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Phase 3 — Final Report

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16. Abstract

Manufacturers are developing and promoting automated vehicles (AVs), which will have to perform in a variety of adverse weather conditions. With recent advancements in AV technology, the Federal Highway Administration is exploring AV needs, opportunities, and potential shortcomings during adverse weather conditions.

The objective for Automated Vehicles and Adverse Weather Phase 3 (AVAW3) testing is to explore how adverse weather and road conditions in different driving environments affect AV dynamics and operations, driver behavior, communications, and AV sensor capabilities.

This report presents scenarios, weather conditions, and driving environments applied for AVAW3 field tests, along with summaries of the test results, stakeholder engagement, and recommendations for potential future research. The first round of field tests occurred in spring/summer road weather conditions and assessed performance of AVs in Work Zone Lane Change with Barrels, Work Zone Lane Closure with Lane Markings, Pavement Markings with Brake Marks, and Pavement Markings with Disappearing Shoulder scenarios. The second round of field tests occurred under winter road conditions and assessed performance of AVs during Lane Keeping, Right Lane Changing, movements at a Green Signalized Intersection, and Stopped Car Detection scenarios.

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Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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ACRONYMS AND ABBREVIATIONS

ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
ADS	automated driving system
AV	automated vehicle
AVAW3	Automated Vehicles and Adverse Weather – Phase 3
FHWA	Federal Highway Administration
FT#1	field test 1
FT#2	field test 2
HD	High-definition
HMI	Human-Machine Interface
IOO	Infrastructure Owner-Operator
ITS	intelligent transportation system
LCA	Lane Centering Assist
LDW	Lane Departure Warning
LiDAR	Light Detection and Ranging
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
POV	Principal Other Vehicle
RWMP	Road Weather Management Program
SAE	Society of Automotive Engineers
TJA	Traffic Jam Assist
TRC Inc.	Transportation Research Center Inc.
USDOT	United States Department of Transportation
VRU	Vulnerable Road Users

EXECUTIVE SUMMARY

With recent advancements in automated vehicle (AV) technology, the Federal Highway Administration (FHWA) Road Weather Management Program (RWMP) continues to explore AV needs, opportunities, and potential shortcomings during adverse weather conditions. The objective of this FHWA Automated Vehicles and Adverse Weather – Phase 3 (AVAW3) project is to explore how adverse weather and road weather conditions in different driving environments (e.g., work zones, signalized intersections, and lane changes) affect AV dynamics and operations, driver behavior, communications, and AV sensor capabilities.

This AVAW3 project includes two rounds of field tests of primarily production vehicles with Society of Automotive Engineers (SAE) International Level 2[1] automation features. In the Winter Field Test 2 (FT#2), a vehicle equipped with prototype SAE International Level 3 automated driving system (ADS) features was used. For the purposes of this report, the SAE International Level 2 vehicles and the Level 3 prototype vehicle are referred to as test vehicles. SAE International Level 2 automation provides steering and brake/acceleration support to the driver. It helps vehicles maintain a safe distance in stop-and-go traffic, while also providing steering assistance by centering the car within the lane. However, an SAE International Level 2 vehicle cannot be programmed to navigate on its own. The SAE International Level 2 automation requires drivers to supervise the driving automation systems and intervene as necessary to maintain operation of the vehicle. An SAE International Level 3 vehicle can perform safety-critical functions such as acceleration, deceleration, and steering. An SAE International Level 3 vehicle can also monitor the road and surroundings but requires the human driver to be aware in the event of driving automation system failures and/or disengagements. For this study, the SAE International Level 3 vehicle was programmed to perform a left turn maneuver at a signalized intersection in Winter FT#2.

The purpose of this final report is to present the literature review, stakeholder engagement, scenarios tested, test results, key findings, and potential future research needs from the AVAW3 project.

Literature Review

The AVAW3 literature review and technology scan updated the Phase 1 and Phase 2 findings with new materials published between January 2018 and January 2020. The literature review examined the relationship between adverse weather and AV performance as well as human factors elements of drivers, driving automation systems, and adverse weather. The literature review also focused on identifying institutional needs and policy concerns about AVs and what is required to achieve higher levels of automation.

Some authors suggested that integration of AVs into the broader transportation system may need to be considered as more of a social system where all users and non-users have a role in the implementation of AVs (Straub and Schaefer, 2019). Social policy considerations are included in the updated findings. Namely, proprietary AV technologies (unique to each automobile manufacturer) impact interactions between AVs, between AVs and manually-operated vehicles, and between AVs and vulnerable road users (VRUs) (e.g., pedestrians, bicyclists, elderly drivers). Adverse weather and roadway conditions further complicate existing

[1] https://www.sae.org/standards/content/j3016_202104/

human factor challenges with AVs including driver trust, driver engagement, and driver takeover protocols. Some authors suggested that safe and successful operation of AVs in adverse weather requires sensor fusion (Yoneda et al., 2019), data sharing between vehicles and infrastructure (Guerra et al., 2018; Horani and Rawashdeh, 2019; Gopalakrishna et al., 2018), incorporation of technologies from other fields of study, and perhaps enhanced roadway infrastructure (Harrington et al., 2018).

Some AVs can leverage redundant information from Connected Vehicle-enabled communication to supplement the information gathered by their sensors. These data serve as “ground truth” data and can help to establish redundancy in a safety-critical system. Supplementing an AV’s sensor suite with information from existing weather programs such as Road Weather Information Systems (RWIS), Integrated Mobile Observations (IMO), and big data weather systems such as Pikalert® and Weather Data Environment (WxDE) has potential to improve AV operations. Supplementing an AV’s sensor suite with information or data obtained from government fleet vehicles or road weather infrastructure systems can support the integration of AVs into the broader transportation system. There is at least one original equipment manufacturer (OEM) with vehicles on the roadway that can navigate through work zones and detect traffic signs. Detection of roadway infrastructure is important for vehicles to identify rules of the road and for verifying map data.

Stakeholder Engagement

The AVAW3 project team engaged stakeholders through a combination of webinars, workshops, and industry meetings or conferences. These stakeholder engagement activities provided opportunities to hear from stakeholders and discuss needs and concerns related to testing AVs in adverse weather conditions. The stakeholders that participated in engagement and outreach activities included representatives from OEMs, AV research and testing communities, material manufacturers, technology and communications developers, environmental sensor manufacturers, and road weather sensor manufacturers.

Field Tests

The first round of field tests (Summer FT#1) covered spring and summer weather conditions, and the second round of field tests (Winter FT#2) covered winter weather conditions. Both field tests challenged the test vehicles across a variety of simulated adverse weather conditions and different driving environments in a controlled outdoor laboratory setting.

In Summer FT#1, four different driving scenarios were designed and executed: 1) Work Zone Lane Change with Barrels, 2) Work Zone Lane Closure with Lane Markings, 3) Pavement Markings with Brake Marks, and 4) Pavement Markings with Disappearing Shoulder. All scenarios were tested during a baseline of fair weather with dry pavement and no glare, wet roadway during daylight, and wet roadway at night conditions. The Crosswind adverse weather condition was applied for testing vehicle behavior only during the Work Zone Lane Change with Barrels scenario. All scenarios were focused on testing the lane detection and tracking system of the AVs under adverse summer road weather conditions.

In Winter FT#2, four different driving scenarios were designed and executed: 1) Lane Keeping, 2) Right Lane Change, 3) Green at Signalized Intersection, and 4) Stopped Car Detection. All Winter FT#2 scenarios were tested under Baseline conditions: clear, daytime, and dry roadway. Lane Keeping, Right Lane Change, and Green at Signalized Intersection scenarios were tested under snow-covered and plowed roadway conditions. Lane Keeping and Stopped Car Detection scenarios were tested under ice-covered roadway conditions. The first three scenarios focused on testing the lane detection and tracking system of the AVs, and the last scenario focused on detecting and braking for a stopped car, all under adverse winter road weather conditions.

In both field tests, test vehicles with differing perception systems were driven through a planned variety of weather and road conditions to assess how well each automation feature performed. The automation features tested included lane centering, lane keeping assist, lane departure warnings, traffic jam assist, and the take steering control command, when applicable.

The test plan was designed to conduct a minimum of seven runs for each scenario. However, more than seven runs were conducted for several scenarios under all weather conditions to gain a deeper understanding of test vehicles' perception systems. The results from both field tests provide data to the United States Department of Transportation (USDOT) and to other stakeholders on how selected perception systems perform in a limited set of adverse road and weather conditions.

Key Findings

Findings from the AVAW3 project include:

- Limitations of the tested vehicles' automation capabilities were successfully challenged through exposure to adverse weather and road weather conditions. Perception limitations were more evident in the Winter FT#2 compared to the Summer FT#1.
- There was a potentially significant amount of inconsistency in test vehicle performance, both across vehicles and between runs for a single vehicle. The performance inconsistencies include localization loss, inability to detect work zone barrels, inability to follow pavement markings during daytime and nighttime glare conditions, inability to follow the desired path when pavement markings were not visible due to glare or varying snow depths on the road, and rapid accelerations and decelerations at snow-covered intersections.
- The need for redundant sensing systems in AVs was evident based on this project's field test results. Redundancy in this study refers to equipping the vehicle with multiple driving automation system components or subsystems that perform the same function. The need for redundant systems is essential in safety-critical applications, such as driving in adverse road weather conditions. During certain adverse weather conditions, the test vehicles lost localization, disengaged steering control, and critically deviated from the desired paths. Test vehicle with Light Detection and Ranging (LiDAR) -based perception system performed better in Winter FT#2 than a multiple camera-based perception system. With a redundant perception system, a vehicle with a camera-based system is expected to perform higher accuracy in decision-making when assessing weather conditions and performing maneuvers. Therefore, test results indicated that redundancy in perception, steering control, localization, braking, actuation, and other systems has the potential to improve the AVs operations under adverse weather, road, and environmental conditions. Further testing may need to be conducted to demonstrate how much improvement can be realized by the use of redundant systems in AVs.
- While the Summer FT#1 results indicated that no one environmental condition produced consistent impacts (i.e., no environmental condition was more, or less, challenging across the four different scenarios), overarching adverse performance impacts of the SAE International Level 2 vehicle were observed in Winter FT#2. The SAE International

Level 3 test vehicle was able to assess and react to adverse winter road weather conditions more efficiently compared to the other Winter FT#2 test vehicle.

- A non-test driver (i.e., drivers of vehicles on non-test track roadways who also have not been trained to perform test maneuvers on closed test tracks) using their vehicle's AV technology to perform expected maneuvers would likely experience minimal AV system disengagements on days with clear to moderate inclement weather. This may lead to over-trust and over-confidence in the abilities of the automation system. However, on days with severe or varying inclement weather conditions (e.g., excessive glare on roadways, varying snow thickness, slippery surfaces, snow-covered or icy lanes and pavement markings), their vehicle may behave drastically differently, as its perception system may be unable to properly interpret the conditions.
- Different perception mechanisms among the test vehicles led to different performance outcomes. Especially during Winter FT#2, the performance of the AV that relied on a multiple-camera-based perception system was lower compared to the AV that relied on LiDAR and a high-definition (HD) map-based perception system. To function properly, LiDAR-based perception systems require access to HD mapping for the routes traveled, pre-recorded sensor data, and a semantic layer representing roadway features such as pavement markings and stop bars. Even though LiDAR performance was good under winter weather conditions in Winter FT#2, it offers limited capabilities in perceiving some roadway features such as pavement markings. The HD map is not typically found on production vehicles with navigation or AV systems.

CHAPTER 1. INTRODUCTION

BACKGROUND

Weather (atmospheric conditions), road weather (pavement conditions), and driving environments (e.g., work zones, lane changes) can adversely affect vehicle and driver behavior. With the advent of automated vehicle (AV) technology—that is, vehicles with driving automation systems and some with automated driving system (ADS) features—research is needed to identify how vehicles equipped with drivers and AV technology will detect and react to adverse weather and road weather conditions. This document is the Final Report for the Federal Highway Administration's (FHWA's) Automated Vehicles and Adverse Weather – Phase 3 (AVAW3) project. It contains test scenarios, weather conditions, and driving environments applied during AVAW3 field tests, along with a summary of the literature findings, stakeholder engagement, test results, and recommendations for potential future research. The objective of the FHWA's Road Weather Management Program (RWMP) AVAW3 project is to explore how adverse weather and road weather conditions in different driving environments affect AV dynamics and operations, driver behavior, and AV sensor capabilities.

The history of the Automated Vehicles and Adverse Weather (AVAW) program includes three phases. Testing for Phase 1 of the AVAW program was conducted in March 2018, testing for Phase 2 was conducted in January 2019, and Phase 3 testing began in 2019 and concluded in 2021. Both Phase 1 and Phase 2 were conducted during winter weather conditions on both straight and curved roadway geometries. The AVAW3 project included two rounds of field testing of production vehicles with Society of Automotive Engineers (SAE) International Level 2[2] automation features. Another vehicle, equipped with prototype SAE International Level 3 ADS, was used in Winter Field Test 2 (Winter FT#2). For the purposes of this report, the SAE International Level 2 vehicles and the Level 3 prototype vehicle are referred to as test vehicles. SAE International Level 2 automation can assist in controlling speed and steering. SAE International Level 2 automation helps vehicles maintain a safe distance in stop-and-go traffic, while also providing steering assistance by centering the car within the lane. However, an SAE International Level 2 vehicle cannot be programmed to navigate on its own. SAE International Level 2 automation requires a driver to supervise the vehicles equipped with driver assistance systems and intervene as necessary to maintain operation of the vehicle. An SAE International Level 3 vehicle can perform safety-critical functions such as acceleration, deceleration, and steering and can also monitor the road and surroundings but requires the human driver to be aware in the event of driving automation system failures and/or disengagements. For AVAW3, the SAE International Level 3 vehicle was programmed to perform a left turn maneuver at a signalized intersection for Winter FT#2 in addition to other test scenarios. For a detailed overview of the levels of automation, weather-related impacts on driving safety, and research impetus for AV testing in adverse weather, please refer to AVAW Phase 1 and Phase 2 Final Reports.[3]

The first round of Phase 3 field tests (Summer FT#1) was intended to evaluate spring- and summer-like weather conditions combined with different driving environments (e.g., work zones and pavement markings). The second round of field tests (Winter FT#2) was intended to valuate

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[2] https://www.sae.org/standards/content/j3016_202104/

[3] https://rosap.ntl.bts.gov/view/dot/32494/dot_32494_DS1.pdf?

winter-like weather conditions combined with different driving environments (e.g. snow-covered pavement markings and ice-covered roadways).

Each test documented each vehicle's driving automation system behavior when tasked to function under the pre-determined conditions for each scenario. It is understood that these vehicles may be pushed to their recommended limits or capabilities and beyond according to their Operational Design Domain (ODD) (i.e., the system detects threshold conditions and disengages driving automation system when the limit is reached). Therefore, the tests were conducted to understand how a select group of vehicles equipped with driving automation systems (test vehicles) performs in a limited set of summer, spring, and winter weather conditions, not to rate the safety of the vehicles or assign a pass/fail to a particular vehicle. The results from the AVAW3 project provide data to the United States Department of Transportation (USDOT) and to other stakeholders on how the test vehicles' perception systems perform in a limited set of adverse road and weather conditions and driving environments.

APPROACH

AVAW3 explored how adverse summer and winter weather, adverse road conditions, and different driving environments affect AVs in three ways: 1) a literature review, 2) listening sessions with stakeholders, and 3) experiments to observe the performance of AVs' perception and control sensor systems under controlled conditions.

Chapter 2 summarizes findings from the literature review and stakeholder engagement activities. The literature review included a review of AV technology and adverse road weather resources as an update to the literature review conducted in the first two phases of the AVAW project. The objectives of the AVAW3 literature review updated previous findings to:

- Research weather impacts on current vehicular automation technology functionality and safety
- Identify other enabling technologies, technology challenges, gaps, performance monitoring, perception systems, owner/operator concerns, industry needs, potential benefits of connected automation, and impacts on driver behavior/human factor issues
- Identify requirements to achieve higher levels of automation

The key objectives of engaging stakeholders were to:

- Identify adverse weather conditions that pose challenges to AV performance
- Determine what gaps exist to achieve higher levels of automation
- Present findings from the field tests

Chapter 3 presents the experiment details and results. SAE International Level 2 and Level 3 prototype automation systems were tested, and precise telematics and video were collected.

The experiments were conducted to observe and analyze the AVs' control and perception systems' abilities to:

- Execute planned and ad hoc maneuvers over a series of repeatable test iterations
- Perform consistently during adverse weather

Chapter 4 summarizes the gaps and challenges associated with AVAW3 testing.

Chapter 5 presents potential research needs for future AV testing in adverse weather conditions.

CHAPTER 2. LITERATURE REVIEW AND STAKEHOLDER ENGAGEMENT

A summary of findings from the literature review and stakeholder engagement tasks follows.

LITERATURE REVIEW AND TECHNOLOGY SCAN

The AVAW3 literature review and technology scan updated the findings from AVAW Phase 1 and Phase 2 with new materials published between January 2018 and January 2020. Findings from the Phase 3 literature review and technology scan addressed how AV technologies are affected by weather and aided in identifying testing scenarios and constructs for the subsequent field tests. In addition, the literature review identified gaps in existing perception and automation technology capabilities, determined the needs to achieve higher levels of automation, examined AVs' performance and human factors related to automated driving in adverse weather, institutional needs, policy concerns about AVs, and requirements for achieving higher levels of automation.

Key findings include:

- Connected vehicle technology through vehicle-to-vehicle and vehicle-to-infrastructure communications has the ability to supplement an AV's suite of sensors with additional information. These data can serve as "ground truth" data and can help to establish redundancy in a safety-critical system.
- USDOT may leverage existing weather programs such as the RWMP and Integrated Mobile Observation (IMO), in addition to big data weather systems that have been developed such as Pikalert® and Weather Data Environment (WxDE) to improve AV operations. Supplementing an AV's sensor suite with information or data obtained from government fleet vehicles or road weather infrastructure systems can support the integration of AVs into the broader transportation system.
- There is at least one original equipment manufacturer (OEM) with vehicles on the roadway that can navigate through work zones and can detect traffic signs such as stop signs. Detection of roadway infrastructure is important for vehicles to identify rules of the road and for verifying map data.
- Adverse weather and roadway conditions complicate existing human factors challenges with AVs including driver trust, driver engagement, and driver takeover protocols.
- The broader transportation system with the integration of AVs may need to be considered as more of a social system, in that the technology behind AVs will impact interactions between AVs, between AVs and manually operated vehicles, and between AVs and vulnerable road users (VRUs) (e.g., pedestrians, bicyclists, elderly drivers) (Straub and Schaefer, 2019). Adverse weather conditions such as sun glare, heavy precipitation, fog, and haze will impact visual and audible communications with VRUs.
- Literature review findings indicate that the safe operation of AVs in adverse weather requires sensor fusion (Yoneda et al., 2019), data sharing between other roadway vehicles and the infrastructure (Guerra et al., 2018; Horani and Rawashdeh, 2019; Gopalakrishna et al., 2018), technology integration from other fields of study, and enhanced roadway infrastructure features (Harrington et al., 2018). Further testing may need to be conducted to determine the details with regards to these findings.

STAKEHOLDER ENGAGEMENT AND OUTREACH

The AVAW3 project team ensured continuous engagement of stakeholders through a combination of webinars, workshops, and industry meetings or conferences. These stakeholder engagement activities provided opportunities to hear and discuss stakeholder needs and concerns regarding testing AVs in adverse weather and road weather conditions and in different driving environments. The stakeholders that participated in the engagement and outreach activities included representatives from OEMs, AV research and testing communities, infrastructure manufacturers, State DOTs, local agencies, highway patrol, automobile manufacturers, technology and communications developers, environmental sensor manufacturers, and road weather sensor manufacturers.

Workshops

One workshop was conducted before Summer FT#1 and before Winter FT#2 to elicit input from stakeholders on the testing scenarios and constructs. The Summer FT#1 workshop was held in December 2019 and the Winter FT#2 workshop was held in May 2020. All attendees from the Summer FT#1 workshop were invited to the Winter FT#2 workshop. The workshops began with a brief overview of the topic by an FHWA representative to provide background for the discussion. During the Summer FT#1 workshop, a list of eight potential scenario ideas during spring/summer weather conditions was presented for prioritized ranking by the stakeholders. During the Winter FT#2 workshop, stakeholders were asked to identify winter weather and road conditions that can create detection and perception challenges for AVs. Following the Winter FT#2 workshop, the project team convened to identify testing scenarios that could be created and safely conducted in a controlled environment. Four testing scenarios were selected for each round of testing.

Webinars

The project team held a debrief webinar after the Summer FT#1 and the Winter FT#2 adverse weather testing, respectively. The Summer FT#1 debrief webinar was held in August 2020. The Winter FT#2 debrief webinar was held in October 2021. The project stakeholders were invited to the debrief webinars. These webinars present the scenarios selected for the field tests, adverse weather conditions tested, test findings, key observations with videos and plots, and lessons learned from the field tests.

In addition to the two debrief webinars, the project team also conducted national webinars to present findings, such as lessons learned, the literature review and technology scan, and both rounds of field testing. The national webinars were conducted as part of the Annual Road Weather Management Stakeholder Meetings, with an open invitation to all AV and ADS enthusiasts.

FHWA Road Weather Management Stakeholder Meetings

The stakeholder meetings were hosted by the FHWA RWMP and serve as peer exchanges between State DOTs, local transportation agencies, vendors, weather service providers (public and private), consultants, and other road weather management stakeholders. The AVAW3 Summer FT#1 and Winter FT#2 findings were presented in the stakeholder meetings held in August 2020 and August 2021, respectively.

CHAPTER 3. COMMONALITIES AMONG THE FIELD TESTS

The AVAW3 project included two rounds of field testing of vehicles with Society of Automotive Engineers (SAE) International Level 2[4] automation features. Another vehicle, equipped with prototype SAE International Level 3 driving automation systems, was used in the Winter Field Test 2 (FT#2). The test vehicles were driven through a planned variety of maneuvers during repeatable simulated and naturally occurring adverse weather conditions. This chapter presents common aspects for both of the field tests. Details and results of Summer FT#1 and Winter FT#2 are presented in Chapter 4 and Chapter 5, respectively.

PURPOSE OF THE FIELD TESTS

AVs have sensors and perception systems to detect objects and events in their vicinity. Using this information, they control the steering or speed or both to move the vehicle along its selected path. AVs' ability to properly perceive the situation and safely execute a maneuver can be affected by atmospheric and road weather.

