Automated Vehicles and Adverse Weather

Final Report

www.its.dot.gov/index.htm

Final Report – June 2019
FHWA-JPO-19-755

U.S. Department of Transportation

Produced by Battelle
U.S. Department of Transportation
Office of the Assistant Secretary for Research and Technology
Federal Highway Administration

Notice

Technical Report Documentation Page

1. Report No. **FHWA-JPO-19-755**	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Automated Vehicles and Adverse Weather: Final Report		**5. Report Date** June 2019 **6. Performing Organization Code** 100105058-5
7. Author(s) Dave Neumeister, Doug Pape		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Battelle Memorial Institute 505 King Avenue Columbus, Ohio 43201-2696		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** DTFH6116D000049 Order 0004
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration 1200 New Jersey Ave. SE Washington, DC 20590		**13. Type of Report and Period Covered** Task Report, December 2017 – June 2019 **14. Sponsoring Agency Code**
15. Supplementary Notes **Road Weather Management Program**		

16. Abstract

Automated vehicles are being developed and promoted by manufacturers. Like other vehicles, they will have to perform in a variety of adverse weather conditions. With recent advancements in automated vehicle (AV) technology, the Federal Highway Administration is exploring AV needs, opportunities, and potential shortcomings during adverse weather conditions.

This project explored how adverse weather and road weather conditions affects automated vehicles through three primary tasks: 1) a literature review, 2) two experiments to observe the performance of AVs and their sensor systems under controlled conditions, and 3) three listening sessions with stakeholders. Following background information presented in Chapter 1, a summary of the research and findings of each primary task is presented in Chapter 2, Chapter 3, and Chapter 4, respectively. The document finishes with conclusions in Chapter 5 and identifies outstanding research needs in Chapter 6.

Limitations of AVs are not fully understood. Level 2 vehicles exposed to adverse weather in this project were challenged and a significant amount of performance inconsistency was observed from vehicle to vehicle. Tested vehicles used different approaches to automation and driver assistance. To improve safety, and achieve higher levels of automation, advancements in data connectivity, infrastructure support, and rulemaking are needed. Better decision support for beginning or continuing trips is also needed. This includes identifying responsibilities and roles for determining that current and forecast conditions are within a vehicle's ODD. State and local agencies must be better equipped to provide advice on AV use in adverse conditions. In the meantime, level 2 AV drivers must avoid over-trusting automation, avoid complacency, and be prepared to engage.

17. Keywords Automated Vehicles, Connected Automated Vehicles, Connected Vehicles, Adverse Weather, Road Weather, Weather		**18. Distribution Statement** No restrictions	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 91	**22. Price**

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

Table of Contents

List of Tables

List of Figures

Executive Summary

Project Background

Weather and road weather conditions can adversely affect vehicle performance and driver behavior, and thus have a direct impact upon safety and mobility. Federal Highway Administration (FHWA) statistics reveal that more than 1 in 5 annual motor vehicle crashes are in fact related to weather, many involving injuries and fatalities. Vehicles with automated features to assist the driver in a variety of driving tasks, including steering and braking, are increasingly available on the road. Although these vehicles are manufactured with sensors, perception systems, and software to allow them to drive in various environmental conditions, most of the currently available systems are not designed to operate in all adverse weather conditions.

With recent advancements in automated vehicle (AV) technology, FHWA is exploring AV needs, opportunities, and potential shortcomings during adverse weather conditions. This report summarizes how adverse weather and road weather conditions affect vehicle sensors and perception systems and how drivers react to or take back control from their vehicles, by discussing the relationship between weather and AV performance. It is intended to inform the USDOT research and development agenda, State and local transportation agency operational and maintenance strategies, and create awareness among private sector developers and designers on effects of adverse weather on AV operations.

This project investigated how adverse weather and road weather conditions affects automated vehicles in three ways: 1) a literature review, 2) two experiments to observe the performance of AVs and their sensor systems under controlled conditions, and 3) three listening sessions with stakeholders.

Literature Review

The literature review and technology survey explored the impacts of adverse weather and road weather conditions on AV perception and control systems, and on driver behavior. The objective of this literature review was to guide the comprehensive understanding of AV technologies and how technologies may be affected by weather. In addition, a goal was to identify gaps in existing perception and automation technology capabilities, and determine what is needed to achieve higher levels of automation.

Several level 2 automated vehicles are currently on the market. Their owner's manuals all caution that the systems cannot function in all weather conditions. They qualify adverse weather conditions under which sensors and automated functions should not be relied upon, and under which drivers should be prepared to take control. The exact wording and conditions vary from manufacturer to manufacturer. Automated control of speed is generally discouraged when visibility is limited by atmospheric conditions or by precipitation on the windshield or sensor lens or when the air temperature is outside an acceptable range. The same conditions limit automated steering control, as does a slippery surface.

Limited research on the human factors of automated vehicles in adverse weather was found. Unfavorable outcomes with a human putting too much trust in a Level 2 automated vehicle and a human putting too little trust in a level 4 vehicle have been documented. Research has been reported on human interaction with an automated vehicle in several specific weather conditions. The transition from automated to human control can be difficult during gusty wind, and visual sensors may not have adequate resolution to recognize small pieces of debris blown by wind. Fog limits a vision system's ability in the same way it limits a human's ability to detect objects. Radar is currently used for adaptive cruise control, and connected vehicle (CV) principles have been shown in research to produce additional benefits of cooperative adaptive cruise control. Rain, too, diminishes visibility. LiDAR, light detection and ranging, provides some improvement to effective visibility in rain and darkness, albeit with limits. Snow and ice on the road surface, and even water in a pothole, pose challenges to perception systems in locating the traveled way. Three-dimensional maps of above-ground features such as trees and roadside appurtenances enable a LiDAR system to locate its position. Modern stability control systems, now required on most vehicles, provides direction control. Systems to assess surface friction and estimate a prudent speed are still in the research stage.

Experiments with Production AVs in Adverse Weather

The task including experiments with production AVs in adverse weather challenged Level 2 AV perception systems across a variety of simulated adverse weather conditions in a controlled outdoor laboratory setting. Adverse weather conditions were produced and experienced in two different test periods. The first focused on spring weather, and the second on winter weather. In test period 1, weather conditions included a baseline of fair weather, ice on sensors, falling rain, blowing snow, and sun glare. Maneuvers in test period 1 included high- and low-speed following, and lane keeping in straight and curved road segments. In test period 2, weather conditions included a baseline of fair weather, full and sporadic snow coverage of lane lines, falling snow, blowing snow, salt brine and snow covered sensors, and sun glare. Maneuvers in test period 2 included high-speed following, and lane keeping in straight and curved road segments.

Five production vehicles with differing perception systems were driven through a planned variety of road and road weather conditions to permit an assessment of how well each automation feature performed. The automation features tested included lane keeping support (inclusive of lane centering, lane keeping assist, lane departure warnings, and take steering control command, if and when applicable) and vehicle following support (inclusive of adaptive cruise control, and if applicable, automatic emergency braking). 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.

The same three strong conclusions stood out for test period two as were in the first test period, but against the backdrop of different adverse weather conditions. First, limitations of the tested AVs were successfully challenged through exposure to adverse weather conditions. Second, a potentially significant amount of inconsistency in AV performance was found, both vehicle-to-vehicle and in some cases run-to-run in a single vehicle. Third, significant differences in AV approaches to automation and driver assistance functionality were evident. This included different methods for sensing and processing environment states, different levels of and approaches to setting and controlling automation, different algorithm-based criteria for automation support, and different ways of presenting status and alerting information to drivers.

Stakeholder Engagement

The stakeholder engagement task held three workshops to hear a discussion of stakeholders on infrastructure issues (particularly signs, markings, and connected vehicle messages) related to automated vehicles and adverse weather. Participant stakeholders represented across these workshops included

State or local transportation agencies, academia, automotive suppliers, and roadway maintenance supervisors and operators. The varied roles and responsibilities of participants provided broad and differing perspective-based input in regard to challenges and concerns with supporting AV operations.

Infrastructure owners and operators (IOOs) expressed that there are currently more questions than answers on how they will support the operation of automated vehicles in adverse weather. Maintenance supervisors and operators expressed several AV-related practical concerns, including the need to recognize and prioritize maintenance support for AV operations with respect to other responsibilities, and recommended publicizing maintenance guidelines for public awareness and use in support of operating vehicles with levels of driving automation where the human driver is responsible for monitoring the driving environment. Additional coordination between vehicle manufacturers, USDOT and its partner agencies, and the research community is needed to define the roles of each in enabling the operation of automated vehicles in adverse weather, and to engineer a system to do so.

Several attendee stakeholders wondered who decides if the weather is suitable for automated vehicles, though the question was framed differently by different stakeholder groups. A decision of starting or continuing a trip with automation may be made by the vehicle occupant, a state or local authority, or perhaps by the vehicle itself. Specific topics included the content of weather information and means of delivering it, and a means of assessing the automated feature’s capability in light of current conditions.

Vehicle manufacturers are developing products that can perform in a variety of weather conditions. The vehicles’ information about the environment comes entirely from their own perception systems, partly because services to provide supplemental information are not widely available or are not being ingested when available. They are able to use their own perception systems because a human driver is always present to take over if the weather is too severe. While component suppliers unsurprisingly expressed optimism that their products will improve in capability, they recognized that vehicles ultimately still need forecasts along their entire route. Weather and road weather forecasting will become especially important at higher levels of automation, where a driver might be paying no attention at all to the approaching storm or where a passenger with special needs may be unable to assume the driving task.

Many representatives of State and local operating agencies wondered what new responsibilities they will have for automated vehicles—what skills they need, what equipment, and most importantly how they will pay for it. There is precedent for agencies to set limits in that they can declare snow emergencies and ban travel or require chains in certain conditions.

USDOT can take a leadership role in ensuring automated vehicles operate as intended in adverse weather conditions. By extending existing programs and bringing together government and industry stakeholders, USDOT can ensure that wise choices are made with respect to starting and continuing trips with driving automation. The biggest challenges USDOT can help solve are: 1) to establish metrics to define weather components of the operational design domain, 2) to help define roles and responsibilities for collecting, quality checking, assimilating, and disseminating external weather and road weather information needed by AVs and AV operators, 3) to facilitate increased understanding and preparations for infrastructure connectivity and security, and 4) to support continued AV technology research and testing to help prioritize resources and strategies for supporting AV operations based on a thorough understanding of the needs of AVs and stakeholders that will support safe and efficient AV operations.

Chapter 1. Background

Adverse weather conditions—rain, sleet, snow, fog, and crosswinds—affect transportation system operations and services, causing delays, traffic flow impediments, major crashes, and life-threatening circumstances. Weather (atmospheric conditions) and road weather (pavement conditions) can adversely affect both vehicle and driver behavior. Weather phenomena can directly influence driving by impairing visibility through precipitation while snow covered roads and high winds can challenge driver capabilities, vehicle performance, and roadway infrastructure, which affect the safety and mobility of drivers, passengers, and pedestrians. With the advent of automated vehicles (AVs), research is needed to identify how vehicles and drivers will detect and react to adverse weather and road weather conditions.

Of the more than 5,891,000 annual motor vehicle crashes, annual average statistics from the 10-year period 2007-2016 reveal that 21 percent occur in the presence of adverse weather and/or slick pavement conditions, while 19 percent of crash injuries and 16 percent of crash fatalities are weather-related (FHWA 2017a.) Today, several vehicle manufacturers are producing vehicles with automated features to assist the driver in a variety of driving tasks, including steering and braking. Vehicles are manufactured with sensors and perception systems, as well as software, that allows them to drive in various environmental conditions and respond to objects and events. However, most of the currently available systems are not designed to operate in all adverse weather conditions. With the arrival of AVs, research is underway to identify how vehicles and drivers will detect and react to adverse weather and road weather conditions during vehicle operations at different levels of automation.

This report summarizes how adverse weather and road weather conditions affect vehicle sensors and perception systems and how drivers react to or take back control from their vehicles, by discussing the relationship between weather and AV performance. It is intended to inform the USDOT research and development agenda, State and local transportation agency operational and maintenance strategies, and create awareness among private sector developers and designers on effects of adverse weather on AV operations.

Automated Vehicles

AVs have sensors and perception systems to detect objects and events in their vicinity. They control the steering or speed or both to move the vehicle along its selected path. The ability of the perception or control systems to function can be affected by atmospheric weather and road surface conditions.

Machine vision (a video camera) is the common way for vehicles to sense their position within the driving lane. Some vehicles create a three-dimensional model of their surroundings with a second video camera or with a LiDAR system. Radar is common for measuring the range to other vehicles. AVs may strictly rely upon on-board technologies, or they may be connected, using dedicated short-range communication (DSRC) or Wi-Fi to communicate with other vehicles, pedestrians, and infrastructure. Connected automated vehicles (CAVs) have the ability to optimize network capacity, reduce congestion, and increase safety. They may also afford environmental benefits.

The Need for Information

A human driver of a conventional vehicle needs weather-related information for a number of reasons. If current conditions are dark or rainy, the driver will turn on the headlights. If the road surface is suspected to be slippery, the human will drive more slowly and avoid sudden maneuvers. If a severe winter storm is predicted to arrive before a trip can be completed, the driver may elect not to make the trip at all.

All of these same scenarios apply to automated vehicles, but they are complicated by the capabilities of the driving automation system. SAE Recommended Practice J3016 strongly relies on the concept of an Operational Design Domain (ODD), which is the set of conditions under which a driving automation system is designed to function. The ODD may include geographic, roadway, and environmental conditions, and the recommended practice explicitly lists weather conditions among the examples.

The human (or, in some cases, the vehicle itself) must decide whether to begin or continue a trip using a driving automation system. Therefore, there is a need for information on current conditions and the conditions forecasted for the planned route. These conditions will include the weather, as it affects the vehicle's ability to perceive its surroundings, and the road weather, as it affects the vehicle's ability to maneuver.

Levels of Automation

NHTSA's Automated Driving Systems 2.0: A Vision for Safety (NHTSA 2017a) summarizes SAE International's automation levels in Table 1. The levels signify a general guideline for how technologically advanced a vehicle must be. Level 5 automation, for instance, requires a more technologically advanced vehicle as it needs no driver input, compared to level 2 automation, which requires the driver to assume primary control of the driving task even though the vehicle has combined automated functions.

Table 1. Automation levels as summarized in NHTSA's Automated Driving Systems 2.0

Level	Name	Description
0	**No Automation**	The driver performs all driving tasks.
1	**Driver Assistance**	Vehicle is controlled by the driver, but some driving assist features may be included in the vehicle design.
2	**Partial Automation**	Vehicle has combined automated functions, like acceleration and steering, but the driver must remain engaged with the driving task and monitor the environment at all times.
3	**Conditional Automation**	Driver is a necessity, but it is not required to monitor the environment. The driver must be ready to take control of the vehicle at all times with notice.
4	**High Automation**	The vehicle is capable of performing all driving functions under certain conditions. The driver may have the option to control the vehicle.
5	**Full Automation**	The vehicle is capable of performing all driving functions under all conditions. The driver may have the option to control the vehicle.

One example of a system that reportedly achieves SAE level 3 under limited conditions is the Audi Traffic Jam Pilot available on 2017 and newer A8s, which fully controls all driving tasks on slow-moving highways at speeds up to 37 mph on highways with a physical barrier separating oncoming traffic. This vehicle is not for sale in the United States. All vehicles currently on the market in the United States operate at level 2 or below. These vehicles require the driver's full attention at all times. Some examples of level 2 vehicle systems include Tesla's Autopilot, Nissan's ProPilot, Subaru's EyeSight, GM's SuperCruise, Honda's Sensing, and Volvo's IntelliSafe with Auto pilot mode. Many additional models that are currently available have electronic safety features for situations such as closing on another car too quickly, changing lanes with a vehicle in the blind spot, or backing into a busy parking lot where all threats may not be visible.

When continuously operating, Advanced Driver Assistance Systems (ADAS) features such as Adaptive Cruise Control (ACC) or Lane Keeping Assistance (LKA) are considered level 1 automation if operating individually. Forward collision warning, blind spot warning, lane departure warning, lane keeping assist, rear cross traffic, and rear-view cameras are standard features on many models. Because they do not operate continuously, they are level 0 in the SAE taxonomy. However, the perception systems for all of these examples are affected by weather, so their performance can inform a study of AVs.

Approach

This project explored how adverse weather and road weather conditions affects automated vehicles in three ways: 1) a literature review, 2) experiments to observe the performance of AVs and their sensor systems under controlled conditions, and 3) listening sessions with stakeholders.

Findings from the literature review task are summarized in Chapter 2 below. This chapter includes a review of AV technology and adverse road weather resources, as well as a summary of human factors implications of automated driving in adverse weather. The objectives of the literature review were to:

- Research how current automation technologies are affected by weather
- Identify safety and functionality gaps in perception and automation technology
- Identify needs for achieving higher automation levels from weather perspective

Details and results of the experiments to observe the performance of AVs and their sensor systems under controlled conditions are presented in Chapter 3 below. Five level 2 AV systems were tested and precise telematics and video collected in order to observe and analyze performance of level 2 AV systems:

- While executing planned and ad hoc maneuvers
- During planned and opportune adverse weather
- Over a series of repeatable test iterations and scenarios

A summary of the Stakeholder Engagement workshop listening sessions and findings are summarized in Chapter 4 below. The key objectives of engaging stakeholders were to:

- Understand how to address adverse weather effects on sensors and human factors
- Understand how connected automation benefits operations in adverse weather
- Determine what gaps exist to achieve higher levels of automation

Chapter 2. Literature Review

This chapter summarizes findings from the literature review task. It is organized into two parts: 1) a review of the state of AV technology and adverse road weather resources, and 2) human factors implications for AV operations in adverse weather.

State of Automated Vehicle Technology and Adverse Road Weather Resources

AVs depend on a series of technologies that help them understand their environment and respond to incidents. Selecting among sensor options that offer varying effectiveness and usability is weighted by factors including cost, data processing ability, and accuracy. Adverse weather conditions limit sensors' ability to identify a vehicle's location relative to other vehicles and lane markings.

The first part of this chapter reviews the sensor technologies used on AVs and discusses how they are affected by adverse weather. It summarizes manufacturers' recommendations to their owners concerning automated operation in adverse weather. Following this, recently developed available resources and initiatives that may facilitate the provision and use of road weather data by AVs, AV drivers, and agencies responsible for maintaining AV operations are explored. This portion of the chapter concludes with a summary of data fusion approaches, higher level processing, and the benefits of connected vehicles.

AV Sensors and Gaps in their Weather-Related Performance

Most manufacturers of AVs use a combination of video cameras and radar to sense the other vehicles, objects, and lane markings in their vicinity. Some vehicles in development also use LiDAR (Luciano 2017).

An AV needs to know its position within the driving lane. Essentially all manufacturers use machine vision to do so. Cameras are efficient in visualizations, and are the least expensive of the sensors. The latest high-definition cameras use millions of pixels per frame to develop intricate imaging, making them ideal for interpreting neighboring scenery. These high-definition cameras use powerful processors for the images they produce, but their use can be extremely costly because Original Equipment Manufacturers (OEMs) tend to place them in numerous areas of the AV to provide an accurate depiction of the surrounding (TRA 2016).

Some research projects supplement the video system with LiDAR. LiDAR allows 360-degree vision of a three-dimensional (3D) scene. The concept is to send infrared light beams to the vehicle's surroundings and collect information on how long it takes the beams to return to the sensor (Cameron 2017). LiDAR does not work well in inclement weather conditions (Rasshofer et al. 2017). A pothole filled with water can be interpreted by LiDAR system as an obstacle (Boudette and Vlasic 2017), and LiDAR can wrongly interpret snowflakes as obstructions on the road (Wong 2016). Due to the amount of data processing power it requires, LiDAR is the most expensive sensor.

Radar has been used by car manufacturers for a long time. Its most common use is to estimate the range to the leading vehicle, for automatic cruise control or automatic emergency braking. Radar, like LiDAR is an active system: it transmits energy and receives reflections from surrounding objects. Radar waves are much longer than the infrared waves used for LiDAR, so they can travel better through airborne precipitation but their resolution is not as fine.

Radar is classified into three types based on the distance range it covers: short-range radar covers distances between 0.2 meters to 30 meters, medium-range radar covers distances between 30 meters to 80 meters, and finally, the long-range radar covers distances between 80 meters to 200 meters (Ors 2017). Long range radar is used in most AVs. Radar can determine the velocity, range, and angle of an object, and performs well in most environmental conditions (Ors 2017). Radar works reliably in adverse weather, seeing through fog, rain, and snow (Marshall 2017). Although its resolution is sufficient for detecting objects, radar cannot sense lane markings.

Ultrasonic systems also transmit energy and sense the reflections. Whereas LiDAR and radar use electromagnetic waves, ultrasonic energy is sound waves in the air. It is best for short distances and is the core of most backup systems.

Adverse Weather Impacts on Driver Assistance Technologies

Not surprisingly, the literature review and technology scan did not reveal much in the way of specific descriptions of the approach OEMs used to develop AV features, or test results detailing the performance of those systems. For this reason, owner's manuals from three automakers producing vehicles with ADAS features were reviewed to determine whether disclosures were made about which sensors and perception system components are used, and for disclosures of the limitations of those sensors or functions in adverse weather conditions. Although not as explicit as test results might be, each of the randomly chosen OEM owner's manuals did describe ADAS functionality offerings and presented adverse weather limitations about the features and sensors used to serve those features. The following table very broadly summarizes findings from this scan. An "X" in a cell represents that one or a number of specified weather phenomena is recognized to impact the specified ADAS function.

Table 2. Weather conditions affecting ADAS functions per OEM owner's manuals

ADAS Function	Sensors	Weather			
		Airborne	Windshield or Camera Lens*	Surface	Temperature**
Speed (throttle and brake)	Either, or a combination of, camera(s) and radar	X	X	--	X
Steering	Primarily camera(s), potentially supported by ultrasonic	X	X	X	X

* This includes weather that may have been disturbed from the road.

**Internal and/or outside air temperature.

Definitions:

- Airborne weather most commonly included extreme airborne conditions, such as:
    - heavy rain
    - blizzard/heavy snow
    - thick fog
    - challenging lighting (either strong light from front/back by the sun or headlights).

One OEM included slush. Additional airborne conditions not considered extreme that were listed by some, but not all OEMs included sand, smoke/steam/exhaust gas, water vapor, and poor lighting due to position of the sun in dawn/dusk.

- Windshield/lens conditions most commonly included:
    - snow
    - ice
    - dirt or mud coverage
    - the windshield being fogged.

