NCHRP
Research Report 1001

National Cooperative Highway Research Program

BTSCRP
Research Report 2

Behavioral Traffic Safety Cooperative Research Program

Framework for Assessing Potential Safety Impacts of Automated Driving Systems

JOINT REPORT

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BTSCRP RESEARCH REPORT 2

Framework for Assessing Potential Safety Impacts of Automated Driving Systems

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TRB TRANSPORTATION RESEARCH BOARD

2022

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation, under Agreement No. 693JJ31950003.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the National Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the FHWA. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

NCHRP RESEARCH REPORT 1001

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BEHAVIORAL TRAFFIC SAFETY COOPERATIVE RESEARCH PROGRAM

Since the widespread introduction of motor vehicles more than a century ago, crashes involving their operation remain a significant public health concern. While there have been enormous improvements in highway design and construction, as well as motor vehicle safety, which have been instrumental in lowering the rate of crashes per million miles in the United States, more than 35,000 people die every year in motor vehicle crashes. In far too many cases, the root causes of the crashes are the unsafe behaviors of motor vehicle operators, cyclists, and pedestrians. Understanding human behaviors and developing effective countermeasures to unsafe ones is difficult and remains a major weakness in our traffic safety efforts.

The Behavioral Traffic Safety Cooperative Research Program (BTSCRP) develops practical solutions to save lives, prevent injuries, and reduce costs of road traffic crashes associated with unsafe behaviors. BTSCRP is a forum for coordinated and collaborative research efforts. It is managed by the Transportation Research Board (TRB) under the direction and oversight of the Governors Highway Safety Association (GHSA) with funding provided by the National Highway Traffic Safety Administration (NHTSA). Funding for the program was originally established in Moving Ahead for Progress in the 21st Century (MAP-21), Subsection 402(c), which created the National Cooperative Research and Evaluation Program (NCREP). Fixing America's Surface Transportation (FAST) Act continued the program. In 2017, GHSA entered into an agreement with TRB to manage the research activities, with the program name changed to Behavioral Traffic Safety Cooperative Research Program. The GHSA Executive Board serves as the governing board for the BTSCRP. The Board consists of officers, representatives of the 10 NHTSA regions, and committee and task force chairs. The Research Committee Chair appoints committee members who recommend projects for funding and provide oversight for the activities of BTSCRP. Its ultimate goal is to oversee a quality research program that is committed to addressing research issues facing State Highway Safety Offices. The Executive Board meets annually to approve research projects. Each selected project is assigned to a panel, appointed by TRB, which provides technical guidance and counsel throughout the life of the project. The majority of panel members represent the intended users of the research projects and have an important role in helping to implement the results. BTSCRP produces a series of research reports and other products such as guidebooks for practitioners. Primary emphasis is placed on disseminating BTSCRP results to the intended users of the research: State Highway Safety Offices and their constituents.

BTSCRP RESEARCH REPORT 2

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FOREWORD

By Richard Retting
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NCHRP Research Report 1001/BTSCRP Research Report 2 presents a framework intended to help state and local transportation agencies, as well as other stakeholders, assess the safety impact of automated driving system (ADS) technologies. The framework supports safety planning, design, operational decisions, and investments on multimodal infrastructure. The report also presents results of a proof-of-concept study that involved pilot testing the framework in partnership with two state departments of transportation.

ADS technologies are quickly advancing and are expected to have disruptive impacts on transportation safety in the coming years. ADS technologies will change planning, design, and operational criteria, which means there is a growing need for roadways that are traditionally planned, designed, and operated with human drivers in mind to begin to adapt to an ADS environment. A framework is needed for practitioners to use in current and future safety planning, design, operational decisions, and investments on multimodal infrastructure.

In NCHRP Project 17-91/BTSCRP Project BTS-07, a research team led by Booz Allen Hamilton was asked to develop a framework for use by practitioners (e.g., transportation infrastructure owners, safety agencies, road users and ADS manufacturers) to assess the safety impact of ADS technologies. ADS technologies include a plethora of applications that impact safety, mobility, human factors, and environmental aspects of driving. The report provides guidance to state and local agencies and other stakeholders on how to adapt the framework for a variety of scenarios. The report also provides a practical application of the framework by summarizing results of a proof-of-concept study that involved pilot testing the framework in partnership with two state departments of transportation.

The framework addresses the following key questions:

- What are the key factors influencing ADS safety and how do they relate to planning, design, and operations decisions and tools?
- With limited ADS safety-related data available, how can the impacts of ADS technologies on safety be estimated and support decision-making?
- What steps can agencies take to achieve safety goals, meet user needs, and prioritize investments in ways that consider the impacts of ADS technologies?

A web video was produced as part of NCHRP Project 17-91/BTSCRP Project BTS-07 to further inform practitioners and the public about the framework. That video, as well several documents, including Proof of Concept Results, an Implementation Plan, and Future Research Needs, can be obtained from the National Academies Press website (www.nap.edu) by searching for *NCHRP Research Report 1001/BTSCRP Research Report 2: Framework for Assessing Potential Safety Impacts of Automated Driving Systems*.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.nap.edu) retains the color versions.

SUMMARY

Framework for Assessing Potential Safety Impacts of Automated Driving Systems

Quickly advancing automated driving system (ADS) technologies (typically, SAE automation Levels 3 through 5) are expected to positively affect transportation safety. ADS includes a plethora of applications that affect safety, mobility, human factors, and environmental aspects of driving. One anticipated disruption is the type of ADS-related crash (both in likelihood and severity) when compared to traditional vehicle crashes. For example, unlike human drivers, ADSs are projected to have a lower probability of certain crashes in traffic due to lower susceptibility to performance issues a human operator may face (distracted driving, drowsiness, etc.). While ADSs have the potential to improve safety, humans still have advantages in certain roadway conditions, such as operating on roads with degraded lane markings and during adverse weather (e.g., heavy rain, snow, ice), two conditions with which the ADS has challenges.

Analysis of the effects of ADS on safety, traffic flow, and other considerations depends on available data. Data sources revealing ADS safety performance are not publicly available, and this lack of data makes this analysis challenging. However, there are other data sources (typically, SAE Levels 1 and 2 automation) that can be used as a strong proxy in the analysis. To forecast safety impacts of ADS with limited data, it is important to understand the underlying factors that influence safety, such as enabling technologies (e.g., sensors, communications), human-machine interaction, and vehicle-to-infrastructure interactions. A framework can help state and local agencies assess when their traditional safety processes and procedures may be affected and characterize the safety impacts of competing options. Such a framework will support a smoother transition to ADS transportation. This framework should include processes and procedures to facilitate the safe, phased integration of ADS under different contexts, timeframes, risks, and opportunities.

This report describes a framework to help state and local agencies assess the safety impact of ADS. It will guide state and local agencies on how to adapt the framework for a variety of scenarios. It starts with an introduction and a high-level background on various technology terms in Chapter 1. Chapter 2 covers the effects of ADS on transportation safety by discussing aspects of the current safety landscape, crash data, and ADS performance. Chapter 3 delves into the six steps of the framework and the key steps that state and local agencies can follow to assess the safety impact of ADS applications. Chapter 4 presents the results of pilot studies of the framework with two state departments of transportation. Finally, Chapter 5 concludes the report with the key points that need to be considered when applying the framework.

The first step in the framework's process identifies ADS features that agencies would like to assess based on their safety concerns, strategic highway safety plans, and commercial deployment plans. This is followed by a thorough understanding of functionalities of the ADS applications of interest. It also suggests estimating the expected market penetration rates of the

ADS under assessment to better estimate potential impacts. In most cases, the ADS developer describes the physical and environmental boundaries within which a particular function is designed to work. In other words, the developer specifies the operational design domain (ODD) of the feature. This ODD helps to define the deployment scenarios in the third step. Once the deployment scenarios are defined, it is important to understand the technology and its infrastructure dependencies, which helps to recognize the risks and opportunities involved. With the scenarios identified, the fourth step is to define safety goals and the associated hypotheses. Step 5 is identifying data sources and metrics to evaluate the hypotheses formulated in the fourth step. The analysis method is also chosen during this step to derive insights from the data. Upon completion of the analysis, Step 6 is to communicate the results and share the safety impact of the ADS feature to support decision-making.

Chapter 4 shows the practical application of the framework by summarizing the results of a proof-of-concept study that involved piloting the framework in partnership with two state departments of transportation. One study evaluated a low-speed shuttle scenario in Minnesota, and the other evaluated the potential deployment of ADS-equipped trucks in Virginia's I-81 corridor. This framework was refined throughout the course of this project based on feedback from stakeholder engagement (obtained in research Phase 3) and the proof-of-concept pilots (obtained in research Phase 4).

CHAPTER 1

Introduction and Background

This chapter describes the need for the framework, goals of the framework, target audience, and the technical definitions and background needed to understand subsequent discussions.

Need for Framework

Automated driving system (ADS) technologies are quickly advancing and are expected to have disruptive impacts on transportation safety in the coming years. ADSs will change planning, design, and operational criteria, which means there is a growing need for roadways that are traditionally planned, designed, and operated with human drivers in mind to begin to adapt to ADS. There will be opportunities and risks in planning and implementing ADS technologies for transportation agencies, technology firms and service providers, automakers, and research organizations. For a smoother transition to ADS transportation, state and local agencies must understand how and when traditional safety-related processes and procedures may be affected and have the tools to assess safety impacts of competing options. In some cases, ADSs may positively impact safety in ways that allow agencies to reprioritize investments, such as lane-marking maintenance. We need to understand better the safety impacts and give transportation stakeholders the tools they need to achieve safety goals. For example, some ADS technologies could mitigate certain crash types and severities while increasing the risk of others.

Consequently, practitioners need a framework to use in current and future safety planning, design, operational decisions, and investments on multimodal infrastructure. This framework should translate the goals and objectives of state and local agencies into a hypothesis on how their policies and actions can influence safety. For instance, the primary goals of state and local agencies deploying a low-speed shuttle pilot may include improving safety and mobility. The hypothesis may be stated as "The rate of vehicle collisions among travelers going to and from transit station X during the pilot is less than before." While this framework focuses on considering the safety performance of ADS under various scenarios, it provides the flexibility to account for other socio-economic impact areas such as public health and safety (e.g., access to healthcare), environment (e.g., air quality), accessibility, equity, etc. For example, this report focuses on helping agencies explore questions such as "Will Level 4 low-speed automated shuttles improve safety performance for road users?" and does not focus on questions such as "Will Level 4 low-speed automated shuttles improve access to healthcare for persons with disabilities?"

Goals of the Framework

This framework addresses the following key questions:

What are the key factors influencing ADS safety and how do they relate to planning, design, and operations decisions and tools?

With limited ADS safety-related data available, how can the impacts of ADS technologies on safety be estimated and support decision-making?

What steps can agencies take to achieve safety goals, meet user needs, and prioritize investments in ways that consider the impacts of ADS?

Target Audience

The primary audience of this framework includes transportation infrastructure owners and operators (IOOs), safety industry and advocacy groups, and ADS manufacturers. Federal agencies may find this useful to understand gaps in data collection, management, and analysis tools. The outputs from the framework may support building trust in road users in ADS technology, and therefore the outputs have been framed in a way that is accessible to a broad audience. ADS developers and manufacturers may benefit from data sources and analysis methods to understand the safety impacts of the technology they seek to commercially deploy. For example, this framework may help industry determine and track target safety levels for commercial deployments without safety drivers. It also may help private and public sector stakeholders build public trust in deployments by quantifying safety impacts.

Technical Background

This section provides the technical background needed for subsequent discussions.

Dynamic Driving Task (DDT): Includes all real-time operational and tactical functions to operate a vehicle in on-road traffic, excluding the strategic functions (e.g., trip scheduling, selection of destinations and waypoints) and including the following (SAE, 2018):

A. Lateral vehicle motion control via steering.
B. Longitudinal vehicle motion control via acceleration and deceleration.
C. Monitoring the driving environment via object and event detection, recognition, classification, and response preparation.
D. Object and event response execution.
E. Maneuver planning.
F. Enhancing conspicuity via lighting, signaling, gesturing, etc.