Perception of an environment for automated driving requires two main sets of information: the type of objects around the vehicle, and the position and velocity of those objects. A wide variety of perception systems may be utilized by AVs which allow a driving automation systems to safely control the vehicle, but most commonly, control is achieved using a combination of perception systems (e.g., cameras and radar sensors). Most production vehicles use cameras in conjunction with machine vision algorithms to identify objects and roadway markings. Some use multiple cameras to add depth perception, through stereo vision. Radar detects objects by measuring the return of electromagnetic radiation, which for automotive applications is generally 77 GHz. By recording both times of flight and frequency shift due to the Doppler Effect, distance to the object and relative velocity are measured. Some vehicles use a combination of Light Detection and Ranging (LiDAR) sensors and high-definition (HD) map data to identify their current orientation in global coordinates. A select few of the LiDAR-based vehicles also use Coordinated Path Following, which allows a driving path to be programmed for those vehicles to follow using the HD map. These vehicles also use the localized position to ensure that the assigned driving path is being followed. Each type of sensor is known to have different strengths and weaknesses in how it perceives the environment. The adverse weather testing was designed to help exemplify these differences.

The AVAW3 tests were developed with the intent to challenge perception systems across a variety of simulated adverse weather conditions in a controlled outdoor laboratory setting. Production vehicles with different perception systems were driven through a planned variety of road and road weather conditions to assess how well each automation feature performed. The results from these tests provide data to USDOT and to other stakeholders on how selected perception systems perform in a limited set of adverse weather conditions. Common aspects of the Summer FT#1 and Winter FT#2 include similarities in vehicle technologies, human-machine interfaces, vehicle instrumentation, the role of the test driver, and the test location.

[4] https://www.sae.org/standards/content/j3016_202104/

TEST CONDITIONS

Vehicle Driver Assistance Systems

While not all test vehicles had the same driver assistance systems, the slate of driver assistance systems present across all tested vehicles include:

- **Adaptive Cruise Control (ACC):** ACC allows a vehicle's cruise control system to adapt the vehicle's speed to that of a lead vehicle within the travel lane. The distance at which the lead vehicle will be followed when ACC is active is typically driver configurable.
- **Lane Centering Assist (LCA):** LCA or Lane Centering is designed to keep a vehicle centered in the lane, assisting the driver in completing the task of steering for a period of time. It controls the steering continuously to keep the vehicle centered within the lane of travel. A driving automation system that provides lane centering but not cruise control is SAE International Level 1 automation according to SAE International recommended practice J3016.[5] LCA is different from the Lane Keeping Assist System, which only provides momentary intervention in lane keeping actions, but does not automate part or all of the dynamic driving task on a sustained basis.
- **Lane Departure Warning (LDW)**: A LDW system is a driver-assistance system that alerts the driver when a vehicle drifting beyond a delineated edge line of the current travel lane is imminent. It does not control the steering at any time.
- **Localization via LiDAR HD Map:** Localization via LiDAR identifies the vehicle's current orientation in global coordinates utilizing data retrieved from the LiDAR sensor(s) and referencing it with HD map data. This process is based on an algorithm that minimizes error within the returned points known as normal distribution transform.
- **Coordinated Path Following:** Coordinated Path Following allows a driving path to be programmed for a vehicle to follow using the HD map. The vehicle will then use the localized position to ensure that the assigned driving path is being followed. If localization fails, the vehicle will think it is in a different part of the map and will deviate from the path.
- **Traffic Jam Assist (TJA):** TJA is designed to control the vehicle's braking and acceleration based on an immediate leading vehicle's position and speed. The primary purpose of this feature is to provide stop-and-go capabilities while maintaining a safe distance from a leading vehicle in dense traffic.

Both ACC and LCA are Level 1 driving automation systems, whereas LDW is a SAE International Level 0 driving assistance system. In Summer FT#1 Vehicle B, LCA cannot be engaged unless ACC is activated, which makes it a SAE International Level 2 vehicle. In Summer FT#1 Vehicle A, both LCA and ACC can be engaged separately, but it also becomes a SAE International Level 2 when both features are engaged together.

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[5] https://www.sae.org/news/press-room/2018/12/sae-international-releases-updated-visual-chart-for-its-%E2%80%9Clevels-of-driving-automation%E2%80%9D-standard-for-self-driving-vehicles

Human-Machine Interface

Visual, audible, and in some cases, vibrotactile feedback are the most used methods by which a vehicle's human-machine interface (HMI) communicates with the human driver. These messages often convey a change in the driving automation system status and an alert for drivers to re-assume control of the vehicle. This information must be relayed to the driver to allow for safe operations.

For this project's specific testing purpose, HMIs for the test vehicles contain the following information:

- HMIs of all test vehicles communicate the status of their driving automation systems including TJA, LCA, LDW, ACC, Localization, and any other system that is active during operation.
- Summer FT#1 Vehicle A's HMI displaying various driving automation systems (ACC, LCA, Lane Keeping Assist System, and LDW) engaged during one of the test runs is presented in Figure 1.
- Summer FT#1 Vehicle B's HMI interface during Work Zone Lane Change with Barrels scenario is presented in Figure 2.
- If detected, HMIs of both Summer FT#1 vehicles and Winter FT#2 Vehicle A display warning signs including lane departure, barrels, objects, brake marks, traction control, icy road, and forward collision. Winter FT#2 Vehicle A can also display stopped vehicles ahead, as shown in Figure 3.
- Winter FT#2 Vehicle B's HMI displays a localization and configuration panel, a part of the aftermarket automation platform integrated with the vehicle for testing, as shown in Figure 4.

Figure 1. Photo. Summer FT#1 Vehicle A's HMI displaying support systems that were engaged during the testing.

Source: FHWA

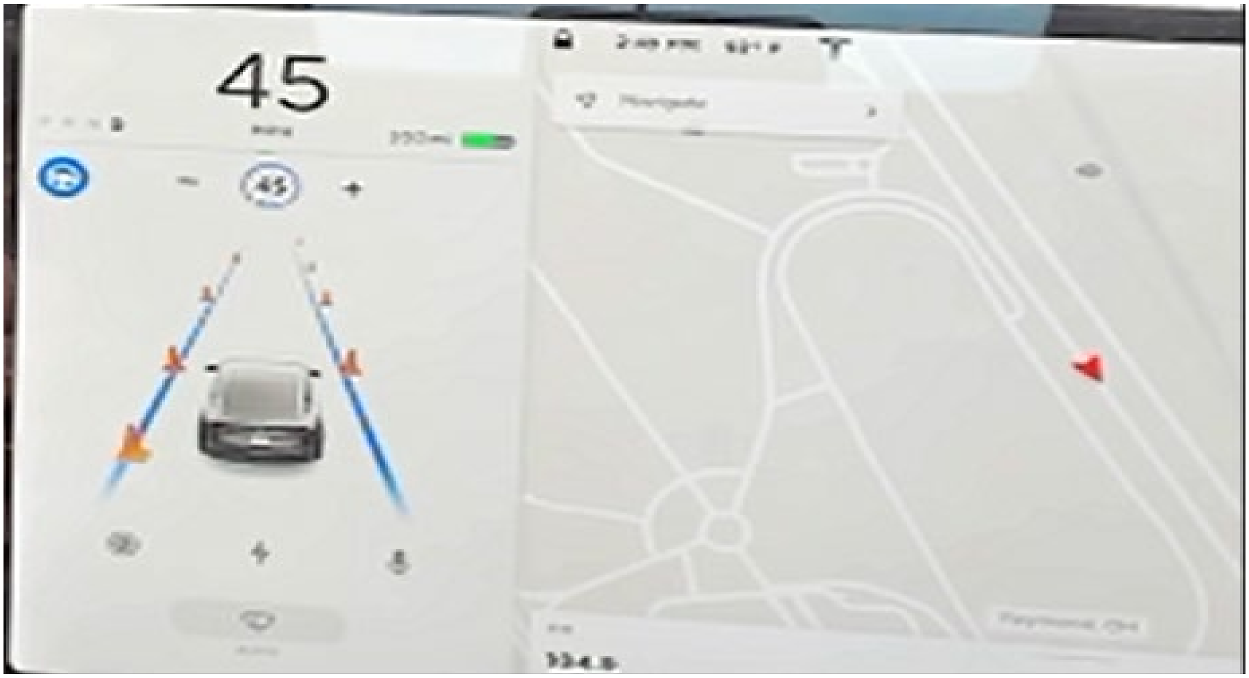

Figure 2. Photo. Summer FT#1 Vehicle B's HMI displaying Work Zone Barrels along its travel path.

Source: FHWA

Figure 3. Photo. Winter FT#2 Vehicle A's HMI displaying a stationary vehicle along its travel path.

Source: FHWA

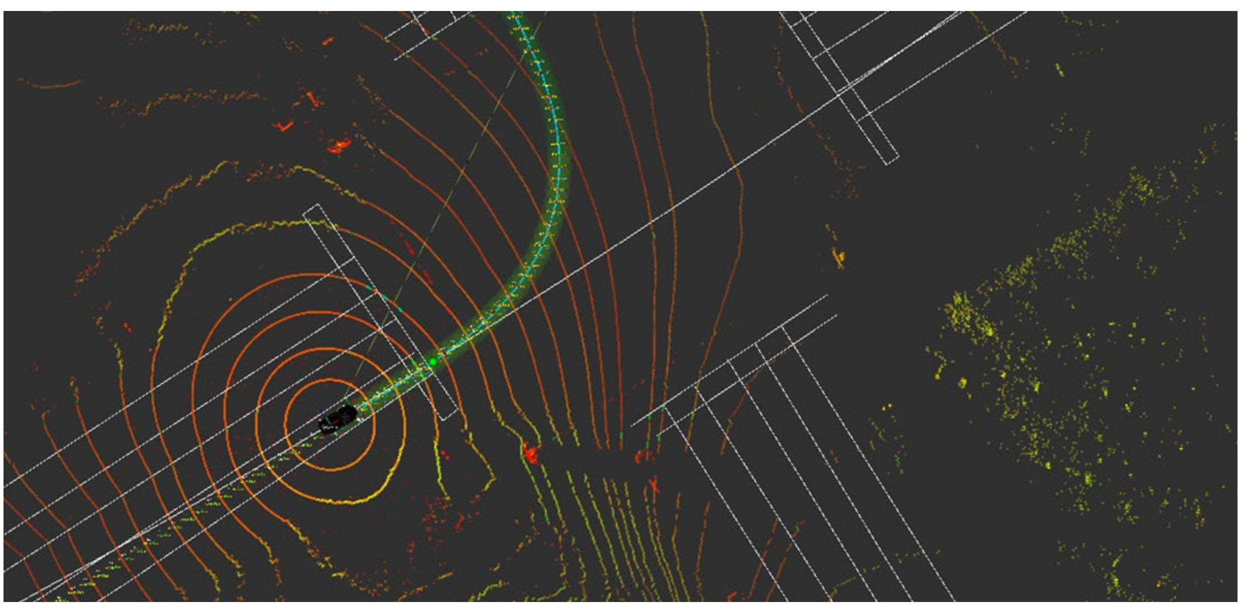

Figure 4. Photo. Winter FT#2 Vehicle B's HMI displaying a coordinated travel path (left turn shown in green hash marks).

Source: FHWA

HMIs can also display speed, vehicle position within travel lane, map, driving gear, temperature reading, odometer reading, fuel level, climate control information, media controls, and other settings. The HMI interface described above is a reiteration of language from the Phase 1 and Phase 2 reports, which is still applicable to Phase 3 because the nature of the field tests remained the same.

Vehicle Instrumentation

For both field tests, the test vehicle's driving automation system capabilities included lateral vehicle motion control via steering, longitudinal vehicle motion control via acceleration and deceleration, object and event detection and response, and following the planned route. To be successful, the test vehicle must be able to detect lane markings (Summer FT#1 Vehicle A, Summer FT#1 Vehicle B and Winter FT#2 Vehicle A) or properly localize in the HD Map (Winter FT#2 Vehicle B), filter out unnecessary or misleading information, and plan the vehicle's movements accordingly. On a typical roadway, where there are clear lane markings on either side of a vehicle with few imperfections in the roadway itself, detection and planning are more straightforward. However, if the pavement markings are affected by sun glare or covered with snow, a vehicle with driving automation systems engaged attempting to maintain its position within a lane must rely on path projection based upon road surface estimates. In addition, if the roadway is wet (water covered conditions) or slick (icy conditions), a vehicle with steering control engaged attempting to stay in the lane may be challenged because of control difficulties. It is the goal of these tests to better understand the effects of summer, spring, and winter weather and road weather conditions on a vehicle's perception and control systems and how they can be exacerbated by adverse weather effects. Table 1 presents the list of instruments used by the test vehicles during AVAW3 to capture telematics and perception data.

Two variables were used to assess the test vehicles' performance through the scenarios: (1) information displayed on the dashboard controls and (2) the test vehicles' lateral deviation within the lane or path. The steering control was engaged, and destination was set (if applicable) before the test vehicle entered the scenario. If the test vehicle was unable to engage steering control, disengaged the steering control during the test run, or deviated more than a foot from the lane for 2 seconds or more, it was documented and the test run, including data collection, ended.

Table 1. Vehicle Instrumentation

Type	Output	Range	Accuracy
Multi-Axis Inertia Measurement Unit	Position	Latitude: ±90 deg Longitude: ±180 deg	Position: ±2cm
	Longitudinal, Lateral, and Vertical Acceleration	Acceleration: ±100 m/s^2	Acceleration: 0.1%
	Roll, Yaw, and Pitch Rate	Angular Rate: ±100°/s	Angular Rate: 0.04%

Type	Output	Range	Accuracy
Data Acquisition System (Amplify, Anti-Alias, and Digitize)	Record Time; Velocity; Distance; Lateral, Longitudinal, and Vertical Accelerations; Roll, Yaw, and Pitch Rates; Steering Wheel Angle.	Sufficient to meet or exceed individual sensors	Sufficient to meet or exceed individual sensors
2x Cameras	Up to 1080p video at 20fps	Field of View: 78 deg	N/A
Real-Time calculation of position and velocity relative to lane and Principal Other Vehicle (POV)	Distance and velocity to lane and POV	Lat Lane Dist: ±30 m	±2 cm
		Lat Lane Vel: ±20 m/sec	±0.02 m/sec
		Long Range to POV: ±200 m	±3 cm
		Long Range Rate: ±50 m/sec	±0.02 m/sec

The Role of The Test Driver

Both AVAW3 field tests used trained drivers to perform the tests in a controlled outdoor test facility with a specific set of instructions. The drivers selected for field testing had completed multiple near-limit driver training sessions. Near-limit training consists of driving a vehicle while pushing it up to 95 percent of its limit capabilities. These test drivers are proficient in maintaining control of the vehicle in understeering and oversteering conditions, safely navigating adverse weather conditions, and handling under sliding conditions. The test drivers also train in:

- Basic driving skills
- Evasive and defensive driving
- High-performance driving techniques

Before testing, test drivers performed the driving scenarios in a practice session to ensure familiarity with the test procedures and the behavior of the automation functions. Further, the test drivers confirmed that the margins available in the test plan provided adequate maneuvering space to mitigate any risk of an incident. During the live test, the drivers remained alert and prepared to control the vehicle to prevent any property damage or injuries.

When faced with these complex scenarios, regular drivers are expected to react differently than trained test drivers. A detailed study on the role of the driver during critical situations and adverse weather conditions was conducted and presented during the first and second phases of the AVAW projects[6].

Location

Both AVAW3 field tests were conducted at the Transportation Research Center Inc. (TRC Inc.) near East Liberty, Ohio. Summer FT#1 was performed during the week of July 6, 2020, and Winter FT#2 was conducted between January 28 and March 3, 2021. Figure 5 is an aerial photograph of part of the TRC proving grounds.

Figure 5. Photo. Summer FT#1 and Winter FT#2 Test Tracks at TRC Proving Grounds used for performing vehicle testing.

Source: Google Maps[7]

[6] Neumeister, D. M., Pape, D. B., & Institute, B. M. (2019, June 01). Automated Vehicles and Adverse Weather: Final Report. Retrieved July 30, 2020, from https://rosap.ntl.bts.gov/view/dot/43772

[7] Google Maps, 2021. Transportation Research Center Inc. 1:23,000. Google Maps [online] Available through: https://goo.gl/maps/MPmrRCo1ph8EZfqn6 [Accessed 10 June 2021].

CHAPTER 4. SUMMER FIELD TEST #1

Two production vehicles with Society of Automotive Engineers (SAE) International Level 2[8] automation features were used for Summer FT#1. This chapter presents details of Summer FT#1 and its results.

SUMMER FT#1 HIGH-LEVEL TEST RESULTS

The following bullets present a high-level performance results summary for tested SAE International Level 2 vehicles while conducting specified maneuvers under adverse weather conditions. A more detailed description of the testing and results conducted can be found in the subsequent sections of this chapter.

During Summer FT#1, no environment or road condition consistently impacted the performance of the test vehicles. Significant inconsistencies were observed in the test vehicle performance, both across vehicles and within runs of the same vehicle. Even though both test vehicles use camera-based perception systems, Summer FT#1 Vehicle B which used multiple cameras displayed better efficiency in detecting road conditions than Summer FT#1 Vehicle A which used a single forward-facing camera, under all weather conditions.

Work Zone Lane Change with Barrels

- Summer FT#1 Vehicle A was not able to detect work zone barrels under Baseline or wet weather conditions.
- Summer FT#1 Vehicle B displayed mixed performance detecting work zone barrels during Baseline and Daytime Wet conditions.
- Nighttime wet conditions with glare posed challenges for Summer FT#1 Vehicle B to detect the barrels.
- Crosswinds at 40 mph did not show any impact on the performance of the test vehicles.

Work Zone Lane Closure with Lane Markings

- Summer FT#1 Vehicle A’s performance was impacted by nighttime wet conditions.
- During all weather and light conditions, Summer FT#1 Vehicle B performed lane change smoothly.

Pavement Markings with Brake Marks

- Both test vehicles maintained lane keeping without responding to the brake marks.

Pavement Markings with Disappearing Shoulder

- Summer FT#1 Vehicle A's ability to detect pavement markings was impacted by nighttime wet conditions.
- Summer FT#1 Vehicle B performed lane changes smoothly during all weather and light conditions.

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[8] https://www.sae.org/standards/content/j3016_202104/

SUMMER FT#1 TEST CONDITIONS

Summer FT#1 Vehicles

The Summer FT#1 used two production vehicles that offer SAE International Level 2 driving automation systems. Vehicles with differing sensor configurations were intentionally selected to compare the abilities of different sensors and processing algorithms to perform in various kinds of adverse weather and different driving conditions. Different driving environments used in the Summer FT#1 included brake marks, degraded pavement markings, and work zones. The test vehicles had differing signal processing and control algorithms that were unknown to the test team, so the tests were limited to evaluation of the entire perception and control system.

Vehicles used for conducting the Summer FT#1 tests are listed in Table 2, along with a list of their sensors and some of their driving automation systems. Vehicle names were anonymized to focus on capabilities and not the manufacturer, as these tests pushed the vehicles outside of standard ODD presented in the user manual. In Summer FT#1 Vehicle A, both LCA and ACC can be engaged separately, but it is categorized as a SAE International Level 2 when both features are engaged together. However, Summer FT#1 Vehicle B's driving automation system design does not allow LCA to be engaged unless ACC is activated. This makes Summer FT#1 Vehicle B a SAE International Level 2 vehicle.

Table 2. Summer FT#1 Test Vehicle capabilities.

Vehicle	Sensors	Driver Assistance Systems
Summer FT#1 Vehicle A	• Forward-facing camera used for control • Forward radar antenna	• Adaptive Cruise Control (SAE International L1) • Lane Centering Assist (SAE International L1) • Lane Departure Warning (SAE International L0)
Summer FT#1 Vehicle B	• Eight video cameras including rear, side, and forward • Forward radar antenna • 12 ultrasonic sensors	• Adaptive Cruise Control and Lane Centering Assist (SAE International L2) • Lane Departure Warning (SAE International L0)

Summer FT#1 Test Track

Summer FT#1 was performed on the test track at TRC Inc., shown in Figure 5. The Summer FT#1 test track has seven 12-foot-wide lanes that run adjacent to a set of crosswind generators, as presented in Figure 6. Directional pointers for Day 1 and Day 2 testing are represented by blue and orange arrows, respectively.

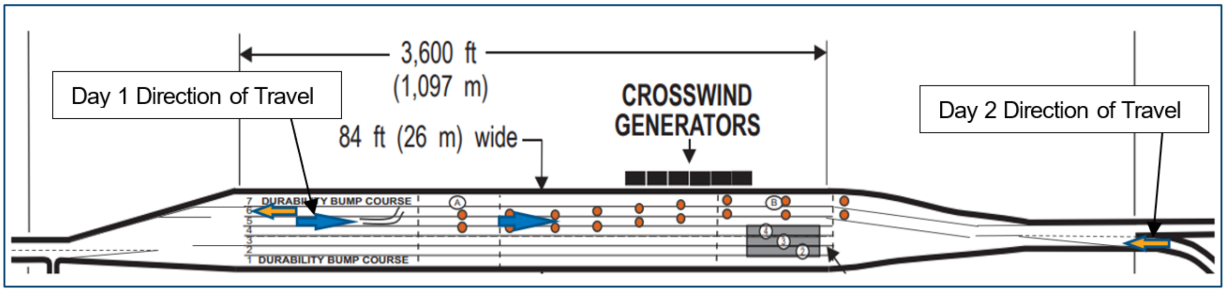

Figure 6. Photo. Summer FT#1 test track layout

Source: FHWA

To ensure safety, all testing was performed on a closed track, and testing activity was isolated through a combination of pre-scheduled facility requests, coordinated dispatch, and access controls.

Summer FT#1 Equipment

The project team leveraged a wide range of equipment to emulate weather, road weather, and different driving conditions required for the field testing. The equipment used in the Summer FT#1 included:

- **Barrels:** Engineer-grade traffic drum barrels with recycled tire bases were used for simulating work zone lanes. Barrel locations were surveyed and marked prior to testing to ensure consistency in barrel placement.
- **Wind Generators:** 70-foot-wide wind generators with a maximum wind speed of 40 mph were used for generating crosswinds during the Work Zone Lane Change with Barrels scenario. Wind generators were placed at the start of the taper to create a challenging lane change scenario. Figure 7 presents the wind generators used for Summer FT#1.
- **Water Trucks:** Water trucks were used to create wet pavements and standing water. Several passes were made through the test track before and in between runs to ensure consistency in pavement wetness throughout testing timeline.
- **Weather Sensors:** A SunCalc™ tool was used to determine the sun angles during the testing. A lux meter was used for capturing the luminosity for nighttime testing. Weather applications were used for tracking outdoor temperature.
- **Black Tape:** In addition to the natural brake marks on the test track, non-reflective black gaffers tape[9] was used to create brake marks on the test track. A test vehicle point of view of brake marks on the test track is presented in Figure 16.