Additional windshield/lens conditions listed by some, but not all OEMs included: oil/film, dust, frost, and droplets or mist. One OEM recognized limitations from windshield washer/wipers.

- Surface conditions recognized as limiting factors by two of the OEMs included weather that could occlude roadway markings and/or provide false perceptions due to reflection or lack of reflection included:
    - snow (covers or color meld)
    - rain/snow water puddle, to perhaps include melting agent
    - slush.

Although not mentioned about ADAS safety features, other ADAS convenience features may be impacted by adverse weather-related conditions such as tire tracks in slush/snow or shadows from guard rails.

Evaluating Automated Vehicles in Adverse Weather

Companies testing AVs in California are required to submit “disengagement reports.” These reports detail the instances when a human driver took control of a test vehicle after suspecting that hardware or software was failing or might fail. Some, but not all, of the reports list the weather conditions at the times of the disengagements. One manufacturer reported that five percent of the test miles were driven under rainy conditions and that rain was never a reason for disengagement. Of the nine manufacturers testing on public roads in California in 2016, one reported a weather-related disengagement: poor sun conditions prevented the vehicle from detecting a traffic signal (State of California Department of Motor Vehicles, 2016).

Adverse Road Weather Resources and Initiatives

Many components of a system to deliver information on adverse weather to automated vehicles have already been contemplated or are in place. A summary of key resources and initiatives follow. These building blocks are likely, in some combination, to support the need for delivering weather and road weather information.

Pathfinder

The Pathfinder initiative is intended to provide travelers with a consistent assessment of the weather's effects on travel. Supported by the Federal Highway Administration (FHWA) and the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS), Pathfinder facilitates collaborative partnerships between the NWS, private sector weather service providers, and State or local departments of transportation. The effort is not simply adding meteorological support from the National Weather Service to departments of transportation. The value of this collaboration is an improved assessment of weather effects on the transportation system.

The service can benefit humans planning a trip with an automated vehicle. As the effects of adverse weather on automated vehicles become better documented and standardized, the Pathfinder concept can be expanded to apply to automated vehicles.

Weather-Related Connected Vehicle Applications

The Intelligent Transportation System Joint Program Office (ITS JPO) and the FHWA Road Weather Management Program (RWMP) have supported the development of a number of applications to take advantage of the communication capability of connected vehicles. These applications serve a variety of general purposes, such as safety in maneuvering, improved traffic flow, and benefits to the environment. The applications' level of development ranges from placeholders for ideas to region-wide pilot deployments. Among the road weather connected vehicle applications are Motorist Advisories and Warnings (MAW) and Road Weather Information (RWINFO) for Freight Carriers.

An automated vehicle that is also equipped with connected vehicle technology can receive these messages and act on them.

Weather Data Environment (WxDE)

The Weather Data Environment collects and shares transportation-related weather data with a particular focus on weather data needed by connected vehicle applications. The WxDE collects data in real time from fixed, transportable, and mobile environmental sensor stations. The WxDE computes value-added enhancements to this data, including quality checks.

The WxDE is intended to support research, analysis, application development, and testing related to weather responsive transportation management by collecting and distributing weather data and weather-related transportation data. The data are distributed via maps that provide access to recent observations, queries that allow a user to select and download large batches of data, and subscriptions that allow users to download recently obtained data. The web site is https://wxde.fhwa.dot.gov.

In an operational setting, weather data similar to this could be provided directly to vehicles, to a dispatcher responsible for a fleet of automated vehicles, or to a service that repackages and transmits the data.

Integrating Modeling for Road Condition Prediction (IMRCP)

The IMRCP provides an integrated view of forecast road weather and traffic conditions for a specified road network. Its model uses inputs from hydrological and traffic data sources, as well as a set of weather event sensors to understand current conditions and develop forecasts of future conditions. Current and forecast atmospheric and hydrological information from the National Weather Service sources are used, while road weather condition details such as pavement temperature are provided by State and local agencies. The IMRCP synthesizes inputs and uses models to predict future conditions.

Users are able to view forecasts and observed road and weather conditions at specified time frames for select road segments or areas. In addition to providing decision support for operational decisions and maintenance planning for transportation agencies, it enables drivers (and potentially automated vehicles) to make forecast-enabled travel and routing decisions.

Pikalert ®

Pikalert® is a system that provides high precision road weather forecasts and recommendations based on observations from connected vehicles, traditional weather data sources (e.g., road weather information stations and radar), and weather model analysis. It forecasts future weather and road conditions out to 72 hours using modelling. Primary weather conditions used include precipitation conditions, road surface conditions, and visibility. Drivers can receive Motorist Advisory Warnings (MAW) in a web or phone-based interface for pre-trip planning out to 24 hours and for real-time tactical decisions during a trip based on Pikalert®-provided hazardous condition details ahead. Automated vehicles could, likewise, benefit from this information.

Road Weather Performance Management (RW-PM)

In addition to providing maintenance decision support to transportation agencies, the Road Weather Performance Management tool was designed to provide integrated congestion and atmospheric road weather hazard awareness and recommendations to vehicle drivers via near real time in-vehicle alerts and advisories. This Vehicle-to-Infrastructure (V2I) tool collects and aggregates location-specific road weather data from infrastructure-based sensors and equipped connected vehicles (through the OBD-II port), shares and processes it using Pikalert® and other algorithms, and disseminates decision support information to users based on their location and need. The mobile interface in connected vehicles keeps drivers abreast of changing road weather conditions.

The in-vehicle advisories can, in principle, be read by the vehicle itself as well as by the human driver.

ARC-IT

The Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) has a series of service packages for weather information. The Weather Information Processing and Distribution service package processes and distributes environmental information. The package detects environmental hazards such as icy road conditions, high winds, dense fog. Among the uses are issuing general traveler advisories or location-specific warnings to drivers. The Spot Weather Impact Warning service package will alert drivers to unsafe conditions or road closures at specific points as a result of weather.

This is a high-level architecture to guide organizations in implementing the services.

Requirements for V2I Weather Applications

A technical committee of SAE International is presently voting on developed requirements to support V2I weather applications (J2945/3). Part of a much larger effort to expand the types of messages that can be communicated through connected vehicle systems, this committee is examining the road weather needs of various road users. Among the applications being considered at a high level is a road weather module for automated vehicles.

Other standards have also addressed weather data. In its Dedicated Short Range Communications (DSRC) Message Set Dictionary (J2735 JAN2016), SAE International defines optional data frame structures for weather probe data (including air temperature, barometric pressure, and vehicle wiper status) and weather report data (including precipitation rate and road friction). In the Environmental Sensor Station (ESS) Interface Protocol standard (NTCIP 1204) published jointly by AASHTO, ITE, and NEMA, definitions for data elements of ESS (including weather and road weather) sensor data are provided.

Critical Review of AV Technologies

An individual sensor can be subject to adverse weather. Combining the information from cameras, radar, and LiDAR—sensor fusion—can provide a better picture of a vehicle's environment than any individual sensor could. In addition, CV technology can supplement information a vehicle can acquire on its own. This section reviews current and emerging data fusion approaches.

Algorithms, Fusion Approaches, and Control Strategies

The progress made in developing safety critical applications and extensively using remote sensing devices in the automotive industry led to the use of tracking and the fusion of information largely used in defense and surveillance related applications (Yenkanchi 2016). Automakers and OEMs developing AVs have been using data fusion to develop applications based on enhanced information derived from multiple individual sensors to provide a more complete description of the vehicle's surroundings. Information processing, extensive networking, and system monitoring using sensor and information fusion systems create flexible architectures within which AVs can operate safely and efficiently. The challenges with further administering fusion approaches come from unpredictable behaviors of obstacles on the road and changing weather conditions.

One approach to resolving this problem is through the utilization of Simultaneous Location and Mapping (SLAM) and the Detection and Tracking of Moving Objects (DATMO), also known as Simultaneous Localization, Mapping, and Moving Object Tracking (SLAMMOT). SLAM, which makes use of artificial intelligence and machine learning, affords the construction or update of an unknown environment through perception sensors including LiDAR and motion sensors, and allows the vehicle to navigate within that environment in real time. By tracking detected moving objects, DATMO predicts the future behavior of those objects and the likelihood of a collision with them. SLAMMOT requires substantial computing resources and power to execute in real time. This suite of technology is presently where much attention is being paid, as it is believed to be crucial for achieving higher levels of automation for AVs (Manz 2017).

AVs receive data from various sources, including the vehicle itself, the communication it has with other vehicles and infrastructure, image sensors, radar, LiDAR, and location. In addition, some AV systems monitor driver performance and alert the driver if it determines the driver is not satisfactorily controlling the vehicle. Collecting all this data and making control decisions requires fusing information to provide the best reaction in a given situation. Data fusion approaches for AV decision-making are showing great potential for improving the performance of vehicular systems (Zardoscht 2016).

Having fully automated vehicles in urban situations with unpredictable traffic requires environment perception, localization, planning, and control achieved by employing algorithms that calibrate sensors, computational hardware, and networking, and software infrastructures. Improved perception and recognition algorithms not only enable the recognition of pedestrians, cyclists, and other vehicles, but do so in various weather conditions and day and night (Levinson et al. 2011). The most common machine learning algorithms being used in AVs are based on object tracking (Quora 2017). These algorithms are aimed at improving vehicle location accuracy by capturing images of their surroundings and evaluating them using a machine learning algorithm that decides if the image is a known pattern. One of the biggest challenges facing object tracking is profiling a new object, i.e., identifying whether an object is a vehicle, a pedestrian, a pothole, etc. Scientists determined a solution that allows pattern recognition and 3D mapping with many images containing objects, but research is still underway to develop algorithms that better understand weather conditions in different environments. Using sensor fusion algorithms, vehicles must be able to detect roads within a tolerable margin of error using sensors such as cameras and laser scanners that must operate under a variety of weather conditions (Lee et al. 2016).

Vehicle Automation to Aid Weather Prediction

The sensors used to support AV operations may additionally be suited to help other vehicles and agencies become aware of localized adverse weather conditions. “Ground truth” conditions detected by the sensor suites of several AVs in a geographical location can provide advance alerts to vehicles approaching that area, DOTs maintaining the roadways, and even agencies providing weather services. The nature of the road weather conditions could be based on some combination of AV sensor failures (e.g., due to road snow/ice/slush) and, perhaps, on-board vehicle sensors (e.g., wiper status) from some number of vehicles equipped to communicate wirelessly via connected vehicle technologies (USDOT 2016, FHWA 2017b).

Human Factors of Automated Driving in Adverse Weather

Safety is paramount in AVs as they are being tested on different terrain and under various weather conditions, including when sensors fail to read the markings on the road. AVs can introduce new kinds of crashes, including automated system failure. AVs that require some human monitoring can lead to driver complacency (Light 2017). For example, after a year-long investigation, NHTSA concluded that a Tesla system capable of automatically steering and controlling a car played a major role in a fatal crash in Florida (NHTSA 2017b). The crash occurred on a sunny day. Incrementally updated functionality and features can become safety risks if vehicle operators are not aware of their car’s capabilities and limitations.

As the prevalence of level 2 automated systems increases, and level 3 and 4 systems are introduced, the role of the driver as it is currently understood will change. The driver will transition from acting as the primary vehicle operator, to a driving system supervisor, and eventually to a passenger (Da Lio et al. 2015). However, in the foreseeable future, situations will arise during driving that level 2 through 4 systems will be incapable of handling safely (Sundararajan and Zohdy, 2016). The exact nature of the human factors challenges faced during this transition will depend on the systems themselves, but they can be broken down into some broad categories. Adverse weather conditions may constitute a significant portion of these critical situations (ITS International 2014, Sundararajan and Zohdy, 2016).

Influence of Driver Trust

One factor that is highly correlated with driver engagement with the system, and that has a significant effect on how drivers interact with the system, is trust (Koglbauer et al. 2017). Driver trust in an automated system varies depending on a number of factors: how accurate their understanding of system operation is, their previous experience with the system or similar systems, and their willingness to give up control of the vehicle (Hergeth et al. 2017, Schwarz et al. 2016). Drivers can be either over-trusting or under-trusting of an automated system, which both present unique human factors challenges. Orthogonal to the dimension of trust are the capabilities of the system itself. This presents approximately four broad categories when driver trust (over/under-trust) and system capabilities (levels 2 and 4) are taken into account (level 3 is omitted for brevity and clarity).

Table 3. Automation level and driver trust

	Under-Trust	**Over-Trust**
Level 2	**1** Driver largely eschews the benefits of the automated features. Dangerous if the system activates unexpectedly and driver overcompensates.	**2** Driver is over-confident in automated features and does not monitor them closely enough or uses them in inappropriately complex situations. Dangerous.
Level 4	**3** Driver prefers own experience to the system. Fights the system for control of the vehicle. Dangerous, could cause vehicle to behave unexpectedly.	**4** Driver is not engaged or is distracted. May have difficulty reengaging if the system encounters a situation it cannot handle. Dangerous in unexpected situations.

Each of these situations presents a different set of challenges to maintaining driver safety. Quadrant 1 (Level 2/Under) is essentially normal driving where the automated systems are not used or are turned off. The primary risks to drivers are the inherent risks of vehicle operation. However, in some circumstances the automated systems may put drivers at risk if they activate and drivers react inappropriately. For example, if drivers are in a new vehicle they have not operated before or are unaware that the systems are in place. The automated system activation could startle drivers and cause them to take unnecessary corrective action (Koglbauer et al. 2017).

Quadrant 2 (Level 2/Over) is a significantly more dangerous situation for drivers. In this situation drivers have excessive trust in the ability of the automated systems in the vehicle they are operating, despite the fact they are still the primary operators in all modes and conditions. This situation can manifest if drivers have a limited understanding of the capabilities of the automated systems. Drivers could place themselves in jeopardy by relying on the automated systems when it is inappropriate. They may disengage from the driving task while the system is active, become more easily distracted by secondary tasks, or use the automation in complex situations it was not intended to handle (Fleming 2012, Hergeth et al. 2017, Schwarz et al. 2016). As level 2 vehicles become more prevalent, crashes that result from this combination of features will likely become more common.

Quadrants 3 and 4 are presently theoretical because level 4 vehicles are still being developed and tested. In a level 4 AV, situations in which the driver must take manual control will likely be rare. Level 4 vehicles are defined as “High Automation” by NHTSA and SAE, wherein all aspects of dynamic driving are controlled by the automation. This means the system is capable of resolving the majority of driving situations, therefore switching to manual control will probably only occur in critical situations where the automation is not equipped to respond safely. The following discussion of level 4 vehicles will focus on these critical situations, precipitated by adverse weather events.

Quadrant 3 (Level 4/Under) is a potential situation in which a driver, perhaps due to a preference for legacy vehicles or an expectation that they can execute a maneuver more effectively, fights the automated system for control of the vehicle. Unless the vehicle is designed to handle this situation, receiving multiple sets of inputs could cause it to behave erratically, placing the driver at risk. This is particularly the case in a situation where the driver tries to take control during a critical moment and the conflict causes the vehicle to respond inappropriately (Hergeth et al. 2017, Schwarz et al. 2016).

Quadrant 4 (Level 4/Over) is a more likely fully automated driving situation. In a vehicle that handles the dynamic driving task for an extended time, human drivers have little incentive, indeed no duty, to maintain their situational awareness about the roadway environment. They may regularly nap, read, watch films, etc. in their vehicle while it drives. Therefore, if a situation does arise that necessitates manual control (i.e., the vehicle reaches an operational domain where level 4 no longer applies), drivers may not be able to respond, or may not be able to acquire sufficient information to make an appropriate decision, quickly enough (Louw et al. 2015).

While automated driving generally has substantial unaddressed human factors issues, these are compounded when considered in conjunction with driving in adverse weather (ITS International 2014). The critical situations that can spur the failures outlined above are more likely to occur in adverse weather situations, when driving conditions are more hazardous and require greater attention on the part of the driver (Sundararajan and Zohdy, 2016). Fortunately, automated and CV technology also provide solutions to these problems. However, the solutions available at any given time are dependent on the technology commercially available, the extent of infrastructural and technological investment, and driver compliance with these systems. While many of these solutions are based on research, some are more speculative and remain unfeasible until the technology develops sufficiently (ITS International 2014, Sundararajan and Zohdy, 2016).

While automated driving presents a number of human factors challenges that must be addressed for successful implementation, it also presents opportunities to integrate the driver and system to take advantage of their capabilities. The concept of “adaptive automation” views the driver as part of the system, or as a co-pilot, who can help monitor certain systems, aid the system in making decisions, or act as an additional monitor for hazards the vehicle may not detect (Da Lio et al. 2015).

Providing the driver with a system to actively monitor can reduce the amount of distraction or disengagement the driver experiences when operating an AV. In level 2 systems, this is more easily accomplished as the automation only controls certain functions in normal driving conditions (Da Lio et al. 2015). The driver is responsible for primary navigation and vehicle safety while tasks such as maintaining speed or lane position, following distance, and parking can be automated. In level 3 and 4 systems, it may be more difficult to provide the driver with a sufficiently engaging task to keep them attentive. The driver could update or monitor the vehicle’s navigation systems, altering the route to avoid unexpected delays or other slowdowns, for example (Da Lio et al. 2015).

In adverse weather, the driver can act as an additional monitoring system (ITS International 2014). They can scan for debris in the roadway and alert the vehicle, or anticipate road closures due to snowfall and suggest alternate routes. Particularly difficult driving situations (heavy snowfall, flooded roadways, etc.) may require manual driving well after level 4 vehicles are commonplace. Making the automation adaptive enough to include the driver in situations where their expertise will be beneficial would help mitigate automation failures by helping ensure the driver has an accurate understanding of the system parameters and is engaged with the driving environment (Da Lio et al. 2015).

The Role of the Driver in Specific Weather

Different types of adverse weather create different challenges to which automated vehicles and drivers must respond (ITS International 2014, Sundararajan and Zohdy, 2016). The following list of adverse weather challenges is not exhaustive, but represents what is available in the research. Much of the research on automated systems is being conducted by the OEMs who intend to manufacture the vehicles, making the research proprietary. The human factors research on the topic is sparse and theoretical, and is intended to inform the work OEMs do. As connected and automated vehicles enter the marketplace and roadways, researchers will have greater access to information with which to conduct research. However, a significant amount of research exists surrounding human performance on similar tasks, so that research can offer concrete guidance on how human operators are likely to respond to automated systems (Hergeth et al. 2017, Schwarz et al. 2016).

Wind

High winds pose an unusual problem for AV drivers, as the presence of strong winds may not be obvious from inside the vehicle. Unless the driver is closely paying attention to the surrounding environment or is actively steering against the wind, the driver may be unaware of the adverse weather at all (ITS International 2014). This is particularly true on stretches of road that are surrounded by flat terrain or on long bridges (Hammit and Young 2015). High winds can push the vehicle and alter its trajectory, introducing new forces that complicate steering. This could be problematic in a couple ways. If the automated systems do not take the force of the wind into account, the vehicle could drift off course. If the vehicle does not warn the driver that it is compensating for high winds, then the driver may not compensate adequately in the event of a transition to manual control (Hergeth et al. 2017, Schwarz et al. 2016).

For example, if a driver is making use of the adaptive cruise control and automated lane keeping (Koglbauer et al. 2017), the vehicle has been compensating for the presence of high winds while driving. If the driver resumes manual control to change lanes or turn, without being aware of the winds, the driver may not adjust the steering sufficiently to safely make the course change (Hergeth et al. 2017, Schwarz et al. 2016). CVs offer the opportunity to warn drivers in advance of areas of localized high wind (bridges, mountain passes, etc.) so the driver is less likely to be surprised by a windy environment (Dannheim et al. 2013, Outay et al. 2017).

High winds also pose the risk of blowing debris onto the roadway and creating hazardous pavement conditions. Road appurtenances, tree limbs, whole trees, downed power lines, etc., can blow onto the roadway during storms or other wind-related events and create obstacles that either partly or entirely block the roadway. Drivers must use their own judgement to determine if they can navigate around the obstacles safely. AVs may not be capable of making the same judgement about the safety of an unusual roadway condition. Level 4 vehicles may simply come to a stop when faced with any object that could puncture a tire and requires more than a minor course correction to avoid (Hergeth et al. 2017, Schwarz et al. 2016). There is some question about the granularity of the sensors level 4 vehicles will use, so it is difficult to predict the size of debris the vehicle will be able to detect and maneuver around (Duthon et al.

2016, Reina et al. 2015). CVs offer the potential for vehicles to identify dangerous or impassable debris and inform other vehicles in the area so they can be safely rerouted (Outay et al. 2017, Pindilli et al. 2013).

Fog

Fog can drastically reduce visibility for drivers and may occur in isolated areas, which can reduce the available braking distances after the driver notices a hazard (Gallen et al. 2013. Li et al. 2017). The increase in water on the roadway can result in reduced braking friction as well (Hammit and Young 2015). This dangerous combination can lead to an increase in crashes, particularly rear-end collisions. If a lead vehicle stops suddenly, following vehicles have less time to stop with a reduced coefficient of friction (Li et al. 2017).

Several automated systems exist currently that can reduce the likelihood of crashes in the event of reduced visibility due to fog. Forward collision warning (FCW) systems alert the driver to the presence of an object in the roadway ahead so the driver can respond (Fleming, 2012. Li et al. 2017). The effectiveness of this type of system may be limited, however, as it depends on the ability of the sensors to pierce fog (Duthon et al. 2016, Reina et al. 2015). This limits the distance at which a forward object can be detected in fog; however, the system may still aid in altering a distracted or sight-impaired driver. FCW is also limited by the driver’s perception reaction time (Li et al. 2017). The system only warns the driver, who must brake manually. A more effective, but similar technology is automatic emergency braking (Fleming, 2012. Li et al. 2017), which automatically applies the brake if the system detects a hazard within a critical distance of the vehicle. In foggy situations where the driver’s perception reaction time is decreased, having the system able to respond more quickly than the driver could make a critical difference between a near miss and a collision (Koglbauer et al. 2017, Li et al. 2017).

Adaptive cruise control (ACC) is another current-generation automotive technology that has the potential to reduce limited sight distance collisions (Dannheim et al. 2013, Koglbauer et al. 2017). The system monitors the forward roadway to adaptively maintain a speed set by the driver and can slow down in response to the presence of traffic (Fleming, 2012. Li et al. 2017). ACC is limited by the same concerns as FCW, however, in that the range of the sensors determines how effective the system would be if a lead vehicle hidden by fog suddenly stops and the system must halt the following vehicle. A solution to this issue would be to use CV technology to create a cooperative adaptive cruise control system (Li et al. 2017), which would communicate with other nearby vehicles, allowing them to account for the movements and speed transitions of other CVs without necessarily being able to see one another. This would allow vehicles to safely slow down in situations where sight distance is limited (Hammit and Young 2015, Li et al. 2017, Outay et al. 2017).