Automated Driving System (ADS): The hardware and software that are collectively capable of performing the entire DDT on a sustained basis. This term is used specifically to describe a Level 3, 4, or 5 driving automation system (SAE, 2018). The different levels of automation are described in Figure 5 in chapter 2.

Operational Design Domain (ODD): Operating conditions under which a given driving automation system or feature is specifically designed to function, including environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics (SAE, 2018). ODD is typically defined by the ADS technology developer and original equipment manufacturer (OEM). More details on the ODD are provided in Chapter 3, Overview of the Framework Elements.

DDT Fallback: This occurs when the ADS is unable to continue to perform the entire DDT (i.e., under normal operating conditions). For Level 3 ADS features, the human fallback-ready user is expected to respond to a request to intervene by either resuming manual driving if the vehicle remains drivable or achieving a minimal risk condition if the vehicle is not drivable. For a Level 4 or 5 ADS, the feature or system performs the fallback by automatically achieving a minimal risk condition (SAE, 2018).

Radio Detection and Ranging (Radar): Radar is a range-finding technology that supports perception. Radars operate by transmitting a radio signal toward a region of interest and detecting the signals reflected back from objects within the field of view. Radar is a popular choice for automated vehicles (AVs) because it is relatively inexpensive and robust (Patole et al., 2017).

Light Detection and Ranging (Lidar): Lidar is a subset of radar and has been growing as a key enabling technology for AVs. Lidar allows generation of high-definition (HD), three-dimensional (3D) maps by sending and receiving high-frequency radar. Lidar works similar to radar: it transmits a wave (in this case, light) and detects the reflected light pulse from an object within the detectable region. Lidar has a much higher resolution and frequency (900–1,500-nm wavelengths) (Yole Développement, 2015).

Communications

Vehicle-to-Everything (V2X) Communication: It is a compendium of V2X communications occurring over the dedicated short-range communication (DSRC) or cellular spectrum to provide vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) communications. An onboard unit (OBU) enables the vehicles to communicate with other vehicles, infrastructure, pedestrians, and cellular network around them to enhance safety, mobility, and environmental aspects of driving. In V2I communication, the OBU communicates with a roadside unit (RSU) to dispatch important information, such as hazardous road conditions (Joseph, 2018).

Dedicated Short-Range Communication (DSRC): The term "dedicated" refers to the fact that the Federal Communications Commission (2002) dedicated 75 MHz of licensed spectrum in the 5.9 GHz band for DSRC, though part of the spectrum is now shared with unlicensed Wi-Fi users and the rest is shared simultaneously with cellular technologies (discussed next). DSRC takes place over hundreds of meters, a shorter distance than other common wireless communications. While the main purpose for deploying DSRC was a collision-prevention application, DSRC has characteristics (e.g., low latency, high reliability, security, and interoperability) that make it ideal for many other applications beyond collision avoidance (Kenney, 2011). Additionally, DSRC experiences little interference, even in extreme weather conditions, due to its short range, making it ideal for handling communications to and from cars moving at high speeds.

Cellular-V2X (C-V2X): C-V2X is a wireless broadcast interface that permits a single platform for V2V, V2N, and V2I communication. C-V2X can operate within a dedicated frequency band for low-latency use cases (5.9 GHz) or use more traditional connectivity channels (Qualcomm, 2019).

Object and Event Detection and Response (OEDR): The subtasks of the DDT that include monitoring the driving environment (detecting, recognizing, and classifying objects and events and preparing to respond as needed) and executing an appropriate response to such objects and events (i.e., as needed to complete the DDT and/or DDT fallback) (SAE, 2018).

HD Maps: These types of maps are designed and made for self-driving cars and AV features operating at Levels 3 and 4. These maps have extremely high precision (to the centimeter level) because the cars need precise instructions on how to maneuver within a particular lane along the route (Vardhan, 2017).

CHAPTER 2

ADS Impacts on Safety

Roadway stakeholders must understand the potential safety impacts of an automated driving system (ADS) before widespread deployment. Insights on safety can help provide inputs into current transportation planning, design, and operations processes. Both the partial and full deployment of ADS will affect current safety practices. This section discusses the current safety methods and processes, followed by matching certain crash types to specific ADS technologies, and concludes with ways in which ADS performance could impact safety.

Current Understanding of Safety Landscape

To best understand the safety impacts of ADS, studying and understanding the current safety landscape can be helpful. ADS will influence both safety and safety processes. Automating driving decisions will force the scope of safety evaluation to assess new inputs from a more interconnected safety system. Mode shifts between walking/cycling and ride hailing, evaluation of service affordability and equitability, and ethics of autonomous decision-making must be factored into a holistic definition of surface transportation safety. New and existing tools may be adapted to account for the partial and full deployment of ADS. Recent studies (Matthews, 2018; LaChance, 2022) suggest a link between existing advanced driver assistance systems (ADASs) and improved safety measures for vehicle testing. As many consider ADS-equipped vehicles as iterations of ADAS-featured vehicles, initial research suggests that ADS-equipped vehicles will likely yield safer test results. Current ADS data may not be available, but ADAS has a testing foundation with standard development organizations (IIHS-HLDI, 2020). The following subsections describe the roadway safety management process and project development process. The roadway safety management process is a focused approach to identify and address safety opportunities. The project development process is an opportunity to consider safety alongside other factors (e.g., project costs, traffic operations, mobility and accessibility, economic impacts, social equity, and environmental impacts) when planning, designing, and maintaining roadway facilities. Both sections describe opportunities for considering the safety impacts of ADS and for adapting current safety processes to address ADS safety.

Roadway Safety Management Process

Figure 1 illustrates the six-step safety management process, starting with network screening and ending with safety effectiveness evaluation.

1: Network Screening

Network screening is the process of analyzing the entire roadway network to identify potential sites or issues for further investigation. It is not possible to conduct a detailed assessment of

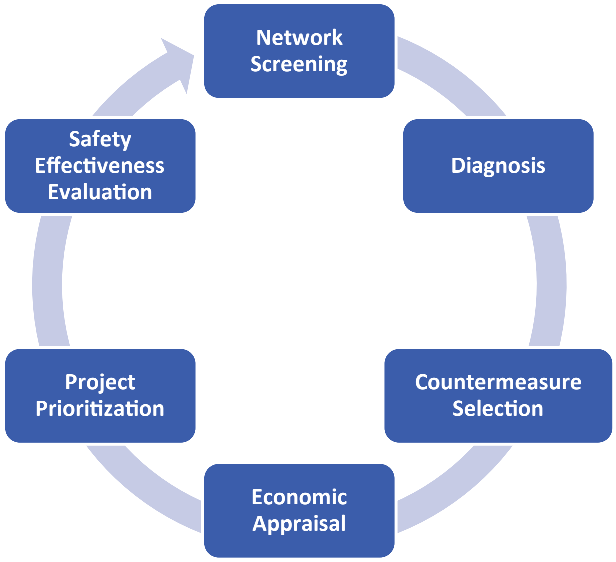


Figure 1. Six-step safety management process (Source: FHWA).

the entire network, so network screening is used to pare down the network to a manageable list. There are two types of screening.

1. **Site-specific:** The objective of site-specific screening is to identify specific sites for further analysis (typically those with high crashes or overrepresented crashes).
2. **Systemic:** The objective of systemic screening is to identify factors that are common among crashes (typically a focus crash type) and are overrepresented in focus crashes compared to total crashes.

While site-specific and systemic screening methods hold potential for identifying and addressing ADS-related safety opportunities, it may not be likely to find "hotspots" (i.e., specific locations with more crashes than expected) involving ADS-equipped vehicles. Instead, it seems more likely that crashes involving ADS-equipped vehicles could share common contributing factors. If this is the case, then there is the potential to employ systemic techniques to identify and address safety opportunities in the future. For example, if crashes involving ADS-equipped vehicles are overrepresented on curves with no signing or pavement markings (or degraded signs and pavement markings), then this could be identified as a factor that increases the risk of ADS-related crashes. Once contributing factors are identified, agencies could search for similar locations (e.g., curves with absent or degraded signs or pavement markings) and address the factors accordingly (e.g., enhance signing and pavement markings or implement a new strategy that would satisfy the needs of the ADS technology).

2: Diagnosis

Diagnosis is the process of further investigating the opportunities (e.g., sites or risk factors) identified in Step 1 (network screening). The objective of diagnosis is to identify existing and potential safety opportunities. Diagnosis often involves a review of the crash history, traffic operations, and general site conditions as well as a field visit to observe road-user behaviors (including behaviors of ADS-equipped vehicles). It is important to consider contributing factors related to the road user, vehicle, roadway, and environment during diagnosis. It is also important to diagnose the underlying crash contributing factors before developing potential countermeasures.

One tool to support this process is the Haddon Matrix. The Haddon Matrix, originally developed for injury prevention, is also directly applicable to highway safety in both diagnosis and countermeasure selection (Haddon, 1972). For diagnosis, the Haddon Matrix is useful in gaining a comprehensive understanding of the human, vehicle, roadway, and environmental factors contributing to the frequency and severity of crashes before, during, and after the crash event. Then analysts can identify targeted reactive and proactive countermeasures to address or mitigate the underlying contributing factors.

The Haddon Matrix is typically composed of nine cells to identify human, vehicle, and roadway factors contributing to the target crash type or severity outcome before, during, and after the crash. This can be expanded to 12 cells to include environmental factors as another column, or these factors could be included with the roadway factors. Table 1 presents an example of the Haddon Matrix with 12 cells to identify crash contributing factors.

The contributing factors originate from careful review of police crash reports, review of design drawings and traffic operations, and observations during field investigations. Examples of human factors include distraction, fatigue, and seat belt use. Examples of vehicle factors include worn brakes, headrest design, and airbag operation. With ADS-equipped vehicles, vehicle factors might also include some failure of the ADS technology. Examples of roadway factors include sharp curve, lack of curve signing, and steep grade. With ADS-equipped vehicles, roadway factors might also include the degraded quality of signs and pavement markings that are no longer detectable by the ADS. Examples of environmental factors include reduced pavement friction (e.g., wet or icy roads) and weather-limiting visibility (e.g., snow, fog, heavy rain). These factors would also apply to ADS-equipped vehicles.

3: Countermeasure Selection

Countermeasure selection is the process of identifying and assessing ways to address or mitigate the underlying contributing factors identified in Step 2 (diagnosis). Countermeasures should directly target the contributing factors, and may include engineering, education, enforcement, and emergency medical service-related measures (i.e., the 4E approach). Several resources are available to help in selecting appropriate countermeasures, but they will need to be updated to reflect strategies for addressing ADS-related crashes.

When selecting countermeasures for crashes involving traditional (non-ADS) vehicles, there is a need to consider the potential impacts on ADS-equipped vehicles. For example, stop ahead warning signs and pavement markings are one strategy to improve driver awareness of an approaching stop condition. Would this be expected to have a safety benefit, disbenefit, or no benefit for ADS-equipped vehicles? The likely answer is, "It depends." Specifically, it depends on the ability and reliability of the ADS to detect and correctly interpret the meaning of the sign or pavement marking. If the ADS can perform this task reliably, then it may provide a benefit. If the ADS interprets the symbol for the stop ahead sign (Figure 2) as an actual stop sign, and performs a stop maneuver, then this could lead to a safety disbenefit (e.g., rear-end crashes if other drivers are not expecting the vehicle to stop at that location). If the ADS is preprogrammed with high-fidelity maps of the roadway segments and intersections, then the sign may provide no additional benefit as the ADS already "knows" of the approaching intersection.

Table 1. Twelve-cell Haddon Matrix template.

Period	Human Factors	Vehicle Factors	Roadway Factors	Environmental Factors
Before (causes of hazardous situation)				
During (causes of crash severity)				
After (factors of crash outcome)				

Figure 2. Examples of stop ahead signs (Source: VHB).