[9] "Gaffer's tape" is a pressure-sensitive tape with a durable cloth backing. The adhesive is designed to be low-residue so it can be removed cleanly and easily and applied to a wide range of surfaces, temperatures, and environments. https://www.tapejungle.com/news/gaffer-tape-vs-duct-tape-whats-the-difference/

- **Overhead lights:** Four 240-watt LED fixtures with a total capacity of 88,000 lumens were used for overhead lighting. Two units of overhead lights were used for all nighttime testing scenarios to create night glare and dark spots.
- **Power Generator:** A 2,200-watt capacity portable inverter generator was used for powering the overhead lights. Two units of generators were used for setting up testing scenarios that occurred simultaneously.

Figure 7. Photo. Wind Generators used for Work Zone Lane Change with Barrels scenario in Summer FT#1.

Source: FHWA

Summer FT#1 Weather Conditions

The project team relied on artificially simulated and naturally occurring adverse weather conditions to challenge the test vehicles' control and perception system across both field tests. Various summer and spring weather conditions were simulated on the facilities at TRC Inc. for the Summer FT#1. For comparison, each vehicle was tested both in baseline and the adverse weather conditions and in different driving environments. The following sections summarize the conditions produced or experienced.

Baseline

All driving scenarios for Summer FT#1 were tested under Baseline weather conditions. The selected weather conditions for Baseline criteria included ambient air temperatures between 20°F and 100°F, peak wind speeds below 22.4 mph, sun position greater than 15° above the horizon, ambient illumination greater than 2,000 lux[10], and dry and clear pavement. Figure 8 shows the Baseline weather conditions from the test vehicle's point of view from one of the Summer FT#1 test runs.

Figure 8. Photo. View from a vehicle depicting the Baseline weather conditions.

Source: FHWA

[10] Illuminance greater than 2,000 lux represent ambient daylight conditions with clear sky.

Wet roadway during daylight

Wet roadway testing was conducted during clear daylight conditions to create glare off the roadway. To ensure consistent glare, the tests with this adverse weather condition were conducted between 1100 ET and 1400 ET for all scenarios. All testing was completed with a sun angle of 15 degrees or more above the horizon, as shown in Figure 9. The sun angle was 166 degrees at the start of the test and 223 degrees at the end of the test. In addition, a water truck was used between the test runs to ensure consistency in pavement wetness across the testing.

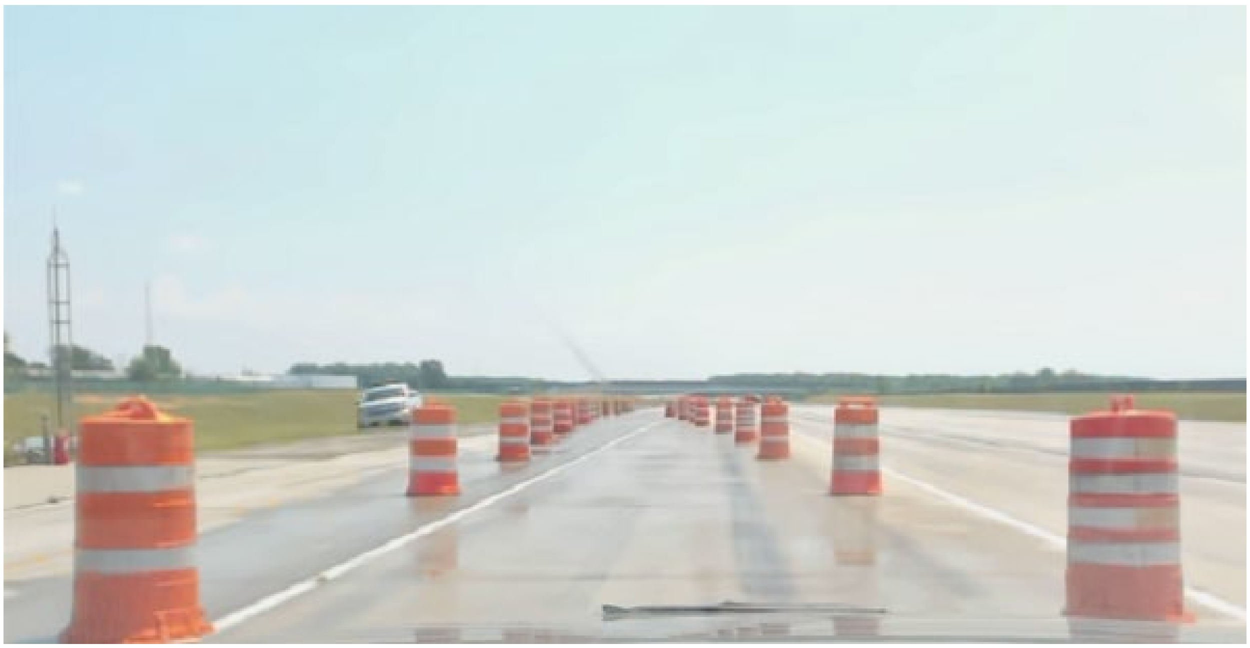

Figure 9. Photo. Test vehicle point of view depicting Work Zone Lane Change with Barrels scenario with wet pavement conditions and sun glare during daytime testing.

Source: FHWA

Wet roadway at night

Wet roadway testing was conducted at night with lighting levels at or below 2 lux[11]. Overhead lighting was installed ahead of the maneuvering locations to aid in creating night glare and dark conditions. A water truck was used in between the test runs to ensure consistency in pavement wetness across the testing. Figure 10 presents the wet pavement with night glare from a test vehicle point of view.

Figure 10. Photo. View from vehicle with night glare.

Source: FHWA

Crosswinds

A 70-foot-long crosswind generator located adjacent to the Summer FT#1 test track was used for creating crosswinds. The wind generator was set to its full speed of 40 mph during the testing. The crosswind adverse weather condition was applied for testing the vehicle behavior only during the work zone lane change scenario. The Summer FT#1 test track was reserved for exclusive use during this adverse weather to ensure safety of the testing. The barrels were placed so that the crosswind generators were at the start of the taper to create challenging crosswind conditions for test vehicles to perform the lane change maneuver through the work zone barrels.

Summer FT#1 Scenarios Tested

Four different scenarios were designed and executed to test the vehicles' perception systems with both changing lane configurations and adverse weather. The test matrix in Table 3 lists the different driving scenarios and road weather conditions that were tested. The scenarios are 1) Work Zone Lane Change with Barrels, 2) Work Zone Lane Closure with Lane Markings, 3) Pavement Markings with Brake Marks, and 4) Pavement Markings with Disappearing

[11] Illuminance less than 2 lux represent clear night sky conditions with moonlight and/or starlight.

Shoulder. All scenarios were tested during a baseline of fair weather with dry pavement and no glare, wet roadway during daylight, and wet roadway at night conditions. The crosswind adverse weather condition was applied for testing the vehicle behavior only during the Work Zone Lane Change with Barrels scenario. Three out of four scenarios (Work Zone Lane Change with Barrels, Pavement Markings with Brake Marks, and Pavement Markings with Disappearing Shoulder) were conducted on straight roadway segments, and the remaining scenario (Work Zone Lane Closure with Lane Markings) was conducted on a curved roadway segment. All four scenarios focused on testing the lane-centering system that relies on the perception systems' ability to track and follow the lane markings. The tests were designed to conduct a minimum of seven runs for each scenario under all weather conditions. However, additional tests were conducted for several scenarios to gain a deeper understanding of test vehicles' perception systems.

Table 3. Minimum number of runs for maneuvers tested in adverse weather conditions.

Scenarios	Baseline Conditions	Wet Nighttime Conditions	Wet Daytime Conditions	Crosswind Conditions	Notes
Work Zone Lane Change with Barrels	7	7	7	7	Lane Centering Assist was tested with a guided lane change using barrels while SAE International L2 longitudinal and lateral control was engaged.
Work Zone Lane Closure with Lane Markings	7	7	7	0	Lane Centering Assist was tested with a guided lane change using lane markings while SAE International L2 longitudinal and lateral control was engaged.
Pavement Markings with Brake Marks	7	7	7	0	Lane Centering Assist was tested on a lane that has brake marks deviating from the roadway while SAE International L2 longitudinal and lateral control was engaged.

Scenarios	Baseline Conditions	Wet Nighttime Conditions	Wet Daytime Conditions	Crosswind Conditions	Notes
Pavement Markings with Disappearing Shoulder	7	7	7	0	Lane Centering Assist was tested on a straight roadway with a disappearing shoulder while SAE International L2 longitudinal and lateral control was engaged.

Work Zone Lane Change with Barrels

The objective of the Work Zone Lane Change with Barrels scenario was to emulate driving in a work zone and test whether the test vehicles make a full lane change to the left by following the barrels. This scenario was tested on lanes 5 and 6 at the Summer FT#1 test track, as shown in Figure 11. Barrels were placed on either side of the lane, emulating a work zone and forcing a vehicle to shift a full lane-width across a solid lane line. Work zone barrels were placed 30 feet apart from each other, following the *Manual on Uniform Traffic Control Device* (MUTCD) standards. The barrel locations were marked with temporary paint to ensure proper placement each time the test was performed. The test vehicle travel lane was one lane-width away from the crosswind generators at the side of the road (Figure 12). The test vehicles were traveling at a speed of 45 mph and engaged LCA and ACC[12] before entering the portion of the test area with barrels. Both vehicles were tested in clear conditions during daylight (baseline), crosswind during daylight, wet roadway during daylight, and wet roadway at night. During each run, the test vehicles proceeded through the barrel-lined section of roadway to determine if they were able to change lanes by crossing a solid lane line in the emulated work zone. The test was determined to be completed once the vehicle exited the final barrels, the test driver took control of the vehicle to avoid coming in contact with the barrels, or LCA or ACC disengaged. The desired path of the test vehicle is to maneuver through the work zone barrels by crossing the solid lane line without hitting the barrels or disengaging LCA or ACC, returning control to the human driver. When the vehicle's perception systems recognize that the test conditions are outside its ODD, the expected action is for the vehicle to disengage LCA or ACC and return control to the human driver.

[12] When both LCA and ACC are engaged together, test vehicle is categorized as an SAE Level 2 vehicle.

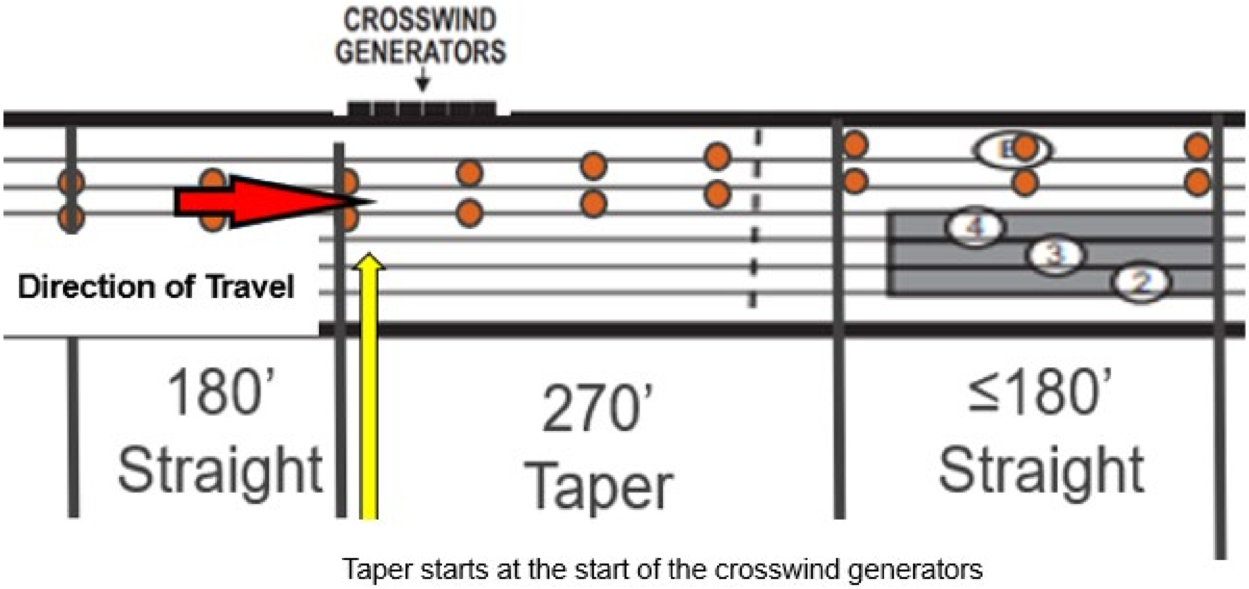

Figure 11. Graphic. Work Zone Lane Change with Barrels scenario.

Source: FHWA

Figure 12. Photo. Test vehicle point of view depicting work zone barrels and crosswind generators. Barrels were placed such that the crosswind generators were at the start of the taper.

Source: FHWA

Work Zone Lane Closure with Lane Markings

The objective of the Work Zone Lane Closure with Lane Markings scenario was to emulate a work zone lane closure and test whether the test vehicles perform a full lane change to the right.

The lane closure with lane markings (as opposed to barrels) scenario took place on the Summer FT#1 test track with the vehicle following the direction of the arrow, as shown in Figure 13. The solid white lane markings in Figure 14 indicate the lane is ending in an attempt to force the vehicle to the right, across a white dashed line, emulating a work zone with a closed lane. The test vehicles traveled at a speed of 45 mph and engaged LCA and ACC before arriving at the dashed lines. Both vehicles were tested in clear conditions during daylight (baseline), wet roadway at night, and wet roadway during daylight. The test was determined to be completed once the vehicle changed lanes, crossed the solid lane by more than one foot, or disengaged LCA or ACC. For this scenario, the expectation was that the test vehicles would be able to detect lane closure, cross the dashed right lane line, and complete the lane change maneuver without crossing the left solid lane line.

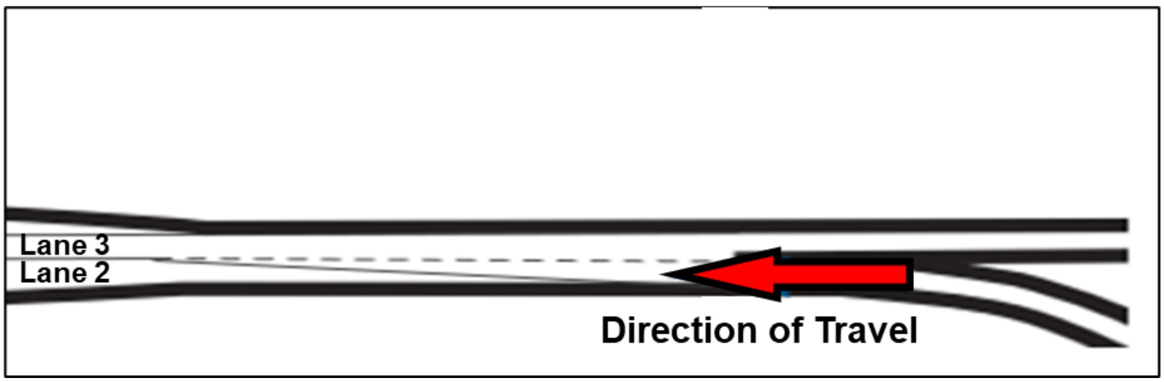

Figure 13. Graphic. Work Zone Lane Closure with Lane Markings scenario.

Source: FHWA

Figure 14. Photo. Test vehicle point of view depicting closing solid lane for the Lane Closure Maneuver scenario.

Source: FHWA

Pavement Markings with Brake Marks

The objective of the Pavement Markings with Brake Marks scenario was to emulate brake marks diverging from the roadway pavement markings and test whether the test vehicles maintain lane keeping without any critical deviations greater than 2.8 feet. Numerous pre-existing brake marks that crossover pavement markings on the Summer FT#1 test track were used for this testing. In addition to the existing brake marks, a pair of emulated diverging brake marks were placed on lanes 5 and 6 as presented in Figure 15 and Figure 16. These served as the primary brake marks for this test scenario. The test vehicles traveled at a speed of 45 mph and engaged LCA and ACC before arriving at the emulated brake marks. Both vehicles were tested in clear conditions during daylight (baseline), wet roadway at night, and wet roadway during daylight conditions. The test was determined to be complete once the vehicle maintained lane centering through the travel lane markings without deviating, crossed the solid lane by more than one foot, deviated to the left by more than 2.8 feet, or disengaged LCA or ACC. The expectation for this scenario was that the test vehicles would be able to maintain lane centering within the travel lane pavement markings at the brake marks without any sudden lane departures.

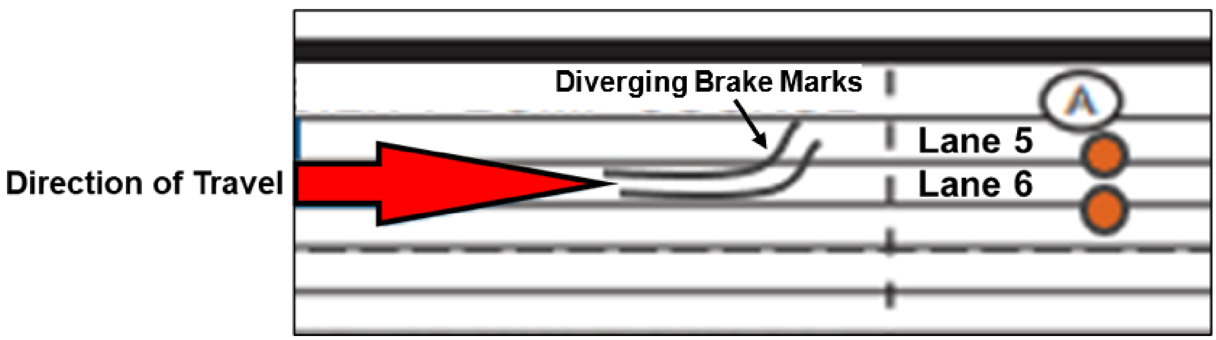

Figure 15. Graphic. Diverging brake marks between travel lanes for Pavement Markings with Brake Marks scenario

Source: FHWA

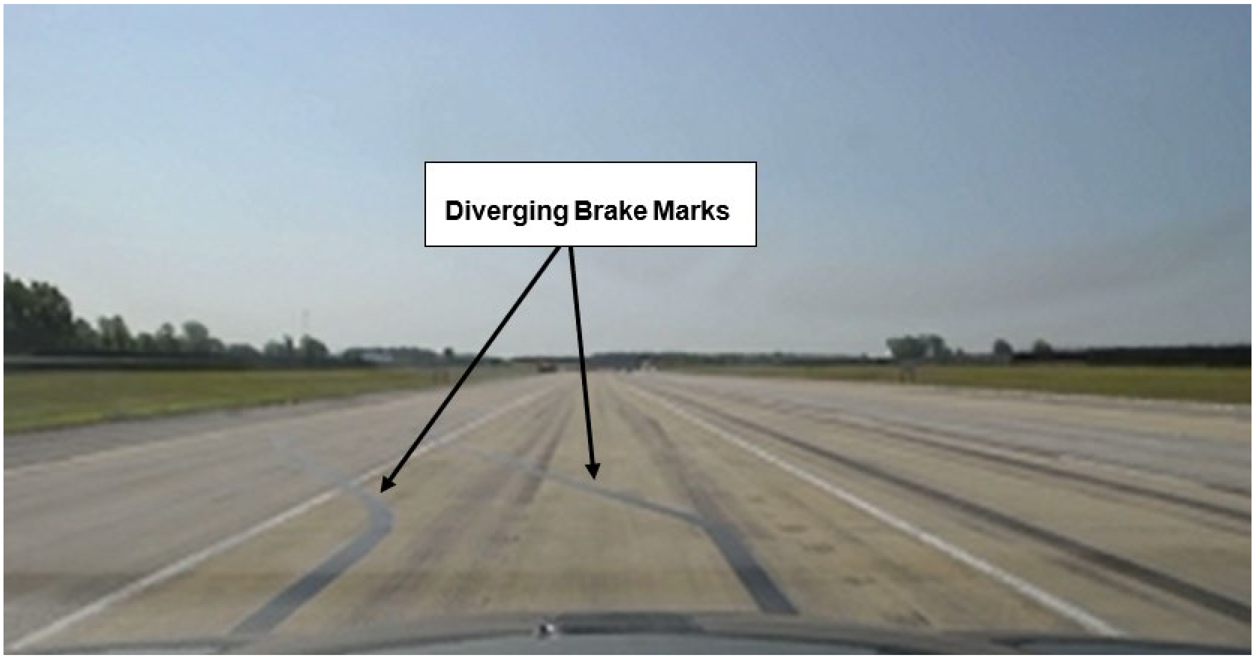

Figure 16. Photo. Test vehicle point of view depicting brake marks diverging from lane 5 to lane 6.

Source: FHWA

Pavement Markings with Disappearing Shoulder

The objective of the Pavement Markings with Disappearing Shoulder scenario was to emulate a disappearing lane line and test whether the AVs maintain lane keeping without any critical deviations greater than 2.8 feet throughout the length of the missing lane line. In this scenario, the test vehicles traveled on the north end of lane 6 of the Summer FT#1 test track, where the right lane line has solid lane markings and left lane line has dashed lane markings. The vehicles proceeded at a set speed of 45 mph with LCA and ACC engaged before the left lane line of lane 6 disappears for over 100 feet, as presented in Figure 17 and Figure 18. Both vehicles were tested in clear conditions during daylight (baseline), wet roadway at night, and wet roadway during daylight conditions. During each run, the vehicle should either maintain lane centering through the lane or deviate from the travel lane. The test was determined to be complete once the vehicle maintained lane centering throughout the length of missing lane line, crossed the solid lane line by more than one foot, deviated to the left by more than 2.8 feet, or disengaged LCA or ACC. The expectation for this scenario was that the test vehicles would be able to maintain lane centering by following the right lane line throughout the length of travel lane with the missing left lane line.

Figure 17. Graphic. Pavement Markings Disappearing Shoulder scenario

Source: FHWA

Figure 18. Photo. Test vehicle point of view depicting disappearing left lane line on lane 6.