Rain

Like fog, rain can reduce the driver’s visibility while creating slick pavement conditions (Gallen et al. 2013). This is especially dangerous on declines, where water flowing downhill can reduce braking friction and cause cars to slide, potentially into other vehicles or pedestrians (Druta and Alden, 2016, Hammit and Young 2015, Jung et al. 2013). In wet and muddy conditions spray or splatter may cover sensors on AVs, causing them to detect objects where none exist or fail to detect objects that do (Duthon et al. 2016, Fröhlich et al. 2014). If humans are not engaged with the driving task, in an automated vehicle for example, then they may fail to notice sensor coverage or performance issues until the vehicle’s behavior changes. They may also neglect tasks such as activating windshield wipers, which could become problematic if they are required to resume manual control.

OEMs are in the process of testing and incorporating multiple types of sensor technology, such as radar and LiDAR, which can pierce through rain to an extent (Reina et al. 2015. Sundararajan and Zohdy, 2016). Certain types of sensors are less easily refracted by rain. By using a diverse sensor package, an AV could compensate for the presence of rain (Duthon et al. 2016). It is unclear from the literature to what degree these sensors could detect if they are compromised by rain and mud, which remains an ongoing issue to be addressed (Hammit and Young 2015, Reina et al 2015). Ideally, sensors would be able to alert the driver if they have become covered so the driver can take manual control and find a safe location in which to clean them (Hergeth et al. 2017, Schwarz et al. 2016). The automation may also be able to detect wet pavement conditions and slow the vehicle down to an appropriate speed to avoid sliding or hydroplaning (Druta and Alden, 2016), provided it is not compromised.

CVs offer another way to expand sensor capabilities in low visibility and rainy conditions. Information from the sensor packages from multiple vehicles could be integrated, along with information from connected infrastructure, to give vehicles a more complete roadway image (Hammit and Young 2015, Pindilli et al, 2013). CVs may also be able to warn other nearby vehicles if they have to shift to manual control, allowing other vehicles to maintain distance in the event of slick pavement and low visibility (Dannheim et al. 2013, Hammit and Young 2015, Hergeth et al. 2017, Schwarz et al. 2016). In certain parts of the country, rain can occur suddenly or in highly localized areas. CVs and connected infrastructure would be able to warn vehicles entering the area about low visibility and low traction conditions so the drivers and vehicles can prepare ahead of time and enter the area safely (Dannheim et al. 2013, Druta and Alden, 2016, Hammit and Young 2015, Outay et al. 2017, Pindilli et al. 2013, Sundararajan and Zohdy, 2016).

Snow and Ice

Snowy and icy conditions are especially hazardous to drive in. A high proportion of weather-related crashes occur in snow and ice (Druta & Alden, 2016). Significantly reduced grip potential can cause vehicles to slide, spin out of control, or crash while limiting the ability of the driver to respond effectively (Gallen et al. 2013). Additionally, black ice may be nearly impossible for a driver to see. Icy build-up on hills can prove challenging to navigate and many vehicles are forced to find alternative routes in the winter. Normal routes may also be blocked by snow banks, including those created by snow plows. Typical navigation systems may not account for these closures. Snow can accumulate on signs, windshields, and pavement, blocking the driver’s view. This reduces the driver’s overall visibility and can cover critical markings, resulting in unintentionally dangerous driving behavior (Druta and Alden, 2016, Gallen et al. 2013).

From the current literature it is unclear how AVs will respond to snowy and icy conditions. Some OEMs have issued statements that they have solutions or potential solutions to winter weather issues, but are not entirely forthcoming about the extent of these solutions. There remain many unaddressed issues when considering the specialized needs of automated winter driving. Notably, the issue of identifying lane markings. During snowy weather, lane markings can become covered or obscured. Current AVs use lane markings to maintain position on the roadway and it is not clear if these vehicles will be able to operate while those markings are covered (Druta and Alden, 2016, Fröhlich et al. 2014). In fact, snow accumulation on roadways frequently forces drivers to ignore lane positions and drive on different sections of road as needed, creating secondary informal traffic lanes. OEMs do not offer predictions as to when AVs will be intelligent enough to conditionally violate roadway rules in this manner, meaning winter driving may remain a manual task for a long time. Furthermore, it is not clear if AVs will be able to make the same judgements that a driver must make in winter driving. For example, the choice about whether or not to attempt to traverse a hill while there is snow on the road, or the decision about when it is appropriate to abandon such an attempt if it seems dangerous. In addition, similar problems for sensor and windshield coverage from snow, water, and mud exist for winter driving as they do in rainy driving (Druta and Alden, 2016, Fröhlich et al. 2014). Snow and ice can accumulate in crevices and alcoves more easily than rain, which could exacerbate the problem in snowy driving as compared to rain. Snow may prove more difficult than rain to penetrate with sensors and can block sight distance more than rain (Duthon et al. 2016, Reina et al. 2015).

Another option for winter driving in AVs is for the car to switch from automation to a support role. While snowy conditions may require the driver to take over manual control from the automated systems, the automated system could use its capabilities to support the driver (Hergeth et al. 2017, Schwarz et al. 2016). The system could monitor for icy pavement or black ice, obstructions buried under snow, encroaching or sliding vehicles, and provide advisories on speed and following distance (Koglbauer et al. 2017).

These support capabilities could be augmented with CV technology. CVs could communicate with one another in low visibility conditions about location, safe following distance, and braking so drivers do not have to rely entirely on limited sight (Dannheim et al. 2013). Vehicles could communicate with one another about particularly dangerous sections of road, patches of black ice, and blocked or closed roads (Dannheim et al. 2013, Druta and Alden, 2016). They could also provide updated information to other drivers about which roads have been plowed, salted, or otherwise cleared to help them choose the safest route. In the event of an emergency, the vehicle could alert emergency services to the location of a crash (Hammit and Young 2015, Outay et al. 2017, Pindilli et al. 2013).

The Role of the Driver in a Critical Situation

During a critical situation, such as one caused by adverse weather, it is incumbent upon the driver to make crucial decisions in a limited time in order to preserve safety. While the features of AVs may help drivers avoid many potential crashes, it is inevitable that these systems will fail at some point, exposing drivers to danger. Therefore, even in level 4 systems, the driver will still bear some responsibility for safety and must be ready to re-engage with the task of driving. If the driver is not ready to re-engage or is distracted, the driver may not have enough time or cognitive capacity to respond to an emergency situation (Fleming, 2012, Louw et al. 2015). The ability of drivers to engage and respond raises ethical dilemmas inherent in AV use.

As situations where the driver must take full control of the vehicle become rarer, drivers will have less reason to stay engaged and aware (Hergeth et al. 2017, Schwarz et al. 2016). If a driver is unaware of a dangerous situation before being required to respond to it, the time it takes to reengage is lengthened, the understanding of what is happening is decreased, and the probability that they will make an inappropriate response is increased (ITS International 2014, Louw et al. 2015).

A number of solutions have been proposed to keep drivers engaged with AVs. Some systems monitor whether the driver is engaged with the task. Camera systems could monitor the driver’s blink rate or eye fixations to evaluate attention to the roadway and warn a driver who loses focus (Dasgupta et al. 2013). While this solution could work for level 2 vehicles, it is not necessarily practical for level 4 vehicles, where any such warning might simply be ignored by drivers who spends most of their time as a passenger (Fleming 2012). This difficulty could be exacerbated with novel seating arrangements in primarily automated vehicles, where time may be required to arrange the seats into a configuration suitable for manual driving (Adient 2017). Another option would be using CV technology to warn drivers of upcoming hazardous situations (fog, black ice, obstructed roadways, etc.) the driver has time to re-engage before reaching the hazardous location (Dannheim et al. 2013). This would mitigate the problem, but because at least one vehicle would have to encounter the hazard before it could warn others, it is not a perfect solution (Outay et al. 2017). Connected infrastructure could assist as well; roadside sensors located near known problem areas could warn approaching vehicles of hazards before any vehicles arrive (Hammit and Young 2015, Outay et al. 2017).

Another solution is to treat the driver and automated system as co-pilots, assigning tasks to both systems as road conditions and demand allow (Da Lio et al. 2015). For example, in heavy traffic conditions the driver could take on the role of navigator, suggesting alternate routes that the vehicle may not be aware of. During adverse weather events, the driver can act as a backup monitoring system, looking for hazards the vehicle may not notice, assisting in navigating around obstacles in the roadway, and checking for vehicles or other drivers in distress. Providing drivers with a task helps them maintain engagement with driving, keeps them aware of the driving environment, speeds their reaction time to any critical situation, and removes some of the burden from the automated system (Da Lio et al. 2015, Koglbauer et al. 2017).

If the automated system is going to share responsibility with the driver in certain situations, the limitations of human drivers should be accounted for (Da Lio et al. 2015). Drivers do not perform well when required to remain vigilant for long periods of time with a low hit rate. In this case a “hit” would be a situation where the driver detects something and alerts the system or takes manual control (Hergeth et al. 2017, Schwarz et al. 2016). A driver who has little to do will lose engagement (Louw et al. 2015). The requirements for what constitutes a hit or critical situation will vary depending on the level of automation. In a level 2 vehicle, a hit may be any situation outside of normal or ideal driving conditions, whereas a level 4 vehicle may be able to handle a wide variety of situations and only require driver input in specific circumstances. The way the system communicates to the driver is important as well. Simply lighting up an icon may not be sufficient to warn the driver about hazardous conditions, or provide sufficient information about the actions to take. The most effective way for the system to communicate with the driver is an area where little information is available, and more research is required (Hergeth et al. 2017, Schwarz et al. 2016).

The final area that requires additional research to make automated driving in adverse weather conditions viable is an examination of when and how AVs should switch to manual control. Little research is available on how mode switching affects driver performance. In other domains, mode switching is consistently associated with a decrease in task performance, an effect that is likely to apply in this case as well (Hergeth et al. 2017, Schwarz et al. 2016). This poses a human factors dilemma when considering mode switching during a critical event. If a mode switch can result in decreased driving performance, is it safe to change modes just before or during a critical event when task demand is highest (Louw et al. 2015)? Can drivers perceive a situation and select an appropriate response fast enough to make a safe choice, particularly if they were previously disengaged from the task? There is not enough domain-specific research to provide a satisfactory response to those questions at this point. The need for additional publicly available information on the human factors of automated driving in adverse weather is pressing as OEMs show no sign of slowing down their plans to introduce AVs to the public soon.

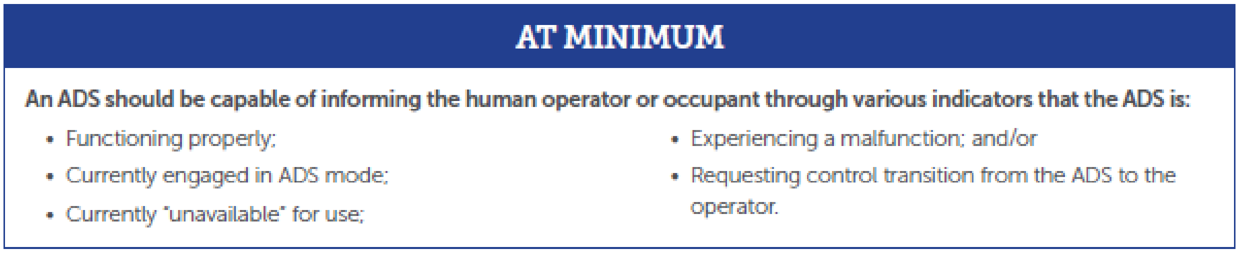
Human-Machine Interface Design

Graphical and text displays, audible sounds, and–in some designs–vibrotactile feedback are the most commonly used methods by which a Human-Machine Interface (HMI) communicates AV system status and state changes, and requests for drivers to re-assume control of the primary driving task. This information and the manner in which it is conveyed is of crucial importance to maintaining safe operations. Ideally, AV automakers would design HMIs that include some level of standardized interface elements and present status and requests similarly. Standardized interfaces could be especially useful for novice AV drivers and those driving more than one AV. However, it is not required. In addition, several factors constrain AV HMI design and make standardization impractical. These factors include that the candidate locations where HMI information may appear varies across AVs, driver assistance system functions differ from AV to AV, and AV logic is unique to AV Original Equipment Manufacturers (OEMs).

Nonetheless, NHTSA recommends that AV HMIs should inform drivers of:

- Automated driving system status (i.e., functioning properly, currently ‘unavailable’, or malfunctioned
- Status of AV engagement in automated driving system modes (i.e., ACC, LKS, etc.)
- Requests for the driver to take control of all aspects of the driving task

Figure 1 presents an excerpt from NHTSA’s Automated Driving Systems 2.0: A Vision for Safety (NHTSA 2017a) that specifies the kinds of status and control requests that AVs should convey to the driver.



AT MINIMUM

An ADS should be capable of informing the human operator or occupant through various indicators that the ADS is:

- Functioning properly;
- Currently engaged in ADS mode;
- Currently "unavailable" for use;
- Experiencing a malfunction; and/or
- Requesting control transition from the ADS to the operator.

Source: NHTSA.

Figure 1. List. Minimum types of information an ADS should be able to communicate to the driver.

Chapter 3. Experiments

Five level 2 vehicle models commercially available in the United States were tested across two test periods on a test track while performing planned maneuvers during repeatable simulated and naturally occurring adverse weather conditions. This chapter presents details of these test experiments and results.

Purpose of the Experiments

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. Their ability to properly perceive the situation and 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 different means are available to achieve this objective, but most commonly control is achieved using a combination of cameras and radar sensors. Most vehicles on the market use cameras in conjunction with machine vision algorithms to identify objects and marking on the roadway. 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 time of flight and frequency shift due to the Doppler Effect, distance to the object and relative velocity are measured. Each type of sensor is known to have different strengths and weakness in how it perceives the environment. The adverse weather testing was designed to help to exemplify these differences.

The tests conducted 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 permit an assessment of how well the automation features of each AV 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.

High-Level Summary of Test Results

The following bullets present a high-level performance results summary for tested 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.

Test Period 1 Results Summary

Dry vs. Rain:

- All AVs performed well in **high-speed following maneuvers**, and most performed well under **low-speed following (traffic jam assist) maneuvers** in dry conditions. However, **heavy or sustained rainfall presented challenges for all AVs.**
- All AVs performed well at **lane-keeping** on straight dry roads and in light rainfalls, but **performance declined for all AVs when rainfall was heavy or sustained**.
- The **performance of some AVs improved when the roadway and lane stripes were wet,** perhaps due to the greater contrast provided by darker asphalt.

Ice and Modest Snow:

- **With any amount of ice coverage over the cameras, none of the AVs were capable of performing lane-keeping**. Even with residual water coverage, one AV had difficulties.
- **With any ice covering the radar sensor, none of the AVs could perform object ranging or following support**. However, one AV performed lane keeping and low-speed following with an iced radar and clear windshield camera.
- Light falling snow did not impact any maneuver, but **even modest amounts of slushy coverage on parts of a heated radar sensor impacted adaptive cruise control functions**.

Sun Glare:

- Performance of the AVs ranged from **no impact to large impacts from low-angle sun glare on lane-keeping tests.**

Test Period 2 Results Summary

Lane Departures in Falling Snow and with Snow on Road

- **Light blowing snow did not challenge any of the AVs**.
- **AVs performed better in full continuous snow coverage than in patchy/sporadic snow coverage of the road**.
- **AVs performed lane centering with differing amount of information**. One AV required visibility of both lane line markings, another AV could track with one lane marking and a road seam, and one AV could track with only one line or contrast edge.
- **AVs were observed to provide different levels of lane-keeping support based on the confidence level of sensor detections.**

Following Maneuvers in Falling Snow

- **None of the AVs had exhibited difficulty following in falling snow**.

Lane Departure with Sun Glare on a Curve

- AVs disengaged and requested takeover about half of the time.

Test Conditions

The following sections summarize the test locations, vehicles tested, maneuvers conducted, and adverse weather conditions simulated or that naturally occurred. The instrumentation used in the SV and POV was consistent for all tests. An Oxford RT 3003 was used to collect speed, position, and acceleration. This allowed for ±2cm position accuracy using GPS and real-time kinematic (RTK) corrections from TRC's local base station. The acceleration data was filtered using a low-pass, 6th order Butterworth filter with cutoff corner frequency of 3 Hz, as is defined for NHTSA's Crash Imminent Braking System Performance Evaluation (Carpenter et al. 2011). For communication between the two vehicles and lane positioning data the Oxford RT Range was used. The data acquisition components and approach used to capture vehicle audible and visual alerts, as well as position and range measurements differed slightly between the two test periods and is detailed further in the test reports for each period.

Location

Testing in both test periods was performed at the Transportation Research Center (TRC) in East Liberty, Ohio. The first test period, conducted the week of March 12, 2018, exposed select level 2 automated vehicles to adverse spring season weather. The second test period, conducted the week of January 28, 2019, focused on providing adverse winter weather conditions. 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. Figure 2 presents an aerial photograph of part of the TRC grounds with test facilities denoted.

Source: TRC Inc.

Figure 2. Photo. Aerial view of TRC with pointers to facilities where tests were run.

Facilities Used in Test Period 1

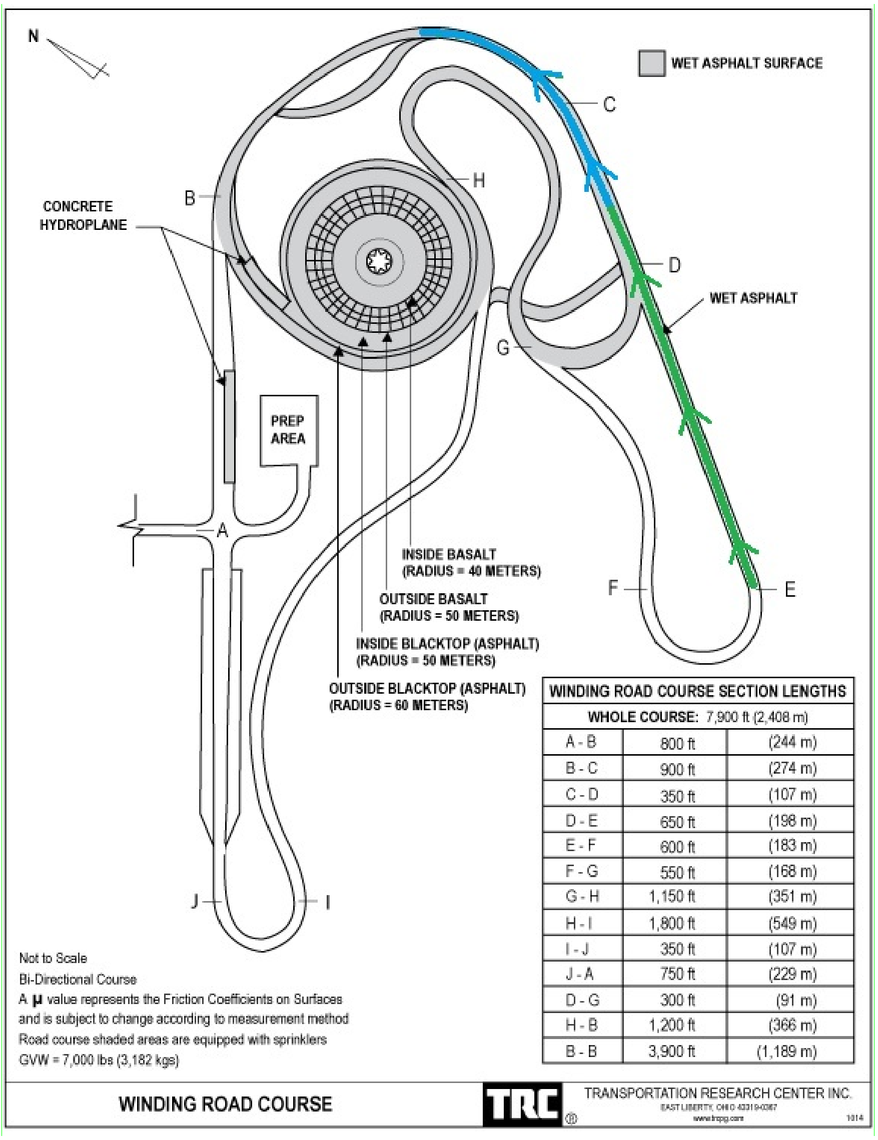
Many tests in period 1 were performed on TRC's Winding Road Course (WRC), which is notated on the facility map in Figure 2. Figure 3 below shows a detailed drawing of the WRC with tests taking place in the areas marked in green and blue. The Winding Road Course curve has a radius of curvature of 300 ft.

Figure 4 shows the water spray area that was used to recreate wet conditions for the vehicles under test. The water was sprayed in front of the vehicle's grille and on the windshield.

The lane path used for evaluating lane keeping on a straight roadway was defined using temporary lane marking tape. The tape demarcated a lane that was 13 ft wide. A solid yellow line to the left of the vehicle and solid white line to the right of the vehicle was applied using 4-in.-wide strips 1000 ft in length. 3M™ Stamark™ Wet Reflective Removable Tape Series 710 was used on this project to provide a highly reflective all-weather pavement marking. Figure 5 shows close-ups of the lane markings.

The south curve of the Vehicle Dynamics Area (VDA) was used to evaluate the sun glare portion of the test matrix. This curve allowed for the vehicle under test to be driven directly into the sun while it was below 15 degrees above the horizon. The south loop of the VDA has a radius of curvature of 775 ft and a width between the lane lines of 13 ft. Lane stripping is painted in this area with a width of 4 in. A dashed white line was on the left and a solid yellow line was on the right. The location of the south curve of the VDA can also be seen in Figure 2.

The north loop of the Skid Pad was used to conduct Low-Speed Following (LSF) vehicle testing, also referred to as Traffic Jam Assist (TJA). In those tests a target vehicle, the National Highway Traffic Safety Administration (NHTSA) Strikable Surrogate Vehicle (SSV), was used. The SSV is used in NHTSA Crash Imminent Braking and Dynamic Brake Support tests (Carpenter et al. 2011). Figure 6 shows the rail used on the facility for the SSV and the carbon fiber shell of the SSV.