4: Economic Appraisal

Economic appraisal is the process of comparing the relative costs and benefits of the various alternatives. It is often not feasible or practical to implement all of the identified countermeasures. As such, it is necessary to estimate the cost and expected benefits of each potential countermeasure. The cost of projects is usually straightforward, but estimating the potential safety benefits is a new component of the data-driven and quantitative safety management process. The *Highway Safety Manual* (HSM) presents a predictive method to estimate the safety performance of a roadway facility under different conditions. Crash modification factors (CMFs) can be used in the predictive method to estimate the expected change in crashes after the implementation of a given countermeasure. The CMF Clearinghouse (www.cmfclearinghouse.org) is the primary source of CMFs, including those presented in the HSM. As ADS-equipped vehicles become more prevalent, the safety impact of common countermeasures may change. For example, widening the clear zone along the roadside may not have as great of an impact if there are fewer roadway departures as a result of lane-keeping technologies. In the future, CMFs will need to be updated to reflect the safety impact of a given countermeasure, considering the penetration rate of ADS-equipped vehicles in the fleet. Below, the “Project Development Process” section discusses the predictive method and opportunities to assess the impacts of ADS.

5: Project Prioritization

Project prioritization is the process of developing a portfolio of projects for a given fiscal year. The final choice of projects is based on the available budget as well as other factors such as agency goals, political pressure, and public acceptance. Project prioritization should consider the safety benefits (and benefits of other factors) under different ADS deployment scenarios. For example, adding a dedicated lane for trucks may seem like a good investment to improve safety and mobility assuming the current vehicle fleet; however, automated trucks that can operate in mixed traffic lanes may provide similar benefits without the need for an added lane.

Project Development Process

The project development process is broader than the safety management process, but the two are related. Figure 3 (Gross et al., 2021) illustrates the relation between the two, whereby the six-step safety management process is condensed to three basic components: planning (which includes Steps 1 through 5 of the safety management process), implementation (which includes the design and construction or implementation of projects), and evaluation (which is Step 6 of the safety

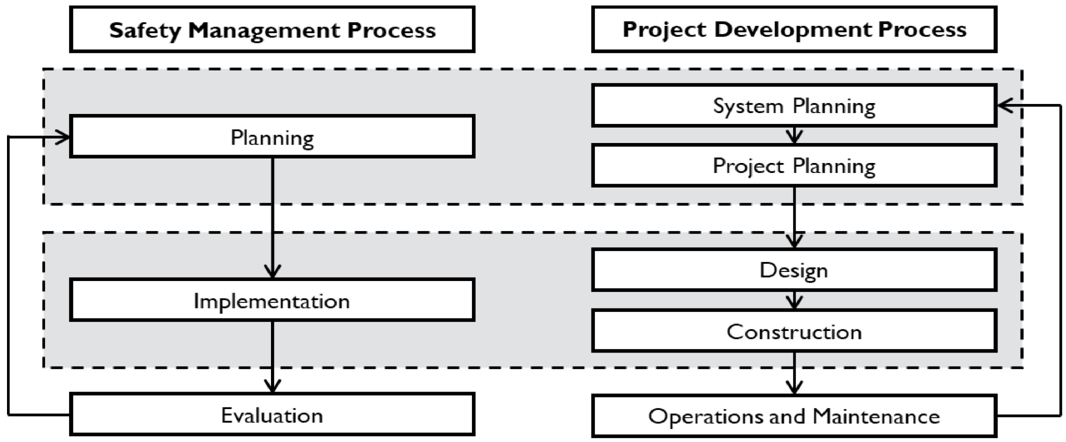


Figure 3. Relation between safety management and project development processes (Source: FHWA).

management process). Once an agency plans projects and allocates resources to implement them, the project (safety-focused or otherwise) enters the broader project development process.

Every phase of the project development process has potential impacts on safety performance. For example, during the planning phase, an agency might consider high-level alternatives such as different roadway cross sections (six-lane undivided, six-lane median-divided, or five-lane with two-way left-turn lane). During the design phase, an agency might consider the detailed aspects of one or more alternatives, including the lane and shoulder width, median width, presence and length of turn lanes, and presence and placement of signs and markings. Agencies can use the HSM and safety analysis tools, such as the Interactive Highway Safety Design Model (IHSDM) and AASHTO Ware Safety Analyst™, to assess the safety performance during the planning, design, and operations stages of a project. Specifically, the HSM provides a predictive method to estimate the frequency and severity of crashes based on the design and operations of the facility of interest. Refer to "Evaluation Method" in Chapter 3 for more details on the potential use of IHSDM. Chapter 4 provides a proof of concept that demonstrates the use of IHSDM in the framework.

While the HSM and related tools provide equations to predict crashes, these equations are based on data prior to 2010 and do not capture the impacts of ADS. The predictive methods can also incorporate historical crashes as a part of the prediction. Again, the historical crash data reflect a fleet of traditional vehicles with limited ADS features. With the widespread deployment of ADS, the existing models for predicting crashes may not be accurate and relevant for predicting future crashes under different ADS deployment scenarios. The predictive methods will need to be updated or calibrated to reflect different deployment scenarios with data or assumptions that represent the safety impacts of ADS-equipped vehicles. Until then, the framework presented in this report can serve as a planning-level tool to help estimate the potential safety performance of ADS under different scenarios and inform related infrastructure investment decisions by IOOs.

6: Safety Effectiveness Evaluation

Safety effectiveness evaluation is the process of estimating the safety impacts of implemented projects. This is the final step of the safety management process but provides a critical feedback link for future planning. Evaluation can and should be conducted at various levels.

1. **Program Level:** The objective of program evaluation is to determine the effectiveness of the overall safety program. The primary performance measures are the number and rate of crashes, injuries, and fatalities on the network. Program evaluation may also include the

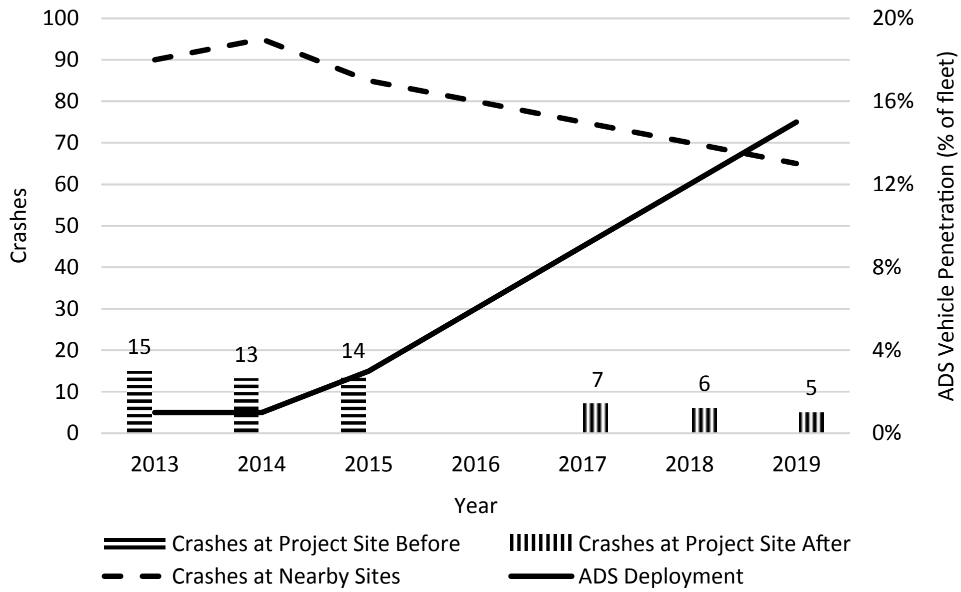


Figure 4. Hypothetical safety evaluation (Source: VHB).

assessment of specific programs such as intersection safety, roadway departure, and pedestrian safety. If the agency is targeting roadway departure crashes, then it might be appropriate to compare the number and cost of related safety improvement projects each year to the number and trend in roadway departure crashes, injuries, and fatalities.

2. **Project Level:** The objective of project evaluation is to determine the effectiveness of individual projects or groups of similar projects. For example, the agency may have installed rumble strips on several sections of two-lane roads. A project-level evaluation could be conducted to determine the safety impacts of each individual rumble strip project. These projects could also be combined to determine the average impact of rumble strips on two-lane roads. This is how CMFs are developed.

Regardless of the level of evaluation, it is important to account for other factors that change over time and could impact safety. For example, if ADS-equipped vehicles are becoming more prevalent and improving safety in general, then it would be important to account for this effect during the evaluation. Figure 4 illustrates a typical project evaluation and a hypothetical ADS effect that should be considered. If analysts only focus on the change in crashes before and after the project, they might erroneously conclude that the project was successful in improving safety at the project site. By considering the background trendline in ADS deployment and the corresponding trendline in crashes at other nearby locations, it may be more accurate to conclude that the safety improvement at the project site could be due, at least in part, to ADS deployment.

Map Crash Data to ADS Functionality

Specific ADS functionalities can be linked to increases or decreases of certain crash types. Crash likelihood and severity are expected to decrease; however, crash populations will change as ADS behaves differently than humans behave. These relationships between crashes and ADS functionality need to be identified in order to identify ADS impacts on safety, assess ADS performance, and inform future investment decisions.

ADS-equipped vehicles are thought to be safer than non-ADS-equipped vehicles, but this has not been rigorously assessed and uncertainty remains. Further, ADS technologies may be limited to operation in specific operational design domains (ODDs) and may target specific crash types. As such, we need to consider the crash types and contributing factors that could be addressed by each ADS technology, individually and in combination, within the facility types where the technology is most likely to operate and under different deployment scenarios.

Table 2 indicates potential crash types impacted by different ADAS features and the expected direction of effect (i.e., downward arrow indicates expected reduction and upward arrow indicates expected increase). These potential impacts are based on a single ADAS feature in the vehicle and are not based on a suite of ADAS features. They are potentially indicative of ADS safety performance. In some cases, ADAS features may be equipped and operated on ADS-equipped vehicles, so the safety benefits for an individual ADS feature may be difficult to determine directly. For example, lane-keeping assist is expected to reduce the frequency of roadway departure crashes. In some cases, the ADS technology could reduce certain crash types while potentially increasing others. For example, automatic emergency braking is expected to reduce rear-end crashes where the trailing vehicle is ADS-equipped but could increase rear-end crashes where the lead vehicle is ADS equipped and the trailing vehicle is not. In other cases, the ADS technology may only apply to certain vehicle types. For example, if autopilot is employed in a fleet of heavy trucks (i.e., ADS-equipped trucks), then the impact on crash types would include the subset of respective truck-related crashes. Note the information in Table 2 is based on current knowledge of ADS feature capabilities and judgment of the expected effects. This should be verified through pilots and supported by more empirical evidence. As more definitive research is conducted to quantify the relationships between ADS technologies and crash types or crash contributing factors, the information in this table should be updated.

Table 2 does not explicitly address crash severity; however, the severity of a crash is related to the type of crash. Crashes involving higher speeds, high angles of impact, and more vulnerable road users are more likely to result in higher severity. The ADS technologies that are expected to reduce impact speeds, impact angles, and crashes with vulnerable road users will likely also

Table 2. Potential safety impacts of ADAS features.

ADAS Technology	RE	RA	SS	HO	ROR	PED	B	A	P
Active park assist	—	—	—	—	—	↓	—	—	↓
Adaptive cruise control (ACC)	↓	—	—	—	—	—	—	—	—
Coordinated ACC	↓	—	—	—	—	—	—	—	—
Automatic emergency braking	↓↑	↓	—	↓	—	↓↑	↓↑	↓↑	↓↑
Autopilot	↓	↓	↓	↓	↓	↓	↓	↓	↓
Forward collision warning	↓↑	—	—	↓	—	↓	↓	↓	—
Lane-keeping assist	—	—	↓	↓	↓	—	↓	—	—
Eco-approach/eco-departure	↓↑	↓↑	—	—	—	↓↑	—	—	—
Lane change warning	—	—	↓	—	—	—	↓	—	—
Blind spot monitoring	—	—	↓	—	—	↓	↓	—	—
Backup warning	—	—	—	—	—	↓	↓	—	↓

Notes:

- **RE = rear-end, RA = right angle, SS = sideswipe, HO = head-on, ROR = run-off-road, PED = pedestrian, B = bike, A = animal, and P = parking.**
- **— indicates no expected impact, ↓ indicates an expected reduction in the crash type, and ↑ indicates an expected increase in the crash type.**

reduce the severity of those crashes as well. For example, automatic emergency braking, autopilot, forward collision warning, and lane-keeping assist are associated with some of the more severe crash types (e.g., right-angle, head-on, run-off-road, pedestrian, and bicycle) and are therefore expected to reduce crash severity. Severity is also related to the age and frailty of the people involved in the crash and the vehicle safety rating. This will not necessarily have a disproportionate impact on crash types but could disproportionately impact safety for different driver populations. If higher-income families are more likely to own ADS-equipped vehicles, then these populations might recognize the greatest benefit.