Source: FHWA

As in other scenarios, the test plan was designed so that the test team would continue collecting data after a test vehicle deviated from the intended path—in this scenario, after crossing the solid lane line up to a distance of one foot or deviating to the left of the intended travel lane by over 2.8 feet. Continuing to collect data enabled the test outcomes for AVAW3 to have enough data for thorough evaluation of the results, leading to a more robust understanding of test vehicles' perception systems.

SUMMER FT#1 RESULTS

Work Zone Lane Change with Barrels

Desired Outcome: The desired performance was for the vehicles to maneuver through the work zone barrels by crossing the solid lane line without the test drivers having to take control of the test vehicle to avoid hitting the barrels, or disengaging LCA or ACC.

Overall, Summer FT#1 Vehicle A was unable to detect barrels, keep engaged with steering controls, and would have driven into the barrels without driver intervention, under baseline and adverse weather conditions. Summer FT#1 Vehicle B displayed mixed performance during baseline, daytime wet and crosswind conditions, but was challenged by the nighttime conditions to detect the barrels. During all runs, Summer FT#1 Vehicle B reduced its speed from 45 to 25 mph as soon as it recognized the first barrel. Table 4[13] presents the summary findings of both test vehicles for Work Zone Lane Change with Barrels scenario across baseline and adverse weather conditions.

Table 4. Summary of Work Zone Lane Change with Barrels during baseline and adverse weather conditions.

Test Condition	Vehicle	Number of Runs	Detected Barrels	Maneuvered through Barrels	Drove into Barrels/ Driver took Control	Lane Centering Assist Disengaged
Baseline	A	8	0	0	8	8
	B	9	9	4	5	5
Daytime Wet	A	9	0	0	9	9
	B	10	10	8	2	0

[13] Summer FT#1 was designed to conduct a minimum of seven runs for each scenario under all weather conditions. However, additional tests were conducted for several scenarios to gain a deeper understanding of test vehicles' perception systems.

Test Condition	Vehicle	Number of Runs	Detected Barrels	Maneuvered through Barrels	Drove into Barrels/ Driver took Control	Lane Centering Assist Disengaged
Nighttime Wet	A	10	0	0	10	10
	B	9	9	0	9	9
Crosswinds	A	10	0	0	10	10
	B	11	11	10	1	0

Baseline

During Baseline conditions, Summer FT#1 Vehicle A did not detect any barrels and would have driven into the barrels without the test driver assuming control. Figure 19 presents a series of photos depicting one of Summer FT#1 Vehicle A's test runs during the baseline scenario, where the vehicle enters the work zone, follows the lane markings, and then nearly steers into work zone barrels, requiring test driver intervention.

Summer FT#1 Vehicle B successfully maneuvered through the barrels four out of nine runs during Baseline conditions. During the remaining baseline runs, Summer FT#1 Vehicle B detected barrels, provided a chime alerting the test driver to takeover control, disengaged LCA and/or ACC, or nearly steered into the barrels without test driver intervention.

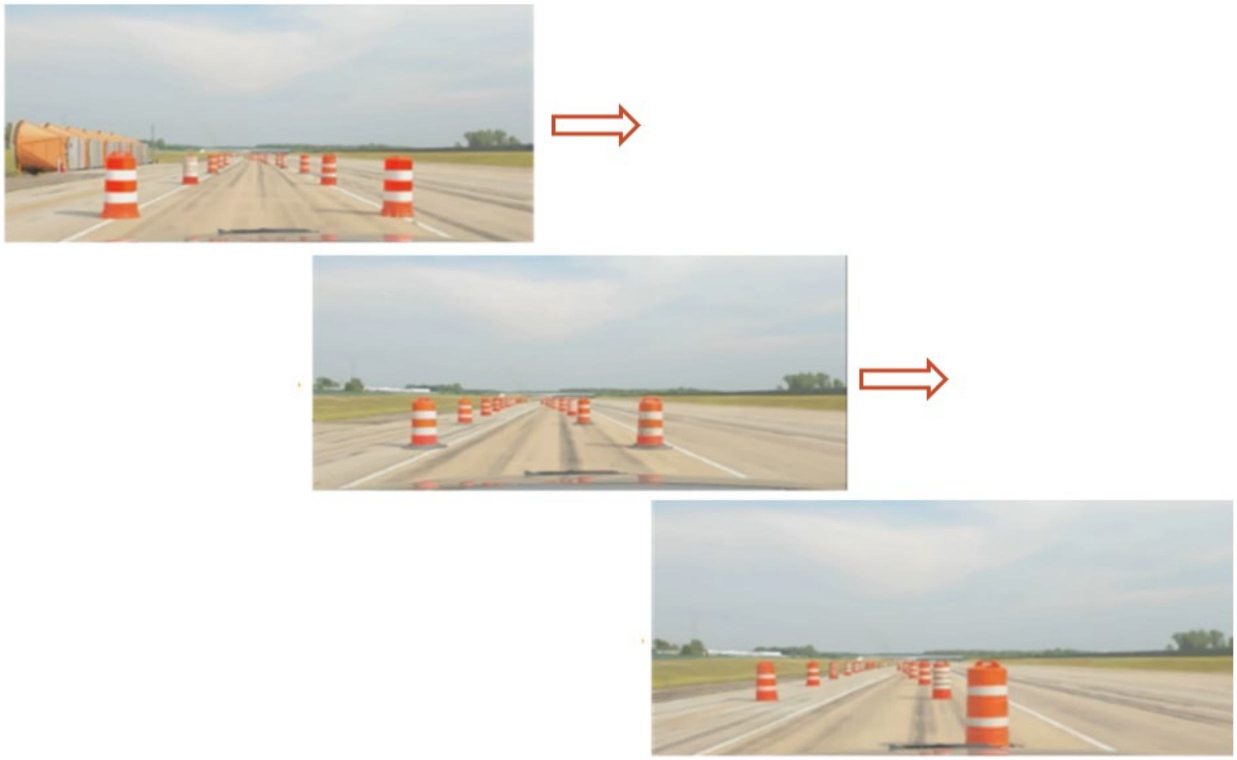

Figure 19. Photo. Summer FT#1 Vehicle A Point of View depicting its deviation into barrels during baseline conditions for Work Zone Lane Change with Barrels scenario.

Source: FHWA

Daytime Wet Roadway

Summer FT#1 Vehicle A did not show any performance improvement during the daytime wet roadway conditions.

Summer FT#1 Vehicle B detected barrels and maneuvered through the work zone in more (eight out of ten) test runs during daytime wet roadway conditions than baseline test runs. During the remaining runs, Summer FT#1 Vehicle B detected barrels, provided a chime alerting the test driver to takeover control, disengaged LCA and/or ACC, or nearly steered into the barrels without test driver intervention. During the runs with undesirable outcomes, Summer FT#1 Vehicle B experienced sharp variations in yaw rates ranging from -6 to +15 deg/s.

Figure 20 represents the distances between Summer FT#1 Vehicle B's right and left bumper corners to the right and left work zone barrels, respectively. The blue dashed line represents test runs with desirable outcomes. Blue dashed lines with an "x" symbol indicate runs with undesirable outcomes that eventually required test driver intervention. To aid in conveying the test scenario, the solid black horizontal line across the x-axis origin represents the placement of right and left work zone barrels. The solid black vertical lines close to the 3-second and 8-second time intervals represent the start and end of the taper for the work zone lane.

Desirable test runs are where Summer FT#1 Vehicle B maintained safe (shown as a positive distance from the right barrels and a negative distance from the left barrels) distance from the barrels as it successfully followed the work zone merge (delineated by barrels) and crossed the solid line in this work zone scenario. During undesirable test results, Summer FT#1 Vehicle B drove close to the right barrels. As presented in Figure 20, Summer FT#1 Vehicle B's distance reduced from 5 feet to 0 feet, between 5 and 7 seconds immediately after crossing the taper. There were two runs with undesirable results. During one of the runs with undesirable results, the human test driver took control of the vehicle and steered it into the work zone lane. Once the test driver took control, the distance between the right bumper and barrels gradually increased between the 7- and 10-second time interval in the plot. For the other run with undesirable results, to assess the vehicle behavior as it neared the right barrels the test driver refrained from taking control. As a result, the vehicle steered into the right barrels before the driver took control. Overall, the variations in distances between Summer FT#1 Vehicle B and left barrels reflect the distance variations observed with the right barrels. For example, as the distance between the test vehicle and right barrels decreased, an increase in distances was observed between the test vehicle and left barrels. Similar patterns were observed for baseline and crosswind conditions. A plot-overview of the Summer FT#1 Vehicle B's distance from the left and right work zone barrels during the work zone lane change with barrels scenario. The blue dashed lines represent the desirable runs where Summer FT#1 Vehicle B was able to maneuver through the WZ lane. Black dashed lines with 'x' represents undesirable runs where Summer FT#1 Vehicle B drove close to the right barrels.

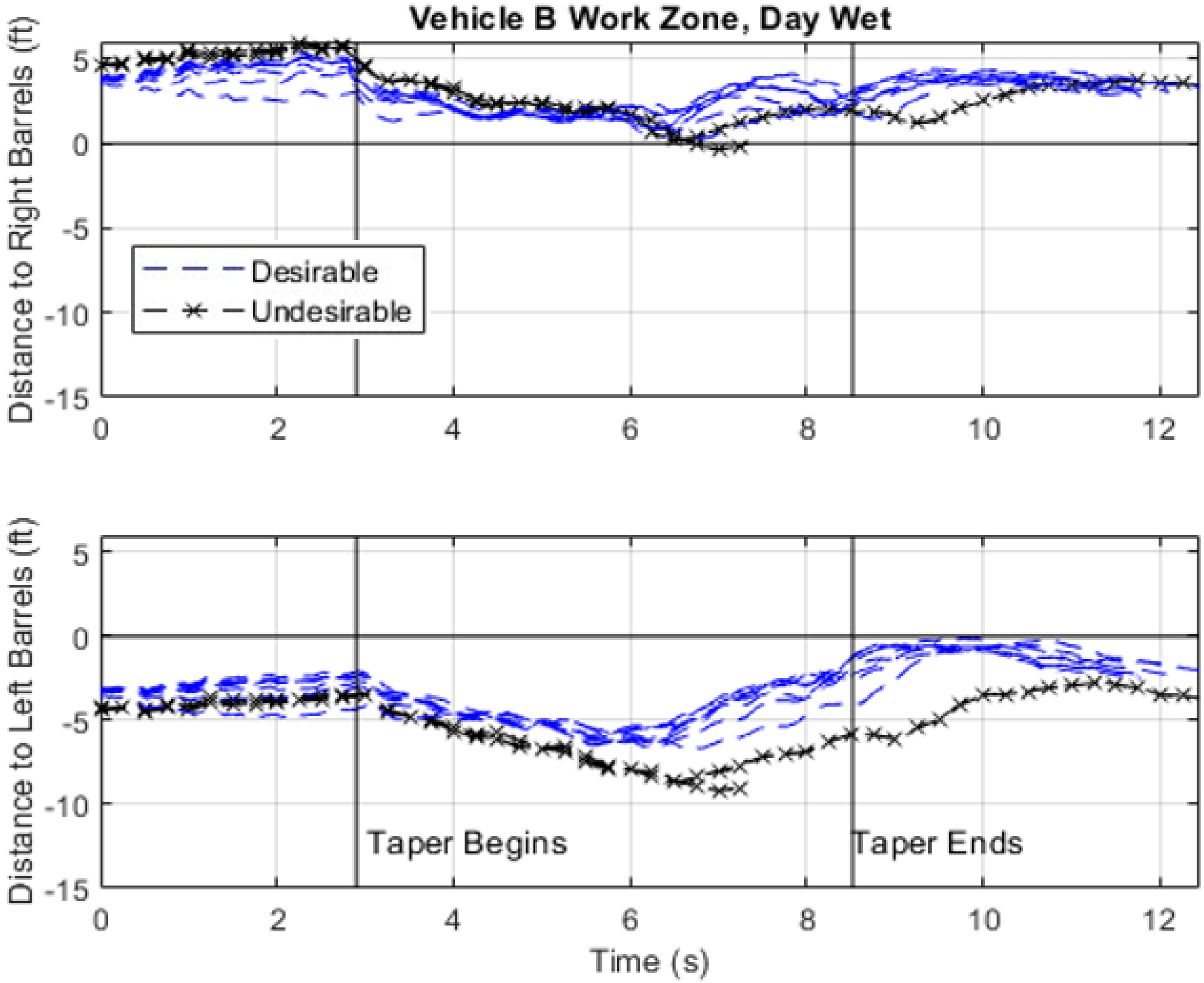

Figure 20. Plot. Distance from right and left barrels to Summer FT#1 Vehicle B during Work Zone Barrels for Daytime Wet Pavement scenario.

Source: FHWA

Nighttime Wet Roadway

During nighttime wet roadway conditions, both test vehicles were unable to perform lane change at the work zone.

- Summer FT#1 Vehicle A's performance was consistent with baseline and daytime wet roadway conditions.
- During all nighttime runs, Summer FT#1 Vehicle B detected the barrels but was unable to perform a lane change by maneuvering through the work zone lane. Summer FT#1 Vehicle B's right bumper drove close to the barrels right after crossing the taper (similar to the black dashed lines with "x" symbols shown in Figure 20) requiring test driver intervention.

Crosswinds

Crosswind conditions did not show any specific impact on the performance of the test vehicles.

- Summer FT#1 Vehicle A consistently drove into the barrels without detecting them or providing any alerts to the test driver.
- Summer FT#1 Vehicle B was able to detect the barrels and performed the desired lane change during ten out of eleven runs under crosswind conditions. No steep variations were observed in Summer FT#1 Vehicle B's yaw rates.

Work Zone Lane Closure with Lane Markings

Desired Outcome: Both test vehicles should be able to detect lane closure, cross the dashed right lane line, and complete the lane change maneuver without crossing the left solid lane line, without the test driver taking control, or merging to the left.

During this scenario, mixed performance was displayed by both vehicles as no environmental condition showed a consistent impact on the ability of test vehicles to detect lane closure and perform lane change maneuvers.

- Summer FT#1 Vehicle A was able to perform the desired lane change maneuver during the majority of baseline and nighttime wet roadway conditions, and all of the daytime wet roadway conditions.
- Summer FT#1 Vehicle B was unable to perform the desired lane change maneuver during Baseline conditions, performed lane change maneuvers with marginal deviations from the centerline of the desired path under daytime wet roadway conditions, and successfully performed lane changes during nighttime wet roadway conditions without any deviations.

Table 5[14] presents the high-level summary findings of both test vehicles for the Work Zone Lane Closure with Lane Markings scenario across baseline and adverse weather conditions.

Table 5. Summary of lane changing in a Work Zone with lane marking during Baseline conditions.

Test Condition	Vehicle	Number of Runs	Detected Solid Lane Ending	Changed Lane Successfully	Crossed Solid Lane	Lane Centering Assist Disengaged
Baseline	A	10	10	6	1	4

[14] Summer FT#1 was designed to conduct a minimum of seven runs for each scenario under all weather conditions. However, additional tests were conducted for several scenarios to gain a deeper understanding of test vehicles' perception systems.

Test Condition	Vehicle	Number of Runs	Detected Solid Lane Ending	Changed Lane Successfully	Crossed Solid Lane	Lane Centering Assist Disengaged
Baseline	B	10	10	0	10	N/A
Daytime Wet	A	10	10	10	0	N/A
	B	9	9	9	9*	N/A
Nighttime Wet	A	9	9	6	1	3
	B	9	9	9	0	N/A

** Summer FT#1 Vehicle B marginally crossed the left solid lane before merging into the right lane during all daytime wet condition runs*

Baseline

During Baseline conditions:

- Summer FT#1 Vehicle A detected the solid lane line ending and performed the lane change maneuver without crossing the left-most solid lane line for six out of ten runs. During three out of ten runs, Summer FT#1 Vehicle A disengaged LCA and ACC, but did not cross the left solid lane line. During the remaining runs, Summer FT#1 Vehicle A disengaged LCA and ACC and crossed the left solid lane line.
- During all test runs, Summer FT#1 Vehicle B detected the solid lane ending and crossed the left solid lane without disengaging the LCA and ACC. For all baseline runs, Summer FT#1 Vehicle B crossed the left lane line by more than 5 feet and merged into the left shoulder lane.

Daytime Wet Roadway

During daytime wet roadway, all runs:

- Summer FT#1 Vehicle A detected the solid lane line ending and performed the lane change maneuver without crossing the left-most solid lane line. Summer FT#1 Vehicle A experienced cloudy conditions during two runs in daytime wet conditions, but no difference was observed in vehicle behavior compared to sunny weather conditions.
- Summer FT#1 Vehicle B detected the solid lane ending, marginally crossed the left solid lane line, and eventually repositioned itself to complete the lane change maneuver during daytime wet pavement conditions.

Nighttime Wet Roadway

Nighttime wet roadway conditions with glare:

- Conditions partially impacted Summer FT#1 Vehicle A's performance, as it was unable to detect the pavement markings and perform lane change maneuvers during three out of nine runs.
- Nighttime wet conditions did not show an impact on Summer FT#1 Vehicle B's ability to detect pavement markings in glare conditions. During all runs, Summer FT#1 Vehicle B was able to successfully perform the lane-change maneuver without any deviations from the centerline of the desired travel path.

Pavement Markings with Brake Marks

Desired Outcome: The desired performance was for the vehicles to maintain lane centering within the travel lane pavement markings at the brake marks without any critical deviations.

No noticeable impacts were created by any of the environmental conditions on the performance of the test vehicles during the Pavement Markings with Brake Marks scenario. During all runs, both test vehicles maintained the lane centering throughout the roadway segment with brake marks.

Table 6[15] presents the high-level summary findings of both test vehicles for Pavement Markings with Brake Marks scenario across baseline and adverse weather conditions.

Table 6. Pavement Markings with Brake Marks scenario Result Summary.

Test Condition	Vehicle	Number of Runs	Maintained Lane Centering	Followed Brake Marks	Lane Centering Assist Disengaged	Additional Comments
Baseline	A	8	8	N/A	N/A	-
	B	9	9	N/A	N/A	-
Daytime Wet	A	9	9	N/A	N/A	-
	B	10	10	N/A	N/A	-

15 Summer FT#1 was designed to conduct a minimum of seven runs for each scenario under all weather conditions. However, additional tests were conducted for several scenarios to gain a deeper understanding of test vehicles' perception systems.

Test Condition	Vehicle	Number of Runs	Maintained Lane Centering	Followed Brake Marks	Lane Centering Assist Disengaged	Additional Comments
Nighttime Wet	A	10	10	N/A	N/A	-
	B	9	9	9	N/A	For all nighttime wet condition runs, Summer FT#1 Vehicle B deviated from center of lane at brake marks but did not follow brake marks

Baseline

For all runs during Baseline conditions, both test vehicles did not experience any deviations at brake marks and performed the desired transition (maintain lane centering at brake marks without any critical deviations).

Daytime Wet Roadway

As the daytime wet roadway conditions with sun glare did not impact either of the test vehicles' performance, both vehicles produced results similar to the Baseline conditions.

Nighttime Wet Roadway

During nighttime conditions:

- Summer FT#1 Vehicle A did not experience any issues for maintaining lane centering at brake marks.
- Summer FT#1 Vehicle B consistently experienced marginal deviations of less than one foot at the brake marks. During all runs, Summer FT#1 Vehicle B experienced slight variations in yaw rates between -1.7 to +1.8 deg/s, as represented by black dotted dash lines in Figure 21. Yaw rates from baseline and daytime wet conditions are represented by solid and dash blues lanes, respectively.

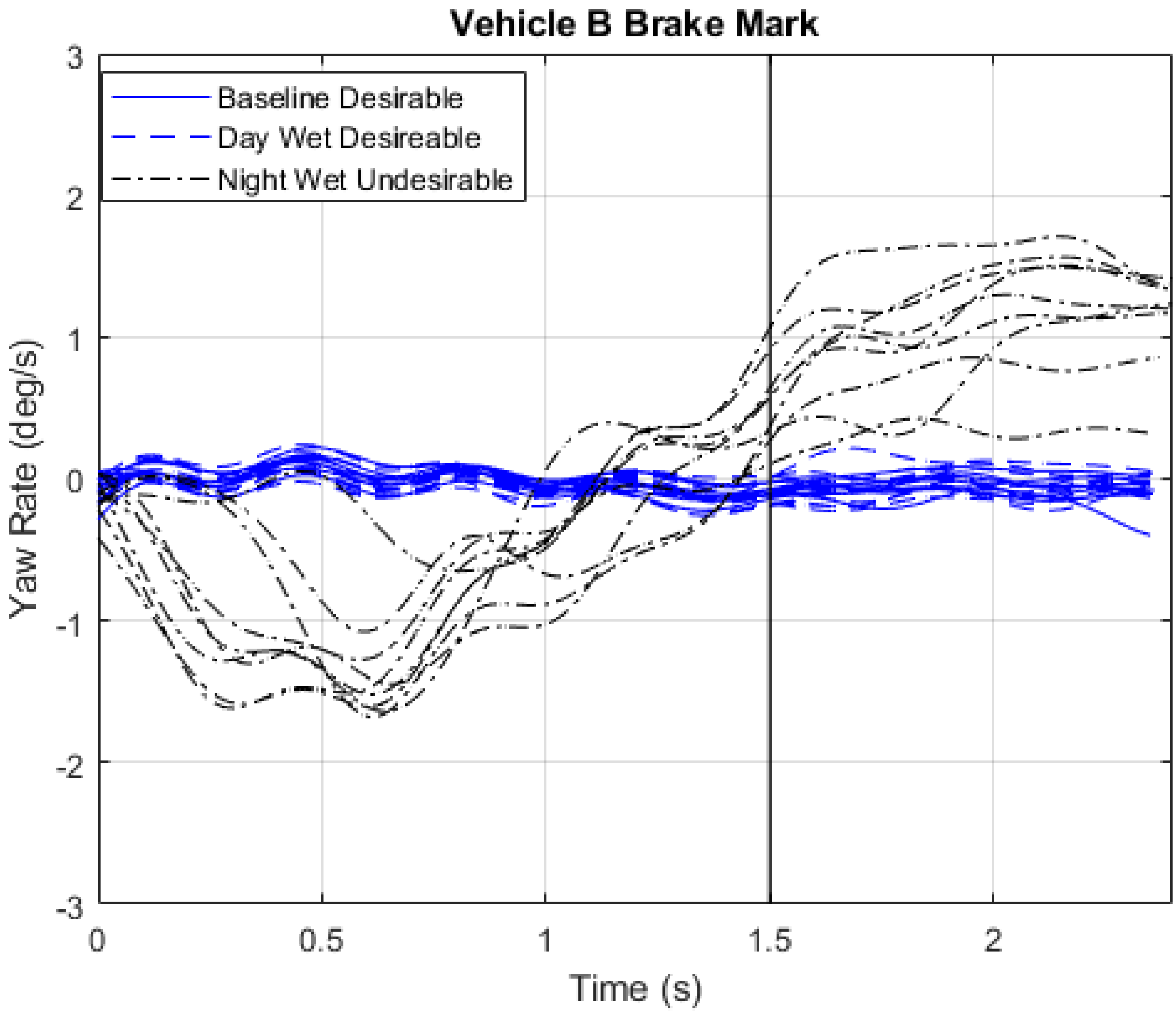

Figure 21. Plot. Summer FT#1 Vehicle B Yaw Rate Plot for Pavement Markings with Brake Marks scenario.