WINDING ROAD COURSE SECTION LENGTHS		
WHOLE COURSE: 7,900 ft (2,408 m)		
A - B	800 ft	(244 m)
B - C	900 ft	(274 m)
C - D	350 ft	(107 m)
D - E	650 ft	(198 m)
E - F	600 ft	(183 m)
F - G	550 ft	(168 m)
G - H	1,150 ft	(351 m)
H - I	1,800 ft	(549 m)
I - J	350 ft	(107 m)
J - A	750 ft	(229 m)
D - G	300 ft	(91 m)
H - B	1,200 ft	(366 m)
B - B	3,900 ft	(1,189 m)

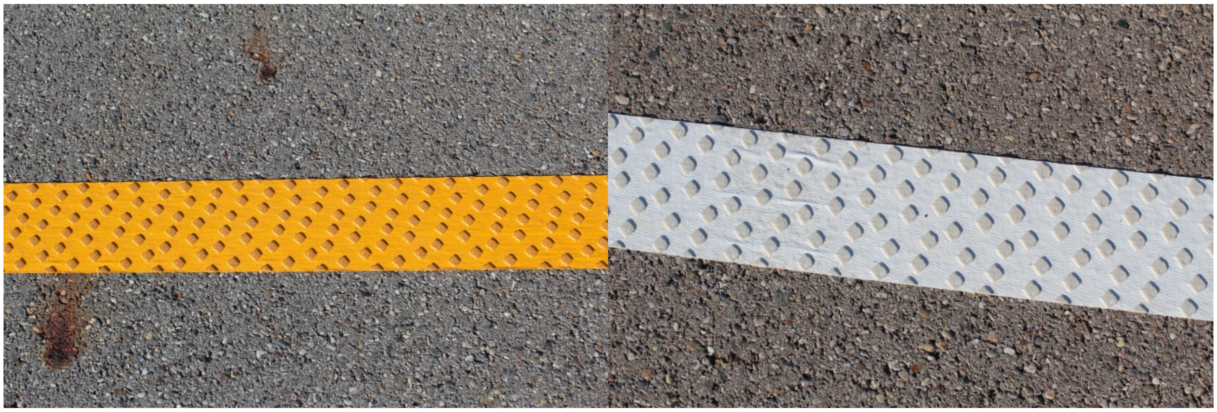
Not to Scale
Bi-Directional Course
A μ value represents the Friction Coefficients on Surfaces and is subject to change according to measurement method
Road course shaded areas are equipped with sprinklers
GVW = 7,000 lbs (3,182 kgs)

Source: TRC Inc.

Figure 3. Diagram. The Winding Road Course. Area marked green shows the test location for Lane Departure Warning and Lane Keeping Support. Area marked blue shows lane departure in a curve testing. Arrows denote the direction of travel.

Source: Battelle.

Figure 4. Photo. Water spraying in the vehicle path on the Winding Road Course as the principal other vehicle (POV) drives through.



Source: Battelle.

Figure 5. Photos. Temporary lane marking tape applied to the Winding Road Course.

Source: Battelle.

Figure 6. Photos. SSV assembly on the north loop of Skid Pad (left) and Strikable Surrogate Vehicle (right).

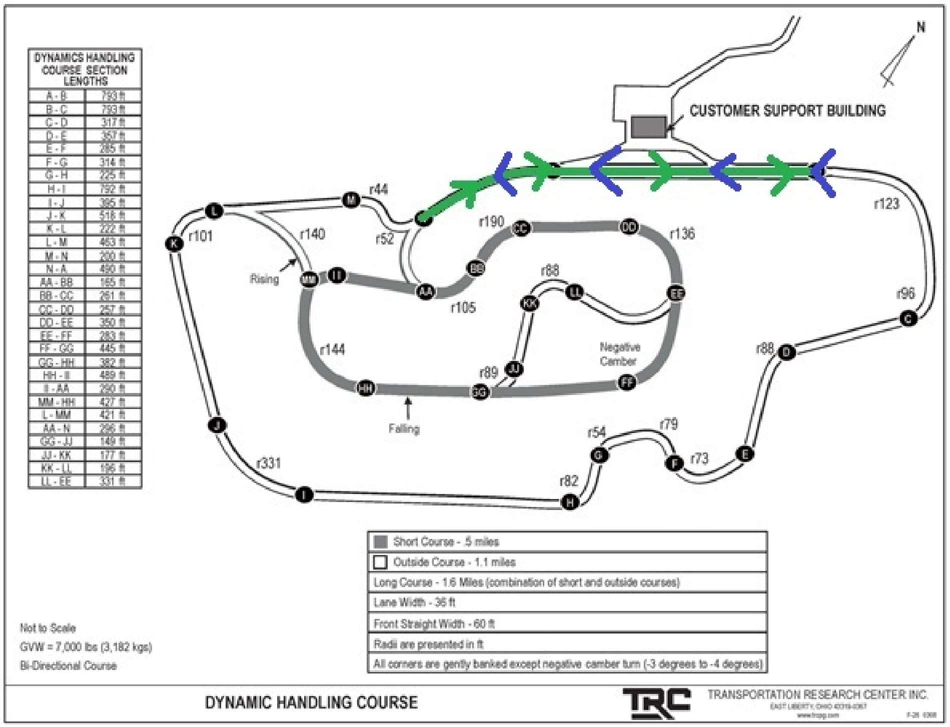
Facilities Used in Test Period 2

Many of the tests in period 2 were performed on TRC's Dynamic Handling Course (DHC). The lane path used for evaluating lane keeping on a straight roadway was defined using permanent pavement markings. A solid white line served as the left lane marking, while a dashed white line defined the right lane marking. Figure 7 shows the lane markings in detail. The location of the DHC is notated on the facility map in Figure 2 above. Figure 8 below shows a detailed drawing of the DHC with testing taking place in the areas marked in green.

Source: TRC Inc.

Figure 7. Photo. Lane markings on the Dynamic Handling Course.

In addition to the DHC, the south curve of the Vehicle Dynamics Area (VDA) was used to evaluate the sun glare portion of the test matrix. This curve allowed for the vehicle under test to be driven directly into the sun while it was less than 15 degrees above the horizon. The south loop of the VDA has a radius of curvature of 775 feet. The curve is marked by 4-inch wide lane lines 13 feet apart. The left lane marking is a dashed white line, while a solid yellow line marks the right. The location of the south curve of the VDA can also be seen in Figure 2 above.



Source: TRC Inc.

Figure 8. Diagram. The Dynamic Handling Course. Area marked green shows the test location for Lane Center and High Speed Follow tests. Green arrows denote direction of travel for Lane Centering and Sun Glare and blue arrows denote direction of travel for High Speed Follow.

Vehicles

Four of the five vehicles tested across the two test periods were from model year 2018, while one was intentionally selected from 2016 to assess the sensor system version available in that model year. The tested vehicle models in test period 2 differed from the three production AV models tested in Period 1, though the two Period 2 AV perception and control systems tested are newer or upgraded AV system versions used by some of the previously tested vehicle models. All tested models strictly relied upon on-board sensor technologies; all models used machine vision (one or more video cameras), and four models used a radar.

All tested vehicles possessed the capability to recognize and respond to lane lines (lateral or steering control) and to recognize and track a lead vehicle (longitudinal control). The subject vehicles (SVs) had different system configurations that were chosen deliberately to compare the ability of different sensors and processing algorithms to perform in various kinds of adverse weather. Testing was limited to evaluation of the entire perception and control system.

Below are definitions of the AV driver assistance systems present on all tested vehicles.

Lane Departure Warning (LDW) - A LDW system is a driver assistance system that alerts the driver when vehicle drift beyond a delineated edge line of its current travel lane is imminent. It does not control the steering at any time.

Lane Keeping Support (LKS) - A LKS system is a driver assistance system that actively adjusts the heading of the vehicle when drift beyond a delineated edge line of its current travel lane is imminent. It controls the steering momentarily, not continuously.

Lane Centering Assist (LCA) – LCA or Lane Centering is designed to keep a car 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 Level 1 automation by the SAE taxonomy.

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 traveled lane. The distance at which the lead vehicle will be followed when ACC is active is driver configurable. The most sensitive ACC distance setting was used for each vehicle tested. With ACC active, the vehicle will dynamically decelerate to match the speed of the lead vehicle down to a stop, using Automatic Emergency Braking (AEB) when necessary. A driving automation system that provides cruise control but without lane centering is Level 1 automation by the SAE taxonomy. A driving automation system that can simultaneously perform lane centering and cruise control is SAE Level 2.

Maneuvers

A series of test maneuvers were designed and executed. Three of the four maneuvers used in test period 1 were executed in test period 2. In order to balance the information gained from this activity, the selected maneuvers were split between evaluation of two different feature groups; lane keeping and vehicle tracking. Lane keeping systems depend on the ability of the perception systems to track the lane markings; vehicle tracking relies on the ability of the perception systems to measure the distance to a Principal Other Vehicle (POV) and discern it from other objects in the space.

The test vehicle and POV were equipped with a Global Positioning System (GPS) and inertial measurement system that records the location and orientation of the vehicle as a function of time. Deviations from the lane centerline or variability in the path were analyzed. In test period 1, three iteration of each test case were conducted, while in test period 2 seven iterations of each case were completed.

The test matrix shown in Table 4 presents the combinations of maneuvers and weather conditions that were tested in test period 1, while the test matrix in Table 5 shows the combinations of maneuvers and weather conditions for test period 2. Each table illustrates where the lane keeping or vehicle following maneuvers were conducted and under which adverse weather condition(s). All vehicles were tested in the baseline condition and then again in the simulated, adverse weather condition(s) specified. The bottom two rows in Table 4 show additional, natural atmospheric or road weather conditions evaluated for two of the three vehicles: while snow was falling or present on the test surface. The bottom three rows in Table 5 show additional testing conducted with snow and salt brine. These conduct of these ad hoc tests in both test period were limited, as noted, and conducted in parallel with planned test activities using other AVs.

Table 4. The four maneuvers tested during specified adverse weather conditions in test period 1.

Conditions	Maneuvers				Notes
	Lane Departure on a Straight Roadway	Lane Keeping Support on a Curve	High Speed Following	Traffic Jam Assist	
Iced Sensors	North Loop of Skid Pad*	--	--	North Loop of Skid Pad	Typically, these were the first tests of day since it required overnight cold chamber preparation.
Sun Glare	--	Vehicle Dynamics Area South Curve	--	--	Testing was completed in the evening when sun angle was less than 15 degrees above horizon.
Wet Road	Winding Road Course	--	Winding Road Course	Winding Road Course	Wet road testing was completed in conjunction with LKS and LDW testing
Falling Rain	Winding Road Course	--	Winding Road Course	Winding Road Course	LDW observed during LKS procedure.
Snow Falling	--	--	Vehicle Dynamics Area	--	Snow was falling for a period of time that allowed for a high-speed-following test maneuver to be run on Vehicle C in these conditions.
Snow on Surface	Winding Road Course**	Winding Road Course**	--	Winding Road Course**	Snow layer on ground lightly covering surface allowed for Ad hoc tests in Vehicle A. No instrumentation was in the vehicle during these Ad hoc tests.

* Ad hoc tests of Vehicle C with radar iced over and windshield cameras both iced over and clear.

** Ad hoc tests of Vehicle A at various venues while other vehicles were tested on TJA maneuvers with Iced Sensors.

Table 5. Maneuvers tested during specified adverse weather conditions in test period 2.

Condition	Maneuvers			Notes
	Lane Departure on a Straightaway	Lane Departure on a Curve	High Speed Following	
Snow Covered Lane Lines	Dynamic Handling Course	--	--	LCA performance, LKS, and LDW were observed during this testing.
Sporadic Snow Covered Lane Lines	Dynamic Handling Course	--	--	LCA performance, LKS, and LDW were observed during this testing.
Falling Snow	--	--	Dynamic Handling Course	
Sun Glare	--	Vehicle Dynamics Area	--	Testing was completed in the evening when sun angle was less than 15 degrees above horizon.
Blowing Snow	Vehicle Dynamics Area	--	--	LCA performance, LKS, and LDW were observed during this testing only on Vehicle D.
Salt Brine	--	--	Dynamic Handling Course	
Sensor Covered Snow	--	--	Dynamic Handling Course	Tested only on Vehicle E to see when functionality stopped.

The following paragraphs summarize the conducted planned maneuvers across the testing periods. Detailed procedures were developed for each test period and are documented separately in the test period reports. Maneuvers were conducted by a professional TRC driver, who exercised discretion in assuming manual control of the vehicle and terminating any test in order to preserve safety, based on indications from the vehicle or data collection equipment, or behavior of the vehicle itself. This included manually braking to preserve safe following distance and manually steering to maintain directional control.

Lane Departure on a Straight Roadway

The test vehicle was driven down a straight roadway at 45 mph using vehicle cruise control. This maneuver began in Section E of Figure 3 in test period 1, and was conducted in the direction noted in the green section of the DHC shown in Figure 8 during test period 2. When the vehicle detected lane lines the driver steered to a desired lateral velocity and released the vehicle handwheel. The lateral velocity used for test period 1 was 0.7 m/s, while the lateral velocity used in test period 2 was more conservative to account for road weather conditions (0.4 m/s). For test period 1 LKS (LCA, if applicable) was engaged prior to lateral steer, while in test period 2 LCA was engaged just after lateral steering was initiated in order to ensure all tested vehicles could be compared without some disengaging due to lack of driver input. This procedure was repeated for both left- and right-side departures in test period 1, while only left departures were tested in test period 2 due to simulated surface conditions. In both test periods, the response of the system regarding LCA and/or LKS, and, if applicable, LDW was recorded. The test was terminated when the vehicle either steered back appropriately towards the center or the vehicle crossed over the lane line.

Lane Keeping on a Curve

The test vehicle entered the curve in the center of the lane of travel at a speed of 45 mph. The path of travel can be seen in the blue portion of Figure 3 for ad hoc tests in period 1 conducted on the WRC. The green denotes the lead up to the curve where the speed was obtained. The blue denotes where the LKS in a curve maneuver was completed. Sun glare tests conducted in both test periods were conducted travelling clockwise in the south loop of the VDA shown in Figure 2. When the curve was reached, the driver released the handwheel and the LKS or lane centering was evaluated through the entirety of the curve. Once the vehicle departed over the lane line without applying enough control authority to continue negotiating the curve, the test was concluded.

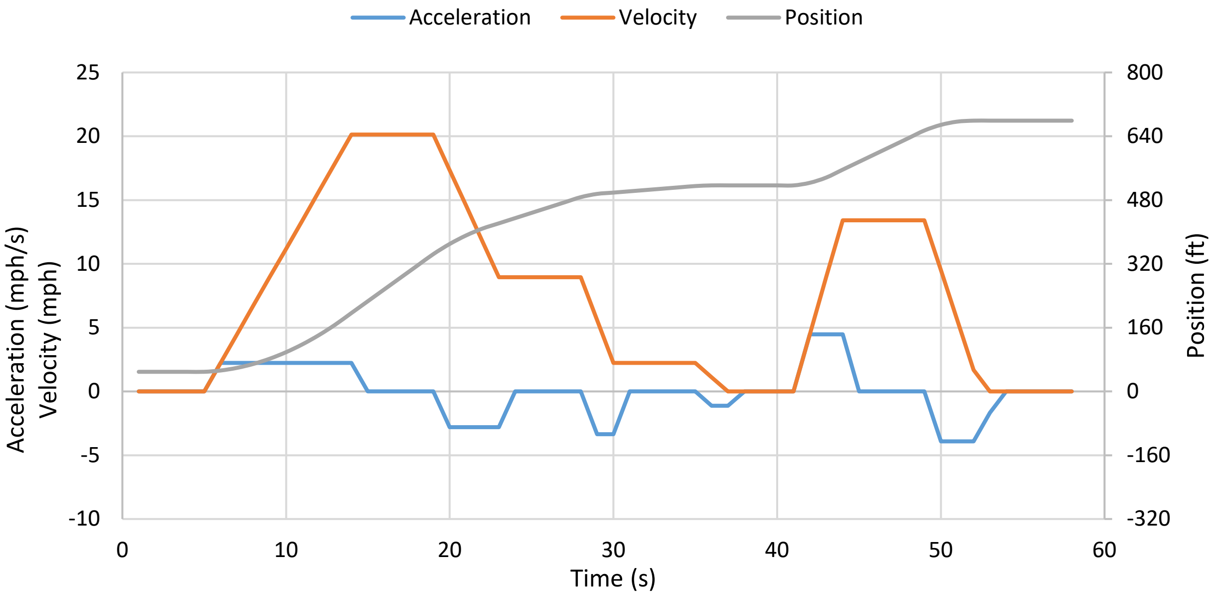
High-Speed Following (HSF)

HSF tests were conducted slightly differently across test period 1 and test period 2 due to the differences in adverse weather conditions, test locations, and vehicle models used. In test period 1, the test vehicle was driven down a straight roadway with the adaptive cruise control set at 5 mph faster than that of the POV. In test period 2, the test vehicle was driven down a straight roadway with the adaptive cruise control set at 45 mph, 15-25 mph faster than that of the POV.

In both test periods, tests were conducted with the POV travelling at target speeds of 20 and 30 mph. As the test vehicle encountered the POV the total range between the two vehicles and time to collision (TTC) was recorded for 1000 ft. If the range between the two vehicles fell below 2.0 seconds TTC, the test run was terminated.

Traffic Jam Assist (TJA)

The TJA testing in test period 1 represented an evaluation of the vehicle’s low-speed start and range-keeping ability. This custom procedure was developed because a standard had not yet been released. Traveling at a speed of 12 mph with the adaptive cruise control engaged, the test vehicle encountered a stopped POV. The test vehicle was expected to come to a stop at the rear of the POV. When it stopped, the POV began a planned series of accelerations and decelerations. Figure 9 presents the speed profile that was followed by the POV. After resuming ACC functionality, following the stop, the test vehicle was expected to accelerate and decelerate to match the speed of the POV. If the range between the two vehicles fell below 3.28 ft (1 m) the test run was terminated.



Source: TRC Inc.

Figure 9. Graph. Speed and acceleration profile of the POV in Traffic Jam Assist test maneuver.

Weather Conditions

Various weather conditions were simulated on the facilities at TRC. For comparison, each of the vehicles was tested both in the adverse weather and in a baseline condition. The following sections summarize the conditions produced or experienced.

Baseline Condition

The baseline condition for all maneuvers conducted in both test periods was unrestricted visibility of lane lines and the POV. The pavement was clear and dry. The air was free of precipitation and the sun was more than 15 degrees above the horizon.

Iced Sensors

This adverse weather condition produced in test period 1 simulated the accumulation of freezing rain resulting in a mostly laminar sheet of ice covering the vehicles sensors. The test vehicle was brought inside a cold chamber set to maintain 15 degrees F. After the vehicle “soaked” at 15 degrees F for 6 hours, water was sprayed on the sensor locations of the vehicle to create a coating of ice, after which the vehicle was left in the cold chamber for an additional 6 hours. A sample of the resulting ice thickness is shown in Figure 10. The thickness of ice was measured at the onset of the test, and was approximately 0.25 in. for each vehicle. In all cases the initial ice thickness was sufficient to disable the system completely. In such cases, the ice was gradually scraped away until the vehicle no longer provided the “system disabled” notification to the driver.

Source: Battelle.

Figure 10. Photos. Sample of ice buildup achieved on test vehicles for testing.

Sun Glare

During both test periods, the vehicle was driven in a curved path with a heading that passed through direct alignment with the setting sun. All testing was completed with a sun angle of 15 degrees or less above the horizon, as shown in Figure 11.

Source: TRC Inc.

Figure 11. View from vehicle with maximum sun glare.

Wet Road

During the falling rain test in test period 1 there was water on the roadway, partially obscuring the lane lines, shown in Figure 12. This weather condition was tested in conjunction with lane departure, high speed following, and traffic jam assist maneuvers.

Source: Battelle.

Figure 12. Photo. Wet road caused by water spray on the Winding Road Course.

Falling Rain

In test period 1, water nozzles on the side of the WRC simulated falling rain for 1000 ft. This contrived condition permitted testing of sensors located on both the grille and windshield of the vehicles to be exposed to simulated rainfall. While driving in the simulated rainfall area, the vehicles windshield wipers were set to the highest setting allowed by the vehicle. Figure 13 shows the conditions as the POV approaches a stationary camera.

Source: Battelle.

Figure 13. Photo. The vehicle that was used as the lead vehicle drives through simulated rain on the Winding Road Course.

Snow on Ground

In test period 2, snow was positioned on the pavement of the dynamic handling course in two configurations. The first configuration was sporadic or patchy snow. Naturally distributed patchy snow partially covered lane markings in the area where lane centering was engaged. The second configuration was full coverage of both the lane markings. Natural snow was harvested from drifts and spread over the lane markings so they were not visible during the lane keeping tests. The air was cold and dry enough that the snow remained powdery throughout testing.

Source: Battelle.

Figure 14. Photos. Snow on ground configurations.

Falling Snow

During test period 2, artificial snow was generated on the DHC using a snow gun. The snow gun itself was outside the lane of travel blowing snow into the path of the vehicles. Although the cloud of snow was narrow, it was sufficient to momentarily obscure the SV's view of the POV as they passed.

Source: TRC Inc.

Figure 15. Photo. Falling snow on DHC.

During test period 1, falling snow and slush on the ground presented by natural atmospheric conditions occurred throughout the duration of some planned tests, enabling these conditions to be evaluated in an ad hoc fashion.

Blowing Snow

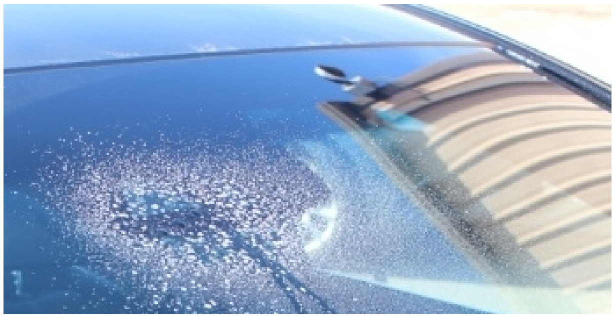
In addition to the planned weather conditions produced during test period 2, an additional weather condition, resulting from an opportunity presented by natural atmospheric conditions occurring during testing, was evaluated. When traveling around the VDA, snow was blowing across the surface in front of the vehicle and across the lane striping. One vehicle attempted the lane centering tests while this weather condition occurred naturally, and it successfully completed them.

Source: TRC Inc.

Figure 16. Blowing snow on the Vehicle Dynamics Area.

Salt Brine on the Sensors

Salt brine was sprayed directly on the radar and camera locations during ad hoc testing in test period 2. The mixture was similar to what is used on public roads.