Beyond crash severity, ADS technologies may not operate in certain conditions (e.g., facility types or weather conditions). The information in Table 2 reflects the ideal conditions but does not indicate the performance and potential ineffectiveness of ADS technologies in certain conditions. The next section, "ADS Performance," provides more context in terms of the factors that may affect performance and could be used to identify subsets of crashes that are most applicable (or not applicable) to the specific technology. For example, lane-keeping assist is expected to reduce sideswipe, head-on, run-off-road, and bicycle crashes; however, if the technology does not work well in heavy rain or snow, then it would not have the potential to reduce crashes in those conditions. As such, the potential crash population would be a subset of sideswipe, head-on, run-off-road, and bicycle crashes (e.g., crashes in clear weather).

ADS Performance

ADS encapsulates hardware and software to perform the dynamic driving task (DDT). ADS uses a variety of sensor components and software to sense, model, plan, and act to operate an automobile with no input from the driver. This complex combination of activities to control the vehicle is performed by electronics and machinery that process inputs and control braking, acceleration, steering, and signaling instead of a human driver. As depicted in Figure 5, the SAE International standard defines six levels of driving automation (J3016). This standard has been adopted by the National Highway Traffic Safety Administration (SAE, 2018).

ADS specifically includes Levels 3, 4, and 5 where Levels 3 and 4 are defined by an ODD. The ODD defines the operating conditions under which the ADS (system or feature) is designed to function and includes environmental, geographical, and time-of-day restrictions and/or the requisite presence or absence of certain traffic or roadway characteristics. ODD is typically defined by the ADS technology developer and original equipment manufacturer (OEM). The ODD would vary based on the ADS feature, maturity of technology, and readiness of infrastructure (degraded signs or pavement markings).

DDT fallback occurs when the ADS is unable to continue to perform the entire DDT (i.e., under normal operating conditions), For Level 3 ADS features, the human fallback-ready user is expected to respond to a request to intervene by either resuming manual driving if the vehicle remains drivable or achieving a minimal risk condition if the vehicle is not drivable. For a Level 4 or 5 ADS, the ADS feature or system performs the fallback by automatically achieving a minimal risk condition (SAE, 2018). For instance, if a Level 4 ADS feature is designed to operate a vehicle at high speeds on freeways and experiences a DDT performance-relevant system failure, then it would automatically remove the vehicle from active lanes and stop on the shoulder of the road.

In Level 3 ADS features, drivers are no longer required to keep their hands on the steering wheel or continuously monitor the vehicle and the road. However, they must be alert and prepared to take over the task of driving when the system prompts them to do so. The literature review on human interactions during emergency takeover request indicates that the driver is susceptible to delayed decision-making following a warning for transition of control. Since the race of ADS

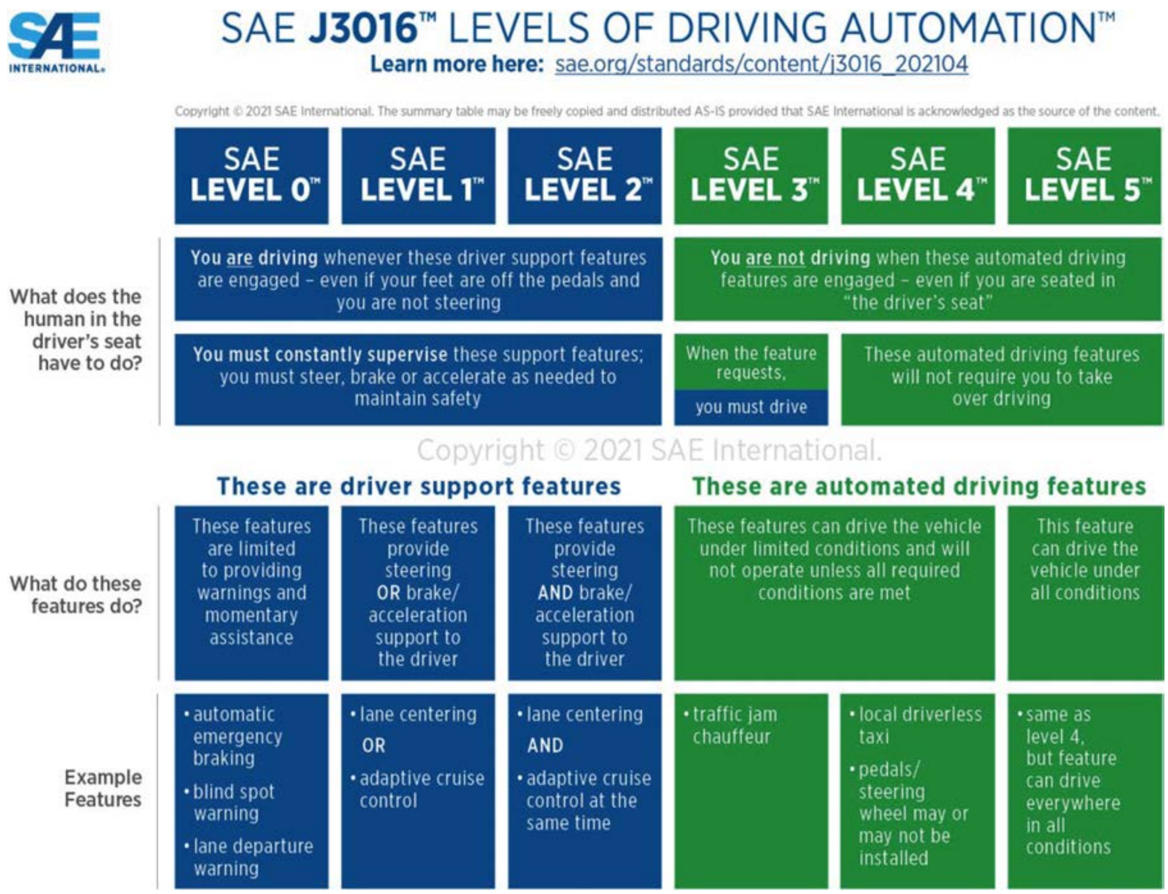


Figure 5. SAE International automation levels with operational design domain (Source: SAE International).

technology began, concerns have risen about the Level 3 automation. Specifically, it is expected that this level will have problems related to delineation in responsibility.

For instance, Tesla's Autopilot and General Motors' Super Cruise are both Level 2 features that are offered in the market today, and it is clear that for these features the driver remains responsible for all driving tasks. In the Level 4 ADS features, responsibility is also clear: the drivers should have zero liability as long as the vehicle is within the specified ODD. Now, considering the Level 3 ADS feature, the situation is more complicated since the responsibility can be exchanged between human and ADS machine since humans are still required in case the system encounters a situation it cannot handle. Expectations of full and complete attentiveness of the driver in this model are unlikely. Several car manufacturers (including Volvo, Ford, and Google, among others) expected the safety and policy concerns associated with this level and decided to skip it and jump directly to full automation vehicles (Levels 4 and 5).

CHAPTER 3

Overview of the Framework Elements

The framework will help state and local agencies follow a systematic methodology to assess the impact of specific automated driving system (ADS) applications on transportation safety. The steps and key elements of the framework are provided in Figure 6.

As shown in Figure 6, the framework starts with identifying the ADS features that agencies would like to assess. The second step is to understand different aspects of the ADS feature such as functionality and expected market penetration rates. The developer describes the route and physical and environmental boundaries within which a particular function is designed to work. In other words, the developer specifies the operational design domain (ODD) of the feature. This ODD defines the deployment scenarios in the third step. Once the deployment scenarios are

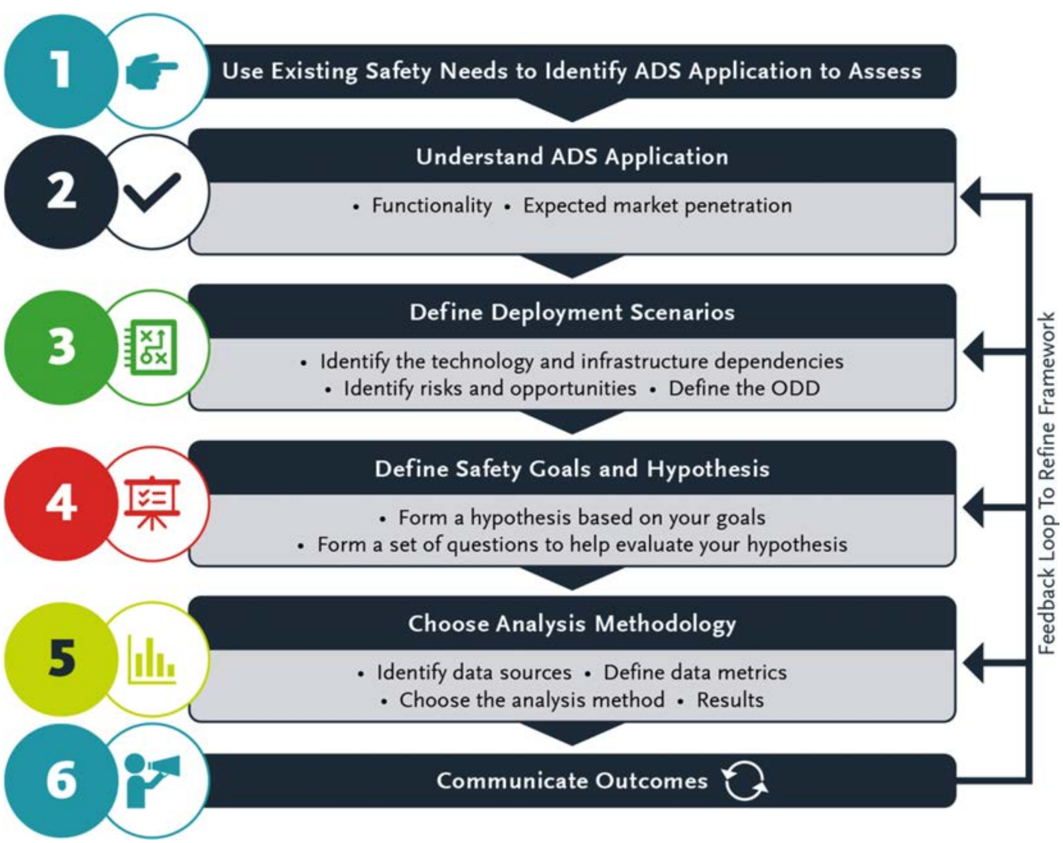


Figure 6. Framework to assess safety impact of ADS (Source: Booz Allen).

defined, it is important to understand the technology and infrastructure dependencies. This helps to understand the risks and opportunities involved. With the scenarios identified, the fourth step is to define safety goals and the associated hypotheses. Step 5 involves identifying data sources and data metrics to help evaluate the stated hypotheses. The analysis method is also chosen during this step to derive insights from the data.

It is important that the framework inherits feedback loops so that it can be refined as new information becomes available and technology advances. The framework should also follow an iterative approach as safety goals, questions, and hypotheses could change throughout the project. To this end, the framework could go through iterations of refinement or feedback loops, as shown in Figure 6. The input for refining the framework depends on the output of Steps 5 and 6. These refinement iterations entail updating the framework at Steps 2, 3, 4, or 5—and consequent steps—depending on the type of new information. For instance, if new information became available regarding the expected market of an ADS feature, the refinement would include Step 2 and all consequent steps. However, if new advances in the ADS technology occurred and were anticipated to expand the feature's ODD, the framework should be updated at Step 3 and all following steps.

Finally, upon completion of Step 5, the results are communicated to internal and external stakeholders involved in the connected and automated vehicle ecosystem. It is important to share the safety impact of the ADS feature with all involved stakeholders and obtain feedback as much as possible to support decision-making.