Source: FHWA

Pavement Markings with Disappearing Shoulder

Desired Outcome: The desired performance was for the vehicles to maintain lane centering by following the right lane line throughout the length of missing left lane line.

Overall, both test vehicles were largely unimpacted by any of the environment conditions in maintaining the lane centering with a disappearing left lane line. The test vehicles followed the right solid lane line to maintain lane centering. Table 7[16] presents the summary findings of both

[16] Summer FT#1 was designed to conduct a minimum of seven runs for each scenario under all weather conditions. However, additional tests were conducted for several scenarios to gain a deeper understanding of test vehicles' perception systems.

test vehicles for Pavement Markings with Disappearing Shoulder scenario across baseline and adverse weather conditions.

Table 7. Pavement Markings with Disappearing Shoulder scenario Result Summary.

Test Condition	Vehicle	Number of Runs	Maintained Lane Centering	Followed Right Solid Lane	Merged into Left Lane	Lane Centering Assist Disengaged
Baseline	A	10	10	10	N/A	N/A
	B	11	11	11	N/A	N/A
Daytime Wet	A	10	10	10	N/A	N/A
	B	9	9	9	N/A	N/A
Nighttime Wet	A	10	9	9	N/A	1
	B	8	8	8	N/A	N/A

Baseline

For all baseline runs, both test vehicles maintained lane centering by following the right solid lane line and smoothly maneuvered through the disappearing lane.

Daytime Wet Roadway

Daytime wet conditions with sun glare did not pose any challenges to the test vehicles in maintaining lane centering. No critical deviations were observed.

Nighttime Wet Roadway

- For nine out of ten runs during nighttime wet conditions, Summer FT#1 Vehicle A was able to maintain the lane centering by following the right solid lane line. For the remaining run, Summer FT#1 Vehicle A disengaged LCA and ACC, displayed “driver input required” alert, and merged into the left lane.
- Summer FT#1 Vehicle B maintained lane centering during all runs but experienced slight deviations (< 1 foot) from the lane centerline as the vehicle was entering the roadway segment with pavement markings covered by night glare.

Figure 22 presents distances from the center of Summer FT#1 Vehicle A’s front bumper to the right and left pavement markings, respectively. In the bottom figure (Distance to Left Line), it can be observed that distance values are missing for the extent of the missing shoulder lane line. In the top figure (Distance to Right Line), for desirable runs, the distance from Summer FT#1

Vehicle A's right bumper to the right lane line approaches zero and the vehicle reaches the end of the merging lane following the right lane line. For the remaining test run represented in the black-colored dashed line with "x" symbols, the distance from Summer FT#1 Vehicle A's right bumper to the right lane line increases from the 2 second time interval and continues through to the 7 second time interval as Summer FT#1 Vehicle A disengaged LCA and ACC, slightly steered to the left, and required test driver input. The test driver took control of the vehicle, applied braking, and steered into the right travel lane. From the trajectory track, it can be observed that without the test driver intervention, Summer FT#1 Vehicle A would have been off the road in less than one second, as the lateral speed was approximately 2 ft/s.

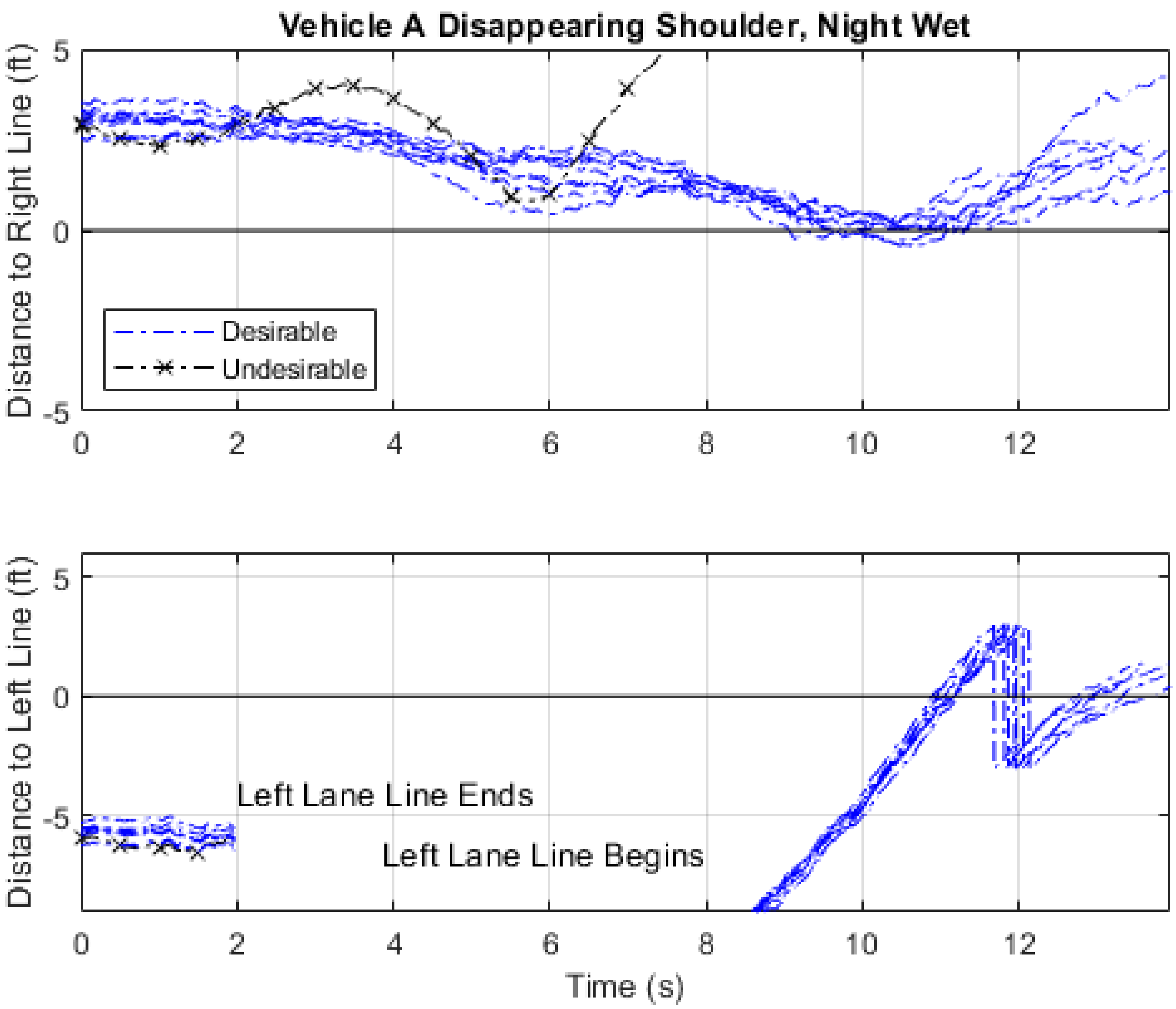

Figure 22. Plot. Distance from Vehicle A to the right and left lane lines for Pavement Markings with Disappearing Shoulder scenario during nighttime wet pavement conditions.

Source: FHWA

CHAPTER 5. WINTER FIELD TEST #2

One production vehicle with Society of Automotive Engineers (SAE) International Level 2[17] automation features and another vehicle equipped with prototype SAE International Level 3 automated driving system (ADS) features were used in the Winter Field Test 2 (FT#2). The test vehicles were driven through a planned variety of maneuvers during repeatable simulated and naturally occurring adverse weather conditions. This chapter presents details of Winter FT#2 and its results.

WINTER FT#2 HIGH-LEVEL TEST RESULTS

The following bullets present a high-level performance results summary for tested SAE International Level 2 and Level 3 vehicles while conducting Winter FT#2 under adverse weather conditions. A more detailed description of the testing and results conducted can be found in the subsequent sections of this chapter.

During Winter FT#2:

- The test vehicle with a multiple camera-based perception system (i.e., Winter FT#2 Vehicle A) experienced challenges during snow-covered road conditions to detect pavement markings, engage steering control, and perform the desired maneuver.
- The test vehicle with LiDAR and HD map-based perception system (i.e., Winter FT#2 Vehicle B) was able to detect the boundaries of a snow-covered travel lane and perform desired maneuvers efficiently, but experienced occasional localization loss under snow-covered road conditions.

These performance limitations in both test vehicles demonstrated the need for redundancy in perception, steering control, localization, braking, actuation, and other systems to successfully operate under winter weather, road, and environmental conditions.

Lane Keeping

- Snow-covered roads with tire ruts significantly affected the ability of Winter FT#2 Vehicle A to detect travel lanes, engage steering control, and maintain lane keeping.
- Winter FT#2 Vehicle A performed well under ice-covered road conditions.
- Winter FT#2 Vehicle B was not affected by winter conditions to maintain lane keeping.

Right Lane Change

- Winter FT#2 Vehicle A was not able to perform lane changes during snow-covered road conditions with tire ruts.
- During the snow-covered road conditions with tire ruts scenario, Winter FT#2 Vehicle B experienced an occasional loss of localization when performing a lane change.
- During the remaining winter conditions, both test vehicles successfully performed the lane change.

[17] https://www.sae.org/standards/content/j3016_202104/

Green at Signalized Intersection (Through and Left Turning Maneuvers)

- Winter FT#2 Vehicle A experienced deviations from the travel lane during all winter weather conditions.
- During snow-covered road conditions, Winter FT#2 Vehicle B experienced an occasional loss of localization when performing a left turn at the intersection.

Stopped Car Detection

- Winter FT#2 Vehicle A detected the stopped soft car and came to a complete stop without disengaging steering control under all weather conditions. Winter FT#2 Vehicle B was not used in this scenario.

WINTER FT#2 TEST CONDITIONS

Winter FT#2 Vehicles

The Winter FT#2 also used two vehicles. One test vehicle was equipped with SAE International Level 2 driving automation system, while the other non-commercially available vehicle was equipped with prototype SAE International Level 3 driving automation systems. Both test vehicles were tested in adverse weather conditions emulating snow- and ice-covered conditions on arterials and neighborhood roads. Different driving environments in winter FT#2 included signalized intersections, stopped vehicles, and missing/disappearing pavement markings.

Vehicles used for Winter FT#2 are listed in Table 8, along with their sensors and some of their driving automation systems. Vehicle names were anonymized to focus on capabilities and not the manufacturer, as these tests pushed the vehicles outside of standard ODD called out by the user manual.

Table 8. Winter FT#2 Test Vehicle capabilities.

Vehicle	Sensors	Driver Assistance Systems
Winter FT #2 Vehicle A (SAE International Level 2)	• Eight video cameras, including rear, side, and forward • Forward radar antenna • 12 ultrasonic sensors	• Adaptive Cruise Control (SAE International L1) • Traffic Jam Assist (SAE International L2) • Lane Centering Assist (SAE International L1)
Winter FT#2 Vehicle B (SAE International Level 3 Prototype)	• 2 HD Cameras • 1 360° LiDAR • 1 forward-facing and 2 rear corner radars	• Localization via LiDAR HD Map (SAE International L2) • Coordinated Path Following (SAE International L3 prototype)

Both ACC and LCA are Level 1 driving assistance systems, whereas LDW is a Level 0 driving assistance system. Winter FT#2 Vehicle A’s driving automation system design does not allow LCA to be engaged unless ACC is activated. This makes Winter FT#2 Vehicle A a SAE International Level 2 vehicle. TJA, which is a combination of ACC and LCA is also considered a SAE International Level 2 feature.

Winter FT#2 Test Track

The portion of the Smart Mobility Advanced Research and Test Center at TRC Inc. where Winter FT#2 tests were conducted is circled in Figure 5. Details of the portion of the Winter FT#2 test track where the tests occurred are shown in Figure 17. The Winter FT#2 test track is a six-lane 1.2-mile test track with a connected and signalized intersection.

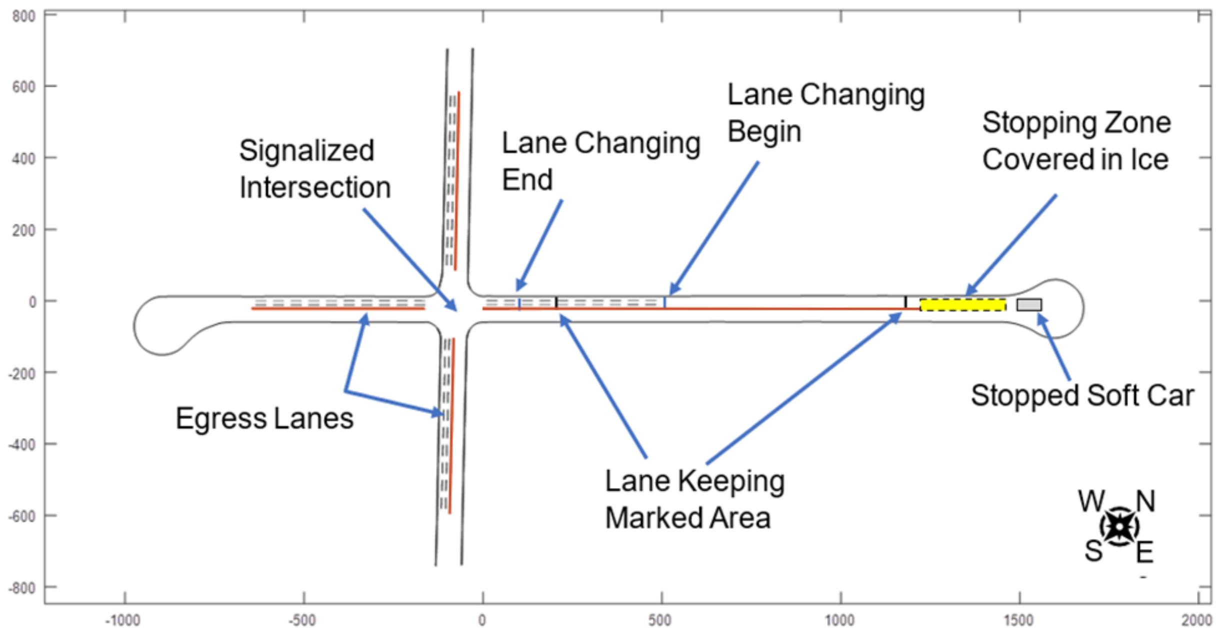

Figure 23. Graphic. Winter FT#2 Test Track

Source: FHWA

To ensure safety, all testing was performed on a closed track and testing activity was isolated through a combination of pre-scheduled facility requests, coordinated dispatch, and access controls.

Winter FT#2 Equipment

This equipment used for the Winter FT#2 included:

- **Weather Sensors:** A SunCalc tool was used to determine the sun angles. Weather applications on mobile phones were used for tracking outdoor temperature during field testing.
- **Snowplow:** A snowplow was used to move snow/ice around the track to create the test scenarios and replicate real-world snow/ice-covered road conditions.
- **Soft Car:** For safety considerations, a visually realistic soft car was used for the Stopped Car Detection scenario. Figure 24 presents a side view of the soft car used for testing.

Figure 24. Photo. Soft Car used for Stopped Car Detection scenario in the Winter FT#2.

Source: FHWA

Winter FT#2 Weather Conditions

The project team relied on artificially simulated and naturally occurring adverse weather conditions to challenge the test vehicles' control and perception system across both field tests.

The Baseline road conditions had smooth pavement, with unmarked shoulder transitioning to gravel. The vehicle stayed one lane away from shoulder during testing. There were no raised curbs or medians. With an ice-covered or wet road surface on the test facility roadway, friction is less than ideal. The vehicles were not driven at speeds or curvatures that challenged the tires' ability to grip the road or engage dynamic stability control, except for the Stopped Soft Car scenario with an Ice-Covered Lane. The tests were intended to challenge the perception systems, not the yaw stability systems. Slippery surfaces were not a test condition.

Baseline

All driving scenarios across both field tests were tested under Baseline weather conditions. The selected weather conditions for Baseline criteria included ambient air temperatures between 20°F and 100°F, peak wind speeds below 22.4 mph, sun position greater than 15° above the horizon, ambient illumination greater than 2,000 lux[18], and dry and clear pavement. Figure 25

[18] Illuminance greater than 2,000 lux represent ambient daylight conditions with clear sky.

shows the Baseline weather conditions from the test vehicle's point of view from one of the Winter FT#2 test runs.

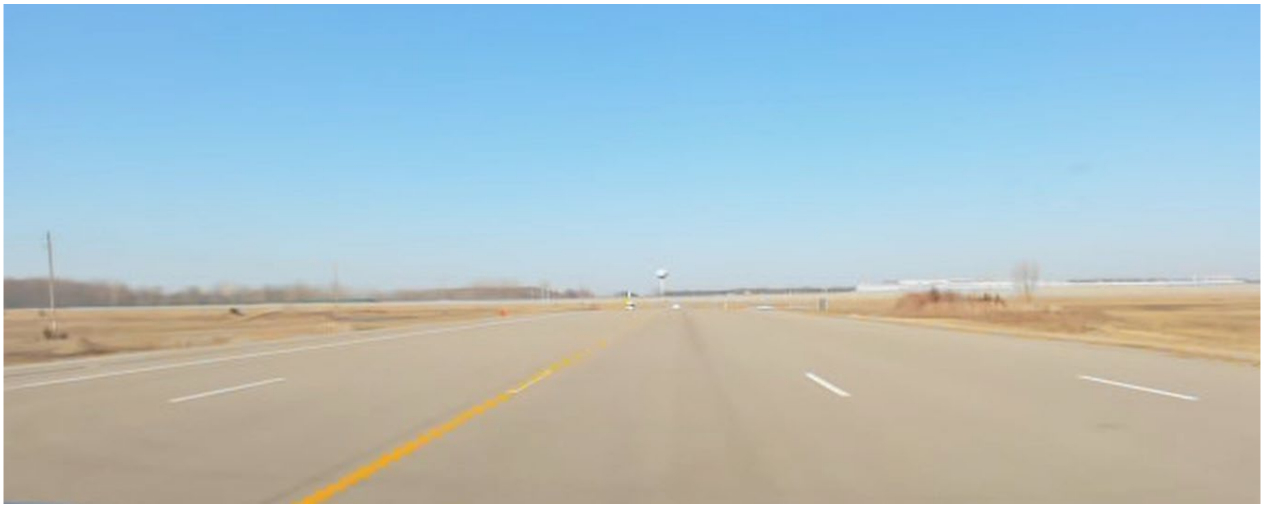

Figure 25. Photo. View from a vehicle depicting the Baseline weather conditions.

Source: FHWA

Various winter weather road conditions were simulated on the TRC test track for the Winter FT#2. For comparison, each vehicle was initially tested under Baseline conditions before the vehicles were tested under the various winter weather conditions where the vehicles were tasked to maneuver different driving scenarios. The following sections summarize the conditions produced or experienced during the Winter FT#2.

Snow- and Slush-Covered

To best replicate winter weather road conditions, tests were conducted at or below freezing temperatures ranging between 0- and 32-degrees Fahrenheit. The snow accumulation varied by the day, with an average between 3 and 6 inches. Natural snow was used to simulate various roadway conditions that may be encountered in actual driving conditions. At the start of non-Baseline test runs, the roadway was covered in snow, which was removed as needed to create tire ruts, reduced width lanes, partially plowed lanes with pavement markings covered, and slush-covered road surfaces. Figure 26 shows the snow-covered roadway.

Figure 26. Photo. View from a vehicle depicting a snow-covered roadway.

Source: FHWA

Ice Covered

Ice naturally occurred on the test track and was used for testing. To best replicate winter weather road conditions, tests were conducted at or below freezing temperatures ranging between 0- and 32-degrees Fahrenheit. The friction on this stretch of road was reduced enough to cause the Anti-lock Braking System (ABS) to engage under normal braking. Figure 27 shows an ice-covered roadway.

Figure 27. Photo. View from a vehicle depicting an ice-covered roadway.

Source: FHWA

Tire Ruts

After snow had accumulated, a test vehicle drove along the track forming tire ruts in the snow approximately the width of the test vehicle's tires. Under this condition, the pavement markings remained covered in snow. Tire ruts were used in scenarios tested on February 3 and February 4 between 1300 and 1600 EST. Figure 28 shows snow-covered roadway with tire ruts.

Figure 28. Photo. View from vehicle depicting a snow-covered roadway with tire ruts.

Source: FHWA

Plowed Lane

A snowplow was driven on the snow-covered lane to create a plowed travel lane for testing. The plowed lane was approximately the width of the snowplow, with the pavement markings remaining covered. A plowed lane was used in scenarios tested on February 4 and February 19 between 1300 and 1700 EST. Figure 29 shows a snow-covered travel lane plowed to vehicle width.

Figure 29. Photo. View from vehicle depicting a travel lane plowed to vehicle width with snow-covered pavement markings.

Source: FHWA

Winter FT#2 Scenarios Tested

Four different driving scenarios were designed and executed to test the vehicles' perception systems under different winter road weather conditions. Figure 30 lists the different driving scenarios and road weather conditions that were tested. The driving scenarios are: 1) Lane Keeping, 2) Right Lane Change, 3) Green at Signalized Intersection, and 4) Stopped Car Detection. All scenarios were tested under Baseline conditions: clear, daytime, dry roadway. Lane Keeping, Right Lane Change, and Green at Signalized Intersection scenarios were tested under snow-covered and plowed roadway conditions. Lane Keeping and Stopped Car Detection scenarios were tested under ice-covered roadway conditions. The first three scenarios were focused on testing the lane detection and tracking system of the AVs, and the last scenario was focused on detecting a stopped car—all under adverse winter road weather conditions. Seven test runs were conducted for each scenario and condition combination.

