash scenario descriptions. Additionally, behavioral competencies and human-driven pre-crash data not covered in Rao et al., (2021) were also considered to further explore possible new elements and properties that may be used to describe these interactions. To achieve this goal, this document is outlined as follows:

1. Introduction: This chapter describes the previous relevant work, gives an introduction to ADS, and details the definitions of terms used in this report.
2. Literature Review: This chapter describes the various sources considered in this report and presents a synopsis of relevant information from each of the sources. Some of the new sources considered are:
    a. California Department of Motor Vehicles Report of Traffic Collision Involving Autonomous Vehicle (State of California, 2022);
    b. NTSB Accident Investigation Reports;
    c. Review of the pre-crash scenarios (Swanson et al., 2019) and behavioral competencies (Nowakowski et al., 2015: Waymo, n.d.) not covered in Rao et al., (2021).
    d. Emergency vehicles and school bus statistics were also considered.
3. Scenario Selection and New Elements and Properties Analysis: This chapter describes the criteria/considerations for scenario selection. It then details the elements and their properties required to define the scenarios selected.
4. Preliminary Set of Elements and Their Properties for Scenario Description: This chapter consolidates all the elements and their properties into categories and presents the consolidated list.

[1] "Ground truth" refers to information that is real and accurate, without any noise or uncertainty associated with measurement or sensing.
[2] SAE level 2 partial driving automation systems are included in the review because these systems include hardware and software that can provide steering, braking, and acceleration, and are capable of performing part or all of the DDT on a sustained basis to support the driver while the driver's feet are off the pedals and hands are off the steering wheel (SAE International, 2021).

Generic ADS Description

To provide context to the selection of elements and properties that may be used to describe ground truth scenario information, a brief introduction of a generic ADS is given. A generic ADS may be considered to operate using four main subsystems as shown in Figure 1: sensing, perception, planning, and control. In general, sensing and perception subsystems translate raw sensor data into objects. As in the previous report, Rao et al., (2021), this document also focuses on the 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. The scope has been limited to planning and control aspects because of the complexities involved with defining and classifying all the sensory and aesthetic details of a scenario. These complexities include determining material properties (sensory and aesthetic details) necessary, such as color, radar/lidar reflectivity, permeability, and how to describe them, which are still ongoing areas of research. These aspects are significant and may be addressed in the future. Also, regarding ADSs, the sensing and perception subsystems can be tested independently of the planning and control systems.

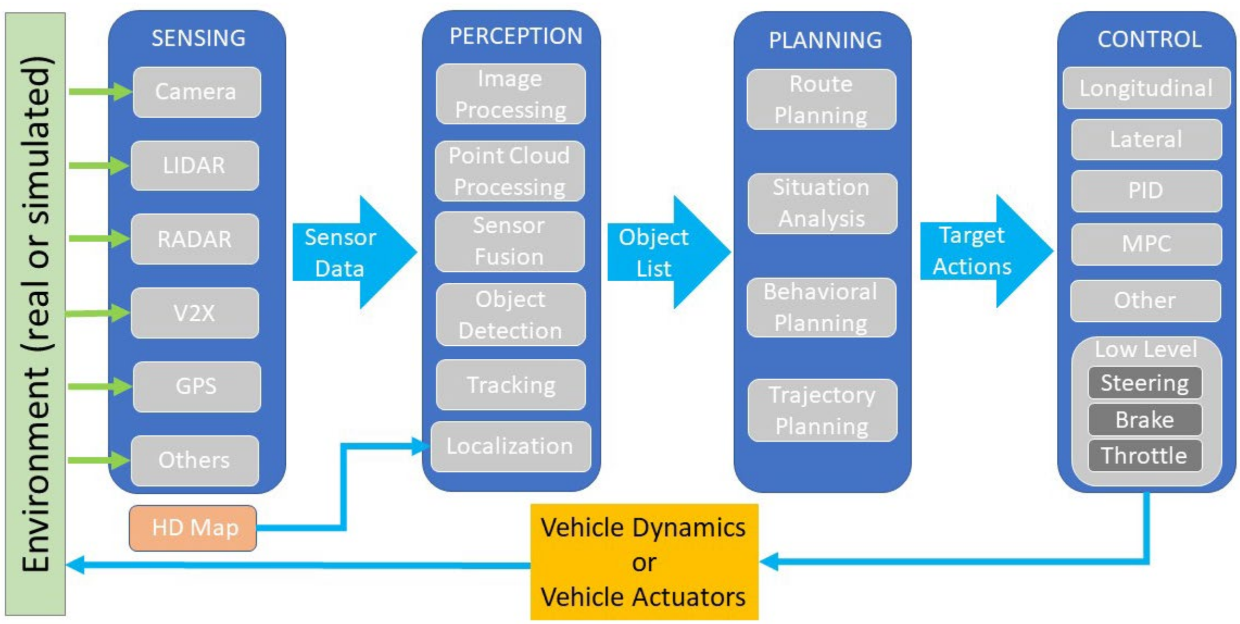

Figure 1. A Generic ADS Overview With Subsystems

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. To this end, a few terms used throughout this document are defined below.

Dynamic Actor
A dynamic actor refers to any scenario element that is physically capable of moving. For most scenarios, these refer to vehicles, pedestrians, pedalcyclists, animals, and other road users. These may refer to objects like traffic cones, barrels, etc., if the scenario involves their motion, either due to being struck or due to environmental condition like wind. Some special dynamic actor categories are defined below:

Subject Vehicle
Since this work primarily focuses on system level testing, the primary system under test is a particular vehicle, referred to as the SV. The SV could be a vehicle-equipped with an ADS or another subsystem under test, or a simulated vehicle.

Principal Other Vehicle
The POV refers to the principal vehicle/vehicles 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 vehicles that may be necessary to facilitate the interaction between the SV and POV.

Vulnerable Road User
VRU refers to actors that could be encountered on the roadway, who are not using a motorized vehicle. These could include pedestrians, pedalcyclists, animals, people in wheelchairs, etc.

Traffic
Traffic elements are other dynamic actors that are part of the scenario and interact with the SV, other than the POV/SOV/VRU. They influence the SV's decision-making process within the scenario. Traffic elements could be, but not limited to, other vehicles, pedestrians, pedalcyclists, or animals.

Driving Scenario
The term "driving scenario" describes the generic act of controlled operation and movement of a vehicle, including cars, pedalcyclists, motorcycles, trucks, and buses. In general, a driving scenario may contain contextual information as more formally described below, for example, driving scenario may specify a specific roadway design element or constraint in general. In other cases, the driving scenario may also define other actors that the vehicle may interact with.

Driving Scenario Elements, Properties, and Parameters
Elements of a scenario refer to actors, objects, road, and environmental aspects of a scenario. Each of these elements have their own set of properties. Each one of these properties can be parameterized and a specific parameter value can be assigned to define a certain property of a driving scenario's element that can facilitate better repeatability, reproducibility, and traceability[3] in approaches used to describe driving scenarios.

[3] Where traceability refers to the ability to trace element and/or properties historical values.

For example, a scenario element could be a pedestrian, and one of its properties is dimension (e.g., height, width, length). Each one of these dimensions would have parameter ranges, with a specific parameter value eventually being selected for a particular test. Another scenario element could be weather, with lighting as a property and a range of values for that property being defined with one parameter value being selected for a repeatable, reproducible, traceable test case.

Basic Scenario Interaction

Basic scenario interaction describes the broad interaction between the SV and other necessary actors of the scenario and/or environmental elements. This includes the primary interaction in the driving scenario and leaves open specific elements and properties like, the number of actors, weather conditions, road geometry, timing, speeds, etc. An example of a basic scenario interaction is a highway merge from an on-ramp into traffic.

Parametrized Driving Scenario

To further define a basic driving scenario interaction, driving scenario elements, their associated properties, and the parameter ranges for those properties can be added to the driving scenario to form a family of testable driving scenarios or parametrized driving scenario set. 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 driving scenario definition that provides enough detail to begin to form a family or class of driving scenarios test cases that belong to the more generic basic scenario interaction.

Scenario Test Case

A scenario test case refers to the selection of a specific set of parameter values for all the specified element properties of the parametrized driving scenario. This would include constrained weather conditions, a specific road geometry, POV/SOV speeds, specific trajectories, timing of the interaction, etc. Hence, a scenario test case is a more specific, more repeatable, and reproducible scenario with a set of parameter values for each element and its various properties in the parametrized driving scenario. The minimum scenario elements, their associated properties, and parameter ranges necessary to unambiguously describe a scenario test case in a repeatable and reproducible manner is still an ongoing area of research. This minimum set depends on many factors, including test mode, desired test fidelity, the specific system under test, and desired outcomes, to name a few. Also, the sensitivity of the device under test to certain elements and properties in the scenario test case is highly variable for different systems. For these reasons, the more details that can be specified in a scenario test case, the less likely for ambiguities to arise in describing or reproducing the test case. This also reinforces the need for standardized scenario taxonomy and definitions to further aid in adding additional clarity and collaboration in driving scenario definitions and sharing.

Ground Truth Scenario Information

Ground truth scenario information is produced by direct observation and not derived by inference. In the context of driving scenarios, ground truth refers to the most precise value of all available driving scenario element properties. Ground truth information in simulation is available by definition since every element of the simulation needs to be created. In real-world tests, whether closed-course or on road, ground truth information refers to the highest level of accuracy that is reasonable given limitations on sensing and data processing. This accuracy could be increased by using multiple sensing modalities, post processing data, and manual review. This ground truth information can then be presented to the SV in a repeatable and reproducible manner, irrespective of the way the SV may perceive it. This may include information such as a list of static and dynamic actors in the driving scenario, their positions, bounding boxes, class type, velocities, heading information, etc.

For environment and road parameters, the ground truth information is provided, e.g., if it is raining or not, if lane lines exist or not, and type and location of lane markers if they do exist. 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. This enables the testing of the ODD and its boundaries without the need for defining all of the aspects necessary for sensing and perception, which is still an ongoing, unstandardized area of research.

This work recognizes the difficulties and safety concerns that sensing and perception entail and by no means disregards them. Rather, an incremental approach is taken to defining scenario elements. As previously stated, this work does not exclude or discourage incorporation of sensing and perception into driving scenario definitions, as it is a vital aspect of testing the complete ADS system.

Literature Review

Building on the research documented in Rao et al., (2021), this chapter examines sources for selecting additional elements and their properties necessary to describe any arbitrary driving scenario. In the Rao report various published reports pertaining to behavioral competencies for ADSs and human driving pre-crash scenarios were reviewed to compile elements and their properties that may be used to describe the driving scenarios considered. In addition to those sources, publicly available SAE level 2 to level 5 driving automation system crash and disengagement databases were reviewed for this report. Sources relating to emergency vehicle and school bus crashes were also studied. These additional data sources provide increased diversity to the previous sources to determine if any additional elements and/or element properties are necessary to describe a general driving scenario.

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

In Swanson et al., (2019), which was published by NHTSA as a follow-up to Najm et al.'s *Pre-Crash Scenario Typology for Crash Avoidance Research* (2009), NHTSA considered crash data that was more recent. This report defines a new set of 36 distinct pre-crash scenarios that represent the light vehicle crash population from 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 a light vehicle made the critical action, based on the 2011-2015 FARS and GES crash databases, respectively. The 36 pre-crash scenarios are listed in Table 1, the order of the pre-crash scenarios has no significance and is taken as-is from the source.

Table 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 stopped
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

No.	Scenario	No.	Scenario
12	Pedalcyclist crash without prior vehicle maneuver	31	Evasive maneuver with prior vehicle maneuver
13	Backing into another vehicle	32	Evasive maneuver without prior vehicle maneuver
14	Vehicles turning – same direction	33	Non-collision incident – no impact
15	Vehicles parking – same direction	34	Object crash with prior vehicle maneuver
16	Vehicles changing lanes – same direction	35	Object crash without prior vehicle maneuver
17	Vehicles 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	Vehicles making a maneuver – opposite direction		
19	Vehicles not making a maneuver – opposite direction		

Though the data presented in this report and Najm et al., (2009) are exclusively from human drivers, they give important insights regarding types of light vehicle pre-crash scenarios and what elements and properties may be used to define them.

The 36 pre-crash scenario types were categorized into scenario groups in Swanson et al., (2019) and crash statistics were provided. Average annual values for the 2011-2015 FARS and GES data sets are presented in Table 2 for each of the scenario groups for crashes involving a light vehicle in the critical event.

Table 2. Scenario Group Crash Statistics – Average Annual Crashes Involving Light Vehicles in the Critical Events

Scenario Group	Scenario Numbers From Table 1 For Each Group	Crashes Involving Light Vehicles in the Critical Events	
		Fatal	All
Control Loss	2, 3	4,529	473,392
Road Departure	4, 5	6,536	562,564
Animal	7, 8	103	298,106
Pedestrian	9, 10	3,732	70,525
Pedalcyclist	11, 12	518	47,927
Lane Change	14, 15, 16, 17	875	697,888
Opposite Direction	18, 19	3,288	100,993
Rear-End	20, 21, 22, 23, 24	1,623	1,756,327
Crossing Paths	25, 26, 27, 28, 29, 30	4,086	1,152,112
Total		**25,289**	**5,159,833**

Note: Scenarios 1, 6, 13, 31, 32, 33, 34, 35, 36, 37 and "other" from Table 1 are not included in the "group" categories.

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

In the Rao group report, the authors reviewed the pre-crash scenario typologies as described in Swanson et al., (2019) and the behavioral competency requirements from PATH (Nowakowski,

2015) and Waymo (n.d.) to determine the elements and properties needed to describe them. The behavioral competencies are listed in Table 3.

Table 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 people 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-and-go)	33	Detect and respond to a merging vehicle
10	Detect and respond to stopped vehicles	34	Detect and respond to pedestrians in road (not walking through intersection or crosswalk)
11	Detect and respond to lane changes	35	Provide safe distance from pedalcyclist traveling on road (with or without bike lane)
12	Detect and 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 and stop/yield signs	39	Navigate around unexpected road closures (lane, intersection, etc.)
16	Respond to traffic signals and stop/yield signs	40	Navigate railroad crossings
17	Navigate intersections and perform turns	41	Make appropriate reversing maneuvers
18	Navigate a parking lot and locate spaces opt	42	Detect and respond to vehicle control loss (e.g., reduced road friction)
19	Detect and respond to access restrictions	43	Detect and respond to unanticipated weather or lighting conditions outside of vehicle's capability (e.g., rainstorm)
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

No.	Behavioral Competency	No.	Behavioral Competency
23	Respond to emergency vehicles	47	Detect and respond to vehicles parking in the roadway
24	Navigate roundabouts		

Of the scenario groups listed in Swanson et al., (2019) (Table 2), five broad groups were selected in Rao et al., (2021) for further consideration. They were:

1. Rear-end scenario;
2. Lead vehicle lane change scenario;
3. Vulnerable road user scenario: which include pedestrian, pedalcyclist and animal scenario groups;
4. Crossing path scenario; and
5. Merge Scenario (a sub-category of lane change scenario group).

The list of elements and properties used to describe the five scenarios considered was compiled by first leveraging existing test-track procedures when available and then modifying them to be applicable to vehicles with higher levels of automation. These scenario descriptions were broken down into five categories: initialization, environment, POV/SOV/VRU, traffic, and SV status. For each one of these categories, necessary elements, and properties, along with required capabilities to unambiguously describe the ground truth scenario information were presented. Descriptions of sensory and aesthetic scenario information were omitted as they are out of scope for this research.

The five selected scenarios were analyzed, and a preliminary list of elements and properties were developed in Rao et al., (2021). Though not all pre-crash scenarios presented in Swanson et al., (2019) were analyzed, the preliminary elements and properties may be used to describe the remaining pre-crash scenarios and behavioral competencies shown in Table 4 and Table 5. As pre-crash scenarios are analyzed for new elements and properties, they may be added to facilitate more complete driving scenario descriptions.

Table 4. Pre-Crash Scenarios Not Analyzed in Rao et al., 2021

No.	Pre-Crash Scenario Description
13	Backing into another vehicle
14	Vehicles turning – same direction
15	Vehicles parking – same direction
18	Vehicles making maneuvers – opposite direction
19	Vehicles not making maneuvers – 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 5. Behavioral Competencies Not Analyzed in Rao et al., 2021

Comp. No.	Behavioral Competency Description
3	Move out of travel lane and park
7	Detect and respond to encroaching oncoming vehicle
18	Navigate parking lot and locate spaces
20	Detect work zones and/or safety officials
21	Navigate work zones and/or safety officials
22	Detect emergency vehicles
23	Respond to emergency vehicles
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 (lane, intersection, etc.)
40	Navigate railroad crossings
41	Make appropriate reversing maneuvers

Summary of California DMV Crash Reports

In addition to human-driven vehicle crash data, there are growing databases of crash data reports for SAE level 2 to level 5 driving automation systems that may contain pre-crash scenario descriptions relevant to this research. Testing of ADSs on public roads is underway in several states. In this report, the analysis of the ADS crashes is focused on California due to the ease of availability and public reporting of crashes dating back to 2014.

The "California Autonomous Vehicle Testing Regulations" (State of California, 2022) require every manufacturer authorized to test ADSs on public roads, to submit to California DMV, reports called, "Traffic Collision Involving an Autonomous Vehicle" within 10 days of the collision, and an annual report summarizing the disengagement of the technology during testing. The California DMV introduced in 2018 a standardized reporting method titled "Annual Report of Autonomous Vehicle Disengagement." Various sources from literature analyzing these reports are discussed below.

As of February 25, 2020, the California DMV had received 251 autonomous vehicle collision reports. The crash reports contain information regarding parties involved other than the automated vehicle, status of vehicles (moving, stationary, etc.), injuries and property damage, and a brief description of the crash, including specifying whether the ADS-equipped vehicle was driving in autonomous or conventional mode (AM or CM). This information may be relevant to determine new elements and properties that may be specific to these types of crashes. Data obtained prior to 2019 has been analyzed previously in Favarò et al., (2017) and Wang and Li (2019) and their results are briefly summarized on the following page.

Favarò et al., (2017) analyzed California DMV reported crashes from September 2014 up to March 2017. The analysis reported that 89 percent of all crashes happened at intersections, and 62 percent of all crashes happened with the ADS-equipped vehicle stationary or travelling at a very low speed. No head-on crashes were reported. One important conclusion drawn from this analysis was that the number of crashes observed had a high correlation to the autonomous miles traveled. The correlation between cumulative accidents and cumulative autonomous miles was reported as 0.968 ($p\text{-value} < 0.001$).

A study by Wang and Li (2019) analyzed 107 California DMV ADS incident reports as of October 24, 2018, and 6 crash reports sourced from NTSB and other sources. For the total of 113 ADS-equipped-vehicle crashes, 76 were in AM, and the remaining 37 occurred in CM. This report stated that most rear-end ADS crashes occurred at intersections when the vehicles were waiting or proceeding slowly at the intersections. Due to the small data sample size, the statistical significance is low, particularly for analyzing fatalities.

For more recent crashes (2019), which did not have published analyses in literate at the time of writing of this report, we reviewed and classified the California DMV crash reports, discussed below.

In 2019 there were 95 ADS-equipped-vehicle crashes reported to the California DMV. The crashes were analyzed and categorized into those covered by the scenarios developed in (Rao et al., 2021) and those that were not. Eighty-five of the 95 crashes mapped to the 5 scenarios analyzed in the Rao group's report and are categorized in Table 6. The remaining 10 crashes are categorized by basic scenario descriptions in Table 7. The crash reports consisted of limited information about the vehicles involved, a checklist to indicate prevailing road, traffic, and environmental conditions, and a short description of the crash. The descriptions provided in the crash reports were not detailed enough to tease out new elements and properties for consideration.