Step 1—Select ADS Feature to Assess

Today, both technology companies and automotive manufacturers are investing heavily to develop automated features for vehicles. These technologies are expected to help transportation system users meet their needs and help agencies achieve their goals. The ADS performs the dynamic driving task (DDT) instead of a human and can reduce human error to improve safety. The driver can focus on other activities during commutes. These automated vehicle (AV) technologies are advancing every day and continue to transform the transportation landscape. A wide range of entities in both the public and private sectors are playing instrumental roles in advancing and implementing AV technologies, including transportation agencies, technology firms and service providers, major automakers, and research organizations. With AV technologies on the rise, state and local infrastructure owners and operators (IOOs) are seeking new approaches to designing, constructing, operating, and maintaining highway infrastructure. A variety of ADS features are out in the market to help meet user needs and to improve safety in the transportation network. IOOs may first identify and select the ADS feature of interest and understand its functionality and potential market penetration rates before going in depth to assess its safety impact. The framework provides the flexibility to assess one ADS feature at a time, or multiple ADS features together, to estimate the combined safety performance.

To identify and select ADS features for safety analysis, IOOs can evaluate their local transportation environment, including user needs and local trends, state and municipal policy and regulations, development and population densities, and local service providers. All of these factors will determine which ADS features enter the market. Stakeholder engagement throughout this step can be beneficial and may help to understand better public opinion, perception, and preference. ADS features in public transportation will likely disrupt urban markets while single-passenger vehicle ADS features will likely be prevalent in commuting suburban communities. Practitioners should take care in evaluating relevant features to maximize both safety and mobility benefits of ADS.

Step 2—Understand the ADS Feature

Description of ADS Feature

The best sources for understanding the functionality of the ADS feature are the original equipment manufacturer's user manuals and online technology reviews. These sources not only provide a high-level description of the feature's functions but can help provide context in terms of technology and infrastructure dependencies. Manuals will help IOOs understand the ODD and assist with defining deployment scenarios. By understanding the ADS feature performance, for example, by sensor suite, IOOs are able to derive performance capability of incoming ADS and validate infrastructure requirement gaps to accommodate minimal thresholds of sensors. For example, if a Level 2 vehicle is equipped only with cameras and radar, then the IOO in question may want to understand the perception capability of the known equipment and identify whether both a human user and Level 2 vehicle can properly identify and react to roadway signs or markings.

Expected Market

Individual ADS features are unique, with disruption rates varying by location and transportation market segment. Understanding penetration trends in specific deployment contexts is helpful to estimate scale and timeframe of safety impacts in an area.

Assessing how the technology will deploy over time is imperative for practitioners because impacts are often not linear with market penetration rate. ADS adoption will likely be uneven, both geographically and temporally, and individual jurisdictions may experience both extremes (i.e., highly automated vehicle fleets in one community and mostly traditional vehicles in another) in the adoption of ADS simultaneously. The uneven geographic deployments could be attributed to the geographical inconsistencies of many factors—at state and local levels—including customer acceptance, willingness to pay, policy and regulation, and willingness to share. Furthermore, this multispeed adoption scenario will affect interagency planning, particularly as funding at a state level is allocated to local priorities.

Envisioned ADS Market, Fleet, and Vehicle Miles Traveled (VMT)

The deployment future of ADS technology or automation level is speculative and typically could follow one of two principal scenarios, namely, low and high disruption scenarios. Accordingly, to account for more realistic scenario planning, this framework predicts two principal timelines—low- and high-disruption scenarios—for the deployment of ADS-equipped vehicles. The key assumptions for these scenarios are outlined in Table 3 (McKinsey & Company, 2016).

For the reasonable evaluation and selection of the scenarios, the penetration rates of ADS-equipped vehicles were forecasted for a 10-year period. This range was based on the current

Table 3. Factors considered in the disruption scenarios.

Factors	High Disruption	Low Disruption
Pace for addressing regulatory challenges	Quick	Slow
Customer acceptance	Enthusiastic	Limited
Willingness to pay	Enthusiastic	Limited
Willingness to share trips	Enthusiastic	Limited
ADS penetration	More	Less

Table 4. ADS-equipped vehicles market penetration and fleet proportion predictions.

Year	High Disruption			Low Disruption		
	Market Share	Fleet Share	VMT Share	Market Share	Fleet Share	VMT Share
2020	1%	<1%	1%	0%	0%	0%
2025	10%	7%	10%	2%	1%	1%
2030	30%	14%	22%	6%	3%	4%

understanding of the rapid advancement of technologies focused on Level 3 and 4 vehicle technologies that directly affect stakeholders. The predictions were extrapolated for both the high- and low-disruption scenarios. Also, a saturation penetration rate of about 29% was assumed, based on surveys of customers' willingness to pay discussed in Appendix A (Mosquet et al., 2015). This saturation value was used as a cap for expected market penetration of the pertinent features over the next 10 to 15 years. The proportion of shared highly automated vehicle (HAV) forecasts and the predictions from the McKinsey study (McKinsey & Company, 2016; Litman, 2019) were used to raise the predictions for the ADS-equipped vehicles at 2030. In this study, the price after launch was assumed to decrease by a compound annual rate of 4% for Level 3 and Level 4 features. Finally, recent reports and market forecasts specific to ADS features were used to scale the prediction values to be as consistent as possible with recent data. Table 4 outlines the envisioned ADS-equipped vehicles market and fleet shares and their proportion.

More details about the statistics and numbers used to obtain these predictions can be found in Appendix A.

Step 3—Define Deployment Scenarios

Deployment scenarios ground the analysis in theory but incorporate realistic timelines that feature potential technical solutions situated within local context. These scenarios serve as the basis for identifying risks and opportunities for ADS technologies. The deployment of ADS technology may take many forms and occur on different timelines depending on a number of factors. This step helps to understand the potential technical solutions and deployment factors and how they relate to user needs and agency goals and processes. Specifically, Step 3 defines the penetration rate, ODD, and limitations of the ADS, which in turn help to identify the potential crashes impacted by ADS. For example, the ODD defines the geographic extent of crashes that could be impacted by the ADS (i.e., the ADS can impact only crashes on facilities over which it operates). The following subsections describe the use of penetration rates, ODD, and limitations of ADS in defining the deployment scenario.

ADS Penetration Rates

Having an estimate of the market penetration rates of ADS-equipped vehicles—and their equivalent proportion of the fleet—is an indispensable element of any planning effort for this technology. Benefits and disbenefits of ADS can vary significantly depending on the proportion of ADS within the ODD. In other words, when both deployment rates of supporting infrastructure and penetration rates of ADS are high, the impacts may be more visible and quantifiable. Depending on the type of investment in the infrastructure, the envisioned benefits are expected to vary significantly based on the expected penetration rate of ADS technology.

On the other hand, the future of the deployment rate of the ADS is speculative and could follow diverse scenarios since it hinges on several interrelated factors, such as reliability of technology, regulatory challenges, and consumer acceptance and willingness to pay. For instance, technology innovations in this area would continuously supersede first-generation technologies by more advanced systems. In such cases, the suitability of ODDs may change and enable more expansive domains (such as active operations in work zones or adverse weather), which may affect the ADS deployment rate.

To account for such a speculative future, state and local agencies typically follow a scenario planning approach to define the set of possible futures and corresponding policy responses that support the community vision and goals. In this approach, planners typically envision multiple scenarios with different assumptions regarding factors such as reliability of technology, regulatory challenges, consumer acceptance and willingness to pay, and private ADS ownership, among others. As a result, this framework first analyzes a synthesis of published reports (both manufacturer-specific and industry) introducing timelines for various levels of automation and forecasted market trends for various ADS features for the next 10 years, and the underlying assumptions. On the basis of this analysis, the framework proposes realistic estimates for the envisioned market penetration. Then, from these estimates, the framework suggests a set of realistic scenarios for the different imminent ADS features and possible futures.

Operational Design Domains

Identifying the ODD of ADS features helps provide a better understanding of how ADS features interact with and rely on various infrastructure elements. While technology companies continue to research and develop ADS technologies, IOOs might consider activities that aid the deployment of such technologies. For example, IOOs may look to modify or update infrastructure design standards and/or policies, maintenance and operations practices, and planning processes. As IOOs make investment decisions that affect these activities, an understanding of the most likely ODDs and their impact on infrastructure will help them prioritize among locations, infrastructure elements, and roadway types.

The identified ADS features cover a broad range of ODDs (e.g., speed range, roadway type, weather, urban roads, and managed lanes) that are likely to impact physical infrastructure. Since these ADS features are likely, in the short to medium term, a realistic prediction, ODDs are key factors in developing realistic deployment scenarios.

If multiple ADS features are evaluated at once, it is necessary to identify the ODD of each ADS feature and determine if any ODD elements overlap. Clearly defining the ODD for each ADS feature can help determine appropriate data sources and evaluation methods that consider the combined impacts of all selected ADS features.

Specific data and corresponding standards may be needed for IOOs to consider when assessing scenarios. Table 5 suggests a notional approach to breaking down essential metrics IOOs need when evaluating deployment scenarios.

Risk Assessment

There are a variety of ADS technologies, and each varies in where and how it impacts safety. For example, a low-speed shuttle may positively impact pedestrian safety in a central business district, whereas an SAE Level 3 traffic jam assist feature operating in a dedicated lane will impact safety on arterials and highways. We need to understand the technical and human factors influencing safety. ADSs are projected to decrease incident likelihood and severity but will also change crash populations as ADS behaves differently than humans do. For example, testing and

Table 5. Notional data and policy standard assessed by ODD for ADS.

Infrastructure Assessment	Data Needed	Standard/Policy Supported	ADS ODD Covered
Accuracy of mapping services	Mapping (global positioning system) accuracy	Vehicle-to-everything (V2X) mapping standard	Densely populated urban area for obstacle detection and avoidance
Performance of ADS in predetermined roadway area	Perception sensor metrics (radar/lidar/ camera field of view ranges)	ISO 26262	Highways and arterials for ADAS features (lane-keeping assist, adaptive cruise control, etc.)
Data thresholds for vehicle-to-infrastructure equipment	Dedicated short-range communication data bus thresholds	V2X communication standards SAE J2945	Local roadways, densely populated urban areas

early deployments of ADS have revealed context-dependent challenges with perception systems in various environmental conditions (e.g., weather) and infrastructure conditions (e.g., lane marking reflectivity) that significantly impact performance.

These technologies are associated with various risks and opportunities based on the way they interact with travel behavior, legacy vehicles and infrastructure, and the pertaining human factors. To identify risks, one can consider the limitations of the technology. The following section presents a list of potential risks for Level 3 traffic jam assist (see Table 6). Chapter 4 presents potential risks for five specific ADS features. In addition, to identify opportunities, one can consider the crash types and road-user populations that the technology could impact. Refer to “Map Crash Data to ADS Functionality” in Chapter 2 for further discussion of the potential impacts of ADS by technology and crash type.

Example Deployment Scenario

The deployment scenario is defined by combining information on the penetration rate, ODD, and limitations of the ADS. Table 6 summarizes elements of an ADS scenario as an example.

Step 4—Defining Goals and Hypotheses

This section explains how to define goals and hypotheses at two levels: (1) the ADS level and (2) the agency level.

ADS-Level Goals and Hypotheses

At the ADS level, once a deployment scenario is established, the next step is to define the safety goals (i.e., desired outcomes) and hypotheses related to the specific scenario. Key components of the goal may include:

Objectives: The goal(s) should indicate the primary and secondary objectives of the ADS technology and the relation to safety. As stated previously, not all ADSs will have a primary goal of improving safety. For example, the primary goal of ADS technologies that support large-truck platooning may be to improve operational efficiency. A secondary goal may be

Table 6. Example deployment scenario categories and descriptions.