Scenario	Conditions				Notes
Lane Keeping	**Baseline**	**Tire Ruts**	**Plowed Lane**	**Covered in Ice**	
Number of runs	7	7	7	7	With steering control engaged, the vehicle will drive straight in a lane. ACC was always on for Vehicle A. Vehicle B does not have the ACC feature.
Right Lane Change	**Baseline**	**Between Ruts**	**Clear to Ruts**		
Number of runs	7	7	7		With steering control engaged, the vehicle will be commanded to change lanes to the right. ACC was always on for Vehicle A. Vehicle B does not have the ACC feature.
Green at Signalized Intersection	**Baseline**	**Clear to Ruts Exiting Roadway**	**Clear to Patchy Slush Covered Intersection**	**Covered/Ruts to Covered/Ruts**	
Number of runs (*Vehicle A – Through at Intersection*)	7	7	7	7	With steering control and ACC engaged, the vehicle will be commanded to make a through maneuver at an intersection with a green light (no stopping).
Number of runs (*Vehicle B – Left Turn at Intersection*)	7	7	7	7	With steering control engaged, the vehicle will be commanded to turn left at an intersection. Vehicle B does not have the ACC feature.
Stopped Car Detection	**Baseline**	**Ice-Covered Lane**			
Number of runs (Vehicle A – *Stop at Soft Car*)	7	7			With steering control and ACC engaged, the vehicle will be commanded to make a through maneuver on a lane with a stopped vehicle (soft car).

Figure 30. Graphic. Scenarios, conditions, and number of test-runs to evaluate performance of AVs during winter road weather conditions.

Source: FHWA

Lane Keeping

The objective of the Lane Keeping scenario was to emulate driving on a roadway with pavement markings covered by either snow or ice, and test whether the lane-keeping system of AVs would keep the vehicle within the lane markings. The winter road weather conditions for this scenario were a Baseline of clear weather conditions, Snow Tire Ruts, Snow Plowed Lane, and Lane Covered in Ice. The test area was a straight road section about 1,500 feet in length. To obtain the desired road weather conditions, the location and travel direction of the test area used for Lane Keeping scenario varied. Most tests for the Lane Keeping scenario were performed on Lane 3 heading westbound. Lane 3 was chosen because one of the lane markings on that lane is orange, which would easily activate the lane keeping system of the AVs. For the Lane Keeping scenario under Covered in Ice conditions, tests were performed on Lane 3 heading eastbound since it offered the best ice-covered roadway conditions. During each test run, the test vehicles proceeded through the marked area. The desired performance was for the vehicles to maintain their traveled lane without drifting to either side of the lane, disengaging the steering wheel, or returning control to the human driver. When the vehicle's perception system recognized that the test conditions are outside its ODD, the expected action was for the vehicle to disengage LCA and return control to the human driver. If the vehicle took aggressive action, then the test drivers took control of the vehicle and steered into a safe path (this happened mainly with Winter FT#2 Vehicle A). Figure 31 shows the location and layout of the road section used to conduct the Lane Keeping scenarios.

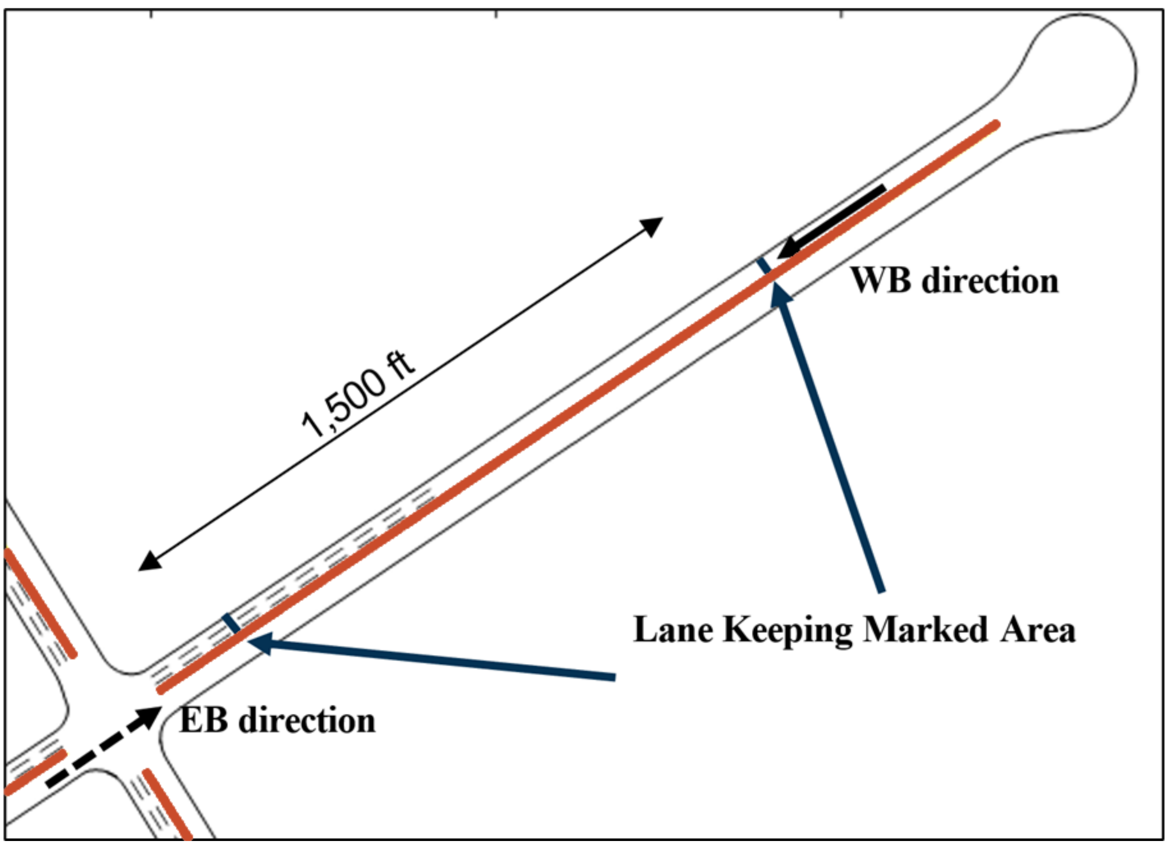

Figure 31. Graphic. Lane configuration used for the Lane Keeping scenario.

Source: FHWA

Right Lane Change

The objective of Right Lane Change scenario was to emulate driving on an exit ramp from the highway main line under two different winter road weather conditions relative to the Baseline of clear road weather condition. The winter road weather conditions considered were driving Between Ruts and driving from Clear to Ruts. The test area was a straight road section about 500 feet long. To create tire ruts, multiple test vehicle passes were performed on the snow-covered lanes prior to the test runs. Similarly, to create a plowed lane, a single snowplow pass was performed on the snow-covered lane prior to the test runs, which resulted in a one-vehicle-width cleared section of the lane, and the pavement markings remained covered in snow. The Right Lane Change scenarios were tested on lanes 2 and 3 at the track with the test vehicles heading in the westbound (entering) direction. Each condition was tested for seven runs. During each run, the test vehicles proceeded through the marked area where the desired maneuver was for the vehicle to successfully change a lane to the right. With the steering control engaged, the vehicle was commanded to change a lane to the right. The desired performance was for the vehicles to smoothly and timely complete the lane change without disengaging the steering control, losing localization, or returning control to the human driver. Figure 32 shows the location and layout of the Right Lane Change scenarios.

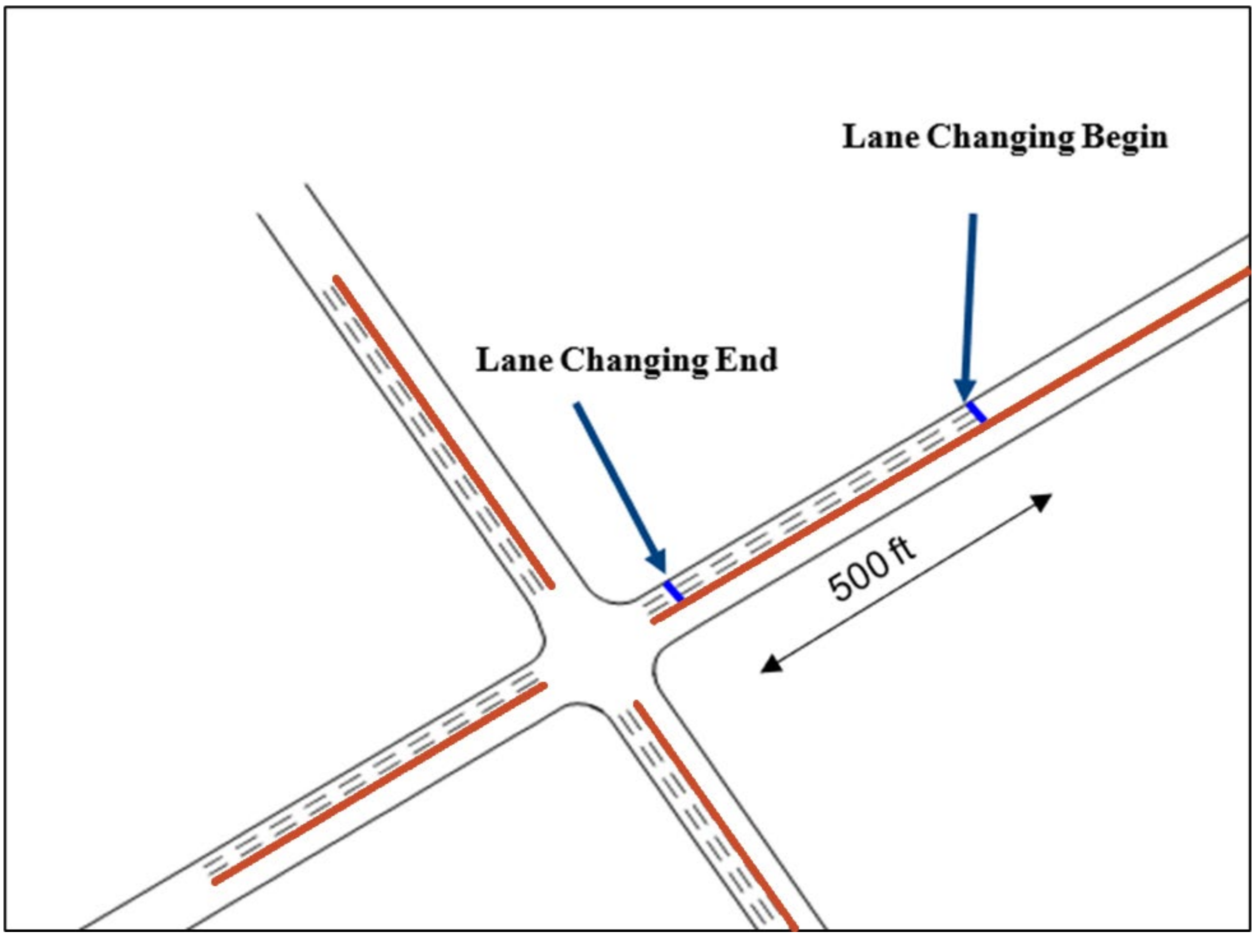

Figure 32. Graphic. Location and lane configuration used for Right Lane Change scenarios.

Source: FHWA

Green at Signalized Intersection

The objective of the Green at Signalized Intersection scenario was to emulate the through and left-turn movements of AVs at a signalized intersection during winter road weather conditions. Based on the turning movement at the intersection, this scenario was further subdivided into two types: 1) Through Maneuver and 2) Left Turning Maneuver.

Through Maneuver during Green at Signalized Intersection (Vehicle A)**:**

Two lane configurations were used for emulating Through Maneuver during Green at Signalized Intersection scenario at the test track. The first lane configuration had the test vehicle heading in the westbound direction in lane 3, then the vehicle continued through the intersection, and remained in lane 3 heading in the westbound direction through and past the intersection. This lane configuration was used to conduct the Green at Signalized Intersection scenario under the Baseline condition, driving from Clear to Patchy Slush-Covered Intersection condition, and driving from Snow-Covered/Ruts lane to Snow-Covered/Ruts lane. The second lane configuration had the test vehicle heading northbound in lane 3, then remain in the same lane, still heading northbound through and past the intersection. This lane configuration was used to emulate driving from Clear to Ruts conditions at an intersection exit:

- To create tire ruts, multiple test vehicle passes were performed on the snow-covered lanes prior to the test runs.
- To create slush conditions, the road surface was initially rutted, then with the temperature warming up, the snow and tire ruts melted to create a slush pavement surface.

Vehicle A was used to test the effect of winter road weather conditions on through maneuvers at a signalized intersection at an approach speed of 45 mph (representative of an intersection on arterial roads). For this scenario, the desired outcome was for the vehicle to complete the through maneuvers from the designated lane at the approach of the intersection to the same destination lane while in and through the intersection. If the vehicle drifted either right or left, disengaged the steering control, lost localization, or returned control to the human driver while making the through movement, it was considered an undesirable test. Figure 33 shows the location and layout of the road section used for Green at Signalized Intersection scenario.

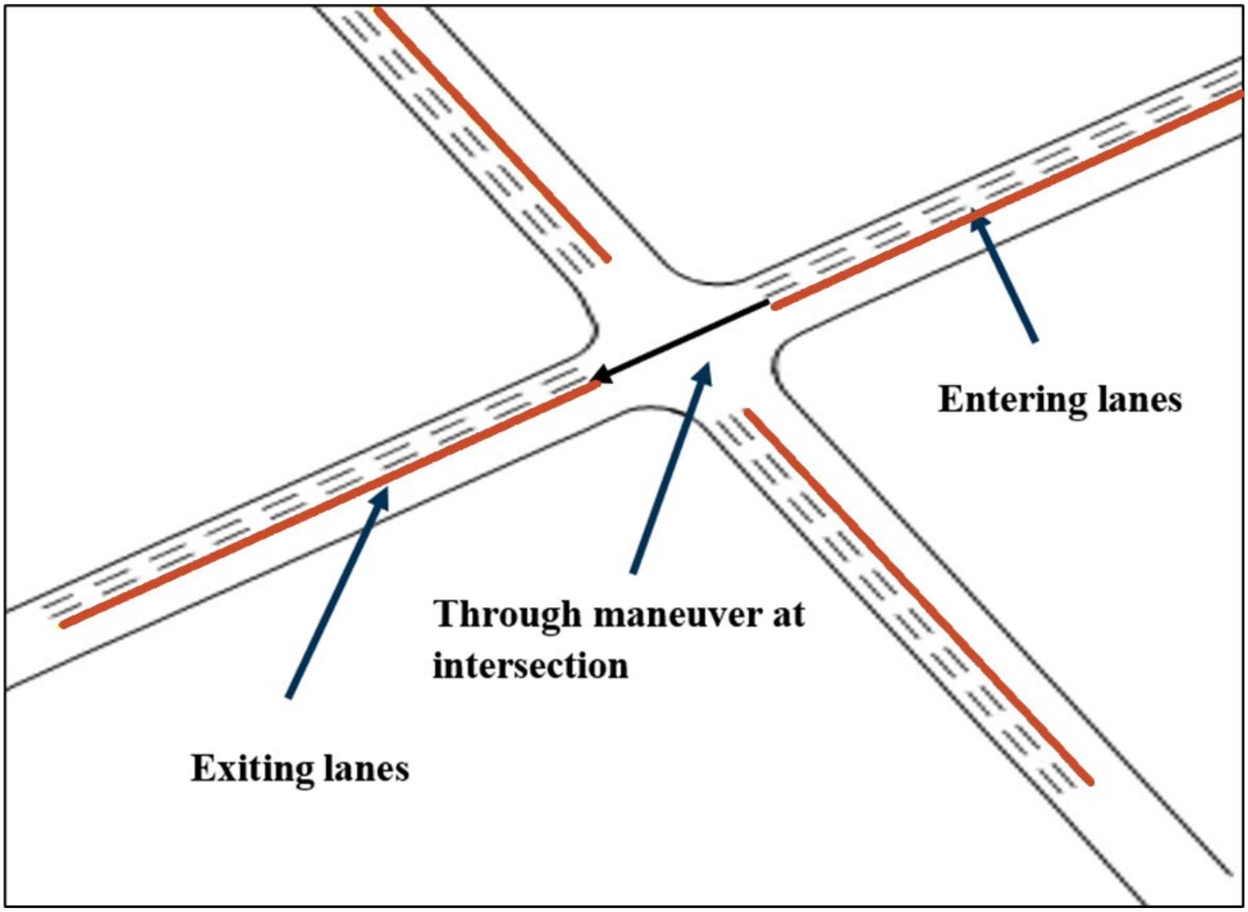

Figure 33. Graphic. Location and lane configuration used for the Through Maneuver during Green at Signalized Intersection scenario.

Source: FHWA

Left Turning Maneuver during Green at Signalized Intersection (Vehicle B):

The objective of the test was to determine if the test vehicle was able to successfully complete a left turning maneuver at an intersection. Vehicle B was used to test the effect of winter road weather conditions on left turn maneuvers at signalized intersections. Vehicle B was used because of its ability to follow a pre-programmed path. This scenario was designed to emulate a signalized intersection on a local street (speed limit of 25 mph). The test setup and lane configuration used for Left Turning Maneuver during Green at Signalized Intersection were approaching from lane 2 or 3 in the westbound (entering) direction then turning left into lane 3 in the southbound direction on the exiting road. The winter road weather conditions considered were Baseline condition of dry and clear road weather, driving from Clear to Patchy Slush-Covered Intersection road condition, driving from Snow-Covered/Ruts lane to Snow-Covered/Ruts lane, and driving from Clear to Ruts conditions at an intersection exit. For this scenario, the desired outcome was that the vehicle completed the left turning maneuvers from the designated lane at the westbound approach of the intersection to the destination lane at the southbound exit of the intersection. If the vehicle drifted to either right or left of the intended destination lane, disengaged the steering control, lost localization, or returned control to the human driver while making the left turning maneuver, it was considered an undesirable test run.

Figure 34 shows the location and layout of the road section used for testing the Left Turning Maneuver during Green at Signalized Intersection.

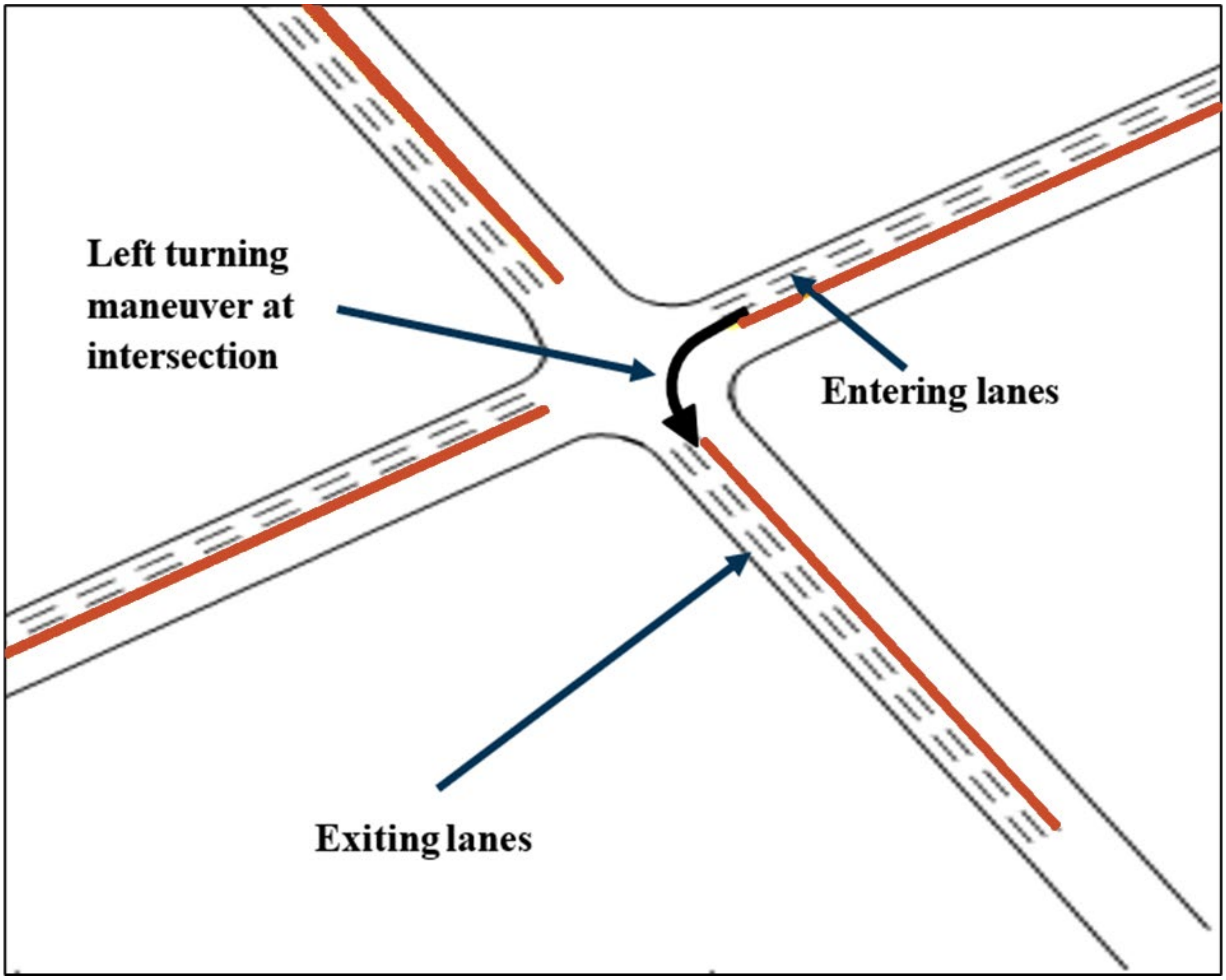

Figure 34. Graphic. Location and lane configuration used for the Left Turning Maneuver during Green at Signalized Intersection scenario.

Source: FHWA

Stopped Car Detection

The objective of this scenario was to determine if the perception system of AVs could detect a stopped car in an ice-covered stopping zone and come to a timely and complete stop without deviating from the traveled lane, skidding, or making contact with the stopped vehicle. For safety considerations, the vehicle to be detected was a visually-realistic soft car instead of a real car. This scenario was tested under Baseline and Ice-Covered Road conditions. The test track used for the Stopped Car Detection scenario runs was lane 3 on eastbound direction of the test track. For the Ice-Covered Road conditions, the adjacent travel lanes were covered with snow and the area where the soft car was located was covered by ice. Only Vehicle A was used for this scenario, since only Vehicle A has a perception system that could detect a stopped car. The desired performance was that when Vehicle A approached the stopped car located downstream of the traveled lane, it should be able to detect or recognize the stopped car and come to a complete stop at a safe distance from the soft car without deviating or skidding from the traveled lane. The approach speed of Vehicle A was 25 mph, which emulates the speed limit of residential streets. Figure 35 and Figure 36 show the test setup and lane configuration where the Stopped Car Detection scenario were performed.