Source: TRC Inc.

Figure 17. Salt brine applied to vehicle windshield in front of camera on vehicle under test.

Sensor Covered Snow

Snow was placed on the grille and windshield in the areas of the radar and camera during ad hoc testing in test period 2. Snow was added until the system became inoperable.

Source: TRC Inc.

Figure 18. Snow applied to sensors on vehicle under test.

Results

Lane Departure on a Straight Roadway

Overall, the vehicles were generally able to detect lane lines on straight roads, in both the baseline and adverse weather conditions (i.e., falling and wet road conditions in test period 1, and snow covered lane marking runs in test period 2). All SVs tested needed some time after first seeing lane lines (several seconds at 40-45 mph) to allow engagement.

All five vehicles tested across the two test periods will disengage Lane Centering Assist (LCA) if the steering wheel is actuated by driver input and some vehicles would disengage LKS when the steering wheel was moved by the driver. As a result, in test period 1 LKS was not engaged for these vehicle models and only LDW testing was completed. Once the vehicle presented a LDW, the driver steered the vehicle back into the lane.

Baseline Performance

For baseline testing in test period 1, lane departure was tested to the right and to the left. All the vehicles detected and provided an alert for lane departure except for one run with Vehicle A, which occurred during a lane departure to the left.

During test period 2, baseline lane centering was tested with a left departure. Vehicle E performed as expected by recognizing lane lines and then centering the vehicle within the lane in all seven trials. The vehicle did not issue a warning of lane departure or that driver steering intervention was required, nor did it need to. Vehicle D did not indicate on its driver display that lane lines were detected – due to a high requisite level of confidence not being attained. It is believed that this was a result of the relatively low contrast between the roadway and the lane markings, as compared with the relatively higher contrast between the roadway and the snow edge covering the lane markings in the full coverage case. This vehicle did, nonetheless, provide lane keeping assistance functions and presented a LDW to the driver on 5 of the 8 runs despite crossing the lane lines on all 8 runs.

With Falling Rain and Wet Road

Falling rain and wet road conditions were tested in conjunction with one another. Vehicles A and C did not show performance degradation of the LDW system in simulated rain during test period 1. Contrary to the expectation, Vehicle A missed lane detection in the baseline (although it was in a different departure direction), whereas it detected all lane departures with rain. More test runs with rain would be needed to determine how often the failure occurs. Only Vehicle B performed worse in rain as compared with the baseline, missing one of three lane detection opportunities. Table 6 summarizes the performance of each vehicle trial in falling rain.

Table 6. Summary of Lane Keeping Support: right-side departures with rain.

Vehicle	Run	Recognized Lane Lines	Lane Departure Warning	Lane Keeping Support	Additional Comments
A	1	Yes	Yes	Yes	Performed as expected
	2	Yes	Yes	No	The vehicle disengaged the LKS and sounded a beep to inform the driver
	3	Yes*	Yes	Yes	*Visual indicator of lane tracking turned off when line was crossed, but active steering continued.
B	1	Yes	Yes	Yes	System displayed to the driver that it was disabled following departure through the rain. Came back on after driving for approximately 30 seconds.
	2	No	Yes	No	Neither lane line was detected before departure occurred. Lane departure warning was given.
	3	Yes	No	No	At the moment of departure, the display indicated it no longer recognized the right lane line.
C	1	Yes	Yes	NA	Performed as expected
	2	Yes	Yes		
	3	Yes	Yes		

Full Snow Coverage on Lane Lines

For the full snow coverage on lane lines scenario in test period 2, Vehicle D indicated that it detected the lane lines on 4 of the 7 test runs. In these runs the vehicle started slightly left of center before initiating departure. In the runs where the vehicle started slightly right of center before initiating departure, it never achieved LKS. This vehicle did provide LKS but not LCA when centered within the lane before initiating a departure. This vehicle appears to rely heavily on lateral proximity to visible lane markings. Vehicle D still departed the lane lines on all test runs but alerted the driver with a lane departure warning on all but 1.

Vehicle D overall performance was better with snow covered lane lines compared to the baseline. Even though the vehicle did not always indicate to the driver that lane lines were detected it still gave issued appropriate LDWs. Vehicle E performed very similarly to the baseline with the exception of 1 run where the vehicle did not recognize the lane lines and departed the lane during the maneuver. Table 7 summarizes the performance of each vehicle in full snow lane line coverage on a straight roadway.

Table 7. Summary of Snow Covered Lane Centering on a straight roadway.

Vehicle	Number of Attempts	Detected Lane Lines	Stayed Within the Lane	Issued LDW	Issued a Take Steering Control Command
D	7	4	0	6	3
E	7	6	6	0	0

Sporadic Snow Coverage on Lane Lines

For the sporadic (or patchy) snow coverage on lane lines scenario, Vehicle D only displayed that it recognized lane lines to the driver on 1 run. It did achieve ACC in one case, but only briefly. LCA was not achieved. Vehicle D only departed the lane lines on 5 of the 9 total runs and gave a LDW to the driver on 3 of the 9 runs. During testing the approach, Vehicle D was changed to offset left within the lane in an attempt to improve performance. Extra test runs were completed because of this lane positioning. Vehicle E performed very similar to the baseline with the exception of 1 run where the vehicle did not recognize the lane lines but was still able to stay within the lane during the maneuver. Table 8 summarizes the performance of each vehicle in sporadic snow lane line coverage on a straight roadway.

Table 8. Summary of Sporadic Snow Lane Centering on a straight roadway.

Vehicle	Number of Attempts	Detected Lane Lines	Stayed Within the Lane	Issued LDW	Issued a Take Steering Control Command
D	9	1	4	3	0
E	7	6	7	0	0

Lane-Keeping Support on a Curve

In test period 1, lane centering or lane keeping was initially attempted on the WRC in order to possibly facilitate rain testing on a curve, but the WRC proved to have too sharp of a curve for the curved testing maneuver. The VDA south loop was instead selected for sun glare tests in both test periods due to its more generous geometry and alignment to sun glare. The VDA south loop curve is also banked, allowing minimal steering wheel turning to be required to maintain lane centering.

Baseline Performance

Using the VDA in test period 1, Vehicle B was able to track the lane for 4-8s, but this was not long enough to reach the part of the curve relevant to the sun angle. Vehicle A was able to successfully lane center in 3 of the 4 runs for most of the curve, between 14 and 24s with an average of 20.7s, but lost lane tracking in the baseline around the location that would have been properly aligned with the sun. For the Vehicle A run that did not activate lane centering, LDWs activated for two of the three lane departures. Vehicle C was able to maintain lane centering for the entire curve.

For baseline testing in test period 2, lane centering was tested with a left departure on the same stretch of road as with the sun glare. Vehicle D departed 6 of 7 times and was able to automatically steer back in all but 1 of those occasions. Vehicle E exhibited smooth lane following throughout the curve in all test attempts, but did hug very close to the right lane. Table 9 summarizes baseline lane keeping and lane centering performance on a curve across the test periods.

Table 9: Summary of baseline lane keeping and lane centering on a curve.

Vehicle	Number of Attempts	Detected Lane Lines	Stayed Within the Lane	Issued LDW	Issued a Take Steering Control Command	Comments
A	4	0*	0	1 (during LCA)	4	* Vehicle A lost lane tracking shortly after entering curve
B	3	0*	0	N/A	3	* Vehicle B lost tracking just prior to sun alignment
C	3	3	3	0	0	Performed as expected
D	7	6	1	5	0	
E	7	7	7	0	0	Performed as expected

With Sun Glare

Sun glare testing could only be successfully conducted for Vehicle C in test period 1 for the reasons described in the Baseline Performance section above. For the three sun glare test runs that were conducted with Vehicle C, lane centering functioned throughout the entirety of the test and no noticeable diminished performance due to sun glare was observed.

In all three runs for Vehicle A, the left and right side lane lines were both detected and an indication was issued to the driver that LKS was operating. As travel continued through the curve, the lane lines disappeared and the vehicle provided an alert to the driver that the LKS disengaged.

In Run 1, Vehicle B detected the left and right side lane lines and presented an indicator to the driver that LKS was operating. As travel through the curve continued, the lane lines disappeared and LKS disengaged. In Runs 2 and 3, Vehicle B detected the lane lines on both the right and left sides, but the vehicle gave no indication to the driver that LKS was operating. As travel through the curve continued, the lane lines disappeared from the icon on the instrument panel and LKS disengaged.

During test period 2, Vehicle D demonstrated that it was able to recognize the lane lines all of the 7 test runs. This vehicle departed the lane lines on 6 of 7 test runs and alerted the driver with a lane departure warning on all but 1 run. Vehicle D issued a take steering control command on 2 of the runs - both near the peak sun glare area. Overall performance of Vehicle D was in line with the baseline test runs, with the exception of the take steering control commands. Vehicle E also performed very similarly to the baseline, where the vehicle followed the curve smoothly hugging tightly to the right, the inside of the curve. Table 10 summarizes lane keeping and lane centering performance on a curve with sun glare across the test periods.

Table 10. Summary of lane keeping and lane centering on a curve with sun glare.

Vehicle	Number of Attempts	Detected Lane Lines	Stayed Within the Lane	Issued LDW	Issued a Take Steering Control Command	Comments
A	7	7	1	5	2	Similar performance to baseline, except take control commands issued by Vehicle A
B	7	7	7	0	0	Similar performance to baseline

Blowing Snow Across the Pavement

Naturally occurring conditions allowed blowing snow tests to be completed on the VDA in test period 2 with vehicle D. LCA, LKS, and LDW functionality was observed while natural snow was blowing across the surface in front of the vehicle. Similar to the baseline testing, Vehicle D did not display lane lines to the driver but would give a lane departure warning and assisted with steering in this scenario. The blowing snow did cause the visibility of the lane line to be reduced.

High-Speed Following

The HSF maneuver was conducted at two speeds, 20 and 30 mph. In the first test period, the maneuver was run three times with clear conditions as a baseline and three additional times with artificial rain and a wet road, while in the second test period the maneuver was performed seven times with clear conditions as a baseline and seven additional times with artificial falling snow. During test period 1, natural weather permitted one run to be attempted with snow for Vehicle C.

Baseline Performance

Across the two test periods for both the 20 and 30 mph test runs, all vehicles were able to regulate speed and maintain tracking of the POV throughout the run. The time to collision or TTC for all vehicle models remained high at steady state operation. TTC is calculated as range divided by range rate ($-r/\dot{r}$).

With Falling Rain and Wet Road

Falling rain and wet road conditions were tested in conjunction with one another. Heavy or sustained rainfall caused all three systems tested in period 1 to intermittently lose POV tracking during the test. Vehicles A and C were able to quickly regain tracking and to maintain a safe following distance at all times. Vehicle B disengaged ACC and applied hard braking, so it failed safe. The minimum distance is shown in Table 11 for each run at 20 mph and in Table 12 for each run at 30 mph.

The minimum distance for all vehicles was greater at the higher speed of the POV. While tracking the POV, Vehicle A accelerated and decelerated slightly more in the rain than it did in the baseline, but the behavior did not diminish safety or comfort. In two trials of the 30-mph test, Vehicle C accelerated briefly when it lost POV tracking. The situation did not subjectively feel dangerous to the occupants at the time, and the TTC was well above 15 s throughout the runs. Comfort levels for braking are defined in "*Crash Warning System Interfaces: Human Factors Insights and Lessons Learned*." (Campbell et al. 2007).

Table 11. Minimum following distance (ft) with POV at 20 mph.

	Baseline			Rain		
	Vehicle A	**Vehicle B**	**Vehicle C**	**Vehicle A**	**Vehicle B**	**Vehicle C**
Run 1	54.9	45.1	48.5	54.5	53.3*	49.3
Run 2	54.1	44.6	49.5	60.7	49.3*	47.8
Run 3	56.5	48.3	48.0	61.8	48.5*	48.6

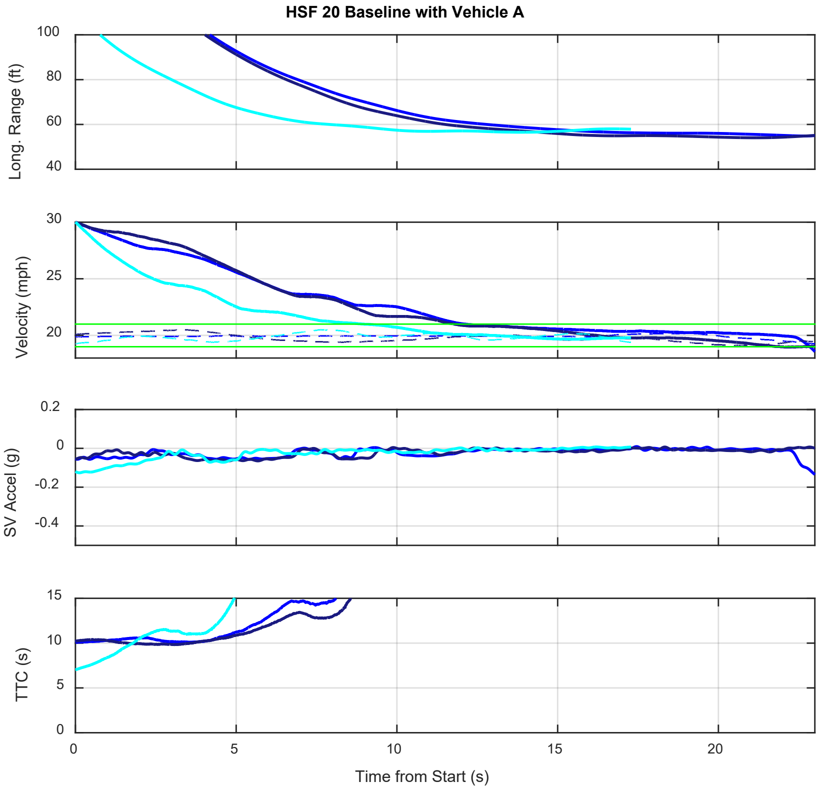
*Hard braking occurred during the test

Table 12. Minimum following distance (ft) with POV at 30 mph.

	Baseline			Rain		
	Vehicle A	**Vehicle B**	**Vehicle C**	**Vehicle A**	**Vehicle B**	**Vehicle C**
Run 1	72.1	65.6	64.5	73.3	88.3*	53.8
Run 2	70.5	91.8	63.6	64.8	104.2*	52.5
Run 3	71.4	71.3	59.8	69.2	93.4*	62.9

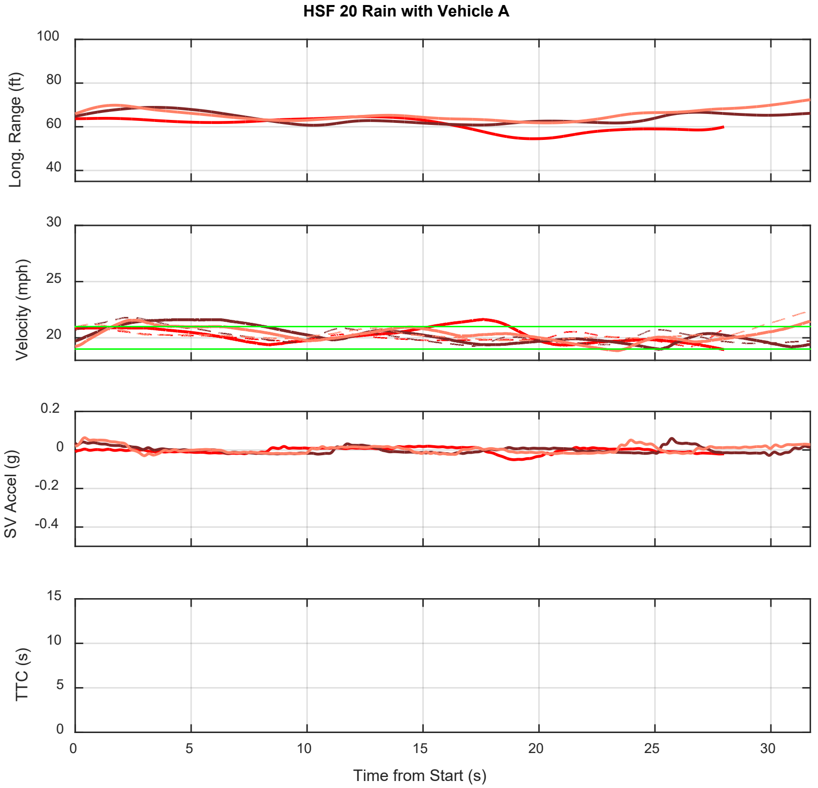
*Hard braking occurred during the test

When following the POV, all SVs in test period 1 maintained a separation distance of more than 40 ft away at 20 mph and approximately 60 ft at 30 mph. Consistent with human driven vehicles, this increase in following distance at higher speeds accounts for reaction time. Figure 19 and Figure 20 are sample data plots showing the longitudinal range, velocity, acceleration, and TTC for all runs performed on Vehicle A at a POV speed of 20 mph. Full data plots containing information for all SVs is documented in the test report for period 1. In all of the plots presenting following performance, a solid blue line represents the SV during baseline tests, a solid red line represents the SV during rain tests, and the corresponding dashed lines represent the POV. In Figure 19, the data indicates that, in response to the slower moving POV, the SV slowed to match the POV's velocity with a maximum deceleration of approximately 0.1 g. This deceleration would be comfortable to passengers.



Source: TRC Inc.

Figure 19. Graphs. Baseline data for Vehicle A following the POV traveling at 20 mph. The shades of blue represent different runs. The SV decelerated as it approached the POV and maintained a constant following distance (longitudinal range) of approximately 55 ft.



Source: TRC Inc.

Figure 20. Graphs. Rain test data for Vehicle A following the POV traveling at 20 mph. These graphs begin after the SV has reached a steady following distance of approximately 60 ft. The speed and following distance varied slightly as the SV passed through the rain.

Vehicle A. For the 20- and 30-mph tests, the rain caused Vehicle A to lose tracking of the POV for periods up to 2 seconds, but that loss of tracking had a minimal effect on performance. Generally, the loss of tracking caused the vehicle to accelerate toward the set speed and resulted in an approximately 2 mph increase in SV speed. In most cases, this deviation was greater when testing with the POV traveling at 30 mph than at 20 mph. Normal ACC control resumed when POV tracking was reacquired. For the 20-mph test, the minimum following distance was on average higher for the rain test runs than the baseline. Vehicle A accelerated slightly at about 14 seconds into the runs with rain at 30 mph. This lowered the following distance but not to a dangerous level. The magnitude of the acceleration was consistently low (<0.2 g) in both the baseline and rain.

Vehicle B. In all runs, at both 20 and 30 mph, Vehicle B behaved as though it was detecting a stopped object when approaching the sprinklers. This resulted in Forward Collision Warning (FCW) and hard braking. In such cases, the control system induced a peak deceleration ranging between 0.33 and 0.42 g. Hard braking of this magnitude would feel uncomfortable to passengers.

Vehicle C. The 20-mph test runs performed very similarly to the baseline test runs, with minimal velocity deviations and steady state acceleration remaining around 0 g. Losses of tracking occurred but at very short intervals. However, the 30-mph test runs resulted in two different errors: one false positive FCW alert and two losses of POV tracking (causing a sudden acceleration). The FCW alert had a minimal effect compared to Vehicle B, with only a 1 mph velocity deviation and a peak deceleration of 0.1 g. The loss of tracking caused an almost 5 mph velocity deviation before tracking resumed. This scenario has a higher chance of affecting safety than Vehicle A, because the larger velocity differential increased the likelihood and potential severity of a collision.

With Natural Falling Snow

A single run was completed during natural snow conditions with Vehicle C during test period 1. During this test the ACC did not activate when requested with the HMI indicating “Reduced Radar Visibility” as the cause.

With Falling Snow

During test period 2, HSF with falling snow was a planned adverse weather condition. In four of the baseline runs at 20 mph, natural snow was experienced. The runs with natural snowfall are treated separately from the rest and provide a good reference for testing. For both systems tested (Vehicle D and Vehicle E), although falling snow did not cause a dramatic differences in performance such that the driver noted, data did reveal slight differences as described below. The tests illustrate the SV’s ability to maintain a safe distance and continuously track the POV with falling snow between the two vehicles. Tracking was not lost due to the snow.

The minimum distance between the two vehicles is shown in Table 13 for each run at 20 mph and in Table 14 for each run at 30 mph. The minimum distance for all vehicles increased with speed of the POV. Additionally, the change in minimum following distance caused by snow is shown in Table 15. Surprisingly a significant change was noticed in both vehicles even before they were near the snow gun. Vehicle D is consistently closer in in the presence of snow and Vehicle E is consistently further. This is most pronounced in the 30 mph test sets where Vehicle D is 20 ft closer and Vehicle E is 22 ft further. However, these changes were not as pronounced during the natural snow fall which occurred in the middle of

Vehicle D’s 20mph Baseline. This suggests that it may have been the result of different environmental effects.

Table 13. Minimum following distance (feet) with POV at 20 mph.

Min Range (ft)	Baseline		Snow Falling		
	Vehicle D	Vehicle E	Vehicle D	Vehicle D+	Vehicle E
Run 1	37.5	48.8	23.4	37.4	61.3
Run 2	37.1	49.0	34.9	36.9	65.8
Run 3	36.3	48.1	38.9	36.8	50.3
Run 4	36.8	48.8	25.7	35.5	9.36*
Run 5	38.8	49.6	39.0		
Run 6		50.6	25.0		
Run 7		51.6			

+Snow falling was natural for these test runs

*In this test run, the POV purposely came to a stop just beyond the snow gun while the following SV was still upstream of the snow gun

Table 14. Minimum following distance (feet) with POV at 30 mph.

Min Range (ft)	Baseline		Snow Falling	
	Vehicle D	Vehicle E	Vehicle D	Vehicle E
Run 1	60.6	62.2	40.0	86.8
Run 2	60.1	63.3	38.3	79.7
Run 3	62.2	61.5	44.7	
Run 4	60.0	58.4	32.0	
Run 5	57.4	62.1		
Run 6	63.6	60.3		

Table 15. Change in average minimum following distance. Snow-Baseline

Speed	Vehicle D	Vehicle E
20 mph	-6.15	9.98
20 mph Natural	-0.65	N/A
30 mph	-19.65	21.95

With Salt Brine

Once salt brine was applied to the sensors of both vehicles, three iterations of each HSF scenario was run. Vehicle D had a much closer following distance with salt brine than it did during the baseline. This was true for both 20 mph and 30 mph, shown in Table 16 and Table 17. Vehicle E did not have a significant change in its following distance, however there was a slight increase for the 30 mph runs.