Scenario Category	Description
ADS feature(s)	Level 3 traffic jam assist
Deployment timeline and market **penetration**	Commercial availability of ADS features (e.g., Audi A8 Level 3 traffic jam assist available in 2018 in Europe), market penetration rate of Level 3 traffic jam assist to increase at 16% compound annual growth rate 2017–2025 according to a 2016 Roland Berger study.[1]
Deployment context (ODD)	The vehicle is on a highway or a multi-lane road with barrier between oncoming lanes and a structure along the edge like guard rails. Slow-moving, nose-to-tail traffic predominates in all neighboring lanes. The vehicle's own speed must not exceed 60 km/h (37.3 mph). No traffic lights or pedestrians may be present within the relevant viewing range of the vehicle's sensors.[2]
Risks	• Standards and practices for roadway planning, design, and operations: screenings, lane marking contrast, lighting strategies. • Human factors and road-user interactions: driver response to requests to intervene. • Road user behavior, as well as travel behavior: increase in lax or risky road-user behaviors as people become complacent. • Impacts of mixed modes, vehicle fleets, and different levels of autonomy: dedicated lanes or mixed. • Impacts on law enforcement and emergency response: enabling first responders to interact with ADS when securing a scene. • Communication between legacy and ADS-equipped vehicles (of various levels) and the infrastructure: architectures and standards. • Legislative and regulatory issues: required event data recorder data elements.
Opportunities	• Enabling pedestrians to be more noticeable to onboard sensors. • Education (e.g., for operators, police, vehicle dealers): new training programs and materials about technology and operational features. • Data (e.g., safety data, reporting, key performance indicators needed): post-crash investigations. • Digital infrastructure (e.g., cybersecurity, mapping, redundancy): work zone data exchange, information sharing and analysis centers.

[1]https://static.seekingalpha.com/uploads/sa_presentations/758/28758/original.pdf.
[2]https://www.audi-mediacenter.com/en/technology-lexicon-7180/driver-assistance-systems-7184.

to improve safety. If safety is not a primary or secondary goal, then the safety goal should be written as "the goal is to not degrade existing safety performance."

Operational design domains: The goal(s) should carry forward information from the deployment scenario to help define the target facility type(s) and area(s) of influence. Continuing with the previous example, the goal could be written as "reduce crashes on freeways" to clearly establish the ODD and potential area of impact. The same principles apply when assessing multiple ADSs at the same time with the added nuance to keep track of the applicable target facility type(s) and area(s) of influence by the ADS. This will support a more detailed analysis in later steps.

Target crashes: The goal(s) should indicate the specific safety performance measure to track progress. Safety performance is quantified by the expected number and severity of crashes, potentially by crash type. It could even be as specific as mitigating one or more precipitating events within a sequence of events that could lead to a crash. For example, the previous goal could be more specific by focusing on long-haul, truck-related crashes that are related to driver fatigue or distraction. When assessing multiple ADSs at the same time, the goals could be combined for the overall scenario or kept separate by ADS and ODD.

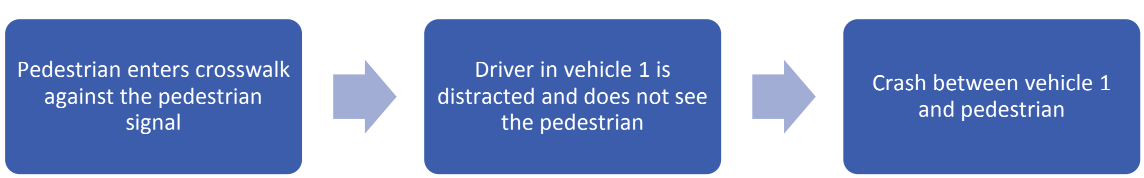
Quantifiable achievement: When possible, the goal(s) should include some measure or threshold to define success. Otherwise, it is difficult to know if and when success is achieved. Continuing with the example, the goal could establish a desired number or percent reduction for these crashes. If it is difficult to assign a value to the desired change in crashes (e.g., when actual or expected market penetration is unknown), then it will be useful to explore a range of scenarios through sensitivity analysis.

Expected timeline: Finally, the goal(s) should include a timeframe for achieving success. This is heavily dependent on the expected timeline for deployment and could include multiple timeframes, depending on the certainty in deployment and penetration rates.

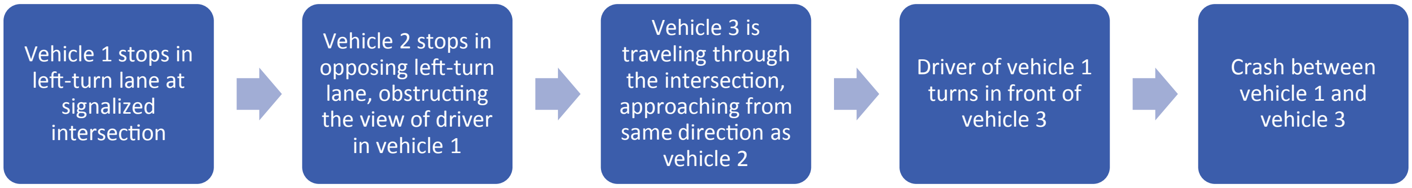
With an overall goal in mind, it will be possible to develop hypotheses to test in support of the goal. The hypotheses should help to uncover potential differential impacts on safety. For example, some ADS technologies could mitigate certain crash types and severities while increasing the risk of others. This is particularly important when assessing multiple ADSs simultaneously in the same ODD. A series of questions may be appropriate to help evaluate the hypotheses, especially in cases when the expected outcomes are less clear. This prevents the study from oversimplifying and categorizing results in totality as all good or all bad. For example, the goal of a low-speed shuttle pilot may include improving safety and mobility. The hypothesis may be stated as "The rate of vehicle collisions among travelers going to and from transit station X during the pilot is less than before." It is also important to ask related questions like "How did the injury and fatality rates from vehicle collisions change?" and "Did the rate of pedestrian and bicyclist collisions change, and to what extent did pedestrian and bicyclist injury and fatality rates change?" The series of questions could also include questions related to human behavior and human factors as many of the related safety relationships have not been quantified or are not well understood. Related questions may include "How does driver performance change over time as the proportion of ADS-operated vehicle-miles increases?" and "How do road-user behaviors change (e.g., increase in lax or risky road-user behavior) as the proportion of ADS-operated vehicle-miles increases?"

A crash sequencing exercise is also useful to think through the contributing factors and precipitating events that lead to a crash. This can help to identify the truly correctable crashes related to the ADS scenario of interest. Similar to the "before crash" row of the Haddon Matrix, mapping the crash sequence of events is an exercise of thinking through the timeline of events and factors that lead to a crash. The difference is that crash sequencing is focused on one crash or a specific type of crash. In the context of this framework, it is helpful to think of the potential interaction of the ADS feature(s). For each event in the sequence, ask if the ADS feature(s) could address the event and thereby mitigate the crash. The following are a few examples of crash sequences.

Example 1: sequence of events for vehicle-pedestrian crash at intersection:



Example 2: sequence of events for vehicle-vehicle crash at intersection:



Mapping the crash sequence is also useful for identifying potential increases in collisions with the introduction of ADS. The following is a continuation of the pedestrian crash example above but now considers an ADS scenario where vehicle 1 is equipped with forward collision warning but vehicle 2 is not. In this case, vehicle 1 is able to stop in time to avoid the collision with the pedestrian, but this creates another sequence in the chain of events as vehicle 2 is not able to stop, resulting in a rear-end collision.

Example 3: sequence of events for ADS-vehicle crash at intersection:

Agency-Level Goals and Hypotheses

Agencies set many goals that can range from high-level strategic goals down to highly specific and localized performance targets. These goals help capture transportation user needs and agency priorities that the agency hopes to achieve through specific actions or countermeasures (e.g., deployment of an ADS feature). At the agency level, all states have developed a Strategic Highway Safety Plan (SHSP). SHSPs establish statewide safety goals and identify specific emphasis areas and strategies that should combine to achieve this overarching goal. For example, Washington State established a goal of zero deaths and serious injuries. Washington also includes a detailed discussion of new technology and traffic safety in the SHSP. The plan recognizes technological advancements but does not quantify the potential impact of this technology on safety.

SHSPs can be used as a foundation or starting point to identify target safety goals. These plans can also help to identify the priority safety issues (emphasis areas) and indicate whether the state has identified ADS or related technologies as a strategy to address one or more emphasis areas. At the agency level, this framework can be adapted to test hypotheses related to the effectiveness of individual ADS technologies, the impacts of infrastructure and operations on ADS safety performance, and the potential contribution of ADS to statewide goals. This can help agencies to understand the potential contributions of ADS toward meeting the state's overall safety goals or the specific safety goals within an emphasis area.

Given that the goals are already established in the SHSP, the application of this framework becomes an exercise of defining and testing hypotheses. For example, the Washington State SHSP indicates that "the anticipated benefits of [autonomous] vehicles include decreased crashes, increased mobility, and an increase in fuel efficiency." The hypotheses to test are numerous, but one opportunity to focus the hypothesis testing is to develop hypotheses related to established emphasis areas. For example, Table 7 presents hypotheses related to common emphasis areas included in state SHSPs. While these hypotheses incorporate crash-based performance measures, it is also possible to develop hypotheses related to other performance metrics, such as those related to public health, human behavior, and human factors. For example, the last row in Table 7 relates to aggressive driving crashes, but one or more additional hypotheses could be developed to explore

Table 7. Specific hypotheses related to common SHSP emphasis areas.

Emphasis Area	Hypothesis
Lane departure	Will conditional automated highway drive reduce lane departure crashes?
Intersections	Will conditional traffic jam assist drive increase rear-end crashes between ADS-equipped and non-ADS-equipped vehicles?
Pedestrians	Will conditional automated highway drive reduce pedestrian crashes in urban areas?
Work zones	Will conditional automated highway drive increase work zone crashes where signing and markings are not clearly identifiable?
Aggressive driving	Will truck platooning increase aggressive driving crashes on freeways?

aggressive driving behaviors, which are a precursor to the crashes (e.g., will conditional traffic jam assist reduce driver frustration and erratic lane-change maneuvers?).

Finally, it is important to identify potential processes and procedures that could impact or be impacted by the goal in the presence of ADS. Table 8 provides example questions to help answer hypotheses for how changes in planning, design, and operations processes and procedures will impact safety goals. It is helpful to recognize that capabilities can vary across state and local agencies, and questions may accommodate the various levels of maturity. While SHSPs are a good starting point for identifying safety goals and developing hypotheses, it is important to consider other sources of safety goals, as shown in Table 8, since SHSPs are typically updated only every 5 years.

Step 5—Choose Method of Analysis

Among all benefit types, traffic safety is envisioned to be the major benefit of ADS technologies. Accordingly, the following subsections discuss the approach for estimating the safety benefits from an envisioned ADS feature.

Traffic Safety Impacts

Information about the benefit analysis for traffic safety savings is expressed in monetary value. This approach requires an estimate of the number of crashes avoided due to the adoption of ADS. The magnitude in traffic safety savings corresponds with the market penetration of ADS to the larger network. For instance, if ADS-equipped trucks represent 10% of the truck vehicle fleet, then it might be assumed that ADS-equipped trucks could mitigate approximately 10% of truck-related crashes. This assumes the ADS technologies work in 100% of crashes, which may not be a reasonable assumption. Thinking back to earlier steps, it is useful to narrow the population of crashes to "correctable crashes." This would include only those crashes within the ODD and those where the ADS feature(s) of interest could address specific events within the sequence of events that led to the crash.

The KABCO injury scale also can be used for establishing crash costs. This scale was developed by the National Safety Council (NSC) and is frequently used by law enforcement for classifying injuries:

- K—Fatal,
- A—Incapacitating injury,
- B—Non-incapacitating injury,
- C—Possible injury, and
- O—No injury.

Table 8. Example questions to test hypothesis.