From Table 6, there were 53 crashes that could be mapped to rear-end pre-crash scenarios. Thirty-three occurred with the ADS vehicle in AM and 20 in CM. There were 16 that mapped to lane change pre-crash scenarios, with 7 occurring with the ADS vehicle in AM and 9 in CM. Three crashes mapped to the vulnerable road user interaction scenario. The ADS was in AM for 2 of the 3 VRU crashes. Twelve crashes were mapped to the crossing path scenario, with 2 cases in AM, and 10 in CM. All of these crashes resulted in no serious injuries and minor to moderate property damage. None of these crashes involved the merge scenario.

Table 6. 2019 Reported California DMV ADS Crashes That Map to the Five Pre-Crash Scenarios From Rao et al., 2021

Mode	Rear-End	Lead Vehicle Lane Change	Vulnerable Road User Interaction	Crossing Path	Merge	Total
AM	33	7	2	2	0	44
CM	20	9	1	10	0	40
Total	**53**	**16**	**3**	**12**	**0**	**84**

Comments in the crash reports state that in many of the ADS crashes that are classified as CM, the ADS operators switched from AM within moments prior to the crashes. Specific details regarding how long the ADS was in each mode, or what control actions each driver took once changing to CM were not reported. No new elements and properties could be found using the limited detail present in the crash reports.

The remaining 10 California DMV ADS crashes reported in 2019 that could not be classified into a category developed in Rao et al., (2021) are categorized in Table 7. This table includes two intentional strikes of ADSs, and one crash each of ADS reversing, POV backing into ADS, and when ADS was stationary in a parking lot while powered off. The remaining five incidents are all low-speed parking maneuvers where the ADS was powered on.

Table 7. California DMV Other Reported Crashes

Scenario Description	**CM**	**AM**
ADS Reversing	1	0
POV Backed Into ADS	1	0
Parking Lot	4	1* (Other vehicle hit ADS)
VRU/POV Intentionally Striking ADS	2	0
ADS Vehicle Off (parked/not running)	1	0
Total	**9**	**1**

By examining the 2019 California DMV crash report data, the five scenarios in Rao et al., (2021) describe many of the scenarios reported. The remaining cases fell into the general categories of low-speed operation in parking lots, reverse operations, or someone intentionally striking the ADS. This report will investigate the additional elements and properties that may be useful to describe the scenarios that were not considered in Rao et al., (2021).

Autonomous Vehicles' Disengagements: Trends, Triggers, and Regulatory Limitations

A published study on disengagements of the ADS conducted by Favarò et. al., (2018) examined in detail the reported situation the ADS was in prior to the crash. It was calculated that 1 event in every 178 reported disengagements led to a crash. The data used in the analysis spanned from September 2014 to July 2017, with a total of 30 crashes out of 5,325 disengagements.

Favarò et. al., (2018) assembled and organized the data in a consistent digital database for ease of analysis. The information was organized for each disengagement according to nine information “buckets”: vehicle type, date, reported cause of disengagement, human factors involved, location, condition, type of disengagement, weather, and other. These buckets were subdivided further to provide more details.

The authors broke down the triggers or contributing factors of ADS disengagements into four macro-categories which were

1. human factors, which refer to when the driver initiated the disengagement due to discomfort or lack of trust in the ADS;
2. system failure, which refers to hardware and/or software failure, like incorrect perception of obstacles on the road, disagreement between onboard GPS and navigation software, etc.;
3. external conditions, which refer to situations that trigger disengagements like debris on the road, extensive pedestrian traffic; and
4. other, which refers to causes where the specific terminology used by the manufacturer was not directly traceable to any of the three listed macro-categories listed above.

Data from September 2014 to December 2016 showed that disengagements were distributed as 52 percent system failure, 30 percent human factors, 11 percent external conditions, and 7 percent as other. Each of these macro-categories was further organized into the micro-categories inspired by the ASRS database. The distribution of disengagements for each macro- and micro-category is listed in Table 8. The data showed that the system failure macro-category was the most predominant cause of disengagements, with the micro-category software-related failure being the most dominant within this macro-category. The human factors macro-category included subcategories for recklessly behaving agent, precautionary spacing (pedalcyclist), and driver discomfort. Driver discomfort was the most dominant cause of disengagement for the human factor macro-category. For the macro-category external condition, poorly marked lanes were the most dominant subcategory. For the weather subcategory (only 0.69% of cases), no specifics were available, like wet roads, visibility, etc. This analysis and methodology are promising and take advantage of advances of aviation industry-developed safety research and applications.

Table 8. Breakdown of Macro-Categories Into Micro-Categories for Disengagement Causes (Favarò et. al., 2018)

Macro-Category	Micro-Categories	Percentage of Total (%)
Human Factors	Recklessly behaving agent,	2.73 %
	Precautionary spacing cyclist	0.50 %
	Driver discomfort	26.87 %
	Total for Human Factors	**30.12 %**
System Failure	Software discrepancy	13.07 %
	Perception discrepancy	6.04 %
	Planner not ready	5.70 %
	Traffic light detection	4.78 %
	Lane change	4.28 %
	Unwanted maneuver of vehicle	3.56 %
	Other system failure factors	14.8 %
	Total for System Failure	**52.22 %**
External Condition	Poorly marked lanes	4.63 %
	Construction zone	2.22 %
	Heavy pedestrian traffic	2.03 %
	Weather condition	0.69 %
	Oher external conditions	1.22 %
	Total for External Condition	**10.79 %**

Macro-Category	Micro-Categories	Percentage of Total (%)
Other	Planner output invalid, Follower output invalid, ACC cancel, Health monitor	6.87 %

The disengagement reports were not detailed enough to offer additional scenario cases, or to check if the developed scenarios cover most of the reported incidents encountered during testing on public roads, but they do offer insights for scenario elements and properties for environment, POV/SOV/VRU states, traffic, and SV status.

System failures were considered as a failure mode in the original element and property list developed in Rao et al., (2021) under the SV status topic, though perception was not addressed and considered out of scope for this preliminary research. In Table 8, perception accounted for 10.8 percent of disengagements between perception discrepancy and traffic light detection. If poorly marked lanes are included as a perception problem, this goes up to 15.5 percent of all disengagements. The data supports the intuition that ADS perception is a non-trivial factor and warrants inclusion in simulation and testing.

Human factors related disengagements are a consequence of the ADS's/other actors' actions and the driver's perceived risk. Existing elements and properties enable the depiction of such motion behaviors of the actors. The disengagement reports do not have enough details to determine what is considered "reckless" behavior, and it is out of scope for this research to determine what causes test driver discomfort. These may be considered and added as needed if they facilitate a more repeatable, reproducible scenario description. The external conditions found could be included in the scenario weather and environmental condition parameters.

National Traffic Safety Board Investigations

The NTSB investigates and reports on civil transportation crashes, as do several NHTSA departments. Six crashes involving SAE level 2 to level 5 driving automation systems were investigated by the NTSB as of May 2020. A summary of each crash is presented in Appendix B. An analysis of whether the existing element and property list in Rao et al., (2021) is sufficient to describe these scenarios is presented below in Table 9.

Table 9. Summary Analysis of SAE Level 2 to Level 5 Vehicle NTSB Crash Reports

No.	Title	Scenario Type	New Elements and Properties Found
1	Collision Between Vehicle Controlled by Developmental Automated Driving System and Pedestrian, Tempe, Arizona (NTSB, 2018a)	Vulnerable road user cross path scenario	No
2	Collision Between a Car Operating With Automated Vehicle Control Systems[4] and a Tractor-Semitrailer Truck, Williston, Florida (NTSB, 2016)	Intersection – left turn across path scenario	No

[4] In this instance the automated vehicle control system was an SAE level 2 ADAS.

No.	Title	Scenario Type	New Elements and Properties Found
3	Rear-End Collision Between a Car Operating With Advanced Driver Assistance Systems and a Stationary Fire Truck, Culver City, California (NTSB, 2019b)	Combination of rear-end and lane change scenarios Stopped vehicle revealed to ADS when lead vehicle changes lanes. Involves an emergency vehicle.	Yes
4	Car Operating With Advanced Driver Assistance Systems Entered Gore Area and Collided With a Previously Damaged Crash Attenuator, Mountain View, California (NTSB, 2018b)	Single vehicle road departure	No
5	Low-Speed Collision Between Truck-Tractor and Autonomous Shuttle, Las Vegas, Nevada (NTSB, 2017)	Vehicle backed into ADS in alley while parking.	No
6	Collision Between a Car Operating With Partial Driving Automation System and a Tractor-Semitrailer Truck, Delray Beach, Florida (NTSB, 2019a)	Intersection – straight crossing path scenario	No

Special Vehicles: Emergency Vehicles and School Buses

Emergency Vehicles

Emergency vehicles are different from other road vehicles in terms of their design and the laws applicable in their presence. Emergency vehicles, when they have their lights/sirens active, have special right-of-way privileges afforded by laws that dictate the behavior of other road users around them. These privileges require other vehicles to change their behavior in the presence of emergency vehicles. The ability of an ADS to respond to emergency vehicles in a safe manner and in accordance with the prevalent laws is important to study. The ability to faithfully reproduce an emergency vehicle in simulation is therefore important.

Table 10 provides details for all fatal emergency vehicle crashes that happened in 2020. This information was sourced from the National Safety Council (n.d.). As of writing this report, the National Safety Council website reports fatal emergency vehicle crash data from 2010 up to 2020, and the data trend shows that emergency vehicle crashes are persistent over the years, with a similar frequency of crashes for every reported year. Preliminary review of the table headings, in particular, the distinction of "lights and sirens in use," suggests further analysis may reveal additional properties that could facilitate better descriptions of driving scenarios involving emergency vehicles. Additionally, vehicle collision is the second leading cause of firefighter fatalities (U.S. Fire Administration, 2020).

Emergency vehicle crash data is further discussed in Appendix C.6.

Table 10. Emergency Vehicles' Fatal Crashes in 2020 (National Safety Council, n.d.)

Type of emergency vehicle involved	Person type	Multi-vehicle crashes		Single-vehicle crashes		Total crashes	
		All crashes	Crashes while emergency lights/sirens in use	All crashes	Crashes while emergency lights/ sirens in use	All crashes	Crashes while emergency lights/ sirens in use
Police Vehicle	Emergency Vehicle Driver	12	5	6	4	18	9
	Emergency Vehicle Passenger	2	1	2	1	4	2
	Other Vehicle Occupant	65	32	3	3	68	35
	Pedestrian	8	5	30	7	38	12
	Other Nonoccupant	0	0	4	1	4	1
	Total	**87**	**43**	**45**	**16**	**132**	**59**
Ambulance	Emergency Vehicle Driver	0	0	0	0	0	0
	Emergency Vehicle Passenger	2	0	2	2	4	2
	Other Vehicle Occupant	21	9	0	0	21	9
	Pedestrian	1	1	3	0	4	1
	Other Nonoccupant	0	0	2	2	2	2
	Total	**24**	**10**	**7**	**4**	**31**	**14**
Fire Truck	Emergency Vehicle Driver	0	0	2	0	2	0
	Emergency Vehicle Passenger	0	0	0	0	0	0
	Other Vehicle Occupant	12	10	0	0	12	10
	Pedestrian	2	1	1	1	3	2
	Other Nonoccupant	0	0	0	0	0	0
	Total	**14**	**11**	**3**	**1**	**17**	**12**

School Buses

School buses are different by design from other specialty vehicles (NHTSA, n.d./b). School buses are designed so that they are highly visible and include safety features such as flashing lights and stop-sign arms. They also include protective seating, high crush standards, and rollover protection features. School buses are governed by additional laws to protect students who are getting off and on a school bus by making it illegal for drivers to pass a school bus while dropping off or picking up passengers, regardless of the direction of approach. Preliminary review of some of the school bus definitions, requirements, and use-cases suggests further analysis may reveal additional properties that could facilitate better descriptions of driving scenarios involving school buses.

School Bus crash data is further discussed in Appendix C.6.

Scenario Selection and New Elements and Properties Analysis

This chapter discusses the rationale for the selected sources and driving scenarios that are used to identify new elements and properties to add to the list identified in Rao et al., (2021). The selection process involved using some of the pre-crash driving scenario descriptions, crash databases, behavioral competencies, and NHTSA ADAS test track procedures that were initially applied in Rao et al., (2021) in combination with the literature review presented in the previous chapter. The chapter also lists the new elements, properties, and capabilities that may be needed to perform each of the scenarios. Detailed analysis of each maneuver and the elements and properties used to define it are presented in Appendix A.

Source and Scenario Selection Considerations

For this research, scenario elements and descriptions for ADSs do not include SV inputs or prescribe test conditions contingent on SV actions. This is due to the fact that, while in operation, 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 assesses 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, were 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, for example, road edge departure or control loss event. 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.

Behavioral competencies that were considered in Rao et al., (2021) were reevaluated to cover the ones that were left out. Behavioral competencies are important since these competencies may be observed in driving scenarios that are frequently encountered in the real world. Testing behavioral competencies might reveal ADS crashes that are not prevalent in human driving statistics.

As introduced in the second chapter , other sources of information covering detailed driving scenarios were also examined for the selection of new scenarios for the purpose of expanding the list of elements and properties for describing driving scenarios. These sources include NHTSA's previous research on ADAS and ADS technology and test procedure development, NTSB reports, California DMV ADS crash reports and related research papers, and special vehicle laws. These test procedures and reports were selected over other sources of information reviewed because they define, in detail, scenario elements and some corresponding parameter ranges for driving scenarios that may be encountered on public roads. Therefore, these existing sources of information were leveraged to continue the development of the elements and properties that can facilitate describing driving scenarios. The six scenarios selected after examining the sources are these.

1. Suddenly Revealed Stopped Vehicle Scenario
2. Straight Crossing Path Scenario
3. Opposing Traffic Scenario
4. Parking/Reversing Scenario With VRU Interaction

5. Detect, Respond to, and Navigate Work Zones
6. Special Vehicles: Emergency Vehicles, and School Buses

The rationale for the selection of the scenarios are covered in the following sections of this chapter.

Suddenly Revealed Stopped Vehicle – Combination of Lane Change and Rear-End Scenario Categories

Scenario Selection

The lane change and rear-end scenario categories were two of the five categories selected in Rao et al., (2021). These two scenario categories account for a large frequency of light vehicle crashes from 2011 to 2015 Swanson et al., (2019) (see Appendix C.1 for crash statistics). The lane change and rear-end categories and corresponding scenarios selected in Rao may provide wide coverage for these types of driving scenarios, however the NTSB report (2019b) (Appendix B.3) describes a scenario that is a unique combination of the rear-end and lane change maneuvers. The elements and properties that were analyzed for the individual pre-crash scenarios may not be sufficient to describe such a combination.

The NTSB report discusses a vehicle-equipped with an ADAS engaged, that encountered a stationary emergency vehicle that was revealed when a lead vehicle changed lanes. In this particular case, the encounter resulted in a crash. For this research, the focus is on the description of the driving scenario prior to the event. This driving scenario combined aspects of the lane change and rear-end scenarios into a single scenario. Since none of the previously examined scenarios combined these scenario types, this additional scenario was selected.

Scenario Description

The SRSV test from the TJA draft test procedure (NHTSA, 2018) combines the lane change and rear-end categories (stopped lead vehicle) into a single scenario. In this test, a stopped lead vehicle is revealed to the SV when a lead vehicle performs a lane change (Figure 2). Hence, the SRSV scenario was referenced as a starting point for the scenario description. It was then parametrized to describe various combinations of speeds, lane-change ranges, etc., to arrive at a large set of scenario test cases (presented in Appendix A.2). When this scenario is applied to higher levels of automation, the “stopping to avoid” pass/fail criteria set in the SRSV test procedure may not apply since the ADS may choose to avoid the stopped vehicle by changing lanes.

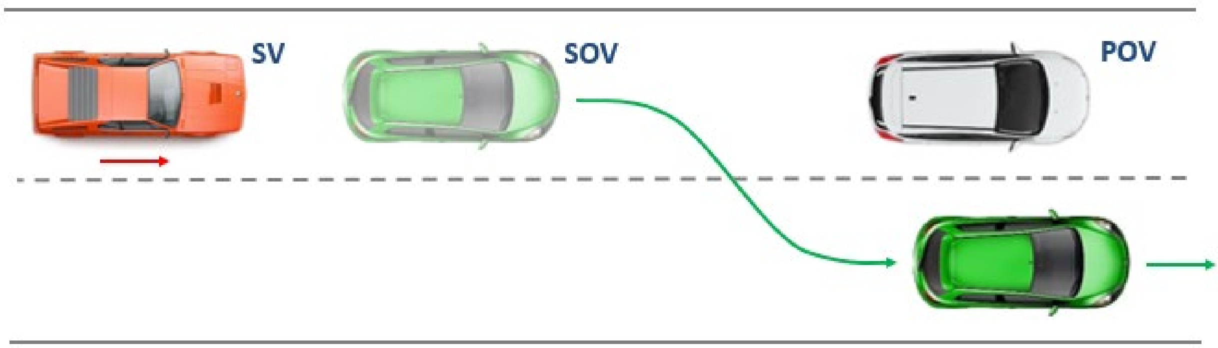

Figure 2. Suddenly Revealed Stopped Vehicle Scenario

New Elements, Properties, and Capabilities

A detailed description of the scenario and analysis of the elements and properties that may be needed to describe this scenario is discussed in Appendix A.2. In the case of this scenario, the SOV, when at a certain headway from the stationary POV, needs to trigger a specific lane change trajectory and braking. This would require the capability to define specific paths and speed profiles/braking for the paths as well as triggering the defined paths depending on certain conditions. Advanced test methodologies can use dynamic scenario control combined with intelligent parameter sweep algorithms to gain further understanding of the ADS. Here, the parameters in question could be headway at lane change, lane change severity of the SOV, and deceleration of the SOV to name a few.

Crossing Path – Straight Crossing Path

Scenario Selection

As noted previously in Section 2.3, a review of California DMV ADS crash reports found a large percentage of crashes occurred at intersections. Favarò et al., (2017) reported that for the analyzed period, 89 percent of all reported California ADS crashes happened at intersections.

For the crossing path scenario group, the LTAP crossing path scenario was selected in Rao et al., (2021). The LTAP scenario covers interactions where a POV crosses the path of the SV in lateral or opposite directions; however, this does not address the straight crossing path scenario, which is the single largest remaining crash type not explicitly considered in Rao et al., (2021). Crash statistics and behavior competency data for the crossing path scenario category are presented in Appendix C.2. Hence, a straight crossing path scenario is added to the crossing path category. The SCP scenario from the NHTSA Intersection Safety Assist System Confirmation Test (NHTSA, 2019b) was selected as a starting point for the scenario description. Parametrization was employed to describe various combinations of speeds, etc., to arrive at a large set of scenario test cases. The SCP scenario will broaden the crossing path category range by addressing the straight crossing path pre-crash scenario.

Scenario Description

The objective of this scenario is to evaluate the ability of the SV to detect and respond to the POV coming across its path either from the near-side or the far-side. In this scenario, the SV attempts to go through an intersection as the POV, coming from either the near- or far-side of the SV, attempts to cross the SV's path. The scenario shown in Figure 3, has the POV crossing into SV's path from the near-side. The POV can cross the path of the SV for various reasons, like failing to stop at a stop sign, or running a red light, etc. Different SV and POV speed combinations and triggers used may result in a near-crash or crash scenario if the SV continues. The specific details of how a given intersection-based scenario unfolds depends on the SV-to-POV speed combination and timing, intersection design, and several other factors.