Table 16. Minimum following distance (feet) with POV at 20 mph.

	Baseline		Salt Brine	
	Vehicle D	Vehicle E	Vehicle D	Vehicle E
Run 1	37.5	48.8	26.3	49.0
Run 2	37.1	49.0	32.1	49.0
Run 3	37.4	48.1	23.4	47.1
Average	37.3	48.6	27.3	48.4

Table 17. Minimum following distance (feet) with POV at 30 mph.

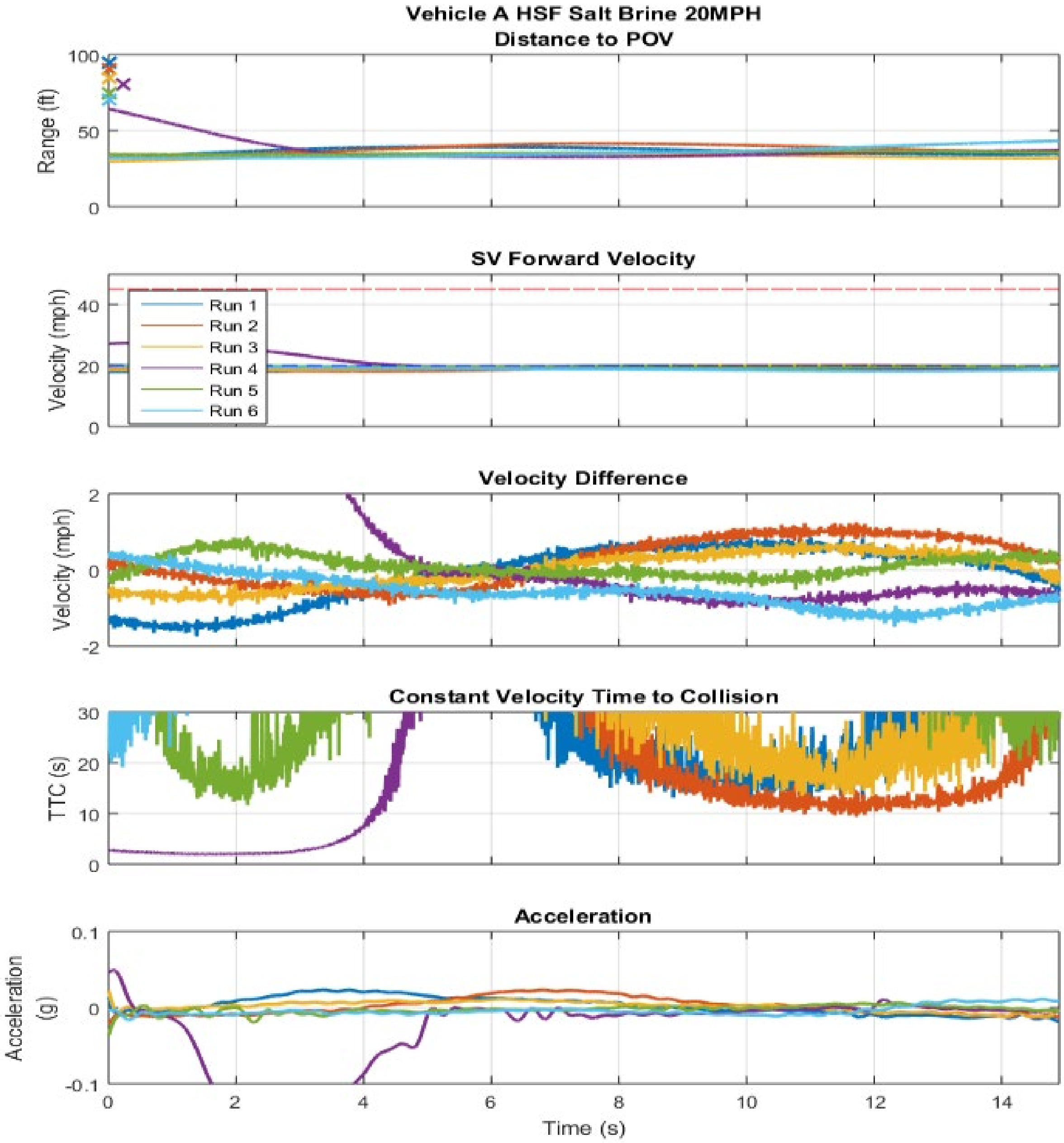
	Baseline		Salt Brine	
	Vehicle D	Vehicle E	Vehicle D	Vehicle E
Run 1	60.6	62.2	45.9	62.7
Run 2	60.1	63.3	49.7	66.3
Run 3	62.2	61.5	49.3	66.6
Average	61.0	62.3	48.3	65.2

With Salt Brine and Falling Snow

Because minimal variation was observed during the salt brine tests, Vehicle D passed under the snow gun to see if combined significant performance difference was observed. However, these conditions did not seem to have an impact. Due to an equipment malfunction, Vehicle E was not tested in this condition, but the expectation is that this AV would likewise not have been challenged. In Figure 21, the first three runs were salt brine only and the last three runs were with both. A significant difference is not evident.

With Compressed Snow

Because the salt brine tests with and without falling snow did not challenge the vehicles, ad hoc testing was conducted where Vehicle E was prepared with compressed snow pack in front of the camera and radar sensors. With a moderate amount of snow pack, the vehicle could not engage LCA or LKS, but was able to successfully follow the lead vehicle using ACC. With heavier snow pack applied the SV was still able to follow a lead vehicle most of the time, but was observed to “lurch” at the lead vehicle in one instance and manual intervention was required.



Source: TRC Inc.

Figure 21. HSF with salt brine at 20 MPH.

Traffic Jam Assist (Low Speed Following)

Traffic Jam Assist (TJA) functionality is tested through Low Speed Following (LSF) maneuvers. The LSF tests used a set of acceleration and decelerations designed to challenge each vehicle's TJA. Vehicles A and C had a greater minimum following distance in the rain compared to the baseline, while Vehicle B followed closer, as shown in Table 18. In the presence of simulated rain, Vehicle B violated the test's minimum following distance safety requirement of 3.28 ft, during Runs 2 and 3. Vehicles A and C exhibited a reduced minimum following distance during the ice test. There is an exception in Run 1 for Vehicle A where the system timed out. The ice test could not be carried out for Vehicle B, per below.

Table 18. Minimum following distance (ft) for TJA baseline runs and runs with rain or ice.

	Baseline			Rain			Ice	
	Vehicle A	Vehicle B	Vehicle C	Vehicle A	Vehicle B	Vehicle C	Vehicle A	Vehicle C
Run 1	16.06	7.60*	14.11	25.56	5.96*	20.79	11.83	4.80
Run 2	18.00	6.18*	13.84	24.61	3.23**	18.35	12.35*	3.45
Run 3	17.20	7.15*	-	20.16	0.87**	18.29	6.07	4.16
Run 4	-	-	-	-	-	18.26	-	-

*Test runs that timed out.

** Test runs that required driver intervention.

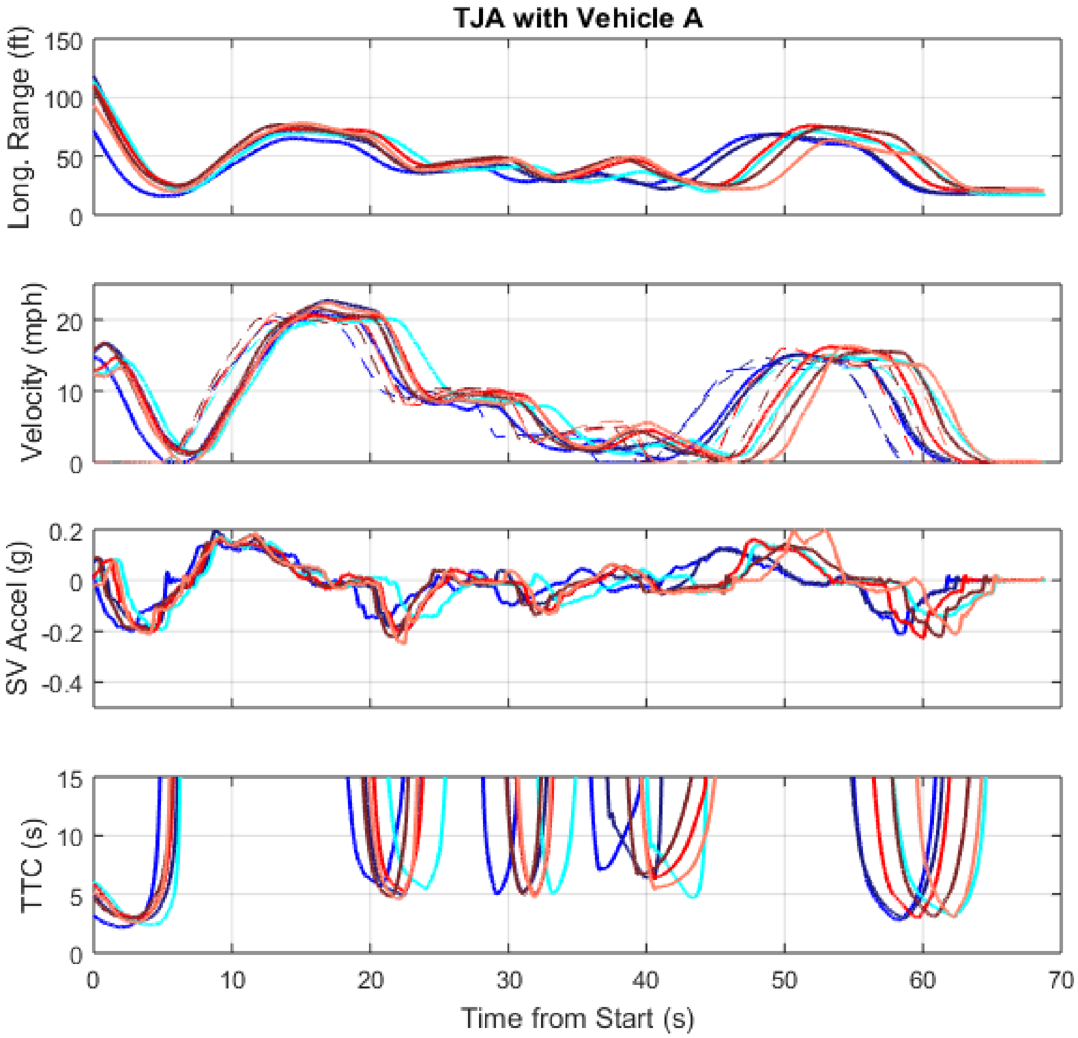
Baseline Performance

Vehicles A and C performed well in dry conditions, following the POV with appropriate spacing. Vehicle B performed well but disengaged at the final POV acceleration. Vehicles A and B had a "time out" feature in the user manual that indicated a stop of 5 seconds would require reactivation of the system. The final POV acceleration had a stop of less than 5 seconds so that the driver would not have to reactivate the system. The driver did not reactivate the system on Vehicle B because the stop was less than 5 seconds.

Simulated Falling Rain

The figures for each of the following vehicles use blue solid lines to represent the SV in baseline runs, red solid lines represent the SV in runs with rain, and correspondingly colored dashed lines represent the POV.

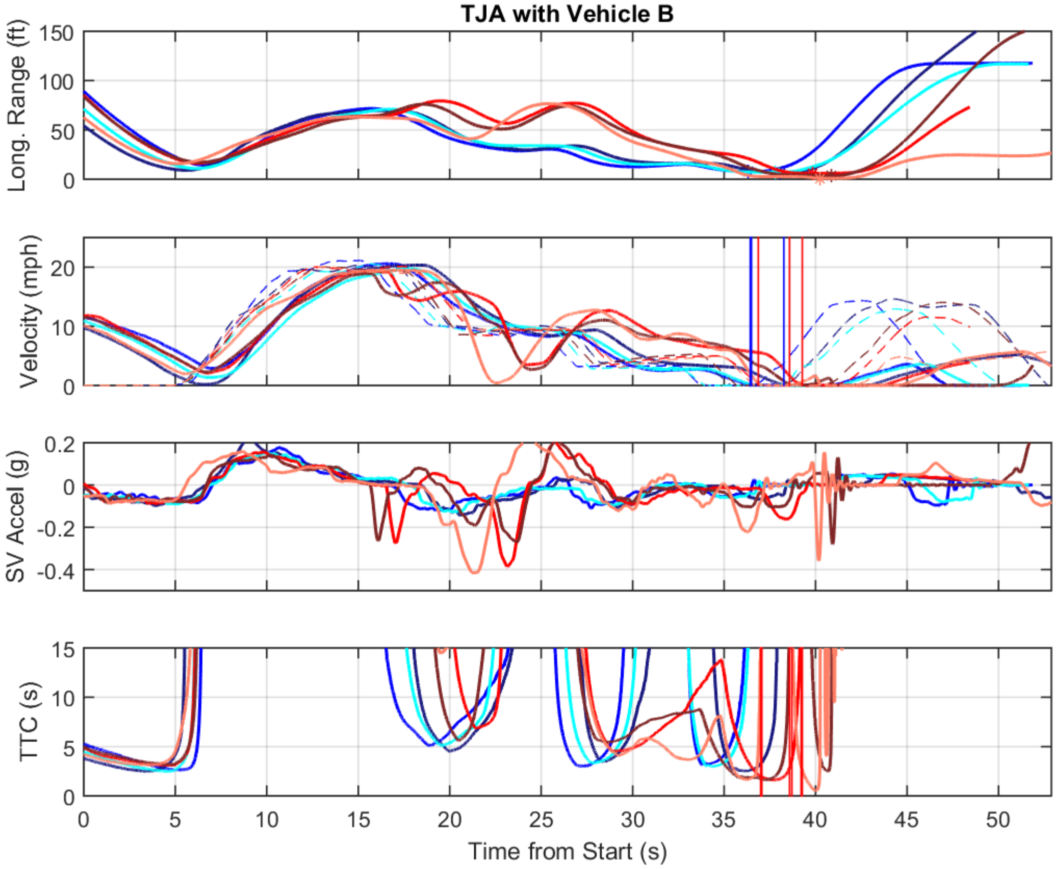
Vehicle A. Vehicle A did not have a significant difference in performance between the baseline and rain testing, as can be seen in Figure 22. There was not a noticeable change in the longitudinal range profile between the runs with rain and the baseline runs.



Source: TRC Inc.

Figure 22. Graphs. Traffic Jam Assist baseline (blue) and rain (red) test runs with Vehicle A.

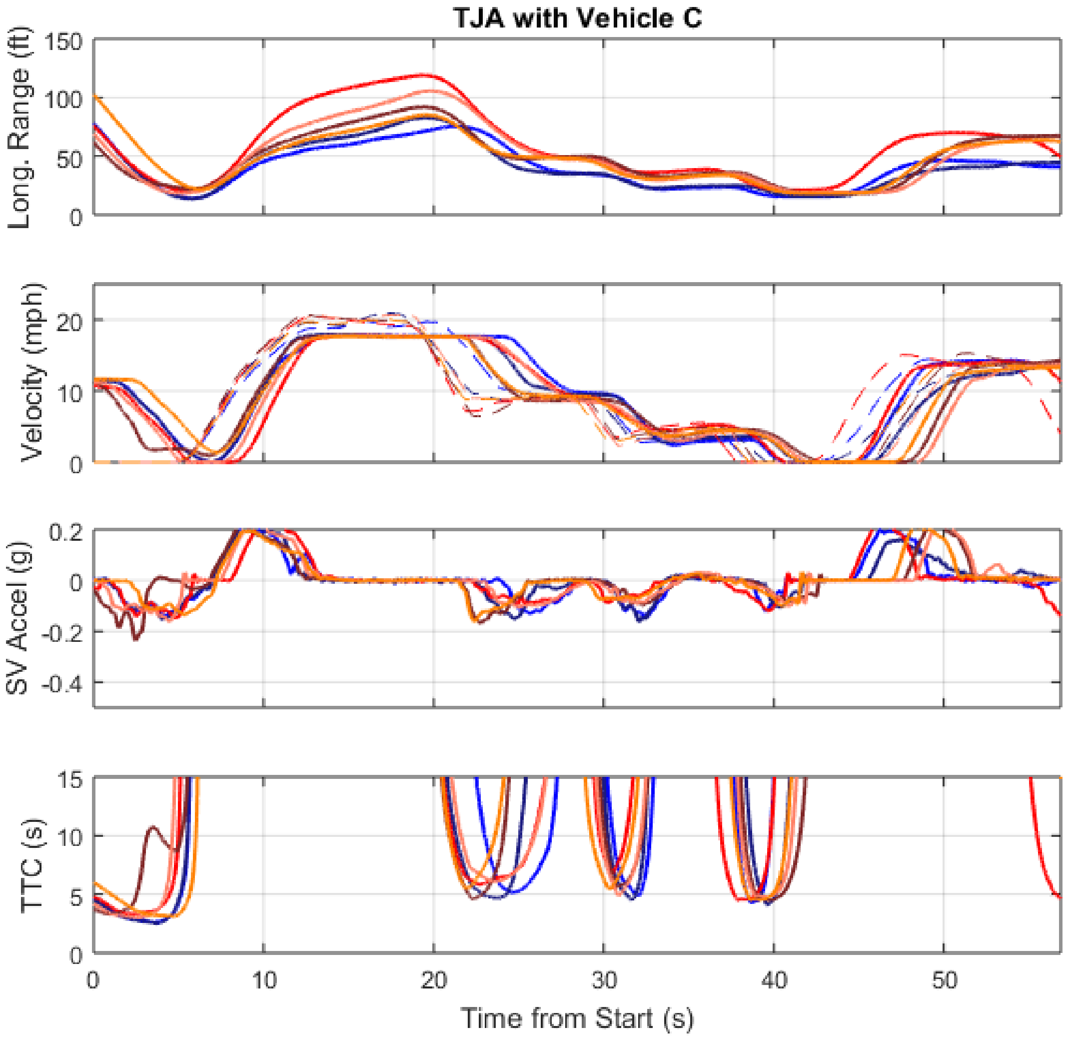
Vehicle B. The rain had a larger effect on Vehicle B than the other two vehicles. Vehicle B's TJA also timed out for the final acceleration on one of the rain test runs. The other two runs required emergency braking when the vehicle's following distance went below the preset safety margin of 3.28 ft, as can be seen in Figure 23. In addition, the following distance was dramatically greater during the middle portion of the test. It can also be seen that, in general, the runs with rain exhibited more speed fluctuations of high magnitude than the baseline runs.



Source: TRC Inc.

Figure 23. Graphs. Traffic Jam Assist baseline (blue) and rain (red) test runs with Vehicle B.

Vehicle C. The performance of Vehicle C was similar across the baseline and rain tests, as shown in Figure 24. A single rain test presented one short loss of tracking. Overall, the average minimum following distance of the rain runs is greater compared to the baseline runs. In addition, the acceleration seems to be more conservative during the rain events, with the vehicle waiting longer to accelerate and decelerating sooner.



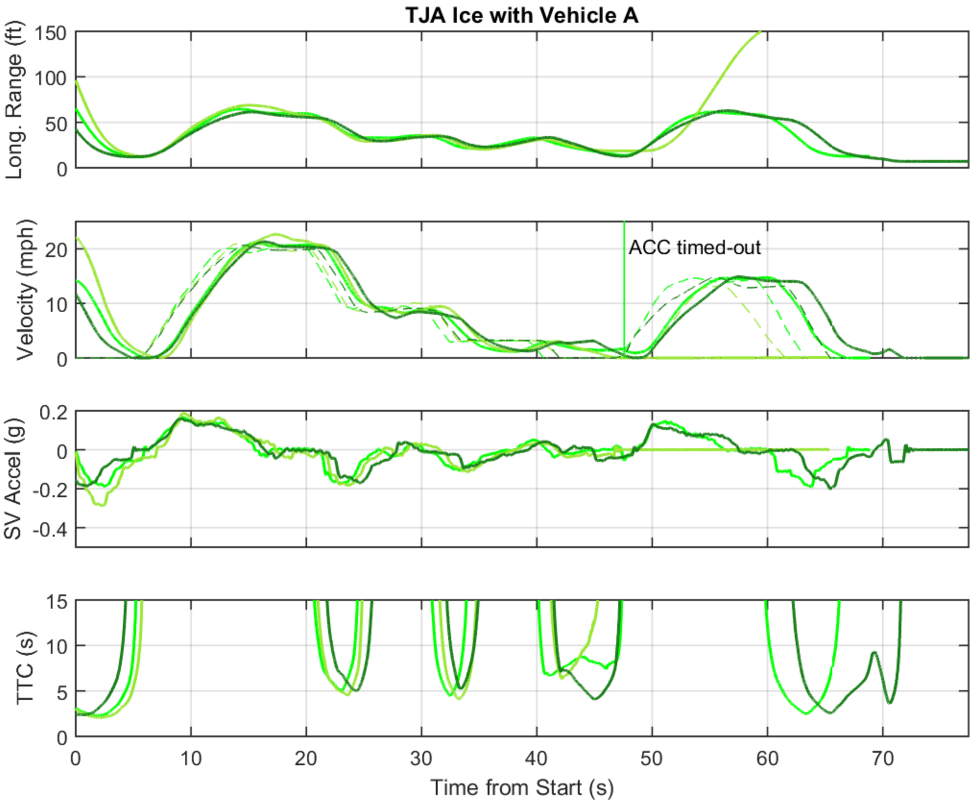
Source: TRC Inc.

Figure 24. Graphs. Traffic Jam Assist baseline (blue) and rain (red) test runs with Vehicle C.

With Ice on Sensor Surfaces

None of the vehicles could engage the POV immediately after they were taken out of overnight cold storage with ice on the sensors. Ice was removed from the camera and radar layer by layer using an ice scraper in a gentle scraping motion, and testing was periodically attempted. However, even thin layers of ice prevented the safety features from being activated. The test procedure was altered to completely clear the ice from one of the sensors when multiple sensors were present.

Vehicle A. The ice on the camera of Vehicle A was cleared off and a thin layer of ice was left on the radar. With ice on the radar and the camera cleared the safety systems could be enabled. For one run, the cruise control timed out after 5 seconds, similar to Vehicle B's response during baseline and rain tests. The minimum following distance for the two full ice test runs were almost half of the baseline test runs, on average, resulting in a much lower safety margin, as shown in Figure 25.