Dimension	Example Processes and Procedures	Example Questions
Planning	• Strategic Highway Safety Plan (SHSP). • Regional intelligent transportation system (ITS) architecture. • ITS Strategic Plan. • Transit Safety Plan. • Nonmotorized (bicycle and pedestrian) plan. • Metropolitan transportation plan statewide and regional long-range transportation plan. • Public involvement plan and public participation plan. • Freight plans. • Financing plans. • Performance management targets.	• What types of trips and geographic areas will early ADS deployments favor? • How do we coordinate across the agency, state, and nation? • How do we balance capabilities in operations of ADS with safety? • What incremental strategies can we invest in now so that ADS will continue to provide benefits as the market grows? • What ADS market penetration do we need to evaluate and analyze operational benefits? • How do we manage expectations and not oversell capabilities?
Design	• Standards and best practices for infrastructure markings, signage, geometry, countermeasures, human factors (bike and pedestrian). • Technology choices, (e.g., materials, interoperability). • Vehicle-to-infrastructure equipment and standards. • Training, knowledge, information sharing. • Communications security and privacy policy.	• What are the safety impacts of design decisions (e.g., what is the difference in the expected safety performance of two viable designs that meet design standards)? • What are the safety impacts and mobility tradeoffs of different intersection traffic control alternatives (e.g., four-way stop-control, two-way stop-control, traffic signal, roundabout)? • What are the safety impacts of design variances and exceptions (e.g., what is the change in safety if a design element does not meet the related design standard)? • What are the safety impacts of implementing safety countermeasures to enhance safety performance at a given location? • Where can design standards be relaxed? • What skills and training are needed for staff, and what is the best delivery format for training?
Operations	• Traffic control device operation. • Access point management. • On-road ADS testing. • Emergency response procedures. • Law enforcement procedures. • Security processes and procedures. • Training, knowledge, information sharing.	• How will vehicles respond to dynamic conditions, (e.g., weather, work zones, and roadway lighting)? • What are the safety impacts and mobility tradeoffs of different traffic signal phasing alternatives (e.g., permitted versus protected left-turn phase)? • How to justify decisions to control or consolidate access points? • How do we leverage opportunities for multimodal benefit—including transit, traditional vehicles, pedestrians, bicyclists, fleets? • What do emergency medical services and law enforcement need to know to control and prepare for an emergency scene? • Will new types of risks be introduced such as limitations in technology, cybersecurity breaches, overreliance on technology that could affect the operations? • How do we embrace interoperability?

Table 9. Crash cost by injury severity level (FHWA's *Crash Cost for Highway Safety Analysis*).[1]

Severity Level	Crash Cost
Fatality (K)	$15,134,325
Disabling injury (A)	$851,749
Evident injury (B)	$282,550
Possible injury (C)	$163,792
Property damage only (O)	$16,175

[1]https://safety.fhwa.dot.gov/hsip/resources/fhwasa09029/sec4.cfm.

There are several sources of crash costs by severity level, including the *Highway Safety Manual* (HSM) and FHWA's *Crash Costs for Highway Safety Analysis* (Harmon et al., 2018). Both resources provide crash costs based on the KABCO scale, but the values in FHWA's *Crash Costs for Highway Safety Analysis* are based on more recent data and are shown in Table 9. If a state has not developed its own crash costs, these costs could be used to calculate safety benefits.

Analysts can use crash costs to convert expected ADS safety benefits into monetary terms as demonstrated in later sections. The sections below describe how to identify appropriate data sources, define metrics and evaluation criteria, and select an appropriate evaluation method to test the hypotheses developed in the previous step.

Define Data Sources

Several pilots are under way across the United States to explore the feasibility and challenges associated with different ADS applications. Still, there are limited ADS datasets that can directly help agencies understand expected safety performance under different ADS scenarios. With limited ADS safety data available, four data categories can prove useful: (1) traditional crash datasets, (2) traditional roadway datasets, (3) advanced safety datasets, and (4) ADS datasets.

Traditional Crash Datasets

Traditional crash datasets provide information on reported crashes, including the date and location of the crash, the type and severity of the crash, and crash contributing factors based on the reporter's investigation of the event. The crash contributing factors may include information on driver and other road-user behaviors, vehicle type and characteristics, roadway attributes, and environmental conditions. The specific variables, amount of detail, and level of accuracy vary by dataset. The following are some of the primary opportunities to use traditional datasets in assessing the safety impacts of ADS.

1. **Establish baseline safety performance for traditional vehicle fleet:** In scenario planning and alternatives analysis, the future performance for the do-nothing scenario is estimated. In this case, traditional crash datasets help quantify and assess the safety performance of traditional vehicles and identify the conditions under which crashes are occurring.
2. **Estimate change in number, type, and severity of crashes under different ADS scenarios:** Traditional crash datasets include information on the number, type, and severity of crashes. If the relationships between the presence of a given ADS technology and the probability of

different crash types are known (or assumed), then these datasets can be used to quantify the number of crashes by type and severity that could be impacted by the various ADS technologies under different deployment scenarios.

3. **Understand crash contributing factors for crashes involving ADS-equipped vehicles:** Traditional crash datasets typically provide some level of detail on the vehicles involved, including the make, model, and year. Knowing the standard ADS features on specific vehicle types, the traditional safety datasets can be used to search for specific vehicle types and assess the factors involved in the crash. This could help identify factors that are common among crashes involving specific technologies. For example, are there common roadway or environmental conditions that are associated with the involvement of vehicles with certain ADS technologies? One limitation is that these datasets will not likely indicate if a vehicle has an aftermarket system or if the driver had turned off the ADS technology (if that is an option for the given technology).

Agencies may want to investigate human factors while analyzing crash contributing factors. These are factors that contribute to a crash and are directly attributable to the driver, such as inattention, distraction, fatigue, and impairment from drugs or alcohol. Human factors that apply to traditional vehicles may not apply to ADS; however, other human factor challenges may arise with greater ADS deployment. These human factors may include drivers' ability to take back control from ADS, legacy vehicle drivers' interaction with ADS-equipped vehicles, and other road users' ability to identify and interact with ADS.

Common datasets under this category include Fatality Analysis Reporting System (FARS), General Estimates System, Highway Safety Information System (HSIS) crash data, and state and local crash datasets.

For example, if the hypothesis is focused on fatal crashes, then the national FARS or the state crash database may be appropriate sources of data. If there is a need to focus on specific facility types and determine the roadway characteristics or average weather conditions, then there will be a need to merge data from other sources such as the state roadway inventory or the FHWA Weather Data Environment.

Traditional Roadway Datasets

Traditional crash data can be augmented with data describing the roadway characteristics at the site of a crash or across a given area or region. Numerous factors contribute to or are associated with the frequency of crashes, including behavioral, vehicular, and roadway characteristics. In many cases, a crash can result from several factors. Joining roadway datasets with crash datasets can maximize the coverage of these factors and provide a clearer picture of safety performance.

There are several potential applications of roadway datasets in estimating the safety impacts of ADS. Often, ADS technologies rely on camera sensors to detect roadway features such as lane striping or crosswalks to keep the vehicle in the correct position on the road. Rich roadway datasets could allow ADS companies and agencies to screen roadways and determine locations that would be candidates for ADS operation, or roadways that might not be desirable for ADS operation. Roadway datasets can also help to identify the population of current crashes that could be impacted. For example, by joining the crash and roadway data, it is possible to identify the number of crashes by crash type that are occurring on different roadways and at different roadway site types (e.g., intersections, horizontal curves, vertical curves). A generic assumption related to ADS might be that a technology will address all crashes of a certain type. However, if the roadway conditions do not allow that technology to operate properly, it is necessary to disaggregate ADS safety performance estimates with and without those conditions. Datasets under this category include Highway Performance Monitoring System, HSIS roadway data, and state and local roadway inventory files.

Advanced Safety Datasets

Advanced safety datasets, created for safety research, include Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS) dataset, SHRP2 Roadway Information Database, Motorcycle Crash Causation Study, Large Truck Crash Causation Study, and National Motor Vehicle Crash Causation Study.

ADS Datasets

The growing presence of ADS technologies and companies has led to the proliferation of datasets related to ADS testing and operation. Many of these datasets originated with companies working to develop ADS technology and train ADS in object identification and other skills. A large subset of these datasets is intended for use in training and benchmarking (i.e., conducting extensive testing to develop a standard for state of the practice). These datasets may provide insights into not only ADS safety performance with the DDT, but also interactions with humans. In addition to these training and benchmarking datasets, several public agencies have begun to implement data systems for addressing the growing ADS environment. They include Camera-Based Self-Driving Object-Detection Datasets, KITTI 3D Object Detection Dataset, nuScenes, Specialized Computer Training Benchmark Datasets, Waymo Open Dataset, Lyft Level 5 Dataset, California DMV Autonomous Vehicle Data, Colorado DOT Autonomous Vehicle Data, and Warrigal Dataset.

Define Metrics

It is essential to define metrics that appropriately capture the ideas presented in the hypotheses and questions. It is also important to note that some metrics, while theoretically computable, may not actually be producible with available data. Researchers are limited by data granularity and availability and may not be able to calculate all desired metrics. Analysts should start by defining preferred metrics and then assess the feasibility of computing those metrics. This is an important step because this process can reveal data gaps that can guide future data collection efforts and potentially be addressed in further research.

The metrics relate to the safety components that are the output of the analysis. Metrics may include safety outcomes, such as crashes, or predictive indicators, such as average time-to-collision violations at an intersection. Crash-based metrics can include a change in crash frequency and/or severity. If specific crash types are anticipated to be affected, they should also be stated as a part of the analysis metrics. The method for identifying the crashes or events of interest is important to state and describe. For example, the crashes of interest might be identified through categorizing and filtering the crashes based on the ODD and specific assumptions. The frequency of crashes can be measured based on occurrences normalized by an exposure metric, for example, crashes per pedestrian encounter. Crash types or situations that are exceedingly rare to experience, and therefore potentially challenging to identify or quantify, are commonly referred to as "edge cases." Other types of safety outcome metrics include public health indicators, such as travel impact assessment. For example, trip rate for persons with disabilities and economic value of those trips can serve as an indicator of societal impact from ADS deployment (Baker et al., 2017).

When assessing multiple ADS features at once, it is necessary to identify target crashes related to each ADS feature and identify any overlap between the target crash types within a given ODD.

This avoids double-counting crashes in the analysis. Potential safety benefits are not simply additive between the ADS features. Whether the ADS features are redundant, complementary, or contradictory should be considered If the ADS features are redundant (i.e., address the same crash type within the same ODD), then it is appropriate to consider the safety benefits of one of the ADS features (presumably the one with the greatest benefits). If the ADS features are complementary (i.e., address different crash types or the same crash types but in different ODDs), then it is appropriate to consider the safety benefits of both ADS features, ignoring any redundant effects. If the ADS features are contradictory (i.e., impact the same crash types in the same ODD but in opposite directions), then it is appropriate to consider the safety impacts of both ADS features; however, in this case, the impacts would offset to some extent. Figure 7 illustrates these scenarios.

Metrics related to human behavior and human factors also relate to safety and could be considered when assessing the safety performance of ADS features. While ADS features present a tremendous opportunity to improve safety, there is also the potential for challenges related to human factors and limitations of the technology. For example, ADS technology may not operate well in all road and weather conditions. If the human operator does not understand the limitations of the technology, there is the potential for an increased delay in responding to requests for manual takeover of vehicle control. Conversely, if the human operator understands the limitations of the technology (e.g., does not operate in rain or snow), then the human operator may be more alert and ready to take control if those conditions are expected along the route.

Cunningham and Regan (2015) indicate that drivers must understand the capabilities (and limitations) of ADS technologies and must maintain situational awareness to improve the chance of safe operation. They also discuss the following factors related to ADS technologies, which could be used to define related metrics:

Driver inattention and distraction: Driver inattention and distraction can pose issues when using ADS features. When cognitive workload is too low, which can occur when ADS features are engaged, drivers can experience passive fatigue (Desmond and Hancock, 2001), and drivers might engage in other tasks. This creates safety-related concerns for scenarios when a driver needs to take (or receive) control of the vehicle (Cunningham and Regan, 2015).

Situational awareness: When ADS features are engaged, drivers might pay attention somewhere else and engage in other tasks. In these situations, drivers may not be fully aware of the environment around them, including the vehicle and road (De Winter et al., 2014), which can lead to issues if the driver needs to take (or receive) control of the vehicle.

Overreliance and trust: When using ADS features, drivers might become over reliant on the features. Drivers may rely on the technology (Cunningham and Regan, 2015), but if the reliance is too high, drivers might assume the feature will alert them if something is wrong or if they need to take control when it might not (Parasuraman and Riley, 1997).