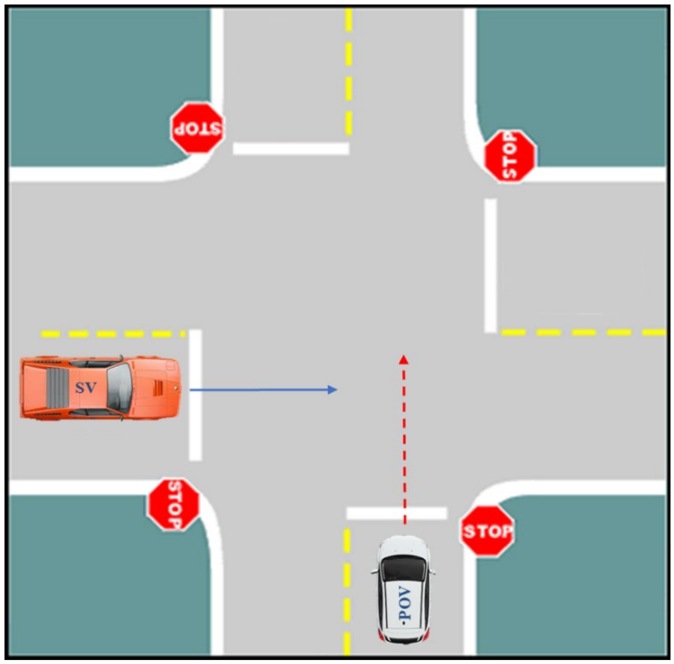

Figure 3. Intersection-Based SCP Scenario Setup

New Elements, Properties, and Capabilities

A detailed description of the scenario and analysis of the elements and properties that may be needed to describe this scenario is discussed in Appendix A.3. It was determined that the elements and properties determined in Rao et al., (2021) were sufficient to describe this scenario.

Opposing Traffic

Scenario Selection

According to the 2011 – 2015 FARS data (Swanson et al., 2019), the total number of opposite direction crashes are a relatively small percentage of the total crashes (1.8%). However, opposite direction crashes were 13.0 percent of fatal crashes, on average, for the 2011-2015 FARS data (Table 2 – 3,288 out of 25,289 fatal crashes) for the scenario group categories. Further crash statistics and behavioral competency data for the opposing traffic scenario category are presented in Appendix C.3. Due to the relatively large number of fatal accidents, an opposing traffic category has been added. The OTSA scenario descriptions in Opposing Traffic Safety Assist System Confirmation Test – Working Draft (Manahan & Forkenbrock, 2021) were selected as a starting point for the scenario descriptions for the opposing traffic scenario category and were expanded to include scenarios more suited for higher levels of automation.

Scenario Description

This scenario involves the SV interacting with an opposing (i.e., oncoming) POV. For such an interaction to occur, either the POV needs to depart its lane into the travel lane of the SV, or the SV needs to leave its lane and move into the travel lane of the POV. Only scenarios where an oncoming POV drifts into the SV's travel lane are considered for this scenario. As mentioned at the beginning of this chapter, while in operation, ADSs are responsible for the complete driving task; instructing the ADS what to do or how to respond does not test the ADS's driving capabilities, but instead assesses its ability to follow commands. Therefore, scenarios directing an ADS to leave its lane are not considered in this research.

The scenarios in the draft NHTSA test procedure for OTSA (Manahan & Forkenbrock, 2021) are used as a starting point. OTSA is an advanced driver assistance system whose active interventions are designed to bring a vehicle back into the original travel lane after a path deviation causes it to move towards an oncoming vehicle in an adjacent lane. As discussed in the previous paragraph, this scenario, which was developed for lower levels of automation, requires adjustments and changes to be applicable to ADS. Instead of the SV drifting, this scenario was modified to have the POV drift into the SV's travel lane (Figure 4).

Figure 4. Oncoming POV Drifting Into SV's Travel Lane

New Elements, Properties, and Capabilities

A detailed description of the scenario and analysis of the elements and properties that may be needed to describe this scenario is discussed in Appendix A.4. It was determined that the elements and properties determined in Rao et al., (2021) were sufficient to describe this scenario.

Parking/Reversing Scenario

Scenario Selection

Parking and reversing-based scenarios account for 3.8 percent of light vehicle crashes in the 2011 – 2015 GES database (Swanson et al., 2019). Further, crash statistics and behavior competency data for the parking/reversing maneuver category are presented in Appendix C.4. Due to the number of pre-crash scenarios and behavioral competencies not previously addressed and the fact that VRUs are particularly vulnerable and present in these situations, a parking/reversing scenario category is included in this report. The NHTSA park-assist test procedure (NHTSA, 2019a) contains some of the elements and properties that can be applied to describe parking spots and surrounding environments. Again, the test procedure is designed for ADAS park-assist technology and would need to be abstracted to be applicable to higher levels of automation.

Scenario Description

The ability of an ADS to safely navigate parking lots and maneuver in and out of parking spots is tested in this scenario. ADSs may be capable of maneuvering through parking lots to find open spots and park in them. These spots may be of different orientations, for example, parallel, perpendicular, or diagonal spots. The parking lot may have one-way traffic lanes and heavy pedestrian traffic in addition to other obstacles like shopping carts. These diverse conditions coupled with varied parking lot designs provide for a potentially complex environment for ADSs capable of automated parking.

New Elements, Properties, and Capabilities

A detailed description of the scenario and analysis of the elements and properties that may be needed to describe this scenario is discussed in Appendix A.5. Elements of road design that involve parking lot design are added to the elements and properties list, since these were not covered by the elements and properties determined in Rao et al., (2021).

New parameters and features include various types of parking spot markings and configurations, including parallel, perpendicular, and oblique parking spots. It may also be necessary to designate spots for parking meters, handicap spots, concrete wheel stops, and other features found in parking spots. Additionally, new types of static and dynamic actors may be required to be defined, for example, shopping carts (of various sizes), parking spaces occupied by cart corrals, etc.

These new elements and properties are listed in Table 11. The finer aspects of parking lot design are not called out specifically since that is out of scope for this document.

Table 11. New Properties for Parking/Reversing Scenario

Elements	Property Level 1	Property Level 2
Road Type	Parking lot	
Parking Lot	Design of parking lot	Shape, size, etc.
	Parking space size, orientation, and markings	Parking meter, permit, concrete stop, etc.
Objects	Static	Cart corral (length, width, height, etc.)
	Dynamic	Shopping carts (length, width, height, etc.)

Detect, Respond to, and Navigate Work Zones

Scenario Selection

Of the 17 behavioral competencies not covered in Rao et al., (2021), listed in Table 5, a work zone scenario addresses seven behavioral competencies. Crash statistics and behavior competency data for the work zone category are presented in Appendix C.5. Work zones cause road closures and changes to navigable road areas, which may present a challenge to ADSs that may rely on on-board maps to navigate. Consider a highway construction zone where the lanes on one direction of travel are completely blocked and traffic is rerouted through a repurposed lane in the opposite direction of travel. High-level ADSs may need to safely navigate such work zones or return the vehicle to the minimum risk fallback state.[5] Hence a detect, respond to, and navigate work zone scenario category has been selected to be developed.

Scenario Description

The objective of this scenario category is to evaluate the capability of the ADS to safely navigate or return the vehicle to the minimum risk fallback condition when presented with work zones. Work zones occur in all road types, sizes, and configurations. They also have different effects on navigable road areas. For example, some work zones may close one lane of travel in one direction, whereas others may close all lanes of travel in a direction and reroute the traffic through makeshift lanes. There also may be temporary traffic control devices or signs manned by construction personnel. To define the wide range of work zones an ADS may encounter requires that these elements be specified more accurately.

New Elements, Properties, and Capabilities

A detailed description of the scenario and analysis of the elements and properties that may be needed to describe this scenario is discussed in Appendix A.6. The demarcation of a construction zone is governed by various standards to ensure the safety of the workers. The specifics of these standards are not called out in this document since they are out of scope. In general, it is identified that various elements required to define a work zone need to be added to the existing list of elements and properties.

To adequately describe work zone environments, it may be necessary to represent the various traffic control devices. These include, but are not limited to, barrels, concrete barriers, cones, detour signs, temporary/electronic speed limit signs, work zone fine signs, signs with flashing lights, flags, etc. A method to convey the ground truth information regarding the signage and the altered roadway to the ADS may be required when testing only the planning and control aspects. If, however, perception is incorporated into the testing, communicating the detailed signage, and rendering the road environment more accurately might be necessary as well. Traffic control devices and signage were not part of any particular scenario considered in Rao et al., (2021) but were already included in the list of elements and properties. An altered roadway due to construction is a new element, and hence the related properties needed to describe this are added to the pre-existing list.

The ability to represent and describe the presence and movement of heavy machinery like bulldozers, backhoes, etc., may also be necessary. The elements and properties used to describe this are already included in dynamic actor properties in the existing list of elements and properties. Workers, bystanders, or police officers directing traffic may also need to be more accurately described. Again, it is necessary to describe in the scenario the ground truth

[5] An example of a minimum risk fallback state could be the vehicle slowing down and coming to a safe stop in the shoulder lane with hazard lights turned on.

information regarding the worker/police officer controlling the traffic so the ADS may respond, when testing only the planning and control aspects. If, however, a higher-fidelity simulation with perception is incorporated into the testing, simulating the construction machinery, and rendering the worker/police officer controlling traffic more accurately in the test scenario might be required as well. The new elements and properties are listed in Table 12 below.

Table 12. New Elements and Properties to Define Construction Zone Scenarios

Element	Property Level 1	Property Level 2	Property Level 3
Dynamic Actor	Special Pedestrian	Type	Construction worker/ bystander/police officer directing traffic
		Hand gestures	Stop, go, etc.
		Hand signs	Stop, slow, etc.
		Other Behaviors	Wheelchair, crawling, etc.
Road Element	Construction Zone	Design of construction zone and rerouting of traffic	

Special Vehicles: Emergency Vehicles and School Buses

In addition to the reported fatalities in crashes involving emergency vehicles and school buses noted in this section, there are five behavioral competencies related to these types of vehicles that were not addressed by the scenarios selected in Rao et al., (2021).

NHTSA worked closely with the National Conference of State Legislatures and the National Committee on Uniform Traffic Laws and Ordinances and developed a “Move Over” model law (NHTSA, n.d./b). Since then, at least 40 States have instituted “Move Over” laws. They all specify that traffic must slow down and, if possible, move over to an adjacent traffic lane when encountering an emergency vehicle. In addition to emergency vehicles, school buses are another category of vehicles that have laws governing the behavior of other road users in their presence. Further, crash statistics and behavior competency data for the special vehicle scenario category are presented in Appendix C.6 as are example laws related to special vehicles. Due to the crash statistics, the number of behavioral competencies not previously addressed, and the fact that these vehicles require special behaviors from an ADS or a human-driven vehicle in their presence, a special vehicle scenario category is included in this report.

Summary of Selected Scenarios

Six new scenarios are selected in this report, covering an additional 12 behavioral competencies that were not covered in Rao et al., (2021). This leaves 3 of the 47 behavioral competencies unexamined, which are: (24) navigate roundabouts, (37) detect and respond to motorcyclists, and (40) navigate railroad crossings. Though not explicitly covered, roundabouts and railroad crossings can be part of the road environment in any scenario and a motorcycle could be substituted for any actor in a scenario. Summary crash statistics and behavior competency data for the selected new pre-crash categories are presented in Appendix C.7.

The scenarios selected in this report can be categorized as either basic or parameterized scenarios depending on the depth to which the scenarios are described. This was based on the level of detail found in literature for each of the selected scenarios. Of the six scenarios studied, four were limited to basic scenario descriptions, while two were further described as parametrized scenarios (see Appendix A).

1. **Basic Scenario Interactions:** As defined in the first chapter, a basic scenario interaction describes the broad interaction between the SV and other necessary actors and/or environmental elements of the scenario. The basic scenario interaction leaves open the specifics like number of actors, weather conditions, specific road geometry, timing, speeds, etc., and describes the general interaction of the scenario. For this research, scenario descriptions with parameterized variables were not available due to the broad scope of these basic scenario interactions. Selected scenarios in this category include
    1) Opposing traffic scenario;
    2) Parking/reversing scenario;
    3) Detect, respond to, and navigate work zones; and
    4) Special vehicles.

2. **Parametrized Driving Scenarios:** These are scenarios that are more strictly defined than the basic scenario. For these scenarios, the basic scenario interaction is described, and then specific scenario parameters are listed. The basic scenario and its parameters portray a more complete scenario description that can form a parameterized driving scenario set. Specific values can be assigned to the parameters to arrive at a scenario test case. Selected scenarios in this category include
    1) Suddenly revealed stopped vehicle scenario; and
    2) Crossing path – straight crossing path scenario.

Preliminary Set of Elements and Their Properties for Scenario Description

This chapter describes the elements and their properties used to describe various aspects of the driving scenarios selected in the previous chapter. Most of the elements and properties described in this chapter have already been identified in Rao et al., (2021) but are presented here for the sake of completeness. The additional elements and properties identified in this report are highlighted in bold. 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 properties for describing the driving scenarios may need to be expanded.

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

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 initiate a given scenario. These include the SV and dynamic actors' starting positions and orientations, along with desired destinations, to name a few. The scenario-specific properties considered are listed in Table 13. These properties provide elements to set the initial conditions of a driving scenario to be presented to an ADS. It is noted that some states may not be able to be achieved based on the ADS under test and the test mode. For example, requiring the ADS to follow a vehicle closer than its control system will allow isn't feasible. Also, in simulation, some states can be instantly achieved or initialized, while on the test track or closed course, those states need to be reached. **This research did not identify any new elements/properties to report for this subsection.**

Table 13. 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.

Environment Elements and Properties

Defining environmental conditions is a 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, roadside signage, and traffic control devices. These aspects are discussed in more detail in the following subsections.

Weather and Time

Weather conditions involve complex interactions with sensing systems and require further research to determine the fidelity required to describe a certain weather condition, such as snow, accurately and sufficiently. 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. For this research, the time and weather conditions for driving scenarios can be used to demonstrate changes in driving behavior. These changes in behavior could include the approach to the minimum risk fallback condition as the environmental conditions deteriorate, which may change road conditions and vehicle dynamics. The high-level ground truth definition of the weather could be used in the scenario description to induce noise/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 fallback state or affect vehicle dynamics. Hence, at least a rudimentary weather model is required even at this stage.

Table 14, as an example, lists some of the weather phenomena of interest and the scenario elements 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 minimum risk fallback performance. **This research did not identify any new weather properties/elements from the scenarios studied in this report.**

Table 14. 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 Elements Affected by Weather	Visibility	
	Road friction	
Date/Time	Time of day	
	Sun angle and direction	
Lighting	Illuminance	

The effects weather phenomena might have on the SV and the scenario are listed in Table 15.

Table 15. 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

Road Properties

Part of the scenario description is a definition of the road layout. This includes the layout of the lanes, speed limits, lane widths, direction of travel, the lane boundaries, etc., that may define the 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 coordinate, the road element description supports the ability to specify the following properties shown in Table 16. Due to the addition of parking and construction zone maneuvers, additional road types have been included in this report. These are shown in bold in the table below.

Table 16. Properties for Road Element

Elements	Property Level 1	Property Level 2
Road Type	Highway, rural, urban, **parking lot, construction zone,** etc.	Speed limit, height limit
Road Surface	Asphalt, concrete, cobble stone, etc.	
	Condition	Good, rutted
		Potholes, etc.
	Surface obscurants[6]	Dust, debris
		Snow, etc.
Lanes	Number of lanes	
	Lane width	
	Direction of travel	
	Lane designation	Shoulder, turn only, bike, **parking, dynamic,** etc.
	Lane marking/barrier type (dashed, yellow, barrier, curb, etc., and more properties)	Left
		Right
		Condition of marking: good, degraded, absent etc.
	Intersection layout	
	Curvature	
	Grade	

[6] Automated Vehicle Safety Consortium, 2020

Lanes (cont.)	Super elevation (banking)	
	Sub-lanes (split lanes further if necessary)	Friction (split mu)
Parking Lot	**Design of parking lot**	
	Parking space size and orientation	

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 so that the SV ADS may navigate the road network in an efficient, safe, and legal manner. This includes the permissible maneuvers from each lane at an intersection connecting multiple roads. The driving scenario elements and properties considered to define road networks are shown in Table 17.

Table 17. Road Network Definition Considerations

Elements	Property Level 1	Property Level 2
Road Section Connectivity	Predecessor and successor	
Junction	Number 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	

Static Objects

The scenario description includes 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, parked car). Depending on the type of object, certain properties may not be applicable. The properties considered for the static objects are shown in Table 18. These properties may 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 test scenarios.

Table 18. 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, etc.	
Light Sources	Luminosity, color, area illuminated, etc.	

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 Appendix A. These could be pedestrians, pedalcyclists, animals, or various other types of vehicles. Depending on the scenario design, the actions of these actors may need to depend on a triggering event or the position or motion of the SV or another actor. The scenario description may 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 properties considered for a dynamic actor are shown in Table 19. Due to the consideration of construction zones as well as special vehicles, additional properties have been added to this category. These are listed in bold in Table 19. These properties may 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 19. Dynamic Actor Properties Considered

<table>
<tr><th>Element</th><th>Property Level 1</th><th colspan="2">Property Level 2</th></tr>
<tr><td rowspan="9">Category Label</td><td>Pedestrian, pedalcyclist, motorcyclist, light vehicle, etc.</td><td colspan="2">Corresponding behaviors: pedestrian gait, pushing a stroller, pedalcyclist pushing bicycle, bicycle pulling a buggy, etc.</td></tr>
<tr><td rowspan="3">Special vehicle</td><td>Vehicle type</td><td>Police car, ambulance, fire truck, etc.</td></tr>
<tr><td>Lights</td><td>Color, intensity, type, etc.</td></tr>
<tr><td>Siren</td><td>Sound, intensity, etc.</td></tr>
<tr><td rowspan="4">Special pedestrian</td><td>Type</td><td>Construction worker/police officer directing traffic</td></tr>
<tr><td>Hand gestures</td><td>Stop, go, etc.</td></tr>
<tr><td>Hand signs</td><td>Stop, slow, etc.</td></tr>
<tr><td>Other behaviors</td><td>Crawling, etc.</td></tr>
<tr style="display:none"></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>Kinematics 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 acceleration</td></tr>
</table>

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 20. In simulation, these status messages could be supplied to the simulated vehicle to study the minimum risk fallback operation when a fault exists. Additionally, a particular vehicle may have different ADS modes which might be in control depending on the ADS status or the ODD. These modes may have certain limitations on the ADS's capabilities. For example, the ADS might have a parking mode in parking lots which restricts vehicle speed, or requests teleoperation or driver input. Another example is when an ADS might perform a minimum risk maneuver due to adverse weather conditions or changes in road layout due to construction. Such ADS modes should also be able to be output to the testing interface in simulation. This category is applicable to all the maneuvers discussed in the report.

Table 20. ADS Status Properties Considered

Elements	Property Level 1
Engine/Motor Fault Codes	Fault information (sensor fault, software failure, etc.)
ADS Sensor Fault	
ADS Software Bug	
Fuel Level/Battery Charge	Status
Mechanical Failure	Component
ESC/ABS Activation	Duration
ADS Mode	**SAE Level of automation, vehicle speed limits, ODD definition, capability, limitations, etc.**

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.

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 documented with examples for ease of use. In particular, the language syntax must be defined, with 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. For example, this information can also be included in the file header.

Test Scenario Control and 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 21 below lists some of the triggers considered.

Table 21. 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: The scenario description may need logical combinations (and, or, etc.) of the above triggers to achieve the desired scenario interaction.