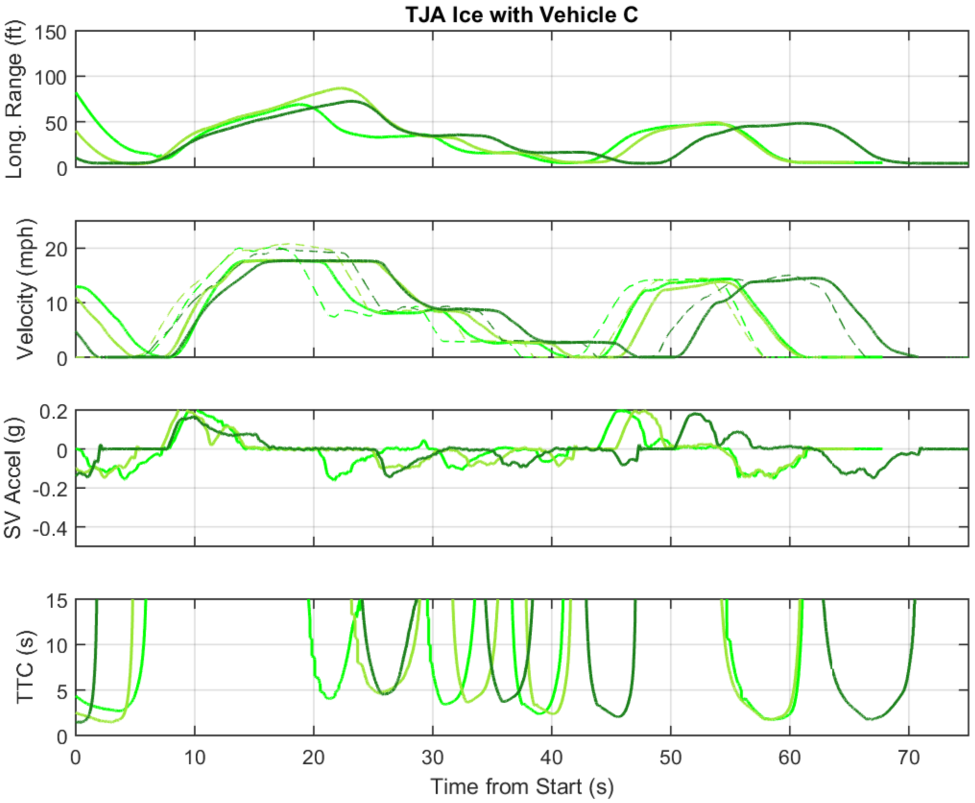


Source: TRC Inc.

Figure 25. Graphs. Traffic Jam Assist ice test runs with Vehicle A.

Vehicle B. Vehicle B was not able to complete any runs with any ice on the sensors. This vehicle's reliance on fewer sensors presented a more adverse effect from a layer of ice.

Vehicle C. Vehicle C can defrost the radar and the camera. However, because the starting ice was so thick a thin layer of ice that did not touch the windshield remained after defrosting. The radar was cleared before the start of the test. After the radar was clear, the vehicle was able to track a POV. The run resulted in a significantly reduced following distance and TTC compared to the baseline and rain runs, almost requiring driver braking intervention, as shown in Figure 26.



Source: TRC Inc.

Figure 26. Graphs. Traffic Jam Assist ice test runs with Vehicle C.

Human Factors Observations

Although a formal human factors assessment was not performed as a part of the Level 2 AV testing conducted, the test team informally documented observations about the AV HMIs while conducting test maneuvers under various conditions from within each model during test period 1. They are presented within a discussion of the differences in how the AV HMIs work. In some cases, the HMI differences are subtle, while in other cases they differ more dramatically. Dramatic differences may in part be explained by the fact that the driver assistance system functions offered in each tested AV varied in terms of the number and types of features. More feature rich designs with related functionality compel the design to present additional details or present them differently.

A driver could not always readily discern whether the driver assistance systems were armed or active. While a Level 2 AV is not expected to advise the driver of its inability to maintain control, that subtlety may be lost on non-technical drivers.

These observations are not exhaustive or conclusive; nor are they an attempt to rate the AV HMIs or to assess deficiencies. Instead, the observations are presented to promote awareness of the approaches used by OEMs to interface the Level 2 AV driver. Because no malfunctions of an AV system were experienced during testing, the observations do not cover information conveyed during failure modes.

Observation 1: Little consistency was observed across AV HMIs in regard to the design approach used for presenting graphical and text display details.

The location in which graphics and text details are presented differed across the AV HMIs. Vehicle A and Vehicle C HMIs presented LKS and ACC status and information solely in the primary instrument cluster area. Although Vehicle B also presented most LKS and ACC status information in the primary instrument cluster, it additionally presented ACC lead vehicle to subject vehicle distance graphics and set speed in a separate multi-function HMI located in the upper center of the dashboard. Interestingly, other model vehicles of the same model year with the same driver assistance system present multi-function HMI details in the primary instrument cluster.

Vehicle B presented a conspicuous and intuitive graphic with text to indicate that driver assistance support is unavailable. A combination of indicators help to inform the driver of driver assistance functions availability, while graphics (some with text, others with color) present the status of functions (on and available, ready but not engaged, or engaged and functioning). Vehicles A and C presented less conspicuous indications when individual driver assistance system functions were unavailable. Vehicle A presented complete, partial, or absolute lack of graphics to indicate engaged, standby, and unavailable states of individual functions. Vehicle C used a combination of text and graphics to indicate the availability and engagement status of its driver assistance system functions. It used text notification to indicate when specific driver assistance system functions were unavailable.

The three AVs communicated LKS availability and engagement status differently. Instrument panels on all AVs had graphical lane markings to convey LKS status, and each, in its unique way, used these lane markings to indicate when LKS was engaged. With a green text indicator denoting lane keeping support present, Vehicle A presented a dotted outline of dashed lane marking outlines to indicate LKS is ON and solid dashed lane markings when LKS was engaged. Vehicle B used continuous lane marking outlines to indicate LKS is on and continuous solid lane markings when LKS was engaged. When lane keeping support is on, Vehicle C presented subtle gray lines that appear more distinctive in color, contrast, and width to indicate when lane keeping is engaged. Vehicles B and C distinguished the tracking or lack of tracking through the independent presentation of left and right lane markings, while Vehicle A did not.

The three AVs varied in the way they communicated ACC details. Vehicles A and B presented the driver-selected following distance similarly, as a series of horizontal solid bars between lane markings. Vehicle C presented a novel graphic and number to represent relative following distance, but only while the setting was being modified. All three vehicles presented a graphical subject car and a moving lead car to represent relative instantaneous distance between the two, but they differed in how they alert the driver of a potential collision. Vehicle A simply presented a warning text alert when applicable. Vehicle B placed a graphical target around the lead vehicle and presented a text alert. Vehicle C displayed the lead vehicle as red and presents associated text notifications while automatically braking.

Vehicle A presented availability of ACC via a text indicator together with a vehicle outline graphic, and it provided set vehicle speed as a numerical value. Vehicle B indicated the ACC mode and mode status by using indicator lights, and it presented set vehicle speed as a displayed numerical value. Vehicle C used a graphic that incorporates numerical speed and uses color to distinguish between when ACC is available versus when it has been engaged.

The display of text notifications was used minimally by Vehicles A and B, primarily displaying warnings or suggested driver action (e.g. lane departure or braking and steering requests). In contrast, Vehicle C presented explanatory text in many cases, to further explain audibles or icons. The Vehicle C text notifications could not be quickly read and understood because they had many words, appeared briefly, and appeared in small font, and were positioned behind parts of the steering wheel.

Observation 2: Little consistency was observed across AV HMIs in regard to the nature and presentation of audible sounds.

All AVs offered configurability for the annunciation of audible sounds. Default sounds were used for these tests. The following observations may depend on the settings chosen.

Only Vehicle C audibly confirmed successful arming and engagement of LKS and ACC functions. This AV used distinct and intuitive audible alerts and graphics to indicate arming and disarming, as well as engagement and disengagement. The Vehicle C HMI additionally alerted the driver to take control through expressive graphics and a tone indicating direction of departure. However, the graphics were presented late and the associated audible tone was subtle, occasionally being confused with other road noises.

Vehicles A and B audibly alerted the driver only when a function disengaged or a warning was issued. Vehicle B did not provide an alert (audible or graphical) when LKS could not be maintained, but it did alert the driver when an LDW was sensed. Vehicle A audibly and graphically notified the driver that LKS was unavailable or could not be engaged. This AV’s HMI alerted the driver when an LDW was detected by a unique graphic; however, there was no associated audible alert.

Observation #3: AV HMIs convey functionality and permit functional configurability differently.

The speed at which the subject vehicle must be going to initiate LKS varies between the three AVs, as do the initiation features (e.g., SV speed, location and speed of lead vehicle or lane markings). How quickly the vehicle will intervene differs across the AVs and appears to be a function of the available functions, and subject vehicle speed and vector of travel relative to lane edges. Vehicle B, for example, does not include lane centering like Vehicles A and C.

The subject vehicle speed constraints for ACC also differ between the three AVs, as does the driver-configurable control following distance setting sensitivity. Vehicles A and B have four setting following distance setpoints, while Vehicle C has seven. Adjustments to the set speed, however, can be set in 1- or 5-mph increments for each AV.

Chapter 4. Stakeholder Engagement

This chapter summarizes the stakeholder workshops and findings. The intention in engaging stakeholders was to understand how to address adverse weather effects on sensors and human factors, to explore how connected automation may benefit operations in adverse weather, and to determine the gaps that challenge the achievement of higher levels of automation.

Summary of the three Workshops

Project staff held sessions at three widely attended conferences. The first workshop was held at the Transportation Research Board annual meeting in Washington, DC on January 9, 2018. Participants represented a variety of backgrounds, with most coming from state or local transportation agencies, as would be expected at this venue. See Appendix A for the slides presented. The second workshop was at the Automated Vehicles Symposium in San Francisco, CA on July 9, 2018. Participants here were primarily from academia and automotive suppliers. See Appendix B for the slides presented. The third workshop was held at the APWA North American Snow Conference in Salt Lake City, UT on May 21, 2019. Participants of this conference primarily included maintenance supervisors and operators of local transportation agencies but, additionally, vendors of maintenance equipment and services. So, interactions at these three workshops included a group of attendees who were complementary in their roles and responsibilities. See Appendix C for the slides presented.

The first two workshops began with a brief overview of the topic by a representative from FHWA to provide background for the discussion. This project’s literature review had been completed before the first workshop, and slides summarizing the findings were shown at the beginning of the session to set the topic for the discussion. The second workshop was held after the tests in adverse weather, and videos and findings from the tests were shown to the second group. The third workshop was held after a second test period in adverse weather, with video and findings from both test periods relayed to third workshop attendees.

Table 19 provides the number of participants in each workshop. Participants were asked to indicate their affiliation by a show of hands, and those details are in the table. Those from industry were primarily from suppliers to state and local agencies (at TRB and APWA) and to vehicle manufacturers (at Automated Vehicles Symposium); no known representatives of vehicle manufacturers were present. As is common in conferences, people entered and left during the session, so the numbers are approximate. Government representatives at TRB were from the USDOT as well as state and local operating agencies. One participant at Automated Vehicles Symposium was from a transit authority; another, a federal agency. As might be expected, most participants at the APWA North American Snow Conference were state and local maintenance operators.

Questions for various stakeholder constituencies were prepared in advance, but the groups were small enough that a single discussion of the entire group was held at all three workshops. The moderator guided the discussion at the workshops, with help from other team members (in first two workshops), with only an occasional need for reference to the prepared questions.

Table 19. The two workshops had complementary participation between government, industry, and academia.

Affiliation	Workshop 1 January 2018 Transportation Research Board	Workshop 2 July 2018 Automated Vehicles Symposium	Workshop 3 May 2019 APWA North American Snow Conference	Total
Federal Government	7	1	0	8
Infrastructure owner operator	10	1	27 (State 12; Local 15)	38
Industry	2	11	12	25
Academia or basic research	8	5	3	16
Total	**60**	**20**	**45**	**125**

Note: Total numbers were counted by Battelle and are approximate because of persons entering and leaving. Not all participants identified their affiliation, so the totals do not sum.

Questions for various stakeholder constituencies were prepared in advance, but the groups were small enough that a single discussion of the entire group was held at all three workshops. The moderator guided the discussion at the workshops, with help from other team members (in first two workshops), with only occasionally need for reference to the prepared questions.

Gaps in Capabilities

Discussions across the three workshops revealed gaps for operating automated vehicles in adverse weather. The most significant is that there are no good ways of deciding whether a trip under automation should begin or continue, and nobody is known to be directly working on developing one. State and local operating agencies are ill equipped to give advice on automation, and manufacturers are not advertising the limitations of their products. Currently, owners are left to make the decisions. That may be satisfactory as vehicle capabilities are only incrementally beyond conventional driving, but the situation will become unworkable as automation features become more sophisticated.

Roles Are Unclear

SAE J3016 is clear that the automation level of a driving automation feature is assigned (by the manufacturer) rather than measured (by a testing agency). The ODD is the set of conditions under which a feature is designed to function. Because design is performed by the manufacturer of the vehicle or the supplier of the automation system, the ODD is also specified by the manufacturer.

What is not so clear is who has the responsibility to determine whether current or forecasted conditions are within the operational design domain. At different levels of automation, a human may request control from the vehicle, or the vehicle may request that the human resume the dynamic driving task. When a trip is being contemplated, one of the decisions is whether the vehicle, any driving automation features, and the human are capable of handling the forecasted conditions. Conceptually, a driver may choose to forego a trip, a vehicle may refuse to initiate a trip, or a remote dispatcher may deny the trip.

One way to make these decisions would be to compare an objective specification of the ODD with weather metrics. However, forecasts are always issued in terms of probabilities. At least at the present, owner’s manuals are vague as to what conditions the automation features can handle.

An idea coming from the second workshop is to develop a series of metrics to describe the environmental component of the ODD. Knowing the environmental limitations of the ODD and how current and forecast conditions are and will affect the roadway will enable decision-makers to compare the current and forecast road weather conditions with the specifications.

State and local operating agencies are concerned that they may be asked to take on a new responsibility that they are not prepared to perform. Decisions of when to close roads or require chains are based on years of experience. Operating agencies do not know the criteria for permitting or forbidding automation in adverse weather. To be sure, systems with differing functionality from various manufacturers will have diverse abilities to handle adverse weather, and the abilities are certain to change over the years. Any new responsibilities that are assigned to operating agencies will have to come with training and funding. In addition, these new responsibilities will need to be prioritized within the broader set of existing responsibilities.

Weather-Related Limits of Automated Vehicles are Unknown

Manufacturers are testing their vehicles in a variety of on-road and controlled conditions. Their publications say that testing includes a variety of weather conditions. This project showed that the five vehicle models tested definitely have limits during adverse weather conditions in which the driving automation features can perform.

The owner’s manuals for the tested vehicles acknowledged limits in weather but gave no guidance on determining whether any particular weather condition were in those limits. Consumers, and even engineers, have no way of knowing whether the manufacturers have determined the boundaries of operation for their various functions.

If manufacturers do test their own vehicles to verify performance throughout the ODD, they may be reluctant to publish the exact specifications for a number of reasons. They do not want to acknowledge that their product has limits and that the limits can be compared with those of competitors. Furthermore, publishing an ODD may be accepting responsibility for whatever happens when the prevailing conditions are within the ODD (or the human operator believes them to be within the ODD).

A system operating at Level 2 or lower leaves responsibility with the human to determine whether conditions are safe. It may be a subjective call, but it is the driver’s responsibility. A system performing at Level 3 or higher has the responsibility to inform the human driver that it is about the exit the ODD. Thus, the vehicle needs to know the weather and road weather conditions and to be able to compare the conditions with the boundaries of its ODD.

A vehicle may be able, through its own internal sensors, to determine that current weather conditions are at the edge of its ODD. (For example, if its vision system cannot detect objects, it may assume that visibility is impaired. This behavior was in fact observed during the tests. When cameras were covered with ice, the systems failed to engage.) However, a vehicle performing at Level 4 or 5 cannot assume that the human will be readily available to intervene. If it encounters adverse weather beyond its ODD and the driver is unavailable, it must enter a minimal risk condition, such as slowing or stopping. If other vehicles are operating at speed, or especially if the passenger has special needs and cannot intervene, this may not be a satisfactory outcome. Therefore, advance information that a planned trip may pass through adverse weather and an assessment of whether that weather is within the ODD are essential.

Either the weather forecast has to be communicated to the vehicle so it can make the assessment, or the vehicles capabilities need to be clear to the human, who must compare them with the forecast.

Distinguishing atmospheric weather from road weather is more important for automated vehicles than conventional vehicles. Two inches of snow has a vastly different effect in Georgia than it does in Minnesota. A human driver may know that intuitively, but the actual surface conditions must be conveyed to a driving automation system.

Chapter 5. Conclusions

Conclusions for this project are organized into each of the three project tasks from which they are derived: literature review, experiments, or stakeholder engagement.

Literature Review

AV OEMs recognize that adverse weather affects the performance of sensors and perception systems used to support automated driving functions in vehicles presently on the market. Although OEMs have not published reports describing these limitations in detail, they have informed drivers of these operational limitations and reminded them that driving with the Level 0-2 automation levels achieved with the ADAS features their vehicles afford, the driver retains the ultimate responsibility for vehicle control. OEMs report that they are testing their AVs in adverse weather conditions, but little quantitative information has been published. There is clearly a need for continued research because owner's manuals for vehicles with AV features advise of the difficulty of handling adverse weather.

Technology is advancing rapidly. LiDAR sensors are getting more powerful, smaller, and less expensive. Machine learning is getting smarter. Cloud computing is also improving. Pilot studies will begin to address performance in adverse weather, and this focus will need to continue through industry and government testing as AV deployments evolve.

In the more distant future, increased safety and efficiency will be achieved once vehicles attain level 4 or level 5 (high levels) of automated driving. In the meantime, however, naturalistic studies of driver interaction with automation should be undertaken to inform short term AV offerings to provide the highest safety possible. Likewise, investigations into how lower-level and higher-level automation vehicles will likely behave when sharing the roads, including in adverse weather conditions, need to be undertaken to understand the complex problems that that phase of AV operations will experience and ways that are promising for maintaining coordinated and safe AV travels.

Finally, advancements in AV technologies alone will not permit the full capability of high-level automated transportation to be achieved. Other developments are needed that support high-level automated driving, including:

- All transportation modes intersecting and sharing the roadways (rail, trucks, transit, bicyclists, pedestrians, etc.) can, when connected with one another, permit coordinated movements and protect against collisions during all weather conditions. In addition, information from CVs in the downstream travel way could, potentially, share localized adverse weather condition details.

- Information exchanged with the roadway infrastructure can provide a safety margin and contribute to coordinated movement, as well as collecting localized traffic and weather conditions to support accurate and timely situational awareness in roadway management. Weather service providers can also benefit from this "ground truth" data. Information from such a connected environment can additionally support planning new and modified roadway network segments.

- The infrastructure must be outfitted and maintained to support the AV technologies employed in all weather conditions. In the short term, this might, for example, include resilient and reliable lane markings, consideration of roadside appurtenance placement and standardization, and illumination that supports AV situational awareness in a wider range of weather conditions. However, outfitting and maintenance tactics and strategies need to evolve as AV technologies advance. As such, government-industry partnerships may be a key approach to ensuring coordinated advancement.

- Government agencies need to consider necessary rulemaking changes for supporting investigation of illegal maneuvers and collisions by AVs operating under adverse weather conditions. Both assessing responsibility for incidents and accidents, and basing adjustments to safety standards could benefit from rulemaking that specifies the required support for AV system performance information collection and sharing during these events

Human factors challenges associated with operating Level 2 AVs include:

- Drivers must avoid "over-trusting" the AV. Research shows that drivers may be susceptible to disengaging from the driving task or become distracted when they over-trust in the automated system. Over-trusting is especially dangerous if drivers use automation in complex scenarios the AV was not intended to handle.

- Drivers must be prepared to engage/re-engage in automated driving tasks. Drivers must be able to quickly make decisions and take actions in critical circumstances, such as those created by adverse weather, regardless of whether the AV yields control or requests control transition. Drivers that are not already cognitively engaged will experience reduced reaction time and the necessary cognitive capacity to quickly make a safe response.

- Drivers must avoid monitoring complacency. The time to re-engage in the driving task is lengthened if the driver is distracted or has lost situational awareness by not monitoring the environment. As the need to take full control of the AV becomes less frequent, drivers will likely monitor less frequently.

Experiments

Across the two testing periods, five production AV models, with different equipment sets and automation approaches, were exposed to a variety of simulated and natural adverse weather conditions. The performance of each AV was assessed while conducting one or more of four planned maneuvers under select conditions representative of early spring (test period 1) and winter (test period 2). Each of the test period experiments were conducted with in a period of five days. Test period 1 permitted a broad, though brief, assessment of performance of the three AVs' perception and control systems. Test period 2 exposed the tested vehicle models to fewer planned conditions than test period 1, but far more tests were executed of maneuvers in each condition to increase the opportunity for collecting significant results. In both test periods, contingency tests were conducted to provide a more complete understanding of the performance of the tested systems.

The same three strong conclusions stand out for Period 2 as observed for Period 1, but across different conditions:

- Limitations of the selected AVs were successfully challenged through exposure to adverse weather conditions.

- A potentially significant amount of inconsistency in AV performance was found, both vehicle-to-vehicle and run-to-run in a single vehicle. This was true for the vehicles tested in period 1. In test period 2, this was especially true for Vehicle A, which possessed a lower level of AV perception and control capability. Snow on the roadway presented significant performance challenges for Vehicle A, but did not present much of a challenge for Vehicle B.

- Differences in AV approaches to automation and driver assistance functionality were evident

AV Limitations Were Documented

The tests were intended to challenge the automated driving features but not to the point of causing them to fail. This indeed happened as AVs were able to function, with some diminished performance, in most of the conditions.

In test period 1, the rain and the water on the pavement did not appreciably affect the ability of the vehicles to recognize and respond to the lane lines. In nearly every test run, warnings of a lane departure were appropriately given and restoring steer input was applied. A surprisingly small amount of blown snow covering one lane line prevented one of the AVs from tracking the line.

The falling rain affected performance of high- and low-speed following on several occasions, but the effect was brief interruptions from which the vehicles quickly recovered. In some cases, the cloud of water prevented the AV from perceiving the vehicle ahead, causing the AV to speed up; in others, the AV perceived a heavy cloud of water as an obstacle and braked. One instance of such braking was strong enough that it would have been uncomfortable to passengers.