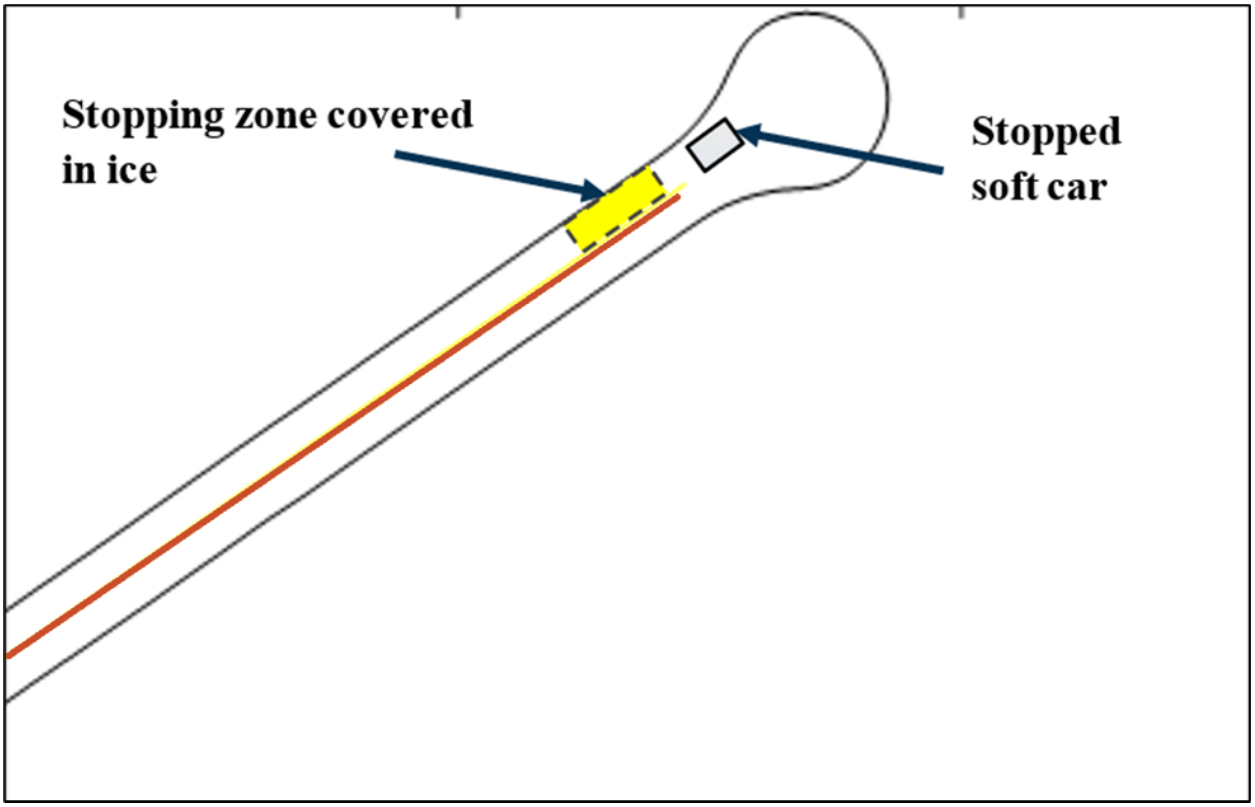

Figure 35. Graphic. Location and lane configuration used for Stopped Car Detection scenario.

Source: FHWA

Figure 36. Photo. Ice-covered stopping zone on the travel lane of Vehicle A and stopped soft car.

Source: FHWA

It is worth noting that the test plan was designed so that the test team would continue collecting data even after a test vehicle deviated from the intended path for all scenarios. Continuing to collect data enabled the test outcomes for AVAW3 to have enough data for thorough evaluation of the results, leading to a more robust understanding of test vehicles' perception systems.

WINTER FT#2 RESULTS

Lane Keeping

Desired Outcome: The desired performance was for the vehicles to maintain lane keeping/to stay within the pavement markings (and not follow the edge of the pavement/plowed snow line) without drifting to either side of the lane or the vehicle's lane keeping system disengaging or returning control to the human driver.

- Winter FT#2 Vehicle A stayed within the pavement markings for three of the four conditions (i.e., except for the test runs of under Tire Ruts conditions, in which it repeatedly was unable to engage the steering control).

- Winter FT#2 Vehicle B stayed within the pavement markings during all four conditions and test runs, except for one test run under the Tire Ruts condition when it lost localization.
- Winter FT#2 Vehicle B's performances when driving on adverse winter road weather conditions were much better because its navigation system is based on LiDAR and HD map as opposed to a navigation and perception system that is camera-based, which is what Winter FT#2 Vehicle A uses.

A high-level summary of findings for the Lane Keeping scenario for both test vehicles is shown in Table 9.

Table 9. Test results for Lane Keeping scenario.

Condition	Vehicle	Number of runs	Maintained lane keeping	Deviated from the desired path*	Disengaged steering control/lost localization	Did not engage steering control
Baseline	A	7	7	N/A	N/A	N/A
	B	7	7	N/A	N/A	N/A
Tire Ruts	A	7	0	N/A	N/A	7
	B	7	6	1	1	N/A
Plowed Lane	A	7	7	N/A	N/A	N/A
	B	7	7	N/A	N/A	N/A
Covered in Ice	A	7	7	N/A	N/A	N/A
	B	7	7	N/A	N/A	N/A

* Critical deviation is greater than 2.8 feet from the centerline of the desired path

Baseline

Both test vehicles were able to maintain lane keeping during all runs under Baseline conditions. No critical deviations or steering control disengagements were observed in this condition.

Tire Ruts

- Winter FT#2 Vehicle A was not able to perform the Lane Keeping under Tire Ruts scenario because the steering controls were not able to engage, as the vehicle's perception system was not able to clearly detect the lane markings. This could be because the lane markings were covered by snow and thus there was not sufficient contrast for them to be easily detected. Based on the findings, it was evident that Winter FT#2 Vehicle A's perception system needs a clear lane marking reference to initialize the steering control, which was not possible under this condition.
- Before entering the test area, Winter FT#2 Vehicle B's steering controls were engaged. It approached the test area of the road condition with Tire Ruts (Lane 3 on westbound exit roadway) at a speed of 15 mph. Although there were multiple tire ruts on the snow-covered test area, Winter FT#2 Vehicle B was able to successfully keep its lane in six of the seven test runs. The only time Winter FT#2 Vehicle B was unable to maintain lane keeping under the Tire Ruts condition was when it lost localization.
- In comparison with Winter FT#2 Vehicle A, Winter FT#2 Vehicle B performed better driving under the Tire Ruts road weather conditions because its navigation system did not depend on tracking pavement markings but instead used LiDAR localization.

Winter FT#2 Vehicle B had the capability to follow a pre-programmed path. The difference between the vehicle's perceived location in the HD map compared to the pre-programmed path can provide additional information on how well the vehicle is localizing and is following the intended path. Figure 37 shows Winter FT#2 Vehicle B's deviations from the pre-programmed path during Lane Keeping scenario under Tire Ruts conditions. The only test run where Winter FT#2 Vehicle B did not keep its lane when driving under Tire Ruts conditions is shown by the sudden drop in distance to the path (black line with "x" symbol) in Figure 37. For this one run with undesirable results, the actual deviation of Winter FT#2 Vehicle B was close to five feet from the centerline of the intended path. However, due to loss of localization, Winter FT#2 Vehicle B perceived that its location was off by more than 80 feet. Adding sensing equipment that provides redundant data would allow the test vehicle to validate the findings and perform more informed decision-making.

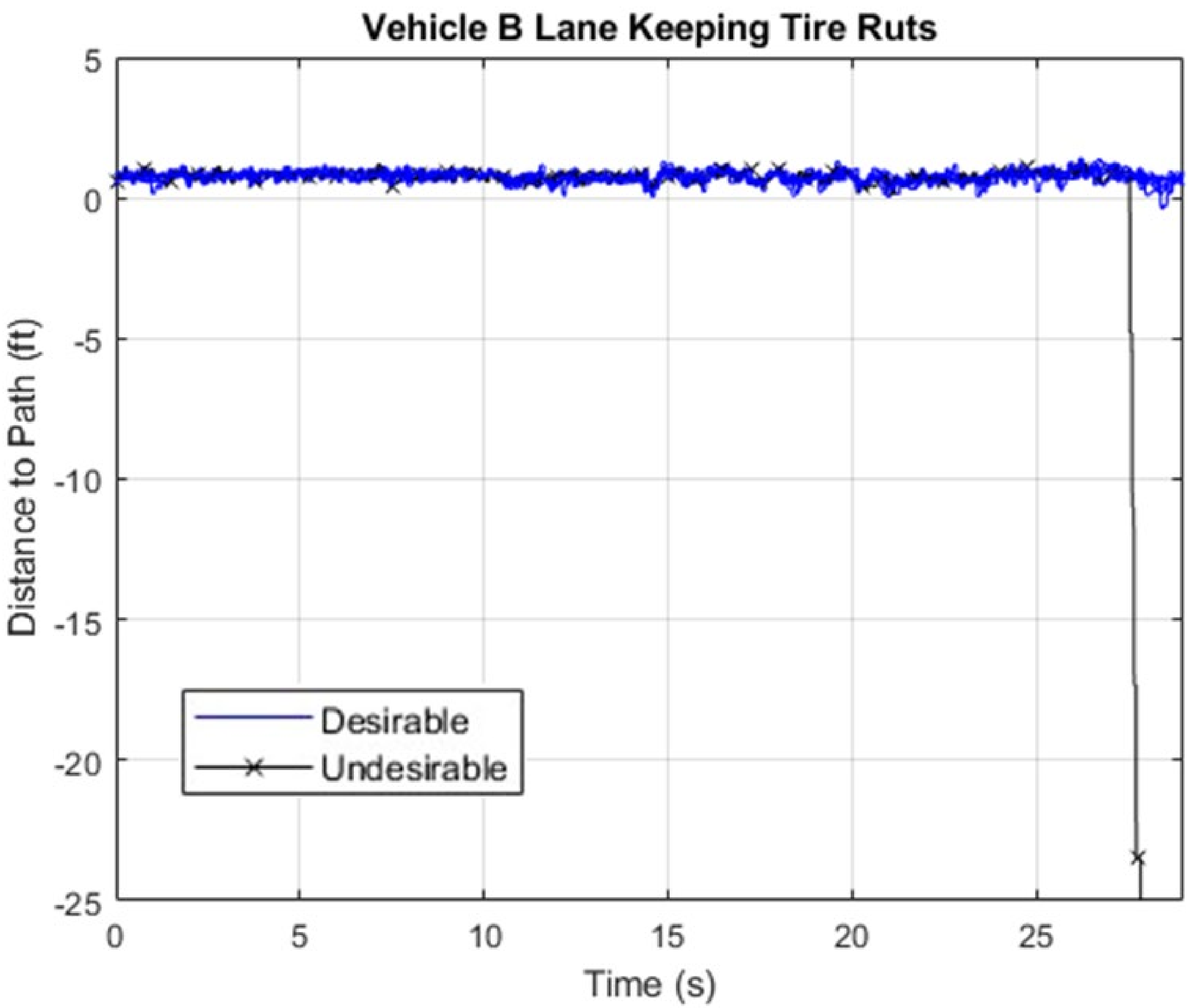

Figure 37. Graph. Winter FT#2 Vehicle B's deviations from pre-programmed path during Lane Keeping scenario under Tire Ruts conditions.

Source: FHWA

Plowed Lane

Similar to Baseline conditions, both test vehicles were able to successfully perform all test runs under Plowed Lane condition.

Covered in Ice

In this scenario, both test vehicles were able to successfully keep their lane as they traveled on the Covered by Ice. The test vehicles did not critically deviate (>2.8 feet) from their traveled lane.

During this condition:

- Winter FT#2 Vehicle A initially moved to the right around a point where the plowing pattern changed and later to the left, but all deviations were within the allowable limit.

There was a constant deviation of Winter FT#2 Vehicle A to the right of the centerline at the 7 second intervals for all runs. This deviation might be due to the plowed lane being perpendicular to the travel lane that starts at the 7 second interval followed by the snow melts located parallel to the travel lane until the 12 second time interval (Figure 38). Winter FT#2 Vehicle A appeared to have perceived the area at the plowed perpendicular lane to be a wider travel lane and started deviating marginally to the left (Figure 39). The snow melts parallel to the travel lane might have contributed to the continued leftward deviation of Winter FT#2 Vehicle A.

- After Winter FT#2 Vehicle A crossed snow melts, more uniform plowing was observed, and it re-centered itself to the centerline of the travel lane.

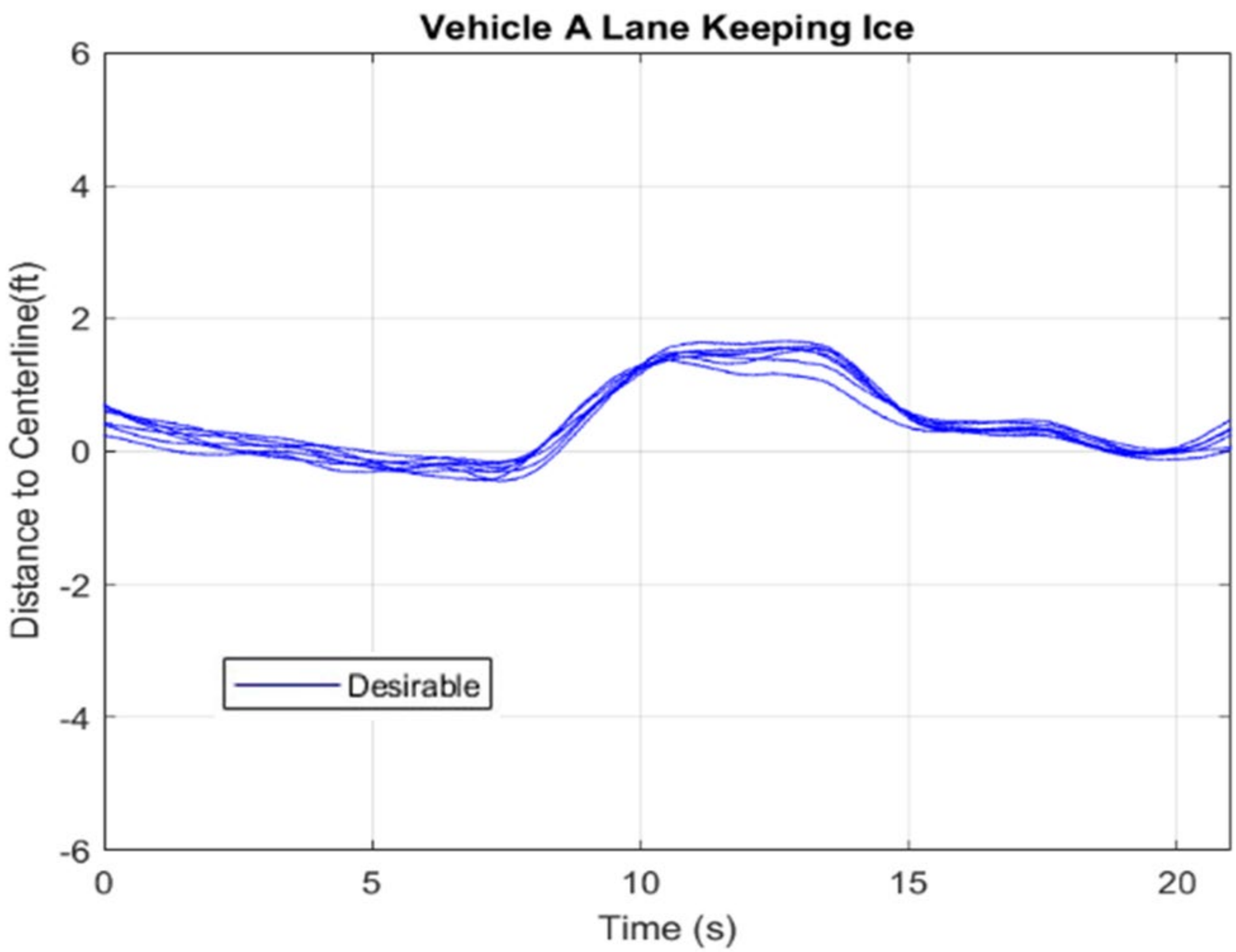

Figure 38. Graph. Winter FT#2 Vehicle A's deviations during Lane Keeping scenario under Covered in Ice conditions.

Source: FHWA

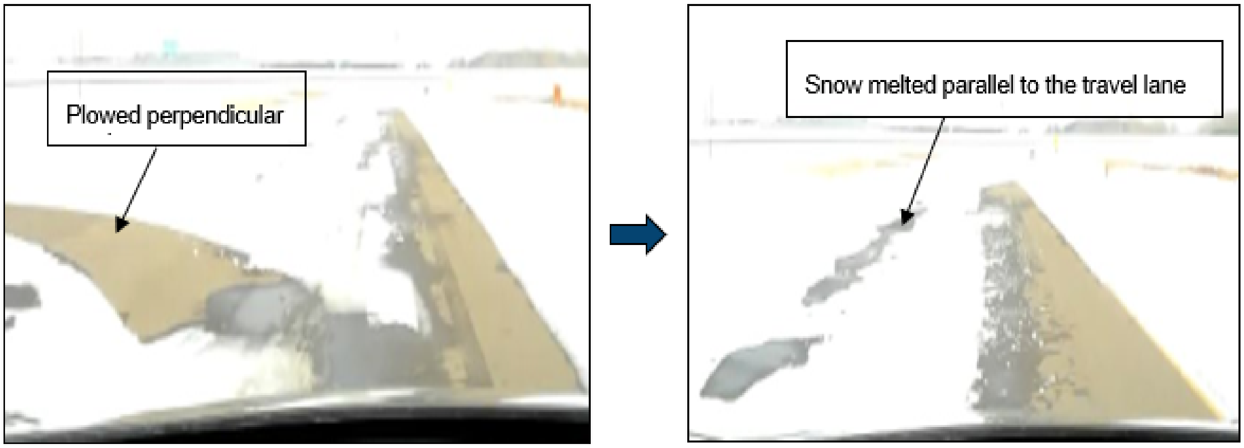

Figure 39. Photo. Westbound Exiting Lane 3 under Covered in Ice condition with plowed perpendicular road (left) and snow melts parallel to the travel lane (right)

Source: FHWA

Right Lane Change

Desired Outcome: Both test vehicles should be able to smoothly and efficiently complete the right lane changes during a Baseline of clear road weather condition as well as when driving Between Ruts and when driving from Clear to Ruts without disengaging the steering control, losing localization, or returning control to the human driver.

Winter FT#2 Vehicle A's performance on Right Lane Change was as desired during Baseline conditions, but its performance declined when changing lane from Clear to Ruts (because it significantly drifted from the intended path) and when changing lane in Between Ruts and snow-covered conditions (because its steering control was not engaged). The performance of Winter FT#2 Vehicle B was as desired, except for the one test run where it lost localization when changing a lane in Between Ruts and Snow-Covered condition.

The main findings from the test runs under the Right Lane Keeping scenario were:

1) Winter FT#2 Vehicle A's performance was not as desired during lane change when there was snow and tire ruts on the approach or destination lanes.
2) Winter FT#2 Vehicle B's performance when driving on adverse winter road weather conditions was much better because its navigation system is based on LiDAR and HD map, as opposed to a navigation and perception system that is camera-based (which Winter FT#2 Vehicle A uses).

Based on the test results, it seems that both test vehicles can benefit by adding multiple components to the driving assistance systems that perform the same function (e.g., lane detection, path projection) and provide redundant data. These redundant data would help ensure the accuracy of decision-making of the test vehicles when assessing weather conditions and performing maneuvers. A summary of the results for Right Lane Change scenario runs is shown in Table 10.

Table 10. Test results for Right Lane Change scenario.

Condition	Vehicle	Number of runs	Performed lane change	Deviated from the desired path*	Disengaged steering control / lost localization	Did not engage steering control
Baseline	A	7	7	N/A	N/A	N/A
	B	7	7	N/A	N/A	N/A
Between Ruts	A	7	0	N/A	N/A	7
	B	7	6	N/A	1	N/A
Clear to Ruts	A	7	0	7	N/A	N/A
	B	7	7	N/A	N/A	N/A

* Critical deviation of greater than 2.8 feet from the centerline of the desired path

Baseline

In this condition, both Winter FT#2 test vehicles performed Right Lane Changes without any critical deviations for all runs during Baseline condition. No steering control disengagements or localization loss were observed during this condition.

Between Ruts

Winter FT#2 Vehicle A was not able to perform the Right Lane Change under Tire Ruts scenario because the steering controls were not able to engage. The reason is that Winter FT#2 Vehicle A's perception system was not able to clearly detect the lane markings. This could be because the lane markings were covered by snow and thus there was not sufficient contrast for them to be easily detected. Based on Winter FT#2 Vehicle A's performance under driving Between Ruts conditions, it is evident that Winter FT#2 Vehicle A's perception system needs a clear lane marking reference to initialize the steering control, which was not possible under this condition. Also, the tire ruts condition may have confused the vehicle's perception system by completely covering the roadway and the pavement markings, which led to the failed engagement of the steering control.

Out of the seven test runs, Winter FT#2 Vehicle B was able to successfully perform six Right Lane Change runs under the Between Ruts condition. Only one time did Winter FT#2 Vehicle B's steering control disengage due to lost localization at the beginning of the test run. After completing the Right

Lane Change scenario runs, Winter FT#2 Vehicle B slightly swerved to the right of the travel lane due to varying depths of snow, but quickly adjusted back to within the travel lane.

Clear to Ruts

During Clear to Ruts conditions:

- Winter FT#2 Vehicle A excessively deviated from the traveled lane when changing a lane to the right with steering controls engaged. When attempting to change lanes from Clear to Ruts condition, Winter FT#2 Vehicle A was straddling between the lanes (i.e., continued to travel between the plowed and snow-covered lanes). The erroneous path projection of Winter FT#2 Vehicle A could have resulted from its perception system not being able to clearly detect the lane markings.
- Winter FT#2 Vehicle B successfully performed right lane changes without any critical deviations.