To achieve coverage of various parameter ranges and behaviors of the ADS, dynamic control of the scenario can also be used. The parameters may not be known in advance but may be inferred iteratively during the testing. Preprogrammed triggered behaviors may be insufficient for such test programs. Rather, dynamic control and scene propagation methods may be used to achieve the desired parameter range. Dynamic control is real time control of scenario actors whose behaviors are not determined beforehand, but who react to the ADS to effect certain interactions. Dynamic scenario control combined with intelligent parameter sweep algorithms can be used to reduce the number of tests required to quantify the overall performance of an ADS. This is a way to control a scenario, but all the elements and properties required are still applicable.

Design of Experiments

For varying use cases, a large number of scenario test cases may be created and executed. Therefore, 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 scenario test cases. 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 scenario test case 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 scenario test case from scratch for each of these iterations may be prohibitive and inefficient. For instance, simulation software may allow for the design of a parameterized scenario with various parametrizations of speeds, distances, and other conditions.

Another aspect of parametrization is the selection of parameter combinations to create test cases. 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 can also result in finer resolution of parameter values when metrics indicate interesting interactions. Such parameter selection algorithms are often iterative, where each test further refines the parameter ranges for future tests. As discussed in Section 4.5.2, dynamic scenario control would offer even finer control by using responses to ADS actions to enable further parameter exploration abilities. There are various parameter exploration and 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 basic or parametrized scenario. Furthermore, 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. Accordingly, it may choose to maintain distances greater than the trigger value such that the deceleration triggering distance of 20 m is never met and the deceleration event never occurs.

Summary

This document builds on the work in Rao et al., (2021) by analyzing six additional scenarios for the purpose of selecting elements and their properties for possible use in scenario descriptions. Rao considered historical crash statistics and behavioral competencies to select five scenarios. Four of the five scenarios used existing test track procedures (a NHTSA test procedure does not exist for the merge scenario) to help explore elements and their properties that may be used to help describe scenarios and test cases.

The six scenarios selected in this document used resources that include California Department of Motor Vehicles Report of Traffic Collision Involving Autonomous Vehicle up to December 2019, and six NTSB Accident Investigation Reports that may be relevant to ADS technologies. In addition, the six scenarios took into consideration some pre-crash scenarios and behavioral competencies not covered in Rao et al., (2021) as well as categories that required further detail like the crossing path scenario, lane-change and stopped vehicle scenarios (suddenly revealed stopped vehicle scenario). The new and previously chosen scenarios considered for selection of elements and their properties are listed in Table 22 (newly considered scenarios in bold type).

Table 22. Consolidated List of Scenarios Studied

Scenarios Considered	New Elements and Properties Found
Rear-End Scenario	These scenarios were considered in Rao et al., (2021)
Lane Change: Lead Vehicle Lane Change	
Lane Change: Highway Merge	
Vulnerable Road User Interaction	
Crossing Path: Left Turn Across Path	
Suddenly Revealed Stopped Vehicle Scenario – Combination of Lane Change and Rear-End Scenario Categories	No
Crossing Path: Straight Crossing Path Scenario	No
Opposing Traffic Scenario	No
Parking/Reversing Scenario	Yes
Detect, Respond to, and Navigate Work Zones	Yes
Special Vehicles: Emergency Vehicles and School Buses	Yes

The selected scenarios were analyzed for new elements and properties that may be used to help describe them and a consolidated list is presented in the previous chapter. These scenarios can then be tested in simulation, on a closed-course, or encountered in the real world to aid in the development, validation, and deployment of ADSs.

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.

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[7] Believed to be 2018.

Appendix A: Additional Selected Scenario Category Descriptions

This appendix summarizes the scenario description for each of the scenarios chosen in the chapter, "Scenario Selection And New Elements and Properties Analysis." 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 assesses its ability to follow commands. The ADSs are assigned a starting location and a goal destination, and while navigating between these two points, a scenario is presented to the vehicle and its response assessed. 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 parametrized driving scenario set could also be tested.

A.1 Parametrized Driving Scenario Elements

In this appendix, each basic scenario interaction is described, followed by the various elements and their properties that were used to create a set of parametrized driving scenarios. These properties could then be varied to generate a large set of scenario test cases, or alternatively to show the types and values of properties tested/encountered in test track and public road testing.[8] This was a way to experiment with both the identified elements and properties and driving scenarios. This may help facilitate more common definitions, descriptions, scenario-to-scenario repeatability, and reproducibility of the types of driving scenarios that may be encountered by humans, ADASs, and ADSs. The elements and properties that may be varied are broadly divided into the following categories:

1. **Initialization:** It is recognized that various ADSs have different ODDs and require certain conditions for system initialization and continued operation. The study intends that these maneuvers will 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 the following.
    - Initial positions, velocities, and orientation of SV, POV, SOVs, and traffic.
    - Initialization period:
        - Time-based event triggering to allow for maneuver initialization time.
    - Define scenario end conditions:
        - Time or duration of maneuver conditions

[8] 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.

        - Collision/no collision, road edge departure, illegal actions, control loss
        - End goal position: absolute or relative
        - Etc.

2. **<u>Environment:</u>** This includes the aspects of the 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[9]
    - Etc.

3. **<u>POV/ SOV/ VRU:</u>** 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/SOVs
    - Dimensions and type of VRU:
        - Adult/child
        - Male/female
        - Animal
        - Pedalcyclist

4. **<u>Traffic:</u>** 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; and
    - Behavior/purpose.

5. **<u>ADS Status:</u>** Another factor that can affect the SV's response is the status of the ADS. These properties could include the following.

    - Normal operation
    - ESC/ABS activation
    - Fault codes/warnings
        - Engine temperature
        - Engine fault code
        - Etc.
    - Low fuel/low battery charge
    - ADS sensor fault
    - Mechanical failure

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

For each scenario, element property ranges can be determined based on ODD, with values falling within and outside, 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 of 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, demonstrating behavior adaptation, design intent, and risk reduction. The authors encourage developers to integrate perception and sensing information into the scenario description, if possible.

A.2 Suddenly Revealed Stopped Vehicle Scenario

The lane change scenario described in Rao et al., 2021) involves lead vehicles drifting and changing lanes into the SV travel lane. This broad scenario involves a lot of different parameters and covers a wide range of lane change interactions encountered on the road. To capture a different type of lane change maneuver and, in particular, one with a potential rear-end impact, a scenario was selected where the lead vehicle changes lanes out of the SV's travel lane and reveals a stopped vehicle in the travel lane ahead of the SV. The selected SRSV scenario is part of the TJA scenarios published by NHTSA (2018).

Initial and final positions of the POV with respect to the SV and SOV for the SRSV scenario are illustrated in Figure A.1. For repeatability, the test procedures specify an explicit lane change path, with tolerances, for the SOV, as shown in Figure A.2. It is important to underscore the need for repeatable and reproducible actor behaviors, such as lane changes, in a scenario description. Any ambiguities in the actor behaviors and actions could lead to different results.

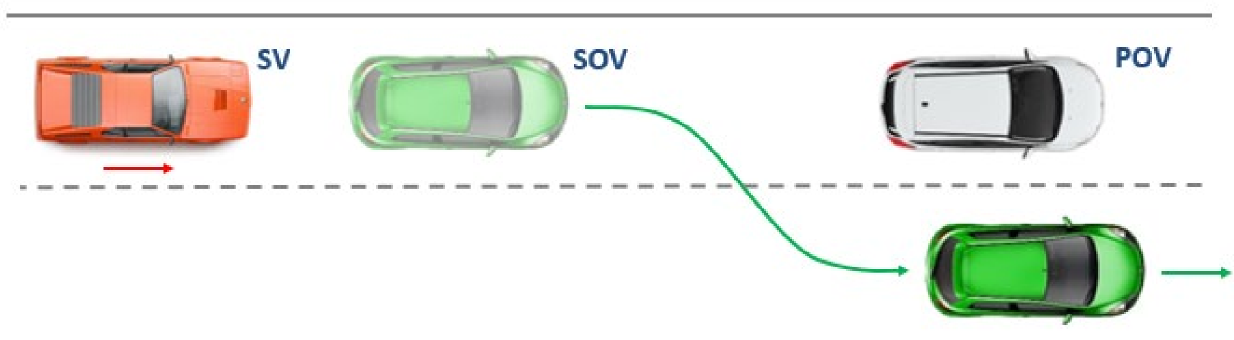


Figure A.1. Suddenly Revealed Stopped Vehicle Scenario

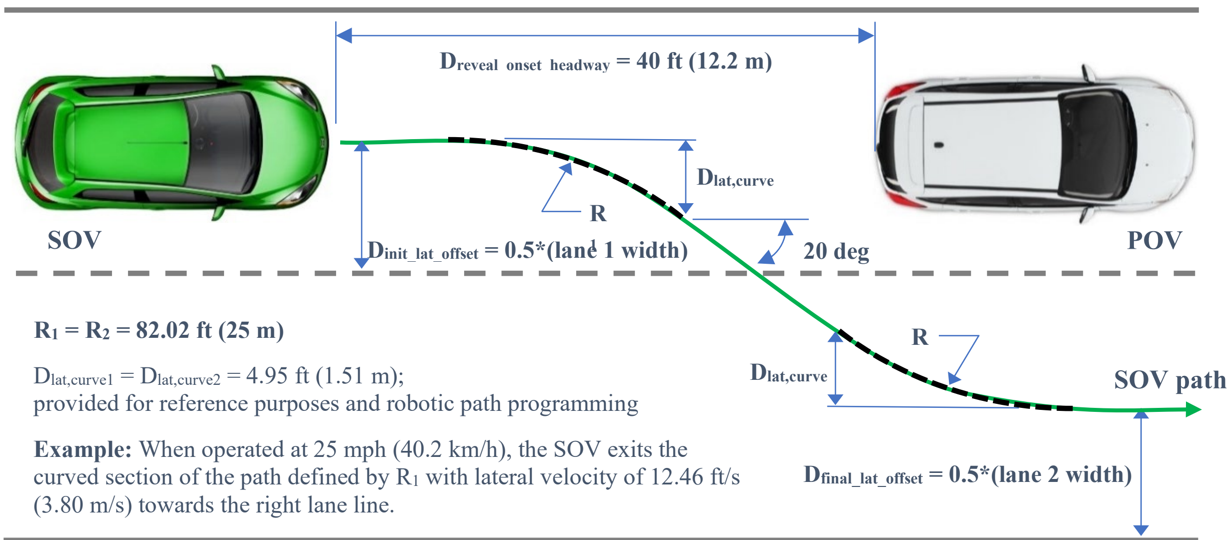


Figure A.2. Suddenly Revealed Stopped Vehicle Path Design

Scenario details from the NHTSA SRSV test procedure are presented in Table A.1. These test procedure scenarios are all performed on an idealized, straight, double lane road with no other traffic other than the POV and SOV. These 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, test-track, and simulation tests.

Table A.1. SRSV Scenario Details

Initial Speed			**SOV-to-POV Distance at Reveal Onset**	**SV and SOV Lateral Path Tolerance**	**SV ACC Setting**	**Test End Condition**
SV[1]	**SOV**	**POV**				
15 mph (24.1 km/h)	15 ± 1 mph (24.1 ± 1.6 km/h)	0	35 ± 1 ft (10.7 ± 0.3 m)	± 0.8 ft (± 0.25 m)	Near	- The SV contacts the POV OR - 1 second after the SV avoids the stopped POV by either stopping or changing lanes.
					Far	
25 mph (40.2 km/h)	25 ± 1 mph (40.2 ± 1.6 km/h)	0	35 ± 1 ft (10.7 ± 0.3 m)	± 0.8 ft (± 0.25 m)	Near	
					Far	

[1] Initial SV speeds are nominal values. The actual SV speeds realized during the SRSV tests will depend on the vehicle's ADS performance and how closely the system matches the POV speed.

A.2.1 Basic Scenario Interaction Description

The objective of this scenario is to evaluate the SV's ability to detect and respond to a stationary POV that is suddenly revealed after an SOV steers around it. In this scenario, the SOV begins in the same lane as the SV and POV and performs a single lane change into an adjacent lane to avoid colliding with the stationary POV (Figure A.1).

A.2.2 Parametrized Driving Scenario Set Parameters

Initialization

Various SVs require different conditions for system initialization and continued operation. These scenarios could be modified to meet the conditions required for each specific SV while maintaining the essence of the scenario. A general list of initialization considerations is listed below:

- The scenario is initiated with the POV, SOV, and SV in the same lane, traveling 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 a position relative to another actor.
- The scenario termination conditions are set to be when either the SV stops/reaches the end/goal position or when the SV contacts the POV.

Environment Parameters

For this scenario, the number of lanes controls the ability of the SV to change lanes to avoid the suddenly revealed stopped POV. The speed limit, road curvature, and lane line markings can also be varied. These parameters and some possible ranges that could be tested in simulation are listed in Table A.2. These ranges are a starting point and can be modified as deemed appropriate.

Table A.2. Environment Parameters for Lane Change Interaction

Parameter	Range
Speed Limit	15 – 70 mph
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	2 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

Parameter	Range
Weather	All conditions listed in Section A.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 Surface	0.1 to 1

<u>POV/SOV Parameters</u>

The longitudinal distance at which the lane change is triggered ($D_{reveal\_onset\_headway}$), as well as the aggressiveness of the lane change, could also be varied to control the severity of this scenario. These parameters relating to the SOV, and other parameters related to both the POV and SOV are listed in Table A.3, along with possible parameter value ranges. These ranges are a starting point and can be modified as deemed appropriate.

Table A.3. POV and SOV Parameters for Lane Change Interaction

Parameter	Range
SOV Speed (Absolute/Relative)	5 - 80 mph absolute
POV Speed (Absolute)	0
$D_{reveal\_onset\_headway}$	16 to 82 feet (5 to 25 m)
Direction of Lane Change	Left/right
Lane ID	1 to 3
Lateral Lane Position	0 to lane width
Vehicle Type	All applicable
Vehicle Length	All applicable
Vehicle Width	All applicable

<u>Traffic Parameters</u>

The presence of a traffic vehicle in the adjacent lane limits the ability of the SV to perform a lane change to avoid the stationary POV. The traffic parameters are listed in Table A.4

Table A.4. Traffic Parameters for Lane Change Interaction

Parameter	Range
Number of Traffic Actors	0 – as required
Purpose for Each	Prevent SV lane change, occlude view, etc.
Relative X Position to SV/POV	All applicable
Relative Y Position to SV/POV	All applicable
Speed (Absolute/Relative)	All applicable
Traffic Vehicle Types	All applicable
Traffic Vehicle Width	All applicable

Parameter	Range
Traffic Vehicle Length	All applicable

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 A.5. In simulation, these status messages could be supplied to the SV to study the minimum risk fallback operation when a fault exists. Additionally, a particular vehicle may have different ADS modes which might be in control depending on the ADS status or the ODD. These modes may have certain limitations on the ADS's capabilities and impose certain restrictions on the human driver. For example, the ADS might have a parking mode in parking lots that restricts vehicle speed, or the ADS may shift from a Level 4 system to a Level 2 system requiring constant human driver monitoring due to adverse weather conditions. Such ADS modes should also be able to be output to the testing interface in simulation. This category is applicable to all the scenarios discussed in this chapter.

Table A.5. ADS Status Parameters for Rear-End Interaction

Parameter	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	All applicable
Mechanical Failure	Component
Emergency Subsystem Activations	ESC/ABS activation, lane keeping, AEB, etc.
ADS Mode	SAE Level of automation, vehicle speed limits, etc.

If a variable is not explicitly stated, it was determined to be outside the minimum requirements for the parametrized driving scenario set description. If a variable is to be included, a reasonable range of values for that variable should be used.

A.2.3 Scenario Examples

Possible scenario test cases from parameter permutations are represented graphically in Figure A.3 on the following page:

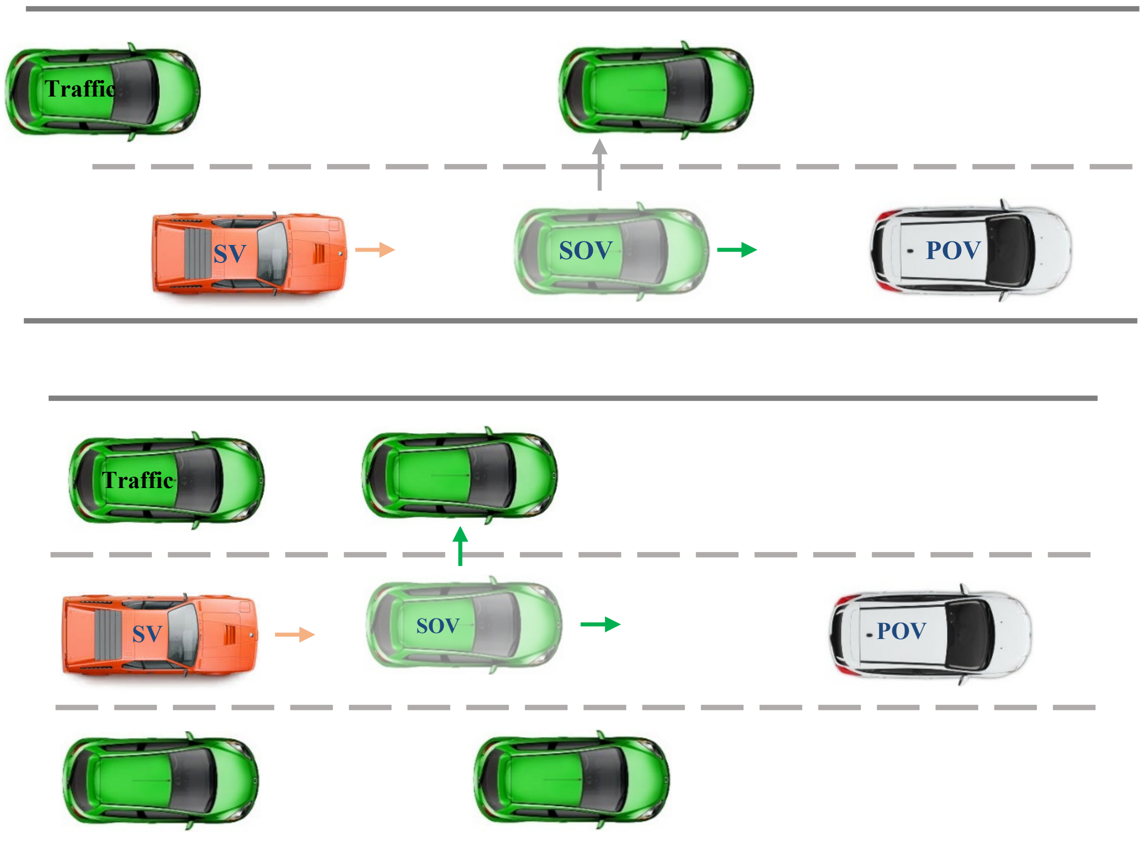


Figure A.3. Possible Permutations of Lane Change Interactions

A.3 Crossing Path – Straight Crossing Path Scenario

The SCP scenario from NHTSA (2019b) was selected as a starting point for the scenario description and parametrization employed to describe various combinations of speeds, etc., to arrive at a large set of scenario test cases. The SCP scenario supplements the previously selected left turn across path scenario from the crossing path category.

A.3.1 Basic Scenario Interaction Description

The objective of this scenario is to evaluate the ability of the SV to detect and respond to the POV coming across its path either from the near-side or the far-side. In this scenario, the SV attempts to go through an intersection as the POV, coming from either the near- or far-side of the SV, attempts to cross the SV's path. The scenario shown in Figure A.4 has the POV coming into SV's path from the near side. The POV can come into the path of the SV for various reasons like failing to stop at the stop sign or not having a stop sign, running a red light, etc. Different SV and POV speed combination and triggers used may result in a near-crash or crash scenario if the SV continues. The specific details of how a given intersection-based scenario unfolds depends on the SV-to-POV speed combination and timing and several other factors, which are presented below.