The one exception in which adverse weather presented a barrier to all AVs tested in period 1 was the artificially applied ice on the sensors. The initial thickness of ice was too much for radar and vision-based system functionality such as lane departure and TJA. However, gradual adjustments to the condition (i.e., scraping and defrosting) eventually permitted a scenario with successful performance. None of the AVs could perform LKS with any amount of ice coverage over the cameras. LKS testing could resume in two vehicles when ice was completely removed from the windshield; on the third the windshield also needed to be cleared of the residual water from the melted ice. One vehicle was able to conduct LKS and TJA with an iced-over radar sensor and a cleared windshield camera. Otherwise, none of the AVs could successfully perform following support with the radar even thinly iced over.

In test period 2, the snow on the pavement appreciably affected the ability of one of the vehicles to recognize and respond to the lane lines. It required an undefined level of confidence in lane line detection (or high contrast edges) of both lane sides to engage or remain engaged and provide LKS with LCA. It provided LKS at lower levels of confidence, but without audible support for LDW and steering control commands. Light naturally blown snow and simulated falling snow did not affect the ability of either vehicle to engage or maintain LKS.

Inconsistencies in AV Performance Were Found

The testing in both periods revealed inconsistency in performance for the same maneuver conducted under the same weather condition, both across AVs and – for most tested vehicles – by the same AV. Interestingly, in test period 1 there was even some inconsistency across runs in the baseline condition for the same AV.

The necessarily small number of test iterations in test period 1 did not afford a high degree of confidence in the results. For this reason, and to better understand the reason for varied performance, more tests iterations were conducted on select weather conditions in test period 2. In test period 2, the capabilities of one vehicle was superior to the other during lane departure tests in both baseline and adverse weather scenarios. The difference was especially noticeable for sporadic snow coverage on the road surface and sun glare. The lower-performing vehicle did not provide LKS or LDWs in about half the lane departure on a curve with sun glare trials - it simply disengaged and issued steering control takeover commands. In the other trials it did provide LKS and LDWs, but not lane centering. This vehicle had problems with lane management around the same point on the curve with and without sun glare. This vehicle's performance may be a reflection of its manufacturer's more conservative approach to driving automation in which control authority is purposely limited.

Differences in AV Approaches Affected Performance

Performance in adverse weather did appear to be a factor of the approach to automation supporting driver assistance by each AV model tested in both periods. Some of the findings that appear to align to the approach taken in test period 1 include:

- Vision only systems were overall the most affected by adverse weather. Radar and camera systems were still susceptible to rain and ice but not as consistently as the vision-only system.
- Sun glare did not seem to impact the one vehicle that was able to be tested.
- Rain had a significant effect on two of the three vehicles for highs-speed following. Rain affected the vision-only system only for lane departure warning and traffic jam assist.
- Ice or snow on the radar and camera disabled all vehicles' safety systems. One vehicle was able to operate with the camera covered and another was able to operate with the radar covered. Due to time constraints the converse for each of the vehicles were not able to be tested.

As observed in Period 1 testing, significant differences in approach were observed across tested vehicles in regard to:

- color, shape, and design aspects of audible/visual/tactile alerting
- location where audible/visual/tactile alerts are presented
- conditions under which alerts are presented (or not)
- the manner in which alerts, advisories, and warnings are presented

- the method by which the driver confirms alertness to the driving automation system
- configurability of driver assistance functions
- levels and sensitivity of timing for LKS intervention and ACC aggressiveness with which LKS, lane centering corrections, and throttle/braking are applied

Stakeholder Engagement

Considerable work has already been done in delivering information to human drivers. General weather forecasts occasionally contain travel advisories. In addition to these are a variety of technologies to acquire and disseminate specific travel-related weather information to motorists. Information outlets range from dynamic message signs, available to all but limited in coverage, to state-wide web sites such as 511, which must be actively queried by a traveler and can be reasonably consulted only when a vehicle is stopped.

Much infrastructure is in place to transmit machine-readable weather information, but no known vehicle model uses such information. Furthermore, there is no objective basis for acting on the information, deciding whether to revert to a different driving mode, restoring control to the human, or avoiding the trip altogether; where responsibility rests for making these decisions has not been settled, either.

Discussions across the three workshops described in Chapter 4 above revealed gaps for operating automated vehicles in adverse weather. The identified gaps include:

- There are no good ways of deciding whether a trip under automation should begin or continue.
- State and local operating agencies are ill equipped to give advice on automation, and manufacturers are not advertising the limitations of their products.
- Although the ODD is to be specified by the vehicle manufacturer, it is not clear who is responsible for determining whether current or forecasted conditions are within the ODD.
- State and local operating agencies are concerned that they may be asked to take on a new responsibility that they are not prepared to perform relative to AV operations, such as make decisions of when to close roads or require chains.
- Weather-related limitations of AVs are not well understood.

Chapter 6. Research Needs

USDOT can take a leadership role in ensuring automated vehicles operate as intended in adverse weather conditions. By extending existing programs and bringing together government and industry stakeholders, USDOT can ensure that wise choices are made with respect to starting and continuing trips with driving automation.

Standards Development

Establish Metrics to Define the Operational Design Domain

There needs to be a way to objectively describe the current and forecasted conditions so that they can be compared with the ODD of an automation system.

One approach is to define categories of weather conditions, such as mild, moderate, and severe. Each category would have a set of weather and road weather conditions, such as visibility distance. Manufacturers would use these categories to specify the environmental component of ODDs for the automation functions they offer. Transportation agencies would announce which category applies (or is forecasted to apply) to each road in their jurisdiction. This approach has an appealing simplicity, but it has several disadvantages. Foremost, rigidly defined categories would not satisfactorily accommodate advances in technology. Also, the categories would have to include a combination of atmospheric and road conditions, not all of which would apply to every feature. A series of test procedures would need to be developed to confirm a feature can perform as specified.

Another approach is to develop a series of metrics that can be measured and reported. A manufacturer would define its ODD in terms of these metrics, and then it could choose to publish or not to publish the metrics. If it publishes its ODD, a human driver or dispatcher can assess the situation. If the exact limits are not published, the vehicle must be able to receive the forecast electronically, and then accept the trip, recommend against it, or outright refuse it. The list of metrics might include:

- Visibility (for the driver's own vision and for all of the sensors on the vehicle)
- Surface friction (an indication of slick conditions such as ice, snow)
- Local conditions (e.g. whether water is standing on the road or a tree has fallen across the road or a rolling work zone is repairing damage)
- Wind speed (sustaining and gusting) and direction

Manufacturers are an essential stakeholder in this process. Either individually or collectively (e.g., through an SAE committee), they must specify the nature of information they need to determine whether current and projected conditions are within the ODDs of their systems. And the manufacturers need to say whether they prefer the information to come in the form of raw data or if they prefer that it be interpreted in a manner following the Pathfinder model. The weather and highway communities have a role in delivering information.

Define Roles and Responsibilities

An entire system that supports AV operations needs to be assembled, from gathering weather data to delivering assessments to the necessary machines and people. Data would include current and forecasted conditions for atmospheric weather and road weather, including spot warnings. Existing standards and programs can be used and adapted, with gaps needing to be filled in to complete the system.

Vehicles with driving automation features need internal sensors to locate their position with respect to the road and detect nearby objects. Manufacturers are installing these sensors as they are necessary to provide the features they offer.

In addition, vehicles that are making more than a short local trip need external sources of information on conditions over their planned route. They need to “see” conditions farther ahead, beyond the range of their own sensors. An open question is what organization or organizations will be responsible to collect, quality check, assimilate, and disseminate the information.

Warnings of spot conditions can be provided directly from other vehicles through vehicle-to-vehicle (V2V) communication. Those messages are useful only to other vehicles that are in the vicinity at the time the V2V messages are transmitted.

Objective reports of conditions can come from conventional sources—the National Weather Service and road weather information systems. Road weather information currently coming from fleet vehicles can be supplemented by information from civilian vehicles through already envisioned V2I communication. Many of the components for gathering information exist. USDOT, along with its State and local partner agencies, need to collaborate with the National Weather Service, private sector weather service providers, and the auto manufacturers on a system level to identify the tasks to be performed, determine which organization is best suited to perform those tasks, and carefully delineate handoffs and interfaces between them.

The pieces of information will be checked for quality and assimilated into an overall picture, with the temporal and spatial specificity needed to support the automated vehicles. These details need to be packaged in a form useful to the vehicles and their operators.

Visibility of Signs and Markings

The automakers, state DOTs, and private entities are working to deliver better situational information to AVs in adverse weather. Projects include striping for AVs (Carlson and Poorsartep 2017), visibility of striping (Davies 2017), machine-readable signs and connected vehicle roadway information (SAE 2016), and three-dimensional mapping (Sairam et al. 2016).

Data Needs and Policies

In addition to advancing technological solutions to address the challenges posed by adverse weather to AV operations, preparations must be made by entities that will plan, build, maintain, and otherwise facilitate AV operations. State and local transportation agencies, network operators, and private companies must prepare for the growing advent of AV technologies that will fundamentally change how people move around and interact with their surroundings. The following are actions found in the literature that agencies, vehicle manufacturers, the government, and OEMs can take to prepare for AVs.

- Enhancing Existing Infrastructure (Murtha n.d.) – Currently existing infrastructure may not be able to support the wireless connectivity CAVs require. As transportation infrastructure is maintained or renewed, state and local agencies should be cognizant of the development and deployment of AVs and their associated technologies, and provide a means to accommodate these technologies. In addition, replacing old infrastructure with digital infrastructure that allows vehicles to communicate wirelessly by providing fast and secure connections between vehicles and traffic management systems is essential.

- Cybersecurity Requirements (Murtha n.d.) – Data and information that AVs produce and use must be protected from external and internal threats to prevent cyber-attacks. Car manufacturers, OEMs, and the government collectively, must have an understanding of the AV network security, and have mitigation strategies in place to deal with real-time threats. NHTSA released proposed guidance for improving motor vehicle cybersecurity in October 2016 (NHTSA n.d.). To ensure a vigorous cybersecurity environment, NHTSA’s guidance focuses on solutions that ensure the protection of consumers’ personal data and safety critical vehicle controls.

- Investing in Research (Australia 2017) – Continuing to invest in AV research, development, and real-world testing, and their technologies will secure a safe transportation network, aiding rulemaking during deployment. In addition, research will identify uncertainties inherent in existing and new contexts, including adverse weather and road weather conditions. AVs are not yet present in traffic streams, so continued research will provide answers to disruptive paradigm shifts in surface transportation.

Testing

In addition to cameras and radar, LiDAR is common on prototype automated driving systems. It is available on a limited group of production vehicles and was omitted from study in this project. Testing LiDAR’s response to adverse weather conditions could be a valuable extension to this work. Based on the way LiDAR works, novel ideas and testing conditions and maneuvers may need to be considered.

The AVs selected for tests comprising this project strictly rely upon on-board technologies. Future vehicles may be connected, using dedicated short-range communication (DSRC) or 5G cellular communication to communicate with other vehicles, pedestrians, and infrastructure. Connected Automated Vehicles (CAVs) have the ability to optimize network capacity, reduce congestion, increase safety, and have environmental benefits. Connected vehicle technology and associated V2V and V2I applications was not part of these tests, but may represent an avenue for further research.

Integration with Other Activities

All three stakeholder engagement workshops spent a good deal of time discussing situation assessment and determination of whether a driving automation function can perform safely.

The infrastructure owner operators at the first and third workshops observed that they will have additional responsibilities in preparing and maintaining the infrastructure for automated vehicles. The most prominent question is how traffic control devices might need to be upgraded. An NCHRP project has investigated visibility of lane markings and another is under way. Attendees of the first workshop also noted that laws, regulations, and policies need to be prepared.

Chapter 7. References

Adient. (2017). Adient unveils new luxury seating concept for level-3 and level-4 automated driving systems. January 9. http://www.adient.com/media/press-releases/2017/01/09/adient-unveils-new-luxury-seating-concept-for-level-3-and-level-4-automated-driving-systems

Australian Department of Infrastructure and Regional Development (Australia). (2017). Preparing for Automated Vehicles. May. https://infrastructure.gov.au/transport/automatedvehicles/preparing-for-automated-vehicles.aspx

Boudette, N.E. and Vlasic, B. (2017). Tesla Self-driving System Faulted by Safety Agency in Crash. *The New York Times*. September 12. https://www.nytimes.com/2017/09/12/business/self-driving-cars.html

Cameron, O. (2017). An Introduction to LIDAR: The key self-driving car sensor. *Voyage*. May 9. https://news.voyage.auto/an-introduction-to-lidar-the-key-self-driving-car-sensor-a7e405590cff

Carlson, P. and Poorsartep, M. (2017). Enhancing the Roadway Physical Infrastructure for Advanced Vehicle Technologies: a case study in pavement markings for machine vision and a roadmap toward a better understanding. *Paper presented at the Transportation Research Board (TRB) 96th Annual Meeting*, Washington D.C.)

Carpenter, Michael G., Feldmann, Michael, Fornari, Thomas M., Moury, M. Todd, Walker, Christopher D., Zwicky, Timothy D., Kiger, Steven M. (2011 September) *Objective Tests for Imminent Crash Automatic Braking Systems.* Final Report. DOT HS 811 521.Retrieved June 6, 2018 from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/811521.pdf

Da Lio, M., Biral, F., Bertolazzi, E., Galvani, M., Bosetti, P., Windridge, D., and Tango, F. (2015). Artificial co-drivers as a universal enabling technology for future intelligent vehicles and transportation systems. *IEEE Transactions on Intelligent Transportation Systems*, 16(1), 244-263.

Dannheim, C., Mader, M., Icking, C., Loewenau, J., and Massow, K. (2013). A novel approach for the enhancement of cooperative ACC by deriving real time weather information. *Intelligent Transportation Systems-(ITSC), 2013 16th International IEEE Conference*. October (2207-2211).

Dasgupta, A., George, A., Happy, S. L., and Routray, A. (2013). A vision-based system for monitoring the loss of attention in automotive drivers. *IEEE Transactions on Intelligent Transportation Systems*, 14(4), 1825-1838.

Davies, C. (2017). Effects of Pavement Marking Characteristics on Machine Vision Technology. *Paper presented at the Transportation Research Board (TRB) 96th Annual Meeting*, Washington D.C.

Druta, C., and Alden, A. S. (2016). *Assessment of Roadway Surface Conditions Using Vehicle-Intrinsic Sensors: Final Report, Phase II* (No. FHWA-JPO-16-361).

Duthon, P., Bernardin, F., Chausse, F., and Colomb, M. (2016). Methodology used to evaluate computer vision algorithms in adverse weather conditions. *Transportation Research Procedia*, 14, 2178-2187.

Fleming, B. (2012). New automotive electronics technologies [automotive electronics]. *IEEE Vehicular Technology Magazine*, 7(4), 4-12.

Federal Highway Administration (FHWA). (2017a) How Do Weather Events Impact Roads? February 1. https://ops.fhwa.dot.gov/weather/q1_roadimpact.htm

FHWA. (2017b). Connected Vehicles and Road Weather: How the public works community can take advantage of these new technologies. August. https://www.its.dot.gov/presentations/2017/Session_5270_ConnectedVehiclesAndRoadWeather.pdf

Fröhlich, B., Bock, J., and Franke, U. (2014). Is it safe to change the lane? Visual exploration of adjacent lanes for autonomous driving. *Intelligent Transportation Systems (ITSC), 2014 IEEE 17th International Conference*. October. 2304-2309.

Gallen, R., Hautiere, N., Cord, A., and Glaser, S. (2013). Supporting drivers in keeping safe speed in adverse weather conditions by mitigating the risk level. *IEEE Transactions on Intelligent Transportation Systems*, 14(4), 1558-1571.

Hammit, B., and Young, R. (2015). *Connected Vehicle Weather Data for Operation of Rural Variable Speed Limit Corridors*. (No. MPC 15-299).

Hergeth, S., Lorenz, L., and Krems, J. F. (2017). Prior familiarization with takeover requests affects drivers' takeover performance and automation trust. *Human Factors*, 59(3), 457-470.

Intelligent Transportation Systems Joint Program Office (ITS JPO). (n.d.). *Road Weather Management*. https://www.its.dot.gov/factsheets/roadweather_management.htm

ITS International (2014). Keeping a weather eye on road conditions. *ITS International*. Accessed at http://www.itsinternational.com/categories/location-based-systems/features/keeping-a-weather-eye-on-road-conditions/

Jung, S., Jang, K., Yoon, Y., and Kang, S. (2013). Impacts of Influential Factors on Vehicle-to-Vehicle Crash Frequency and Severity in Rainy Weather. *Transportation Research Board 92nd Annual Meeting* (No. 13-3308).

Koglbauer, I., Holzinger, J., Eichberger, A., and Lex, C. (2017). Drivers' Interaction with Adaptive Cruise Control on Dry and Snowy Roads with Various Tire-Road Grip Potentials. *Journal of Advanced Transportation*.

Lee, U., Jung, J., and Shin, S. (2016). EureCar turbo: A self-driving car that can handle adverse weather conditions. Conference on Intelligent Robots and Systems (IROS), 2016 http://ieeexplore.ieee.org/document/7759359/

Levinson, J., Askeland, J., Becker, J., Dolson, J., Held, D., Kammel, S., Kolter, J.Z., Langer, D., Pink, O., Pratt, V., Sokolsky, M., Stanek, G., Stavens, D., Teichman, A., Werling, M., and Thrun, S. (2011). Towards Fully Autonomous Driving: Systems and Algorithms. https://www.cs.cmu.edu/~zkolter/pubs/levinson-iv2011.pdf

Li, Y., Xing, L., Wang, W., Wang, H., Dong, C., and Liu, S. (2017). Evaluating impacts of different longitudinal driver assistance systems on reducing multi-vehicle rear-end crashes during small-scale inclement weather. *Crash Analysis & Prevention*, 107, 63-76.

Light, S. (2017). Autonomous Vehicle Bill Leaves Safety Gaps. *The Regulatory Review*. September 25. https://www.theregreview.org/2017/09/25/light-autonomous-vehicle-bill-gaps/

Louw, T., Kountouriotis, G., Carsten, O., and Merat, N. (2015). Driver Inattention During Vehicle Automation: How Does Driver Engagement Affect Resumption Of Control. *4th International Conference on Driver Distraction and Inattention (DDI2015)*. ARRB Group.

Luciano, M. (2017). Three Sensors That "Drive" Autonomous Vehicles. *Wireless Design*. May 5. https://www.wirelessdesignmag.com/blog/2017/05/three-sensors-drive-autonomous-vehicles

Manz, B. (2017). The Role of Sensor Fusion in Advanced Driver Assistance Systems. *Electronic Design*. October 12. http://www.electronicdesign.com/automotive/role-sensor-fusion-advanced-driver-assistance-systems

Marshall, A. (2017). To let self-driving cars go anywhere, train them everywhere. *Wired*. October 17. https://www.wired.com/story/waymo-self-driving-michigan-testing/

Murtha, S. (n.d.) Connected & Autonomous Vehicles. Atkins. http://www.atkinsglobal.com/~/media/Files/A/Atkins-Corporate/north-america/sectors-documents/highways-and-bridges/library-docs/brochures/CAV_Report-NorthAmerica_v2.pdf

National Highway Traffic Safety Administration (NHTSA). (2017a). *Automated Safety Systems 2.0: A Vision for Safety*. September. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13069a-ads2.0_090617_v9a_tag.pdf

NHTSA. (2017b). ODI Resume PE 16-007. January 19. https://static.nhtsa.gov/odi/inv/2016/INCLA-PE16007-7876.PDF

NHTSA. (n.d.) Vehicle Cybersecurity. https://www.nhtsa.gov/technology-innovation/vehicle-cybersecurity

Outay, F., Kamoun, F., Yasar, A., Shakshuki, E., and El-Amine, S. (2017). ConVeh: Driving Safely into a Connected Future. *Procedia Computer Science*, 113, 460-465.

Pindilli, E. J., Glassman, J. L., and Freckleton, D. R. (2013). *Road Weather Connected Vehicle Applications: Benefit-Cost Analysis Interim Report*. (No. FHWA-JPO-14-124).

Quora. (2017). What kind of machine learning algorithms do the driverless cars use? https://www.quora.com/What-kind-of-machine-learning-algorithms-do-the-driverless-cars-use

Rasshofer, R.H., Spies, M., and Spies, H. (2011). *Influences of weather phenomena on automotive laser radar systems*. Advances in Radio Science 9, 49–60. https://www.adv-radio-sci.net/9/49/2011/ars-9-49-2011.pdf

Reina, G., Johnson, D., and Underwood, J. (2015). Radar sensing for intelligent vehicles in urban environments. *Sensors*, 15(6), 14661-14678.

SAE. (2016). *Dedicated Short Range Communications (DSRC) Message Set Dictionary*. Standard J2735_2016. http://standards.sae.org/j2735_201603/

Sairam, N., Nagarajan, S., and Ornitz, S. (2016). Development of Mobile Mapping System for 3D Road Asset Inventory. *Sensors*, *16*(3), 367.

Schwarz, C., Brown, T., Gaspar, J., and Keum, C. (2016). Transfer from Highly Automated to Manual Control: Performance and Trust. *Proceedings of the 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV)*.

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

Sundararajan, S., and Zohdy, I. (2016). *Vehicle Automation and Weather: Challenges and Opportunities*. (No. FHWA-JPO-17-494).

Transportation Research Associates (TRA). (2016). Staying in Control: Bridging the gaps in autonomous vehicle safety. September. https://www.traonline.com/wp-content/uploads/2016/08/Staying-in-Control-Bridging-the-Gaps-in-Autonomous-Vehicle-Safety-TRA-Sept-2016.pdf

USDOT. (2016). Prototype Road Weather Performance Management Tool. November. FHWA-JPO-17-486.

Wong, J.I. Driverless cars have a new way to navigate in rain or snow. *Quartz*. March 14. https://qz.com/637509/driverless-cars-have-a-new-way-to-navigate-in-rain-or-snow/

Yenkanchi, S. (2016). Multi sensor data fusion for autonomous vehicles. *Scholarship at UWindsor*. January 21. http://scholar.uwindsor.ca/cgi/viewcontent.cgi?article=6679&context=etd

Zardoscht, B. (2016). A data fusion approach to automated decision making in intelligent vehicles. Dissertation, Univ. of Western Ontario. http://ir.lib.uwo.ca/cgi/viewcontent.cgi?article=5662&context=etd

U.S. Department of Transportation
ITS Joint Program Office – HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free “Help Line” 866-367-7487

www.its.dot.gov

FHWA JPO-19-755

U.S. Department of Transportation