Green at Signalized Intersection (Through and Left Turn)

Desired Outcome: The test vehicle should be able to successfully complete Through (for Winter FT#2 Vehicle A) and Left Turn (for Winter FT#2 Vehicle B) movements at a signalized intersection under various road weather conditions without drifting, disengaging the steering control, losing localization, or returning control to the human driver.

Through Maneuver: Winter FT#2 Vehicle A's consistently performed the Through Maneuver during Green at Signalized Intersection scenario without any deviations during Baseline conditions. However, it significantly deviated from the desired path for all Through Maneuvers when driving from Clear Intersection to Ruts Exiting Roadway and Clear to Patchy Slush-Covered Intersection. During Through Maneuver when driving from Covered/Ruts to Covered/Ruts, Winter FT#2 Vehicle A's steering control was not engaged. Overall, Winter FT#2 Vehicle A was challenged to successfully complete the Through Movement under adverse winter road weather conditions.

A Summary of the results for the through maneuver for Winter FT#2 Vehicle A during Green at Signalized Intersection scenario is shown in Table 11.

Table 11. Test results for Through Maneuver during Green at Signalized Intersection scenario (Winter FT#2 Vehicle A).

Condition	Vehicle	Number of Runs	Performed Through Maneuver	Deviated from the Desired Path*	Disengaged Steering Control	Did not engage Steering Control
Baseline	A	7	7	N/A	N/A	N/A

Condition	Vehicle	Number of Runs	Performed Through Maneuver	Deviated from the Desired Path*	Disengaged Steering Control	Did not engage Steering Control
Clear Intersection to Ruts Exiting Roadway	A	7	0	7	N/A	N/A
Clear to Patchy Slush-Covered Intersection	A	7	0	7	N/A	N/A
Covered/Ruts to Covered/Ruts	A	7	0	N/A	N/A	7

* Critical deviation of greater than 2.8 feet from the centerline of the desired path

Left Turn Maneuver: Winter FT#2 Vehicle B successfully performed all test runs on Left Turning Maneuver during Green at Signalized Intersection during Baseline condition and when turning from Clear Intersection to Ruts Exiting Roadway scenario. Winter FT#2 Vehicle B also successfully performed six of the seven test runs emulating the conditions turning left maneuver when driving from Clear to Patchy Slush-Covered Intersection and when driving from Covered/Ruts to Covered/Ruts. Winter FT#2 Vehicle B lost localization and deviated from the desired path during the two unsuccessful left turning maneuvers.

The main findings from the test runs when emulating Through and Left Turning maneuvers during Green at Signalized Intersection are:

1) Through Maneuver: Winter FT#2 Vehicle A's performance was not as desired when there was snow and tire ruts on the entering and exiting roads of the intersection, as it was unable to maintain the intended lane.
2) Left Turn Maneuver: Winter FT#2 Vehicle B's performance on intersection turning movements during adverse winter road weather conditions was much better because its navigation system is based on LiDAR and HD map as opposed to navigation and perception system that is camera-based but remained inconsistent.

By adding redundancy (i.e., adding multiple components that perform the same or similar functions such as lane detection, obstacle detection, and improved path projection) to their driving assistance systems, Winter FT#2 Vehicle A and Winter FT#2 Vehicle B are likely to have performed as desired. These redundant sensors or systems provide additional data that can be used to validate the sensor perceptions and aid in enabling the vehicle's systems in making more confident decisions during adverse road weather conditions and when performing maneuvers. Table 12 shows a summary of the test results for the Left Turning Maneuver during Green at Signalized Intersection scenario for Winter FT#2 Vehicle B..

Table 12. Test results for Left Turning Maneuver during Green at Signalized Intersection scenario.

Condition	Vehicle	Number of runs	Performed Left Turn Maneuver	Deviated from the Desired Path* / Lost Localization	Disengaged Steering Control
Baseline	B	7	7	N/A	N/A
Clear Intersection to Ruts Exiting Roadway	B	7	7	N/A	N/A
Clear to Patchy Slush-Covered Intersection	B	7	6	1	N/A
Covered/Ruts to Covered/Ruts	B	7	6	1	N/A

Baseline

Winter FT#2 Vehicle A and Winter FT#2 Vehicle B performed the Through and Left Turn maneuvers, respectively, during Green at Signalized Intersection under the Baseline condition without any critical deviations or steering control disengagements.

Clear Intersection to Ruts Exiting Roadway

Winter FT#2 Vehicle A approached the cleared entering intersection at 25 mph and performed the through maneuver on a snow-covered intersection with the steering control engaged. As the vehicle approached the exit lane, sudden braking occurred on multiple runs. In addition, it was misled by a ridge of snow, and traveled into a neighboring lane by perceiving it as the new roadway surface. Therefore, Winter FT#2 Vehicle A was not able to successfully perform the Through Maneuver during Green at Signalized Intersection scenario. The test team determined that the vehicle made a sound decision in not entering the ridge of snow, but changing lanes and drifting was viewed as potentially dangerous in snow-covered areas. This determination was made based on the testing conditions where there was no cleared path to make through maneuver and the height of the snow would have created an unsafe condition given the low ground clearance of Winter FT#2 Vehicle A. Figure 40 shows photos of Winter FT#2 Vehicle A's path during this test. When traversing the intersection from Clear Intersection to Ruts Exiting Roadway scenario, Winter FT#2 Vehicle A displayed a sudden drop in speed from 11 m/s (25 mph) to 4 m/s (9 mph) within the intersection and accelerated back to 11 m/s (25 mph) after it crossed the intersection. Also, Winter FT#2 Vehicle A veered to the left from the centerline of lane 3 (intended lane) along the intersection and ended up in exit lane 2 when traversing the intersection from Clear Intersection to Ruts Exiting Roadway scenario runs.

Clear to Patchy Slush-Covered Intersection

As Winter FT#2 Vehicle A approached the intersection, it began to drift to the right (like the Lane Change scenario). The intersection had varying levels of snow thicknesses and multiple ruts. By the time Winter FT#2 Vehicle A traversed the intersection box and reached the exit roadway, it had already changed a full lane width. As a result, it was not able to successfully perform the Through Maneuver during Green at Signalized Intersection scenario when driving from Clear to Patchy Slush-Covered Intersection and deviated by more than 2.5 feet from the centerline of the desired path.

Winter FT#2 Vehicle B was able to successfully complete six of the seven test runs emulating Left Turning Maneuver during Green at Signalized Intersection scenario when driving from Clear to Patchy Slush-Covered Intersection. Winter FT#2 Vehicle B was unable to perform a left tuning maneuver during only one test run because it lost localization. During this test run, Winter FT#2 Vehicle B perceived that it deviated approximately 80 feet from the pre-programmed path due to loss of localization when the actual deviation was close to 5 feet.

Covered/Ruts to Covered/Ruts

Winter FT#2 Vehicle A was not able to perform the Through Maneuvers during Green at Signalized Intersection scenario when driving from Covered/Ruts roadways to Covered/Ruts roadways. As the lane was completely covered with snow, Winter FT#2 Vehicle A was not able to detect the lane markings and engage steering controls under this condition. Consequently, Winter FT#2 Vehicle A's steering control was not engaged and thus it was not able to perform the Through Maneuver during Green at Signalized Intersections when entering Covered/Ruts roadways or exiting Covered/Ruts roadways.

Winter FT#2 Vehicle B was able to successfully complete six of the seven test runs emulating the Left Turning Maneuver during Green at Signalized Intersection scenario when driving from Covered/Ruts to Covered/Ruts. Winter FT#2 Vehicle B was unable to perform the left tuning maneuver during only one test run because it lost localization.

Stopped Car Detection

Desired Outcome: The test vehicle should be able to timely detect a stopped car and come to a complete stop before reaching a soft car located downstream on an ice-covered road without swerving or deviating from the travel lane.

Only Winter FT#2 Vehicle A was tested during this scenario as Winter FT#2 Vehicle B does not offer the TJA driver assistance system. Winter FT#2 Vehicle A's performance on the Stopped Car Detection scenario was good. The camera-based perception system of Winter FT#2 Vehicle A was able to detect the soft car and come to a complete stop without disengaging steering control during all road weather conditions. A summary of the results for Stopped Car Detection during Ice-Covered Road condition is shown in Table 13.

Table 13. Summary of test results for Stopped Car Detection scenario.

Condition	Vehicle	Number of runs	Number of runs soft car was detected	Number of runs vehicle came to a complete stop	Number of runs steering control disengaged
Baseline	A	7	7	7	N/A
Ice-covered Road	A	7	7	7	N/A

Baseline

Winter FT#2 Vehicle A was able to come to a complete stop at a safe distance from the soft car during Baseline condition. No critical deviations or steering control disengagements were observed.

Ice-Covered Road

When conducting the test runs, Winter FT#2 Vehicle A came to a complete stop at a safe distance from the soft car during Ice-Covered Road conditions. Although the ice-covered road was slippery, Winter FT#2 Vehicle A was able to timely stop without deviating from the traveled lane. Upon detecting the soft car, Winter FT#2 Vehicle A activated the ABS, which timely stopped the vehicle without disengaging the steering control for all test runs. During Ice-Covered Road test runs, Winter FT#2 Vehicle A's ABS pulsated the brakes as soon as the system detected the tires skidding when completing the runs. For the Through Maneuver for Green at Signalized Intersection test runs a tire slip caused disengagement of the steering system in Winter FT#2 Vehicle A. The steering system disengagement did not occur in Ice-Covered Road test runs.

A summary of Winter FT#2 Vehicle A's time elapsed for the vehicle to come to a complete stop when conducting the Stopped Car Detection during Ice-Covered Road scenario is shown in Table 14. Stopping time was determined by calculating the time taken by Winter FT#2 Vehicle A to decelerate from 11 m/s (25 mph) to 0.02 m/s (0.04 mph). When TJA was engaged at the same location from the stopped soft car, on average, Winter FT#2 Vehicle A took at least 3.9 seconds longer to come to a complete stop at a safe distance from the stopped soft car during Ice-Covered Road compared to Baseline conditions. This indicates that Winter FT#2 Vehicle A chose a safer deceleration rate during Ice-Covered conditions.

Table 14. Winter FT#2 Vehicle A's stopping time when conducting Stopped Car Detection during Ice-Covered Road conditions.

Vehicle A - Stopping Time	Baseline (sec)	Ice-Covered Road (sec)
Average	11.7	15.6
Minimum	11.4	10.8
Maximum	11.8	19.0

CHAPTER 6. OBSERVATIONS AND LIMITATIONS

In the AVAW3 project, technology-enabled test vehicles with SAE International Level 2 and Level 3 automation capabilities that were able to sustain both longitudinal and lateral control were exposed to a variety of adverse weather conditions, road weather, and different driving environments.

During testing, quantitative (telematics) and qualitative (on-field observations) were collected for each field test. Both quantitative and qualitative data were analyzed to assess the performance of technology-enabled test vehicles' control and perception systems when exposed to adverse weather conditions and different driving environments. This section highlights the important findings, discusses the limitations of the AVAW3 research effort, and identifies potential areas for potential future research.

PERFORMANCES AND LIMITATIONS OF DIFFERENT PERCEPTION SYSTEMS WERE DOCUMENTED

Operational Design Domain limitations of the tested vehicles were successfully challenged through exposure to adverse weather conditions and different driving environments. During Summer FT#1, Work Zone Lane Change with Barrels and Work Zone Lane Closure with Pavement Markings driving environments affected the performance of the test vehicles when presented with differing weather conditions. During Winter FT#2, the test vehicle with a camera-based perception system (Winter FT#2 Vehicle A) was significantly challenged when maneuvering in scenarios that reflect adverse winter road weather conditions. Winter FT#2 Vehicle A could not consistently determine the center of the lane when maneuvering in snow-covered conditions, as indicated by Lane Keeping, Right Lane Change, and Green at Signalized Intersection scenario findings. On the other hand, Winter FT#2 Vehicle B's LiDAR and HD map-based navigation system was less impacted by the winter road weather conditions. Perception limitations were more evident in this second field test compared to the first field test (non-winter weather).

INCONSISTENCIES IN PERFORMANCE WERE FOUND

A potentially significant amount of inconsistency in the tested vehicles' performance was found, both across vehicles and between runs for a single vehicle. The inconsistencies in performance included localization loss, rapid accelerations and decelerations at snow-covered intersections, inability to follow the desired path when snow on the road had varying depths, and inability to follow the desired path when daytime or nighttime glare is covering the pavement markings.

ENVIRONMENTAL CONDITION IMPACTS WERE INCONSISTENT ACROSS SUMMER FT#1 TEST SCENARIOS AND VEHICLES

Out of the four Summer FT#1 scenarios, no environmental condition was any more challenging than the other environmental conditions. It is not possible to identify the impact of weather conditions on the test vehicles' performance without identifying the vehicle type and driving environment tested. For example, nighttime glare conditions sometimes were worse for some scenarios and driving environments, but not always.

OVERARCHING ADVERSE WEATHER IMPACTS WERE OBSERVED DURING WINTER FT#2

Adverse winter road weather conditions significantly impacted the performance of Winter FT#2 Vehicle A (the test vehicle with the multiple camera-based perception system). Winter FT#2 Vehicle B with the LiDAR-based perception system was able to capture, assess, and react to adverse weather and road weather conditions more efficiently than Winter FT#2 Vehicle A. Therefore, the driving capability of AVs with camera-based perception system is not reliable under winter road weather conditions. LiDAR-based perception systems requires access to HD map for the travel route. Most of the current technologies on production vehicles have not incorporated the HD map feature due to cost and complexity. Even though LiDAR performance was good under winter weather conditions, it offers limited capabilities in perceiving some roadway conditions including pavement marking detection.

THE NEED FOR REDUNDANT SENSING SYSTEMS IN AVS WAS EVIDENT

Redundancy in this study refers to equipping the vehicle with multiple driving automation system components or subsystems that perform the same function is essential in safety-critical applications, such as driving in adverse road weather conditions. During certain adverse weather conditions, the test vehicles lost localization, disengaged steering control, and critically deviated from the desired paths. The test vehicle with LiDAR-based perception system performed better in Winter FT#2 than a multiple-camera-based perception system. With a redundant perception system, we expect the vehicle with a camera-based system to achieve higher accuracy of decision-making when assessing weather conditions and performing maneuvers. Therefore, redundancy in perception, steering control, localization, braking, actuation, and other systems is essential to successfully operate AVs under all weather, road, and environmental conditions.

AUTOMATED VEHICLE’S ABILITY TO COMPLETE EXPECTED MANEUVERS MIGHT LEAD TO DRIVER OVER-CONFIDENCE

A non-test driver using their vehicle’s AV technology to perform expected maneuvers might experience robust performance during the majority of the days with clear and moderate inclement weather. This might lead to over-trust and over-confidence in the abilities of the automation systems. For example, on days with varying inclement weather conditions (e.g., glare on roadways, wet pavements, varying snow thickness, slippery surfaces, ice- or snow-covered pavement markings), their vehicle might behave drastically differently, as its perception system would be unable to read the conditions. Researchers have suggested that this may lead to distracted driving, complete disengagement, and an inappropriate use of automation (i.e., reliance on automation in complex situations that were not listed or listed as exceptions in the owner’s manual) (Banks et al., 2018; Victor et al., 2018; Fleming, 2012; Hergeth et al., 2017; Schwarz et al., 2016).

CHAPTER 7. POTENTIAL FUTURE RESEARCH

Given the objectives and scope of this project, both rounds of field tests presented reliable insights on the performance of AVs with various levels of driving automation during different summer, spring, and winter road weather conditions. However, the test results do have three major limitations:

- Tests were conducted in a controlled environment with no interaction with other vehicles and pedestrians. To obtain a complete understanding of the performance of AVs, conducting such tests in real-world situations is essential.
- Tests represent a limited number of scenarios and test runs. Expanding the scenarios tested and increasing the number of test runs would provide repeatable test results.
- Tests during Winter FT#2 were performed at lower speeds under adverse weather conditions when compared to Baseline conditions. This reduction in testing speeds was applied to ensure safe testing conditions. Performing both the baseline and adverse weather runs at the same speeds would result in a better comparison of the impact of speed on test vehicle performance.

Potential future research should attempt to address the limitations discussed. Below are some of the potential future research activities that can be conducted to expand the scope of the field tests:

ADVANCED TESTING USING EXISTING AND OPEN-SOURCE SOCIETY OF AUTOMOTIVE ENGINEERS (SAE) INTERNATIONAL LEVEL 3 ALGORITHMS

As the Phases 1, 2, and 3 AVAW field tests focus on assessing the performance of test vehicles by pushing their Operational Design Domain limits, it becomes increasingly important to conduct similar tests on vehicles with existing and open-source SAE International Level 3 (or ADS) algorithms (e.g., Cooperative Automation Research Mobility Applications, Autoware) and document the differences in capabilities of perception and control systems between different SAE International Levels of Automation. These variabilities can be used by auto manufacturers to learn the best practices and underperforming conditions. Infrastructure Owner Operators (IOOs) can consider such test results when assessing roadways to accommodate safe and efficient travel of ADS-equipped vehicles during adverse weather and different driving environments.

USE SENSORS THAT ENABLE FURTHER INSIGHT INTO PERFORMANCE

AVAW3 is limited to assessing the performance of test vehicles' control and perception systems. With the testing of other brands of advanced sensors, testing can be expanded to gain a deeper understanding of the reasoning behind vehicle performance to adverse weather conditions and different driving environments. A thorough understanding of gaps in the abilities of vehicle control and perception systems, along with the effectiveness of different roadway infrastructure settings in communicating the intended information, can be captured.

EXAMINE THE EFFECT OF CRITICAL DRIVING CONDITIONS ON STEERING TORQUE

AVAW3 tests included scenarios that require test vehicles to perform lane change maneuvers in complex driving environments and weather conditions (e.g., crosswinds, sharp maneuvers, and sudden obstructions). It is important to capture the impact of critical driving conditions on the steering torque of the vehicles so that scenarios with higher variances in steering torque could be identified and addressed.

EXPAND THE TESTING WITH MORE CHALLENGING TRAFFIC SCENARIOS

Across Phase 1 and 2 field testing, test vehicles were exposed to a wide range of weather conditions. In Phase 3, different driving environments (e.g., work zone scenarios, lane markings) were introduced in addition to adverse weather conditions to assess the performance of commercially available production SAE International Level 2 and non-commercial SAE International Level 3 capable test vehicles. The next phase for AVAW will likely seek to increase the variety and complexity of driving environments (e.g., oncoming traffic, signalized intersections, stop signs) in adverse weather and possibly to test the performance of SAE International Level 3 and above vehicles. These research findings will be helpful for AV manufacturers, developers, and IOOs to collaboratively seek to continuously improve the safety of ADS-equipped vehicles as they are introduced on the Nation’s roadways.

COLLABORATION WITH AUTOMATION PARTNERS

To get a better understanding of new and prototype ADS technology’s performance in adverse weather, more collaboration with the vehicle automation companies is encouraged. Conducting an early outreach with vehicle automation companies at the beginning of the next phase of AVAW testing could be valuable in pursuing and possibly prototyping the vehicles from automation partners for testing in adverse weather. This outreach would not be limited to traditional passenger vehicles but also could include on-road delivery vehicles, non-traditional passenger vehicles without a steering wheel, and heavy trucks. This level of cooperation would allow more insight to be gathered about the actual state of current and upcoming ADS technology.

TESTING THE VISION-BASED TRAFFIC-SIGN RECOGNITION TECHNOLOGY DURING ADVERSE WEATHER CONDITIONS

During Phases 1, 2, and 3, the AVAW project focused on evaluating the capabilities of control and perception systems of AVs in detecting the pavement conditions (e.g., brake marks, missing/covered pavement markings, work zone barrels) under adverse weather. Expanding this evaluation to test the AVs’ capabilities in detecting static and variable road signs (e.g., variable speed limits, merging or exit lane signs, stop signs) and performing the required maneuvers during adverse weather conditions would provide key insights into the performance of AVs under changing road conditions.

EXAMINE THE PERFORMANCE OF AV CONTROL AND PERCEPTION SYSTEMS WITH CHANGING ROAD CONFIGURATIONS

The AVAW3 Winter FT#2 tested the performance of the SAE International Level 3 prototype vehicle when driving under adverse winter road conditions with the help of LiDAR and a pre-programmed HD map. During the next phase of the AVAW project, testing the vehicles with SAE International Level 3 or higher levels of automation by modifying (i.e., degrading or changing) road configurations from the original HD map provided to the test vehicle would provide insights into vehicle control and perception system behavior in critically challenging situations. This testing can be done in two parts:

- In the first part, vehicles would be driven on a roadway that matches the HD map configurations.

- In the second part, the vehicle would be driven on a modified/degraded roadway. By comparing the performance in both parts, insights can be gained about the behavior of SAE International Level 3 or higher automation vehicles in conditions with changing road configurations.

Further, a third part of the testing can be conducted by installing the vehicles with additional detection equipment that provides redundant data on the roadway configurations. The results from the third part can inform the AV practitioners about the advantages and limitations of redundant data sources for decision-making in adverse weather conditions.

EXPLORING THE CHALLENGES CAUSED BY LIMITED/OBSTRUCTED FIELD OF VIEW

Changes in elevation (uphill or downhill) and curvature of roads can obstruct or limit the field of view of AVs that rely on cameras or radars for detecting roadway conditions (i.e., vehicles stopped beyond the crest/nadir of a hill, hidden driveways, or blocked turning movement line of sight views. Adverse weather can add further challenges to the visibility of road conditions and limit the functioning of driver assistance system features. Testing the vehicles with SAE International Level 3 or higher automation capabilities under these conditions would allow the members of AV and IOO communities to learn about the improvements required for detection systems, as well as roadway design aspects that mitigate the field of view obstructions for an AV.

CONSIDERATION OF DRIVER AS A FALLBACK-READY USER

Progressive deployment of AVs with higher levels of autonomy into real-world situations will require them to function in a mixed driving environment of other drivers, pedestrians, and external events (e.g., work zone, incidents, emergency response). The first three phases of AVAW testing considered adverse and challenging weather and road weather conditions but testing occurred under ideal traffic conditions with minimal to no traffic-related conflicts. Testing the AVs in a more comprehensive traffic environment will provide critical information about how adverse traffic conditions can impact the driving capabilities of AVs. For example, driver state monitoring is critical to enable the proper transition of control from the vehicle to the driver and vice-versa at different levels of automation. Similarly, it is important to understand driver behavior in different weather conditions to enable the development of effective AV control algorithms. The focus of future AVAW projects may consider testing the timeliness and effectiveness of driver alert transition of control warnings or systems (before the ADS disengages).

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