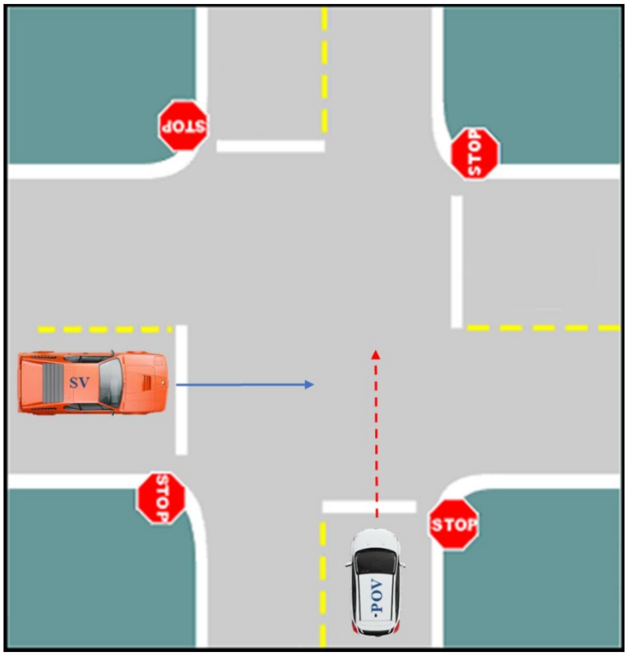


Figure A.4. Intersection-Based SCP Scenario Setup

A.3.2 Parametrized Driving Scenario Set Parameters

The following subsections list the parameters and some possible ranges that could be used for the scenario description.

Initialization

Various SVs require different conditions for system initialization and continued operation. These scenarios could be modified to meet the conditions required for each specific SV while maintaining the essence of the scenario. A general list of initialization considerations is listed below:

- The POV is initialized in the direction perpendicular to the path of the SV and can be initialized to start either on the near-side (as shown in Figure) or far-side 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.
- The scenario termination conditions are set to be when either the SV reaches the end goal position or when the SV contacts the POV.

Environment Parameters

The intersection design could greatly affect the SV's response to a POV crossing its path. For example, an SV approaching an intersection with a green light will likely maintain its speed, whereas if the intersection is a 4-way stop, the SV would be required to come to a stop. In another case, the POV may be required to come to a stop at a stop sign in its path but may fail to stop and will instead cross the SV's path. Another variation of this scenario could be that the SV needs to yield to the POV at the intersection. The presence of adverse weather conditions may affect the ADS performance and may even deactivate the ADS if it violates its ODD requirements. These parameters can be varied for a more comprehensive scenario description. The environment parameters and some initial ranges are listed in Table A.6. These ranges are a starting point and can be modified as deemed appropriate.

Table A.6. Environment Parameters for Intersection-Based Scenarios

Parameter	Range
Speed Limit	15 – 55 mph
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
Pedestrian Crossing	Yes/no
Signage	All applicable
Weather	All conditions listed in Section A.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	0.1 – 1

POV/SOV Parameters

The POV speed and SCP timing may be varied such that the SV can potentially impact the POV at different locations along the length of the POV or to miss the POV completely. The length of the POV is a critical variable, as a car would clear the SV's path much quicker than a bus or a truck. The parameters and some initial ranges are shown in Table A.7. These ranges are a starting point and can be modified as deemed appropriate.

Table A.7. POV/SOV Parameters for Intersection-Based Scenario

Parameter	Range
POV Approach Direction	Crossing, near/far side
POV Impact Point	0 – 120 % of track width
Speed (Absolute/Relative)	5 – 55 mph absolute
Lane ID	1 to 3
Lateral Lane Position	0 to lane width
Vehicle Type	Car, truck, etc.
Vehicle Length	All applicable
Vehicle Width	All applicable

Traffic Parameters

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 occlude the sensing capabilities of the SV in a scenario where the POV is approaching from the far-side and as a result, may reduce the reaction time available. Such parameters and some initial ranges are shown in Table A.8. These ranges are a starting point and can be modified as deemed appropriate.

Table A.8. Traffic Parameters for Intersection-Based Scenarios

Parameter	Range
Traffic Vehicles	0 – as required
Purpose for Each	Prevent lane change, block lane change, occlude view, etc.
Relative X Position to SV/POV	All applicable
Relative Y Position to SV/POV	All applicable
Speed (Absolute/Relative)	All applicable
Vehicle Type	All applicable
Vehicle Width	All applicable
Vehicle Length	All applicable

ADS Status:

Refer to the ADS Status section in Section A.2.2

A.3.3 Scenario Examples

Two possible scenario test cases from parameter permutations are represented graphically in Figure A.5 and are described on the following page.

Scenario 1: POV approaching from the near-side of SV at a stop sign-controlled intersection.
For this scenario, an SV approaches an intersection and only the traffic flow across the SV travel direction is controlled by stop signs. The POV is approaching the intersection from the near-side of the SV. The scenario could be set up in such a way that the POV fails to stop at the stop sign and as a result, enters the junction and comes into SV's path. This scenario presents a challenging situation where the SV must respond to a vehicle directly coming into its path.

Scenario 2: POV approaching from the far-side of SV at a signalized intersection with an SOV in left turn-only lane.
Scenario 1 can be further complicated by having the POV come from the far-side of SV at a signalized intersection with two lanes in each direction of travel. The traffic vehicle (SOV) is making a left turn from SV's adjacent lane and blocks the SV's view. This scenario setup could occlude the SV's view and reduce the available time the SV has to respond to a POV crossing its path.

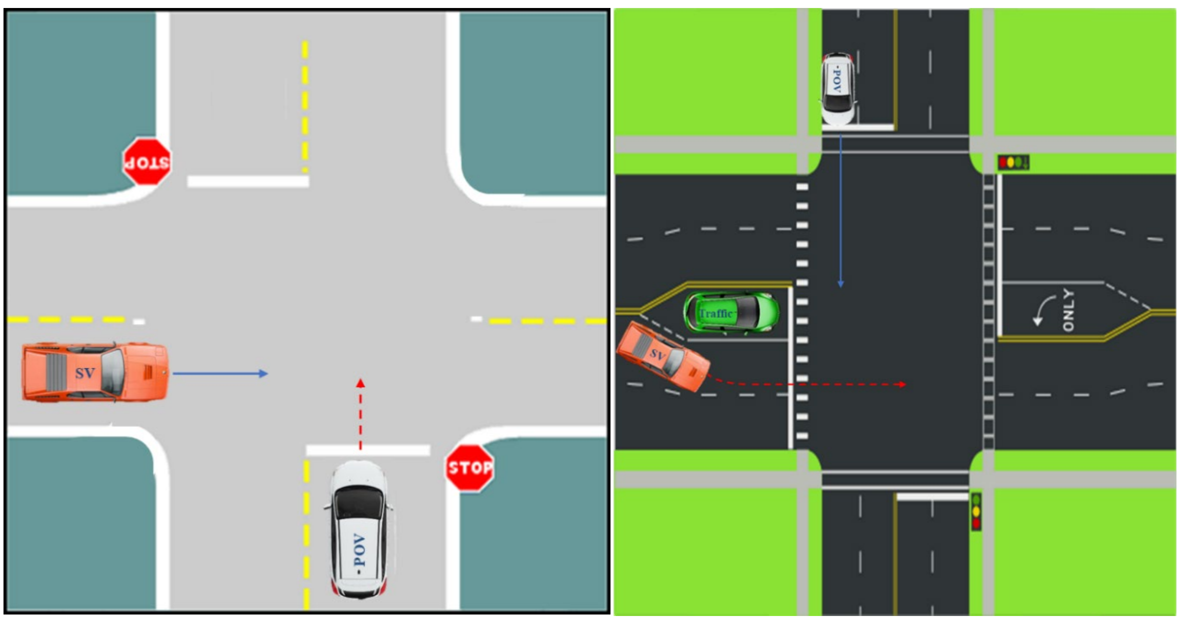


Figure A.5. Possible Variations of SCP Intersection Scenario
Left: Scenario 1, Right: Scenario 2

A.4 Opposing Traffic Scenario

This scenario involves the SV interacting with an opposing (oncoming) POV. For such an interaction to occur, either the POV needs to depart its lane into the travel lane of the SV, or the SV needs to leave its lane and move into the travel lane of the POV. For high-level ADSs, the system is not expected to leave the lane unexpectedly, and the ADS operation during a scenario does not call for specific driver actions, like turn signal use or drifting. Hence, only scenarios where an oncoming POV drifts into the SV's travel lane are considered.

The scenarios selected are principally like those described in the draft NHTSA test procedure for OTSA in Manahan and Forkenbrock (2021). OTSA is an advanced driver assistance system whose active interventions are designed to bring a vehicle back into the original travel lane after a path deviation causes it to move towards an oncoming vehicle in an adjacent lane. As discussed in the previous paragraph, this scenario, which was developed for lower levels of automation, requires adjustments and changes to be applicable to ADS. Instead of the SV drifting into the POV's travel lane, this scenario was modified to have the POV drift into the SV's travel lane.

The scenario descriptions in Manahan and Forkenbrock (2021) state that each test scenario begins with the SV driven straight behind an LV. At the same time, a single POV is driven in a lane to the left of the SV, but in the opposite direction. As the SV and POV approach each other, an SV lane deviation towards the POV is initiated. The deviation can be either unintentional drift with low lateral velocity, or an intentional lane change with the turn signal turned on and higher lateral velocity. Figure A.6 illustrates a drift scenario.

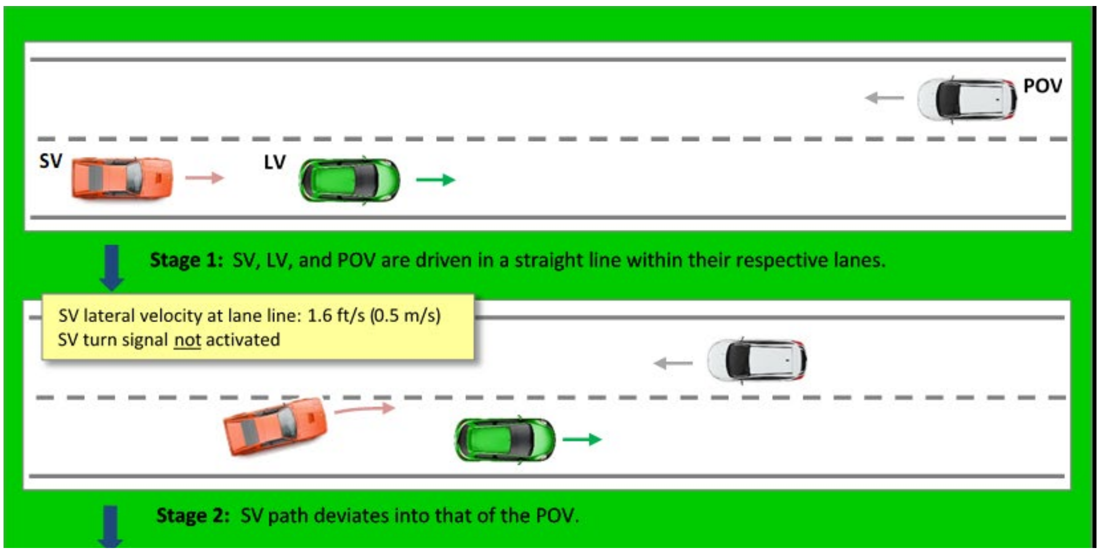


Figure A.6. OTSA Scenario

The focus of the OTSA scenarios in Manahan and Forkenbrock (2021) are for when the SV drifts or changes lanes into the path of the oncoming POV.

As discussed in the previous paragraphs, this scenario, which was developed for lower levels of automation, requires adjustments and changes to be applicable to ADS. Instead of the SV drifting, this scenario was modified to have the POV drift into the SV's travel lane (Figure A.7).

Figure A.7. Oncoming POV Drifting Into SV's Travel Lane

A.4.1 Basic Scenario Interaction Description

The ability of the ADS to recognize and avoid an oncoming vehicle is tested in this scenario. This scenario may occur when a vehicle traveling in the opposite direction enters the travel lane of the ADS (intentionally or unintentionally). An example of a false positive scenario as described above in Figure A.7 is also considered.

A.4.2 Parametrized Driving Scenario Set Considerations and New Parameters

A wide range of parameters could be used to describe oncoming scenarios to test an ADS's ability to avoid or mitigate head-on collisions depending on the scenario. The following subsections discuss the various considerations for setting up such a test and the new parameters/capabilities needed to perform such tests in simulation.

Initialization

Various SVs require different conditions for system initialization and continued operation. These scenarios could be modified to meet the conditions required for each specific SV while maintaining the essence of the scenario. A general list of initialization considerations is listed below:

1. The POV and ADS (i.e., SV) are oriented in opposite directions, on separate lanes with no physical barriers between the opposing travel lanes. The number of lanes is decided by the scenario type.
2. Road obstacles, POVs, SOVs, and traffic actors are initialized according to the scenario needs. For example, obstacles to limit SV responses could be used.
3. The start and end positions of the SV and POV should be specified. The end positions can be specified when the SV passes by the POV.
4. The scenario termination conditions are set to be when either the SV reaches the end goal position or when the SV contacts the POV.

Environment Parameters

For the oncoming traffic scenario, the roadway may not have a physical barrier between the opposing traffic lanes. However, the SV may encounter an oncoming traffic vehicle even on a divided one-way travel roadway.

POV/SOV/VRU Parameters

Depending on the scenario, the POV either drives straight in its travel lane or drifts into the path of the SV's travel lane. The parameters for these two behaviors are different. For the case where the POV drifts into the SV's lane, the timing and range at which the drift occurs is the main parameter of interest. This capability has already been discussed for other scenarios and is not new.

Traffic Parameters

The presence of traffic vehicles, or lack thereof, may interfere with the SV's decision for path planning. Here again, this is a set of all actors that can be encountered on the road.

ADS Status:
Refer to the ADS Status section in Section A.2.2

A.4.3 Scenario Examples

Five example scenarios are presented to show various oncoming vehicle interactions, including examples of false-positive scenarios.

Scenario 1 - Oncoming POV drifts into SV travel lane.
The SV drives straight while the POV approaches on the adjacent lane from the opposite direction. The POV starts to drift or swerve into the SV's travel lane, as illustrated in Figure A.8. The timing and the overlap between the POV and SV path can be varied. The SV might steer or brake to avoid or mitigate the severity of the collision.

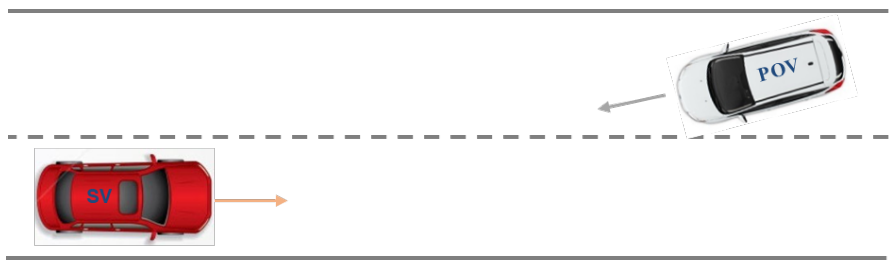


Figure A.8. Oncoming POV Drifts Into SV's Travel Lane

Scenario 2 - False positive, SV changes lanes into a lane adjacent to the path of an approaching POV.
The SV is induced to change lanes as a POV approaches in the adjacent lane, as shown in Figure A.9.

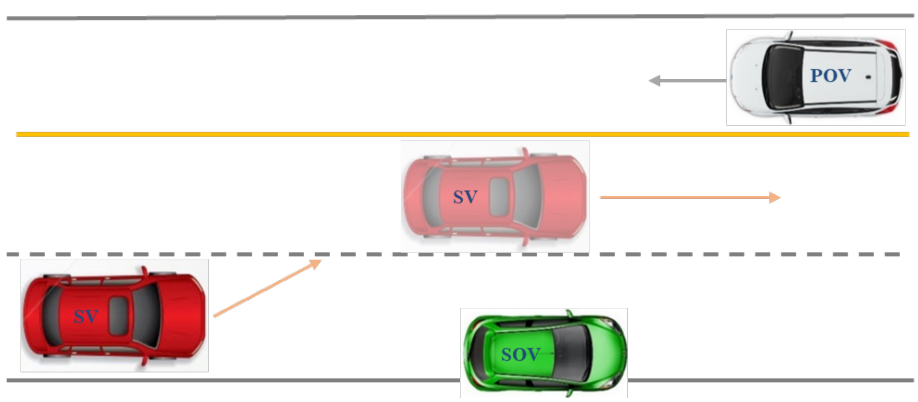


Figure A.9. False Positive, SV Changes Lanes Into a Lane Adjacent to the Path of an Approaching POV

Scenario 3 - False positives, POV changes lanes into a lane separating the path of SV and POV.
The POV performs a lane change into a lane adjacent to the approaching SVs, as shown in Figure A.10.

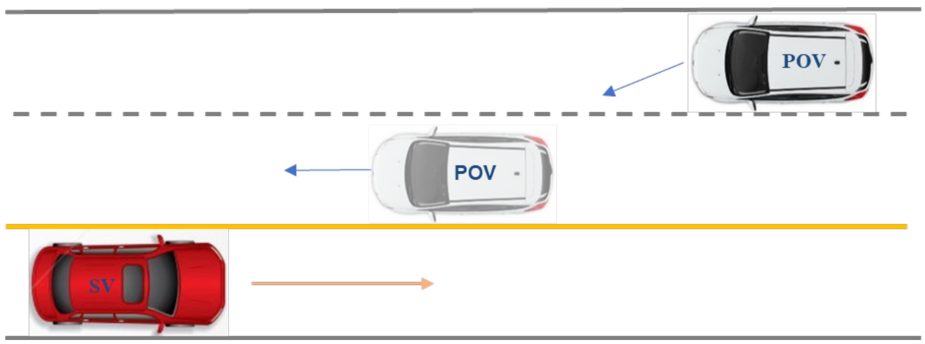


Figure A.10. False Positive, POV Changes Lanes Into a Lane Separating the Path of SV and POV

A.5 Parking/Reversing Scenario

High-level ADSs may have self-parking capabilities like valet parking and summoning. The ability of the systems to navigate potentially congested parking lots or parallel park/exit a parking spot along a busy road is tested in this scenario.

A.5.1 Basic Scenario Interaction Description

The ability for the ADS to safely navigate parking lots, park, and reverse out of parking spots of various dimensions and orientations is tested in this scenario.

A.5.2 Parametrized Driving Scenario Set Considerations and New Requirements

Initialization
Various SVs require different conditions for system initialization and continued operation. These scenarios could be modified to meet the conditions required for each specific SV while maintaining the essence of the scenario. For this scenario, the SV may start from rest in a parking spot and must move out of the spot or, may start elsewhere and go find a suitable parking spot and park itself.

The scenario ends when the vehicle completes the parking task safely, or exits the parking spot/lot safely, returns to a minimum risk fallback state, or crashes.

Environment Parameters
Vehicles are parked in various public road environments as well as private areas like parking lots, parking garages, driveways, etc. Depending on the scenario, the environment parameters vary greatly.

New parameters: New parameters and features include various types of parking spot markings and configurations including parallel, perpendicular, and oblique parking spots. It may be required to designate spots for parking meters, handicap spots, concrete wheel stops, and other features found in parking spots.

POV/SOV/VRU Parameters
Parking lots are potentially busy environments with pedestrians, bicyclists, shopping carts, and other potential objects inhabiting the environment. Parking scenarios performed on the side of the road could have to interact with other fast-moving vehicles on the road. Depending on the interaction being tested, the POV/SOV/VRU parameters for this interaction can be a large set.

New parameters: Here, in addition to already established types of actors, it may be required to simulate shopping carts (of various sizes), parking spaces occupied by cart corrals, etc.

Traffic Parameters
The presence of vehicle/pedestrian traffic can influence the behavior of the vehicle during parking/reversing scenarios by limiting the action space though this might not be the main interaction being studied. Fast-moving traffic on the street while the SV is trying to parallel park is one example. In a parking lot situation, foot traffic, other vehicles, etc., can be a factor. Again, depending on the environment and interaction being tested, traffic parameters can be varied over a large set.

ADS Status:
Refer to the ADS Status section in Section A.2.2

A.5.3 Scenario Examples

A few possible parking test scenarios are presented below. Figure A.11 depicts the SV approaching a row of parked cars where it is required to identify the empty spot and complete the parking maneuver. Figure A.12 depicts a similar situation except the parking spots are oblique and one of the empty parking spots is a handicap spot. Here the SV has to choose the appropriate spot depending on the occupant of the vehicle and complete the parking maneuver.

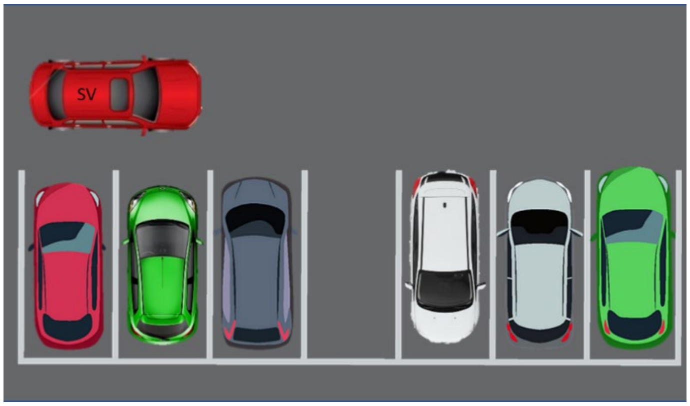


Figure A.11. Identifying Empty Perpendicular Spot and Completing Parking Maneuver

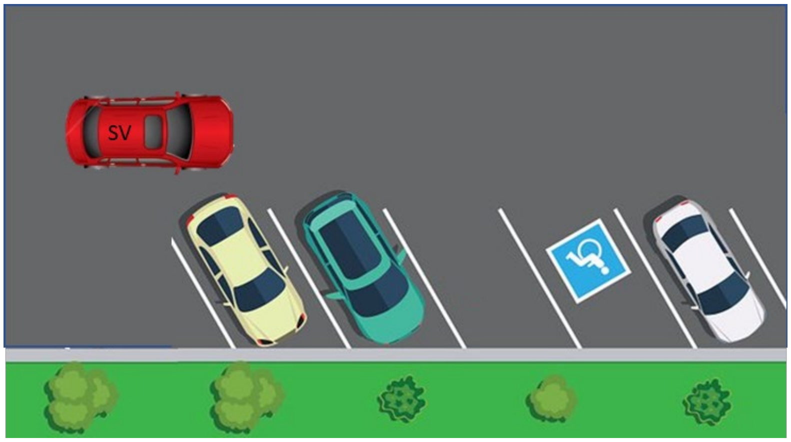


Figure A.12. Identifying Empty Oblique Parking Spot and Completing Maneuver Into Legally Allowed Spot

Two parallel parking scenarios are depicted in Figure A.13. The SV is required to identify an available spot and safely maneuver into the spot. Such spots are frequently on the edges of roads that may have other vehicles driving on them. This is depicted in the right image in Figure A.13.

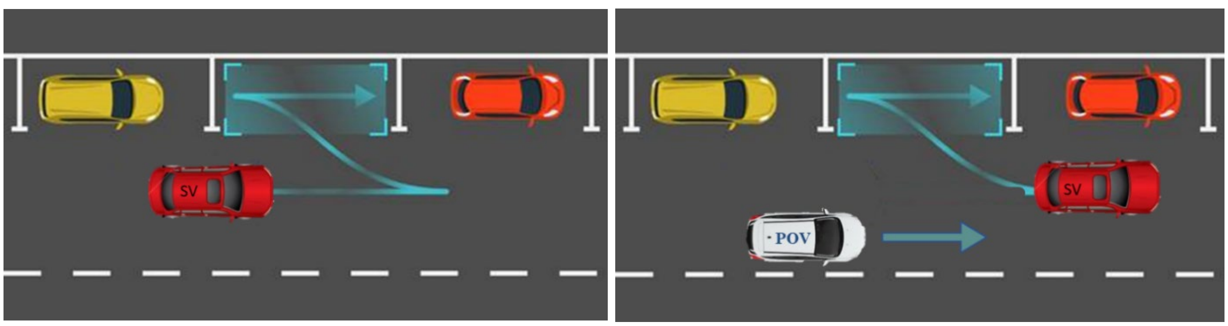


Figure A.13. Identifying Empty Parallel Parking Spot and Completing Parking Maneuver

A.6 Detect, Respond to, and Navigate Work Zones

A.6.1 Basic Scenario Interaction Description

The objective of this scenario category is to evaluate the capability of the ADS to safely navigate or return the vehicle to the minimum risk fallback condition when presented with work zones. Work zones occur for all road types, sizes, and configurations. They also have different effects on navigable road areas. For example, some work zones may close one lane of travel in one direction, whereas others may close all lanes of travel in a direction and reroute the traffic through makeshift lanes. The ability of the ADS to identify and navigate the wide range of work zones it may encounter needs to be studied.

A.6.2 Parametrized Driving Scenario Set Considerations and New Requirements

Initialization

Various SVs require different conditions for system initialization and continued operation. These scenarios could be modified to meet the conditions required for each specific SV while maintaining the essence of the scenario. To maintain the essence of this scenario, it is not just sufficient to produce interactions between the ADS and work zones, but the simulation team may be required to ensure that the maps stored in the ADS do not reflect the change to the roadway due to the presence work zone.

The scenario is complete when the ADS navigates safely through the work zone to its end goal position, reaches minimum risk fallback state, or crashes.

Environment Parameters

Work zones may alter the flow of traffic and even change the lane assignments of the roadway. These changes are marked using various types of signs or even by workers with handheld signs. Work zones are demarcated using various means, including barrels, cones, signs, reduced speed limits, flashing lights, etc. Different work zones are not marked exactly alike or cause the same changes to traffic flow. Signage types and their positioning can be varied to simulate a wider range of work zone configurations. It is not possible to list all possible combinations, but some of the new requirements arising from simulating work zones are discussed below.

New requirements: To adequately simulate these environments, it may be required to represent the various traffic control devices in simulation. These include, but are not limited to, barrels, concrete barriers, cones, detour signs, speed limit signs, work zone fine signs, signs with flashing lights, flags, etc. A method to convey the ground truth information regarding the signage and the altered roadway to the ADS is required when testing only the planning and control aspects. If, however, perception is incorporated into the testing, simulating the exact signage, and rendering the road environment accurately, might be required as well.

POV/SOV/VRU Parameters

Interaction with other vehicles is not the primary goal of this test, and so there are no POV, SOV, or VRU parameters presented. However, other vehicles and/or pedestrians may be present, and these cases are covered in the next section (Traffic Parameters).

Traffic Parameters

The presence of a traffic vehicle in the adjacent lane limits the ability of the SV to perform a lane change in response to the work zone. There may be workers and heavy machinery present in the work zone. A worker or a police officer may be directing traffic around the work zone.

New requirements: The ability to simulate the presence and movement of heavy machinery like bulldozers, backhoes, etc., may be necessary. Workers or police officers directing traffic may also need to be simulated. Again, a method to convey the ground truth information regarding the worker/police officer controlling the traffic to the ADS is required when testing only the planning and control aspects. If, however, perception is incorporated into the testing, simulating the construction machinery, and rendering the worker/police officer controlling traffic accurately, might be required as well.

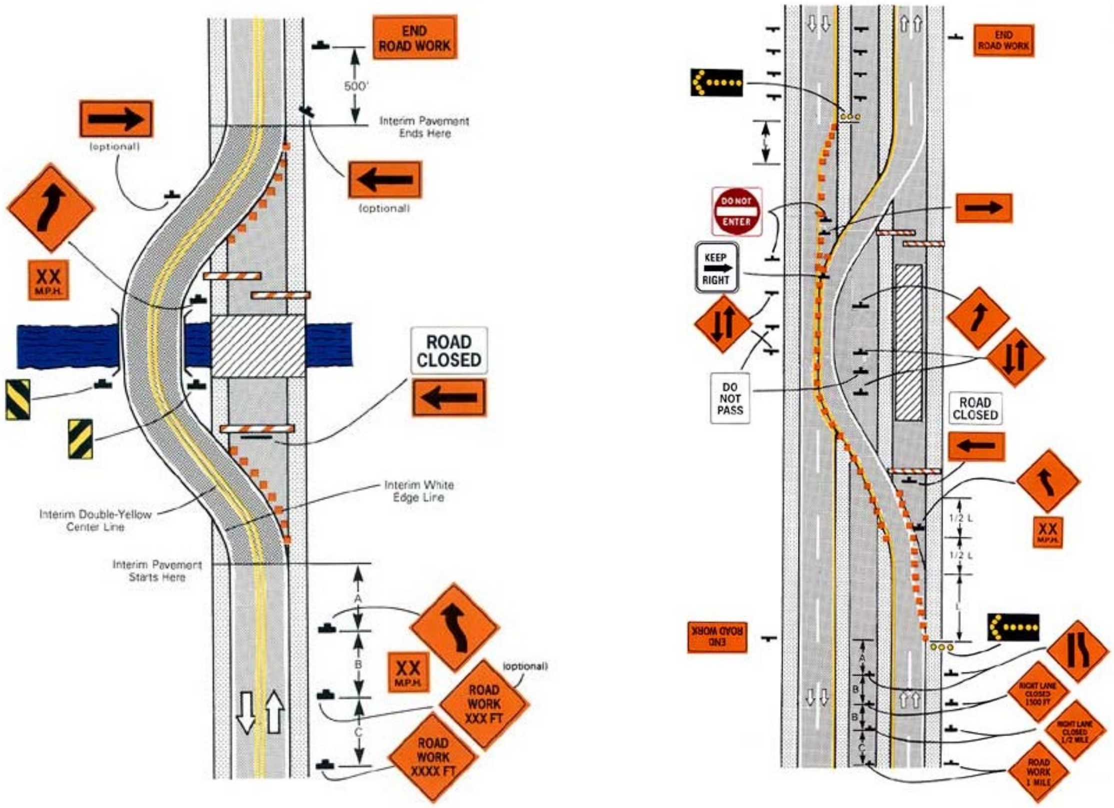
ADS Status
Refer to the ADS Status section in Section A.2.2

A.6.3 Scenario Examples

Example work zones classified by their effects are shown below. These are sourced from the Federal Highway Administration's (2009) manual on uniform traffic control devices website and portal at https://mutcd.fhwa.dot.gov/. Titled *Manual on Uniform Traffic Control Devices for Streets and Highways, 2009 Edition Including Revision 1 Dated May 2012 and Revision 2 Dated May 2012* can be downloaded from this web page.

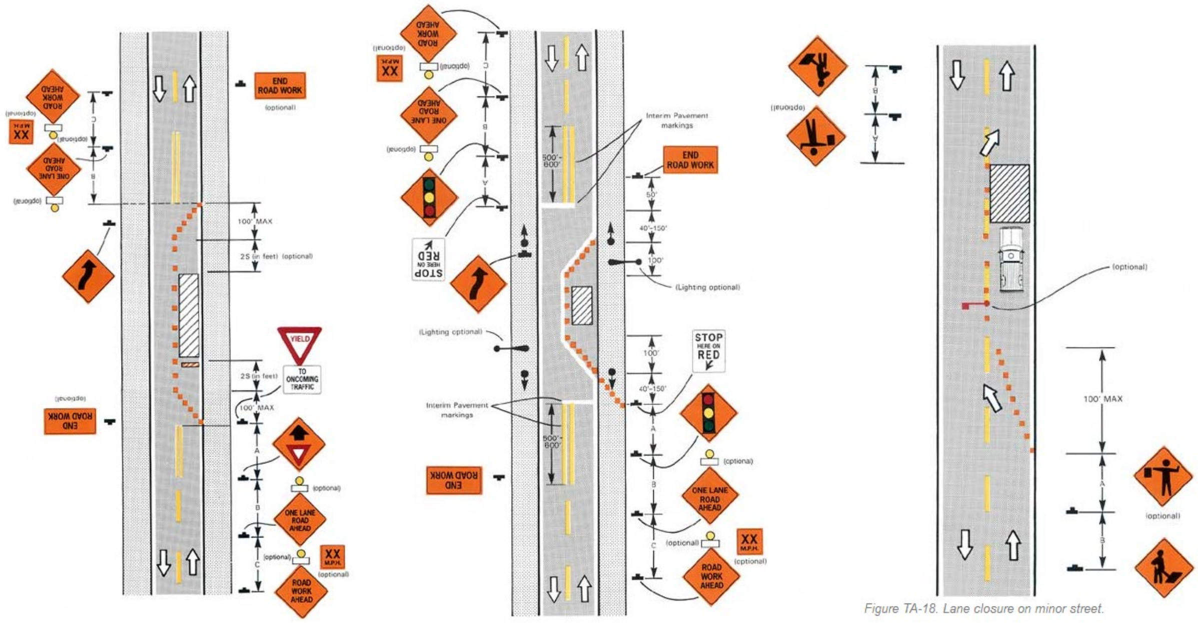
The examples in Figure A.14 show instances where the work zone has caused major changes to the road map. These changes are significant and drastic enough to contradict the internal map stored on the ADS. The example in Figure A.14(a) would require the ADS to divert from its route and use a new road that may not be included in its onboard map. The example in Figure A.14(b) would require the ADS to divert and traverse on a lane designated for oncoming traffic in its onboard map.

The examples in Figure A.15 show instances of similar work zones with different traffic control mechanisms in place. The ADS would be required to act accordingly to each signaling mechanism. Examples of work zones in complex road environments are shown in Figure A.16. Here, in addition to the complex road laws the ADS would have to adhere to, the work zone creates more challenges.



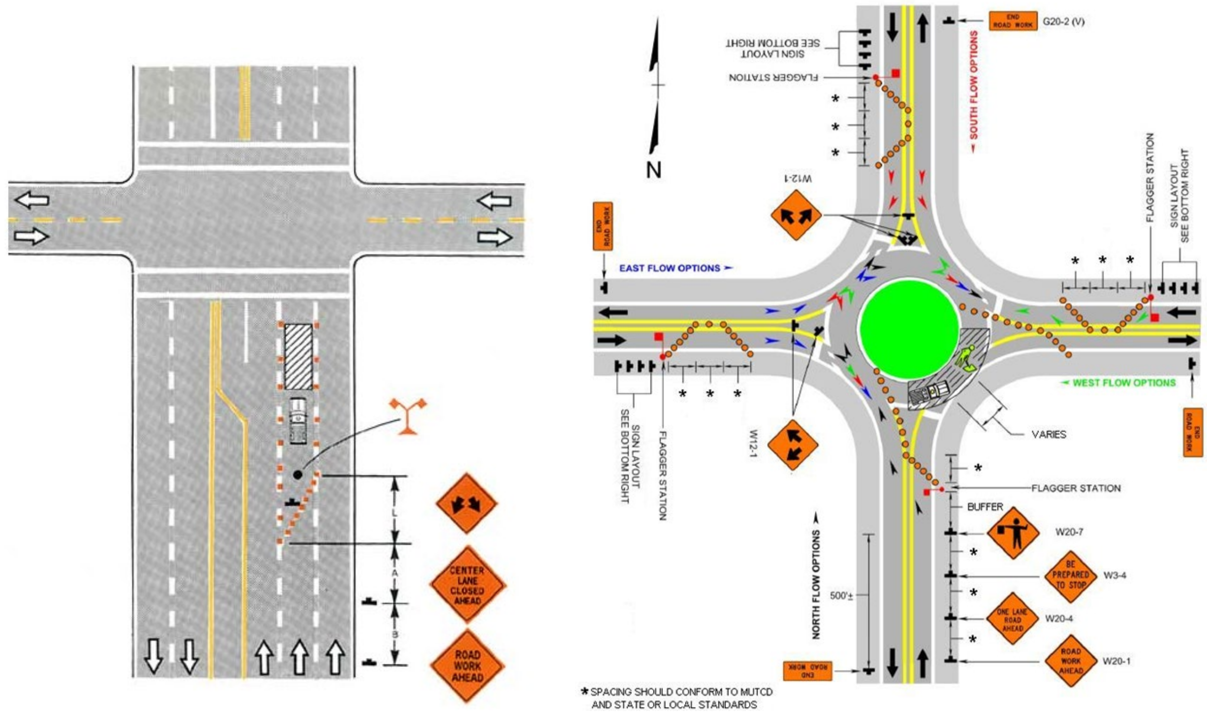
(a) Road Closed with Diversion (b) Median Crossover on Freeway

Figure A.14. Work Zones With Significant Changes to Road Maps



(a) Yield Sign (b) Traffic Lights (c) Flagger

Figure A.15. Work Zones With Different Traffic Control Devices



(a) Lane Closure Near Intersection (b) Partially Closed Single Lane Roundabout *

Figure A.16. Work Zones in Different Road Environments

Source: Virginia Department of Transportation, 2015.

A.7 Special Vehicles: Emergency Vehicles and School Buses

This scenario tests the ability of the SV to recognize an emergency vehicle within close vicinity and act properly following traffic laws. When an emergency vehicle, such as an ambulance, fire truck, or police car, approaches the SV while displaying flashing lights and sounding a siren, the SV must pull to the right and stop if it is on a two-way road. This is one of the requirements that is based on a simple road. Roads can have multiple lanes with divided or undivided lanes, or an intersection. The emergency vehicle can be stationary on the road providing help at a crash incident, approaching from behind, or in the opposite lane.

A.7.1 Basic Scenario Interaction Description

This scenario category tests the ability of the SV to detect a special vehicle, distinguish it from other traffic vehicles, and proceed properly toward the destination by obeying the applicable laws for the special vehicles. These laws vary by States and municipalities, yet they share commonsense practices that are established nationally. The focus of this scenario is to provide a simulation setting to test SV functions through its behavioral competencies. The SV must obey all these laws and other special vehicle requirements, as required by other States and different municipalities. It is not possible to include and discuss all differences, but the list for Ohio is presented in Section C.6 and can be used as baseline to define and generate scenarios to address behavioral competencies.

A.7.2 Parametrized Driving Scenario Set Consideration and New Requirements

A wide range of parameters could be used to describe school bus, emergency vehicle, public safety vehicle, and public road service vehicle conditions and states on the road, and how the SVs need to react and behave according to public safety laws. The following subsections list the parameters and some possible settings that could be used for scenario description.

Initialization

Various SVs require different conditions for system initialization and continued operation. These scenarios could be modified to meet the conditions required for each specific SV while maintaining the essence of the scenario. Special vehicles can be part of any scenario; hence, it is necessary that conditions are met so that the SV's ADS has activated and remains active when it encounters the special vehicle. Some examples for initialization for various scenarios are listed below:

1. School buses, emergency vehicles, public safety vehicles, and public road service vehicles are defined as POVs in the scenario.
2. For a stopped POV, the SV could be initialized to be travelling in the same lane or adjacent lane. For the case of a school bus, the SV could be travelling in the opposite direction on a two-lane road.
3. For scenarios with intersections, the SV could be initialized to be traveling on a lane perpendicular to the POV, with priority to go through if no emergency vehicles are present (like a green traffic light, first to arrive at a four-way stop sign, etc.).
4. The start and end positions of the SV and POV should be specified. The end position can be specified when the SV stops or crosses (passes or departs) the POV.

5. The scenario termination conditions are set to be when either the SV reaches the end goal position, breaks a law, or when the SV contacts the POV or other actors (e.g., child from behind a school bus).

Environment Parameters
As specified above, the SV can encounter a special vehicle almost anywhere the SV is able to traverse and can be part of any scenario. Hence, the environmental parameters for this scenario are comprised of a super set of all possible environments the SV can encounter in the real world.

POV Parameters
The various types of the special vehicles have different characterizing features. This introduces a few new requirements for the simulation software that are discussed below.

New requirements: Again, a method to convey the ground truth information regarding the special vehicles to the ADS is required when testing only the planning and control aspects. If, however, perception is incorporated into the testing, accurately simulating the appearance (for both camera and lidar) and sounds of the special vehicles will become essential. This includes color schemes of special vehicles (yellow school buses, etc.), flashing lights (blue and red for police cars, red for fire trucks, etc.), different siren sounds, and accurate rendering of the road environment.

Traffic Parameters
The presence of traffic vehicles, or lack thereof, may interfere with the ADS's decision for path planning. For example, the presence of a large truck ahead of the ADS may obscure the presence of a stopped school bus in the adjacent lane. Since emergency vehicles and school buses are encountered everywhere the ADS can traverse, traffic parameters are a super set of all possible interactions with all types of traffic actors.

ADS Status:
Refer to the ADS Status section in Section A.2.2

A.7.3 Scenario Examples

Scenario 1 - Stationary emergency vehicle.
The SV drives straight on a two-way road and approaches a stationary emergency vehicle (i.e., a police car) with flashing lights. In the case of no oncoming traffic, the SV moves to the left and passes the emergency vehicle. Other scenario conditions can be simulated with a stationary public safety vehicle on a single lane road, where the SV must slow down and carefully pass the emergency vehicle to the left as far away as safely possible.

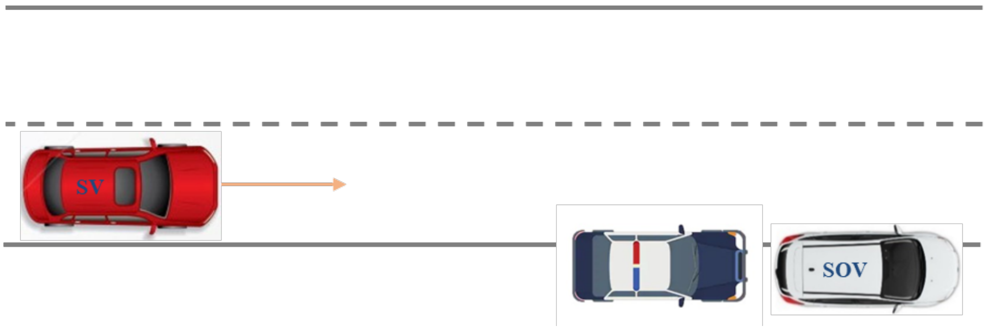


Figure A.17. Stationary Emergency Vehicle

Scenario 2 – Emergency vehicle approaching from behind.
An emergency vehicle is approaching the SV from behind in the same lane or in an adjacent lane. The SV needs to steer to the right and stop until the emergency vehicle passes.

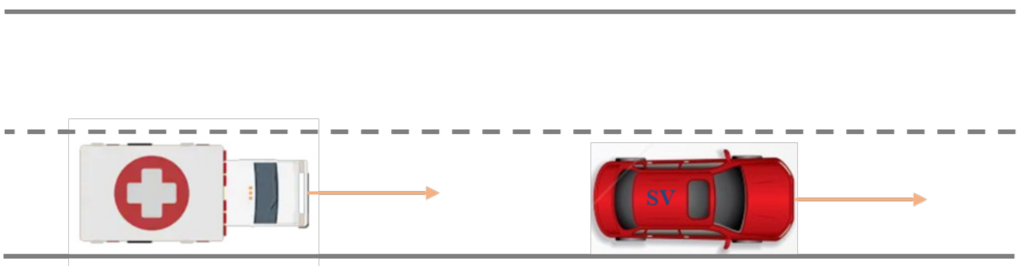


Figure A.18. Emergency Vehicle Approaching From Behind

Scenario 3 – Oncoming emergency vehicle.
The emergency vehicle is coming from the opposite lane, and the SV must steer to the right and stop until the emergency vehicle passes.

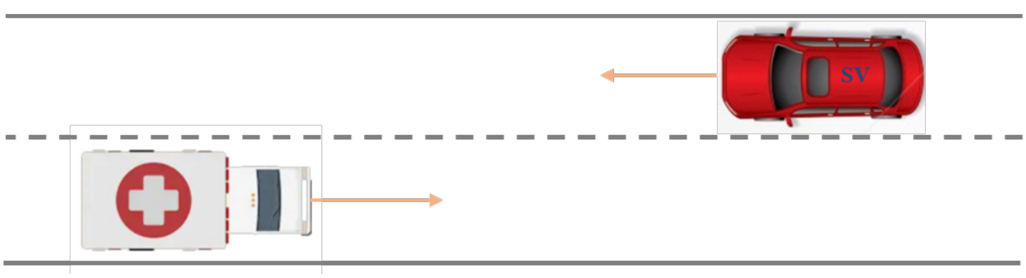


Figure A.19. Oncoming Emergency Vehicle

Scenario 4 – Emergency vehicle approaching an intersection.
The SV reaches the four-way stop intersection before the emergency vehicle but must stop until the emergency vehicle goes through the intersection.

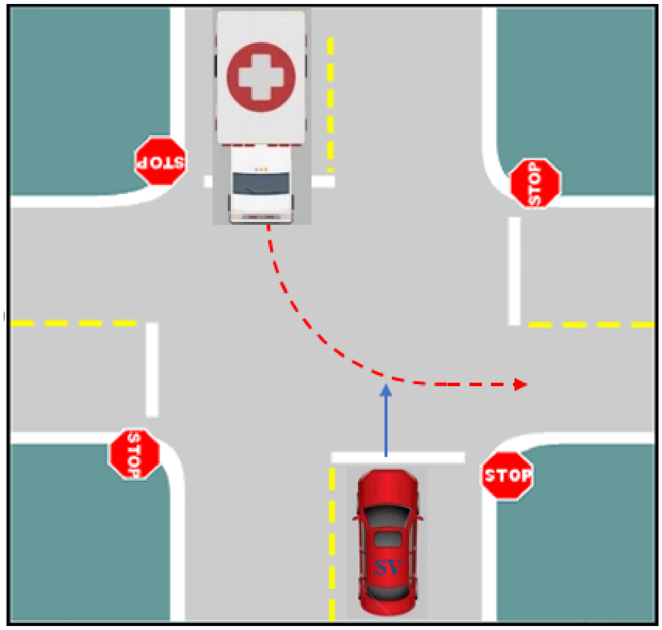


Figure A.20. Emergency Vehicle Approaching an Intersection

Scenario 5 – SV approaching a stationary school bus.
The SV approaches a stationary school bus on a two-lane road. The SV is expected to come to a stop and stay stationary until the stop sign on the side of the bus is retracted and it starts to move.

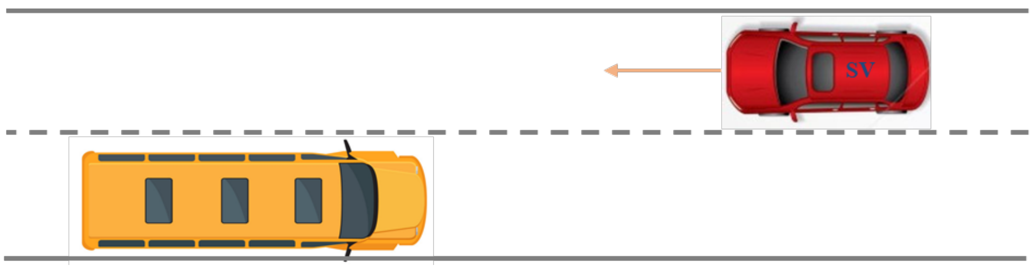


Figure A.21. SV Approaching a Stationary School Bus on a Two-Lane Road

Appendix B: NTSB Report Review and Analysis

The National Traffic Safety Board investigates and reports on civil transportation accidents. Six crashes involving ADAS or ADS operation were investigated by the NTSB as of May 2020. A brief summary of the full report of each crash is presented below.

B.1 NTSB Report: Collision Between Vehicle Controlled by Developmental Automated Driving System and Pedestrian, Tempe, Arizona, March 18, 2018 (NTSB, 2018a)

On the evening of March 18, 2018, an automated test vehicle operated by Uber Technologies, Inc., struck and fatally injured a pedestrian crossing N. Mill Avenue, outside a crosswalk in Tempe, Arizona. The ADS was a proprietary developmental automated driving system (a modified 2017 Volvo SC90 SUV), which was active at the time of the crash. The operator had been operating the vehicle for about 19 minutes before the crash.

In the area of the crash (Figure B.1), northbound Mill Avenue consists of two left-turn lanes, two through lanes, and one bike lane. The crash occurred before the formation of a right-turn lane. The sun had set (time was 9:58 p.m.) but roadway lighting was present, the pavement was dry. The posted speed limit was 45 mph.

The crash occurred as the pedestrian walked a bicycle east across Mill Avenue. The Uber test vehicle was traveling in the right through lane when its right front side struck the pedestrian.

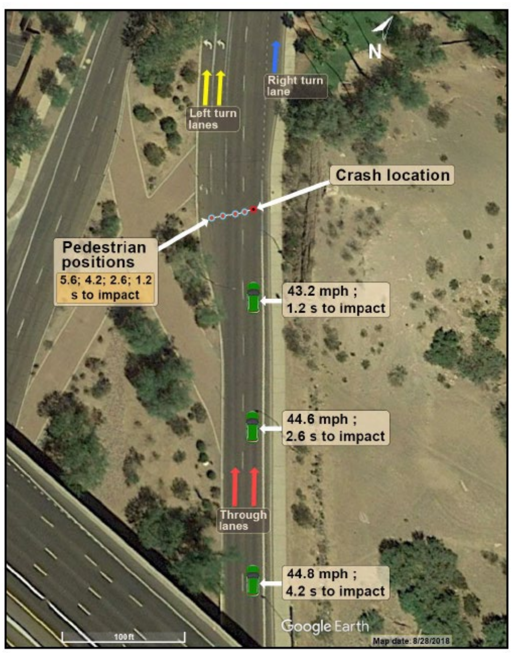


Figure B.1. Aerial View of Crash Location With Pedestrian Path and SUV Movement at Three Points Before Impact (NTSB, 2018a)

Analysis:
This crash is a typical VRU crossing path scenario, which was one of the 5 scenario categories initially selected for evaluation in Rao et al., (2021). In this scenario, the VRU is a person pushing a bike, which could be covered in the parameter sweeps of the VRU type in the scenario. Since this crash is representative of a scenario category previously selected in Rao et al., (2021) no additional scenarios are necessary to represent this pre-crash scenario. A VRU parameter type for a person pushing a bike could be added to make a scenario test case.

B.2 NTSB Report: Collision Between a Car Operating With Automated Vehicle Control Systems[10] and a Tractor-Semitrailer Truck Near Williston, Florida, May 7, 2016 (NTSB, 2016)

At 4:36 p.m. on Saturday, May 7, 2016, a 2015 Tesla Model S 70D car, traveling eastbound on U.S. Highway 27A, west of Williston, Florida, struck a refrigerated semitrailer powered by a 2014 Freightliner Cascadia truck-tractor. At the time of the collision the truck was making a left turn from westbound US-27A across the two eastbound travel lanes onto NE 140th Court, a local paved road. The car struck the right side of the semitrailer, crossed underneath it, and then went off the right roadside at a shallow angle. The crash location is shown in Figure B.2, along with the vehicle maneuvers prior to the crash.

The driver and sole occupant of the car died in the crash; the commercial truck driver was not injured. System performance data downloaded from the car indicated that the driver was operating it using Traffic-Aware Cruise Control and Autosteer (a lane-keeping system), which are part of the ADAS within Tesla's Autopilot suite.

Figure B.2. Ariel View of Crash Location With ADS and Tractor-Semi Trailer Path (NTSB, 2016)

[10] In this instance, the automated vehicle control system is an SAE level 2 ADAS.

Analysis:
This crash is a typical LTAP scenario that is part of the crossing path scenario category previously selected in Rao et al., (2021). In this case, the vehicle making the left turn is a tractor semi-trailer and the road is a divided highway. Many of the details for this crash are represented in the parameter sweeps of the LTAP scenario selected in Rao et al., (2021). Since this scenario is already covered in the crossing path category, no additional scenarios or scenario parameters are necessary to represent this pre-crash scenario. According to the NTSB report, there was no record indicating that the Tesla's automation system identified the truck that was crossing in the car's path or that it recognized the impending crash. As noted in the first chapter, perception is not part of the simulations being developed in this research program and therefore a key aspect of this crash would not be evaluated. Inclusion of the ADS perception stack and environmental factors that led to, or may have led to, the lack of perception would be required to fully simulate this crash.

B.3 NTSB Report: Rear-End Collision Between a Car Operating With Advanced Driver Assistance Systems and a Stationary Fire Truck, Culver City, California, January 22, 2018 (NTSB, 2019b)

About 8:40 a.m. on Monday, January 22, 2018, a 2014 Tesla Model S P85 car was traveling in the high-occupancy vehicle lane of southbound Interstate 405 in Culver City, California. The Tesla was behind another vehicle. Because of a collision in the northbound freeway lanes that happened about 25 minutes earlier, a California Highway Patrol (CHP) vehicle was parked on the left shoulder of southbound I-405, and a Culver City Fire Department truck was parked diagonally across the southbound HOV lane. The emergency lights were active on both the CHP vehicle and the fire truck. When the vehicle ahead of the Tesla changed lanes to the right to go around the fire truck, the Tesla remained in the HOV lane, accelerated, and struck the rear of the fire truck at a recorded speed of 31 mph (Figure B.3).

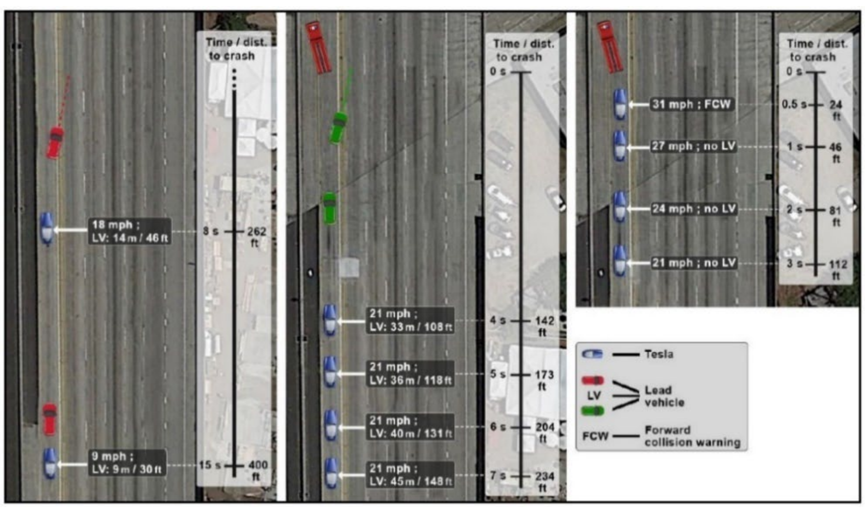


Figure B.3. Accident Reconstruction With Movement of Tesla and Vehicles Traveling Ahead in Same Lane (NTSB, 2019b)

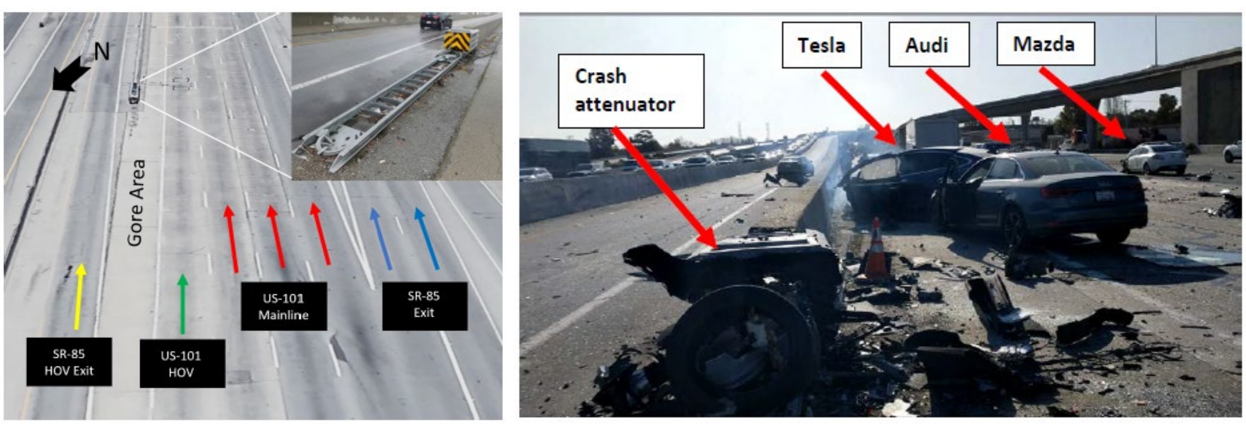
The car was-equipped with an ADAS, including autopilot. Based on the driver's statements and on performance data downloaded from the car after the crash, autopilot was engaged at the time of the collision.

Analysis:
This crash combines lane change and rear-end scenarios to create a potentially hazardous scenario. The rear-end and the lane change pre-crash scenarios combined comprise a large proportion of the crashes analyzed in Swanson et al., (2019). This crash is like the SRSV test in NHTSA's TJA Confirmation tests (NHTSA, 2018a). Behavioral competencies for responding to emergency vehicles are also applicable to this crash. This pre-crash scenario is not covered by the scenarios described in Rao et al., (2021) but falls into the broad category of lane change testing and could be simulated using a scenario similar to the SRSV test described in that NHTSA report.

B.4 NTSB Report: Car Operating With Advanced Driver Assistance Systems Entered Gore Area and Collided With a Previously Damaged Crash Attenuator (NHTSA, 2018b)

On Friday, March 23, 2018, about 9:27 a.m., a 2017 Tesla Model X P100D electric-powered passenger vehicle occupied by a 38-year-old driver, was traveling south on U.S. Highway 101 in Mountain View, Santa Clara County, California. As the vehicle approached the US-101/SH-8 interchange, it was traveling in the second lane from the left, which was an HOV lane for continued travel on US-101.

According to performance data downloaded from the vehicle, the driver was using the Tesla ADAS features Traffic-Aware Cruise Control and Autosteer (lane-keeping assistance). As the Tesla approached the paved gore area dividing the main travel lanes of US-101 from the SH-85 exit ramp, it moved to the left and entered the gore area. The Tesla continued traveling through the gore area and struck a previously damaged crash attenuator at a speed of about 71 mph. The crash attenuator was located at the end of a concrete median barrier. The speed limit on this area of roadway is 65 mph. Preliminary recorded data indicate that the traffic-aware cruise control speed was set to 75 mph at the time of the crash.



(a) (b)

Figure B.4. (a) Overhead View of Accident Scene and Crushed Crash Cushion, (b) Southbound View of US-101 Showing Tesla, Audi, and Mazda Vehicles at Final Rest (NHTSA, 2018b)

Analysis:
This crash is a single-vehicle lane departure and crashing into a stationary object on the side of the road. Though this crash is not explicitly covered in the scenarios described in Rao et al., (2021), a single-vehicle road departure can occur during any scenario described in Rao and is considered as part of the general crash types applicable to all scenarios. Additionally, any road departure could involve hitting a roadside object if there happened to be one in the place where the road departure occurred. Hence no additional scenario or scenario parameters needs to be added to cover this pre-crash scenario.

B.5 NTSB Report: Low-Speed Collision Between Truck-Tractor and Autonomous Shuttle, Las Vegas, Nevada, November 8, 2017 (NTSB, 2017).

About 12:07 p.m. on Wednesday, November 8, 2017, a minor collision (Figure B.5) occurred on South 6th Street in downtown Las Vegas, Clark County, Nevada, between a truck-tractor combination vehicle, operated by a driver, and a 2017 Navya Arma autonomous shuttle, carrying 7 passengers and an attendant. The shuttle was on a 0.6-mile designated loop beginning and ending at a downtown shopping center known as Container Park. The combination vehicle, a 2006 International truck-tractor pulling a 2010 Utility refrigerated trailer, was backing into an alley west of South 6th Street when it struck the shuttle.

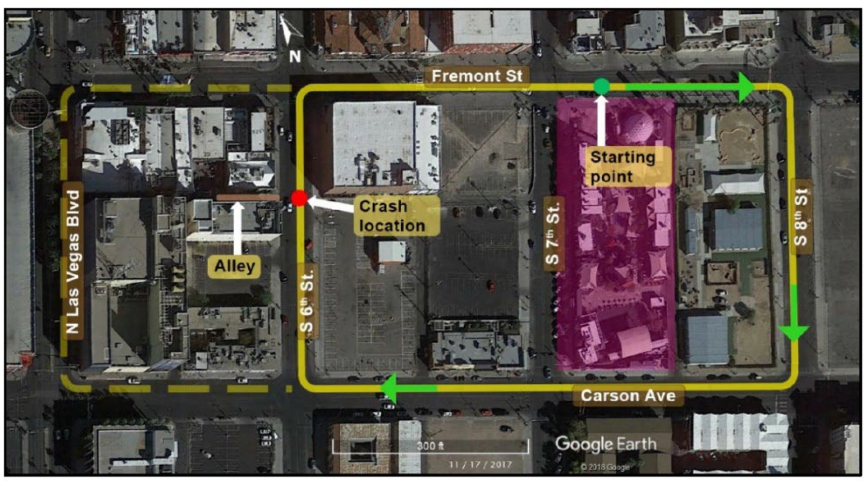


Figure B.5. Shuttle's Looped Route on Day of Collision (Google Earth, and in NTSB, 2017)

Analysis:
The National Transportation Safety Board determined that the probable cause of the collision "…was the truck driver's action of backing into an alley, and his expectation that the shuttle would stop at a sufficient distance from his vehicle to allow him to complete his backup maneuver. Contributing to the cause of the collision was the attendant's not being in a position to take manual control of the vehicle in an emergency." An ADS would not have a driver attendant and therefore would have to determine on its own to stop earlier or to take other evasive action to avoid the backing truck.

Testing the capabilities of ADSs to perform evasive maneuvers, even if the potential pre-crash scenario is not its fault, should be considered for evaluation. Pre-crash scenarios like this were not covered by the scenario categories selected in Rao et al., (2021).

B.6 NTSB Report: Collision Between Car Operating With Partial Driving Automation and Truck-Tractor Semitrailer, Delray Beach, Florida, March 1, 2019 (NTSB, 2019a)

On Friday, March 1, 2019, about 6:17 a.m., a 2018 Tesla Model 3 electric-powered passenger vehicle was southbound in the right through lane of the 14000 block of State Highway 441 in Delray Beach, Palm Beach County, Florida, when it struck an eastbound 2019 International truck-tractor in combination with a semitrailer. At the crash site southbound US 441 consists of two through travel lanes divided from the northbound lanes by an earthen median (Figure B.7). A left-turn lane allows vehicles to change direction and enter the northbound lanes. A right-turn lane allows access to a private driveway. As the Tesla approached the private driveway, the combination vehicle pulled from the driveway and traveled east across the southbound lanes of US 441. The truck driver was trying to cross the highway's southbound lanes and turn left into the northbound lanes. According to surveillance video in the area and forward-facing video from the Tesla, the combination vehicle slowed as it crossed the southbound lanes, blocking the Tesla's path. The Tesla struck the left side of the semitrailer. The roof of the Tesla was sheared off as the vehicle rode under the semitrailer.

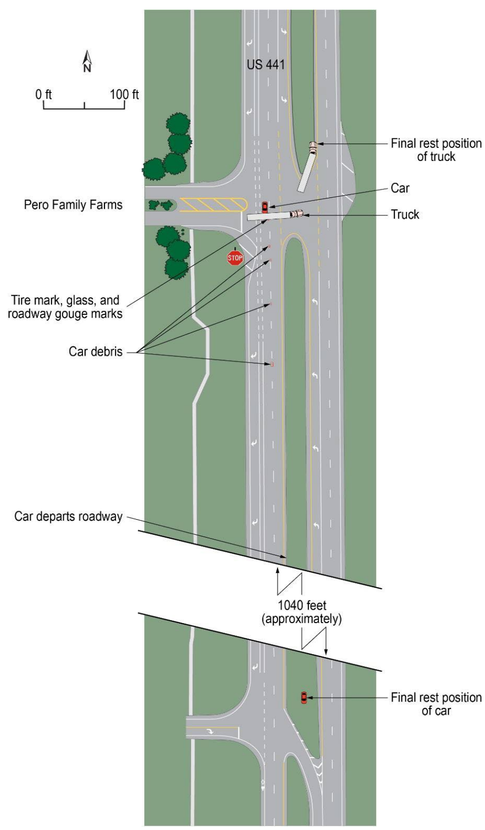


Figure B.6. Diagram Showing Positions of Car and Truck at Impact and Final Rest

Figure B.7. Left Side of Combination Vehicle. Damage to Lower Edge of Semitrailer Sidewall Rails Is Circled in Red

Figure B.8. Right Side of Car in Post-Crash Damaged Condition

Based on data from the Tesla, the car was traveling in the right lane of US 441 when, 12.3 seconds before the impact, the driver activated Traffic Aware Cruise Control at a cruise speed of 69 mph. The driver engaged Autosteer 2.4 seconds later, which activated the Autopilot partial automation driving system. Autopilot's driver monitoring system can detect driver-applied steering wheel torque; the system did not detect wheel torque for the final 7.7 seconds before the collision. The car's FCW and AEB systems did not activate before the crash. There was no evidence of system- or driver-applied braking or steering before impact.

Analysis:

According to the report, "The Autopilot system and collision avoidance systems did not identify the crossing truck as a hazard and did not attempt to slow the car. In addition, the driver did not receive an FCW alert, and the AEB system did not activate. Tesla informed the NTSB that the installed FCW and AEB systems were not designed to activate for crossing traffic or to prevent crashes at high speeds. The Tesla AEB system is a radar/camera fusion system designed for front-to-rear collision mitigation or avoidance. According to the company, the system requires agreement from both the radar and the camera to initiate AEB; complex or unusual vehicle shapes can delay or prevent the system from classifying the vehicles as targets or threats. In this crash, according to Tesla, the Autopilot vision system did not consistently detect and track the truck as an object or threat as it crossed the path of the car. In addition, at no time was there an object detection match between the car's vision system and its radar data."

This appears to be a crossing path scenario or potentially a stopped object scenario. This scenario is different than the current LTAP scenario selected for the crossing path scenario category in Rao et al., (2021). It is a straight crossing path scenario (pre-crash scenario type 27). Again here, a failure to properly perceive the crossing truck caused the Autopilot system to not react. As noted in the first chapter, perception is not part of the simulations being developed in this research program and therefore a key aspect of this crash would not be evaluated. Inclusion of the ADS perception stack and environmental factors that led to, or may have led to, the lack of perception would be required to fully simulate this pre-crash scenario.

Appendix C: Scenario Selection by Crash Statistic and Behavioral Competency Matching

A detailed rationale for the selection of each scenario is presented in the sections below.

C.1 Suddenly Revealed Stopped Vehicle – Combination of Lane Change and Rear-End Scenario Categories

The lane change and rear-end scenario categories were two of the 5 categories selected in Rao et al., (2021). The pre-crash scenario typologies determined in Swanson et al., (2019) that fall into the rear-end and lane-change categories are shown in Table C.1 along with the average annual frequency of occurrence and overall relative frequency when compared to all 36 pre-crash scenarios. These two categories account for 39.4 percent of all of light vehicle crashes from the 2011 – 2015 GES database Swanson et al., (2019). The two categories map to 6 behavioral competencies from Waymo (n.d.), Nowakowski et al., (2015), and NHTSA (2016), which are listed in Table C.2.

Table C.1. Lane Change and Rear-End Scenarios Involving Light Vehicles

Sc. No.	Scenario Description	Avg. Annual Frequency	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
16	Vehicles changing lanes – same direction	348,464	6.2
17	Vehicles drifting – same direction	120,223	2.1
Total		**2,454,215**	**39.4**

Table C.2. Behavioral Competencies Mapped by Lane Change and Rear-End Scenarios

Competency No.	Behavioral Competency Description
9	Perform car following (including stop-and-go)
10	Detect and respond to stopped vehicles
11	Detect and respond to lane changes
12	Detect and respond to static obstacles in road
33	Detect and respond to a merging vehicle
47	Detect and respond to vehicles parking in the roadway

C.2 Crossing Path – Straight Crossing Path

For the Crossing Path category, the LTAP crossing path scenario was selected in Rao et al., (2021). The LTAP scenario did not address the straight crossing path scenario, which is the single largest remaining crash type not explicitly addressed in Rao. This scenario covers an additional 7.7 percent of light vehicle crashes from the 2011 – 2015 GES database Swanson et al., (2019) (Table C.3). Hence, a straight crossing path scenario is added to the crossing path category.

Table C.3. Straight Crossing Path Scenarios Involving Light Vehicles

Sc. No.	Pre-Crash Scenario Description	Avg. Annual Frequency	Rel. Frequency (%)
27	Straight crossing paths	434,374	7.7

C.3 Opposing Traffic

The total number of opposite direction crashes are listed in Table 2, and repeated below in Table C.4. Pre-crash scenario numbers 18 and 19 are a relatively a small percentage of the total crashes (1.8 percent). However, opposite direction crashes were 13 percent of fatal crashes, on average, for the 2011-2015 FARS data (Table 2 – 3,288 out of 25,289 fatal crashes) for the scenario group categories. Excluding the road departure and control loss categories, opposite direction fatal crashes were the third highest scenario category following the crossing path and pedestrian categories. The pre-crash scenarios and behavioral competencies that map to the opposing traffic scenario are listed in Table C.4 and Table C.5, respectively.

Table C.4. Opposing Traffic Scenarios Involving Light Vehicles

Sc. No.	Pre-Crash Scenario Description	Avg. Annual Frequency	Rel. Frequency (%)
18	Vehicles making a maneuver – opposite direction	4,897	0.1
19	Vehicles not making a maneuver – opposite direction	96,095	1.7
Total		**100,992**	**1.8**

Table C.5. Behavioral Competencies Mapped by Oncoming Traffic Scenario

Comp. No.	Behavioral Competency Description
7	Detect and respond to encroaching oncoming vehicle

C.4 Parking/Reversing Scenario With VRU Interaction

Parking- and reversing-based scenarios account for 3.8 percent of light vehicle crashes from the 2011 – 2015 GES database Swanson et al., (2019). The pre-crash scenarios and crash statistics for these types of crashes are shown in Table C.6. However, the agency only tracks crashes on public roadways, so counting parking lot and private driveway crashes would push the number higher. On one of their websites, State Farm Insurance claims that based on IIHS data, up to 20 percent of all crashes occur in a parking lot (State Farm Mutual Automobile Insurance Company, n.d.). Parking lots are also areas of high foot traffic. Hence, aspects of VRU safety also need to be considered in this scenario, which would push the number of crashes in parking/reversing type maneuvers even higher. Children are particularly vulnerable in backing situations. The Cameron Gulbransen Kids Transportation Safety Act of 2007 required NHTSA to "initiate a rulemaking to revise Federal Motor Vehicle Safety Standard 111 to expand the required field of view to enable the driver of a motor vehicle to detect areas behind the motor vehicle to reduce death and injury resulting from backing incidents, particularly incidents involving small children and disabled persons." FMVSS 111 now includes requirements for rear visibility systems (back-up cameras).

Table C.6. Parking/Reversing Scenarios Involving Light Vehicles

Sc. No.	Pre-Crash Scenario Description	Avg. Annual Frequency	Rel. Frequency (%)
6	Road edge departure while backing up	70,025	1.2
13	Backing into another vehicle	113,685	2.0
15	Vehicles parking – same direction	34,898	0.6
Total		**218,608**	**3.8**

Additionally, parking and reversing maneuvers account for 3 of the 15 behavioral competencies that were not addressed by the scenarios selected in Rao et al., (2021). These are listed in Table C.7. Moreover, California DMV crashes reported in Table 7 include seven parking incidents that are not part of the scenarios selected in Rao.

Table C.7. Behavioral Competencies Mapped by Parking/Reversing Maneuvers

Comp. No.	Behavioral Competency Description
3	Move out of travel lane and park
18	Navigate parking lot and locate spaces
41	Make appropriate reversing maneuvers

C.5 Detect, Respond to and Navigate Work Zones

Of the 15 behavioral competencies not covered in Rao et al., (2021), listed in Table 5, a work zone scenario addresses seven behavioral competencies. These are listed below in Table C.8.

Table C.8. Behavioral Competencies Mapped by Work Zone Scenario

Comp. No.	Behavioral Competency Description
20	Detect work zones and/or safety officials
21	Navigate work zones and/or safety officials
27	Follow law enforcement officer/first responder controlling traffic (overriding or acting as traffic control device)
28	Respond to people 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
39	Navigate around unexpected road closures (lane, intersection, etc.)

The FHWA reports that, in the United States, one work zone fatality occurs for every 4 billion vehicle-miles of travel and for every $112 million worth of roadway construction expenditures

(FHWA, n.d.). According to the same source, fatal crashes in work zones increased by 3 percent from 2016 to 2017 while fatal crashes outside of work zones decreased by 1.5 percent. Table C.9 shows the work zone fatalities by transportation mode according to the National Work Zone Safety Information Clearinghouse (n.d.).

Table C.9. Work Zone Fatalities by Transportation Mode Involved

Year	Work Zone		Truck-Involved Work Zone[11]		Bus-Involved Work Zone		Pedestrian-Involved Work Zone[12]		Work Zone Worker[13]
	Fatal Crashes	Fatalities	Fatal Crashes	Fatalities	Fatal Crashes	Fatalities	Fatal Crashes	Fatalities	Fatalities
2016	687	781	186	233	3	15	113	112	143
2017	720	809	219	268	6	9	130	127	132
2018	671	754	203	228	8	10	121	122	124

Source: Crash data shown here are from the 50 States, the District of Columbia, and Puerto Rico. The numbers for Fatal Crashes for Work Zone, Truck-Involved Work Zone, Bus-Involved Work Zone, and Pedestrian-Involved Work Zone come from the Fatality Analysis Reporting System, National Highway Traffic Safety Administration, The numbers for Work Zone Worker fatalities come from the Bureau of Labor Statistics, U.S. Department of Labor.

C.6 Special Vehicles: Emergency Vehicles and School Buses

In addition to the reported fatalities in crashes involving emergency vehicles noted in Section 2.6, Table C.10 lists 5 behavioral competencies that were not addressed by the scenarios selected in Rao et al., (2021).

Table C.10. Behavioral Competencies Mapped by Special Vehicles Category

Comp. No.	Behavioral Competency Description
20	Detect work zones and/or safety officials
21	Navigate work zones and/or safety officials
27	Follow law enforcement officer/first responder controlling traffic (overriding or acting as traffic control device)
28	Respond to people directing traffic after a crash
38	Detect and respond to school buses

As an example of emergency vehicle laws, for Ohio, and specified by the Ohio Department of Public Safety (2016):

- "By State law, when driving, you must yield to the right for all moving public safety vehicles, and yield to the left for all stationary public safety vehicles.
- At an intersection vehicle must stop and pull to the right, and always yield to all public safety vehicles turning left.

[11] Involvement does not always imply causation. Also, in some cases, the large truck struck another vehicle, pedestrian, or object. In other cases, another vehicle struck the large truck.

[12] In some cases, the driver of the vehicle, rather than the pedestrian involved, was the person killed. As a result, the number of pedestrian-involved fatal crashes in work zones may be higher than the number of pedestrians killed in work zones.

[13] Worker fatality numbers from the Bureau of Labor Statistics include both traffic-related and non-traffic-related occupational accidents.

- Vehicles must make sure all public safety vehicles have passed before proceeding.
- When approaching a stationary public safety, emergency, or road service vehicle displaying flashing lights, a driver must slow down and move as far to the left as road conditions will allow while passing the public safety vehicle. Motorists must change lanes away from the public safety vehicle if traveling on a multi-lane highway. If motorists are unable to change lanes safely, or if traveling on a two-lane highway, they must slow down and proceed with caution."

As an example of the school bus laws, for Ohio, and specified by the Ohio Revised Code Title 45, Section 4511.75:

- (A) The driver of a vehicle upon meeting or overtaking from either direction any school bus stopped for the purpose of receiving or discharging any school child, shall stop at least ten feet from the front or rear of the school bus and shall not proceed until such school bus resumes motion, or until signaled by the school bus driver to proceed.
- (B) Where a highway has been divided into four or more traffic lanes, a driver of a vehicle, need not stop for a school bus approaching from the opposite direction which has stopped for the purpose of receiving or discharging any school child. The driver of any vehicle, streetcar, or trackless trolley overtaking the school bus shall comply with division (A) of this section.

C.7 Summary of Selected Scenarios

The behavior competencies for the 6 new scenarios selected in this report that were not covered in Rao et al., (2021) are listed in Table C.11. Only three behavioral competencies considered remain uncovered, which are: (24) navigate roundabouts, (37) detect and respond to motorcyclists, and (40) navigate railroad crossings.

These 6 scenarios also explicitly cover 5 new pre-crash scenarios which account for another 15.5 percent of light vehicle crashes from the 2011 – 2015 GES database Swanson et al., (2019). These pre-crash scenarios and their frequency of occurrence are listed in Table C.12.

Table C.11. Additional Behavioral Competencies Covered by Scenarios Selected in This Report

Comp. No.	Behavioral Competency Description
3	Move out of travel lane and park
7	Detect and respond to encroaching oncoming vehicle
18	Navigate parking lot and locate spaces
20	Detect work zones and/or safety officials
21	Navigate work zones and/or safety officials
27	Follow law enforcement officer/first responder controlling traffic (overriding or acting as traffic control device)
28	Respond to people directing traffic after a crash
29	Detect and respond to temporary traffic control devices

Comp. No.	Behavioral Competency Description
32	Detect and respond to detours and/or other temporary changes in traffic patterns
38	Detect and respond to school buses
39	Navigate around unexpected road closures (lane, intersection, etc.)
41	Make appropriate reversing maneuvers

Table C.12. Additional Pre-Crash Scenarios Covered by the Six Scenarios Selected in This Report

No.	Pre-Crash Scenario Description	Avg. Annual Frequency	Relative Frequency (%)
13	Backing into another vehicle	113,685	2.0
15	Vehicles parking – same direction	34,898	0.6
18	Vehicles making a maneuver – opposite direction	4,897	0.1
19	Vehicles not making a maneuver – opposite direction	96,095	1.7
27	Straight crossing paths	434,374	7.7

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