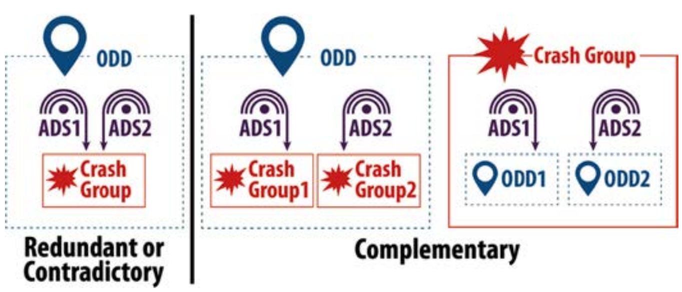


Figure 7. Examples of redundant, complementary, or contradictory ADS effects (Source: VHB).

Skill degradation: When drivers use ADS features frequently and do not use their own driving skills often, they might lose or diminish their driving skills (Parasuraman et al., 2000).

Motion sickness: The use of ADS features could also cause motion sickness to the driver or occupants of the vehicle. This is due to drivers losing control over the actions of the vehicle (Rolnick and Lubow, 1991) and losing awareness of what actions will be made next (Golding and Gresty, 2005).

Evaluation Method

The defined metrics are used with an evaluation method to estimate the safety impact of each ADS feature. The evaluation method needs to be stated and described. For example, if the evaluation method is a percent crash reduction using total crashes and the specific crashes expected to be impacted by an ADS feature, an equation for the percent crash reduction should be included in the evaluation method. The evaluation method can also be further disaggregated by specific crash type and severity levels. In addition, artificial intelligence/machine learning and big data solutions can help evaluate and parse large volumes of safety-related data (e.g., probe data, NDS data) efficiently.

The HSM is one opportunity to support the evaluation method. Specifically, Part C of the HSM provides a predictive method for several facility types. The predictive method allows analysts to estimate the number of crashes for alternative scenarios based on roadway and traffic characteristics. This is useful for establishing the safety performance for a base condition (e.g., existing conditions or future conditions with changes to the infrastructure or traffic volume). The analyst could use the predicted crashes for the base condition in conjunction with other methods to estimate the expected change in crashes assuming different ADS scenarios and penetration rates.

IHSDM is an advanced safety analysis tool that uses the HSM Part C predictive method to estimate the safety performance of existing and future conditions under the current vehicle fleet. Users can input roads and road networks into IHSDM to automatically analyze their safety performance. Figure 8 displays an example of a road network input into IHSDM, which includes road segments and intersections. Different road elements (e.g., roadway geometry or traffic conditions) can easily and quickly be adjusted (using the editor in Figure 9) to obtain new outputs and compare safety performance results. Users can change road and traffic characteristics to account for ADS features to obtain their potential safety impact prior to deploying an ADS feature.

While the predictive method in the HSM and associated safety analysis tools provide an opportunity to estimate the safety performance of specific roadway design and traffic operations scenarios, the methods were developed without capturing the impacts of ADS features. To differentiate the use of this framework, the primary use is for planning-level decisions that are more likely associated with Part B of the HSM. The evaluation method presented in this framework is not meant to replace the HSM predictive method, but over time, could provide valuable insights for updating or adjusting the HSM predictive method. For example, by tracking ADS implementations and evaluating the post implementation effectiveness of ADS, it might be possible to produce adjustment factors (or CMFs) that represent a change in crashes due to certain ADS features. The result from this framework could also be used in conjunction with the predictive method in the HSM to compare the safety performance associated with the different scenarios, including scenarios with different levels of ADS deployment.

The monetary value of ADS safety benefits would be the difference in estimated crash costs between the scenario with a specific ADS feature deployed versus the estimated crash costs without the ADS feature. The following equation can be used to identify the monetary value of

Figure 8. Example of road network in IHSDM (Source: IHSDM Project Output).

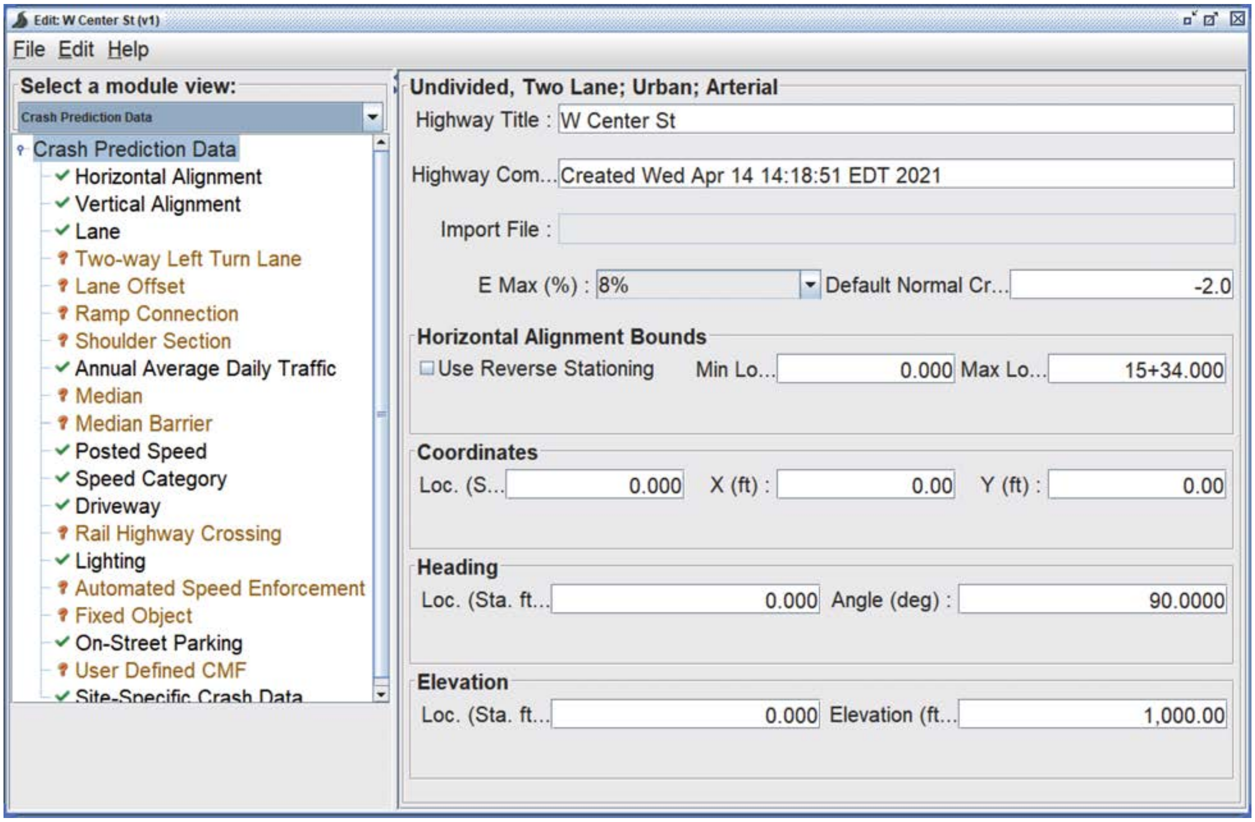


Figure 9. Example of IHSDM Highway Editor used to change road characteristics (Source: IHSDM Project Output).

crashes, for a particular ADS feature, as a function of crash severity type, ADS market penetration, corresponding crash cost, and CMF for ADS.

$$\text{Monetary value of crashes after } ADS\ deployment = \sum_{sev} N_{Crash} * MP_{ADS} * Cost_{sev} * CMF_{ADS} \qquad \textbf{Eq. 1}$$

where:

N_{Crash} = Total crash by severity type (crash count by type)
MP_{ADS} = ADS market penetration (decimal)
$Cost_{sev}$ = Monetary cost by severity type (dollar value)
CMF_{ADS} = Crash modification factor for ADS implementation (decimal)

CMF is defined in the HSM as a value that quantifies the expected change in crash frequency at a site as a result of implementing a specific countermeasure. Countermeasures can also be called "treatments" or "safety treatments." A CMF can estimate the expected change in crash frequency for total crashes, a particular crash type, or a particular severity.

CMF is expressed as the following:

$$CMF = \frac{Expected\ crash\ frequency\ with\ treatment}{Expected\ crash\ frequency\ without\ treatment} \qquad \textbf{Eq. 2}$$

Currently, there are no CMFs for ADS features; however, as demonstrated later in the framework (Chapter 4), state and local officials can apply their understanding of the ADS technology to historical crash data to estimate the number and types of crashes that could be mitigated by ADS. From these values, agencies could estimate a CMF for ADS.

Historical crash data broken down by severity type following the KABCO classification can be obtained from local and state law enforcement or transportation agencies. The data should be classified by annual occurrence to find the annual vehicle crash cost and savings. The crash savings can be expressed as the following equation:

$$ADS\ safety\ benefits = Crash\ cost\ without\ ADS\ deployment - Crash\ cost\ with\ ADS\ deployment \quad \textbf{Eq. 3}$$

For more information on converting crash-based estimates to monetary benefits, refer to FHWA's *Highway Safety Benefit-Cost Analysis* (Lawrence et al., 2018).

Results

The previously defined evaluation methods are used with the crash data to estimate the safety impact of the various ADS features. The results can be disaggregated by timeline (e.g., separate analysis for short- and medium-term timelines). Typically, the different timelines have different ODD elements and different VMT share. The results should highlight this difference, which also shows how the expected safety performance changes based on the timelines and if the ODD is expanded and VMT share changes.

A sensitivity analysis can be included in the analysis to estimate the potential range of safety impacts based on varying penetration levels, expected ADS effectiveness (and failure rates), and other assumptions. For instance, the sensitivity analysis can include different assumptions to estimate the safety impact of ADS features if the VMT share is not fully reached or to estimate the impact at different penetration levels. Similarly, the analyst can adjust the expected level of effectiveness (e.g., percent change in crashes) and potential failure rate of ADS to determine how these assumptions affect the results under different deployment scenarios. For example, it might be of interest to estimate the change in the number of crashes by severity assuming 100% effectiveness, 75% effectiveness, and 50% effectiveness. When the deployment scenario includes multiple ADS features, and these ADS features provide redundancy in terms of the target crashes, it may be appropriate to assume a higher level of confidence and higher percent effectiveness in the sensitivity analysis. Further, it may be appropriate to assume a higher percent effectiveness as the analysis focuses on specific crashes under specific conditions (i.e., those most likely corrected or mitigated by the particular ADS application). The sensitivity analysis can also help account for human behaviors and human factors (or related uncertainties) and the expected change in safety performance. Specific examples of human behavior and human factor considerations are discussed with respect to each ADS feature in Chapter 4.

The following paragraphs present an example analysis of potential fatalities mitigated with the implementation of low-speed ADS shuttles, at the national level, with mitigating fatalities. The US DOT maintains detailed fatality reports through the NHTSA FARS database. Table 10 shows a breakdown of the reported vehicle fatalities for year 2018 reported to the NHTSA FARS database.

The implementation of a low-speed ADS shuttle is expected to reduce bus-related vehicle crashes. For the following example, it is assumed the implementation of the ADS shuttle will reduce the risk of all types of bus-related vehicle crashes by 70%. This value should be updated as more research is completed on the safety impacts of ADS-equipped buses. A 70% reduction in the risk of vehicle crashes is equivalent to a CMF value of 0.3. Figure 10 and Table 11 show the monetary costs and savings in bus fatalities for various ADS market penetrations, assuming a growth factor of 2%. The baseline of 234 bus-related fatalities in Table 10 is used to substitute the N_{crash} as the total annual fatality-related crashes described in Equation 1.

The same methodology described in the examples shown above that analyzes the cost and savings at a national scale over the market penetration period of ADS can be scaled down to a

Table 10. National fatalities by vehicle type for year 2018 (Fatality Analysis Reporting System).[1]

Body Type	Year 2018
Passenger cars	20,333
Light trucks	19,775
Large trucks	4,862
Motorcycles	5,115
Buses	234
Other/unknown	1,553

[1]https://www-fars.nhtsa.dot.gov/Vehicles/VehiclesAllVehicles.aspx.

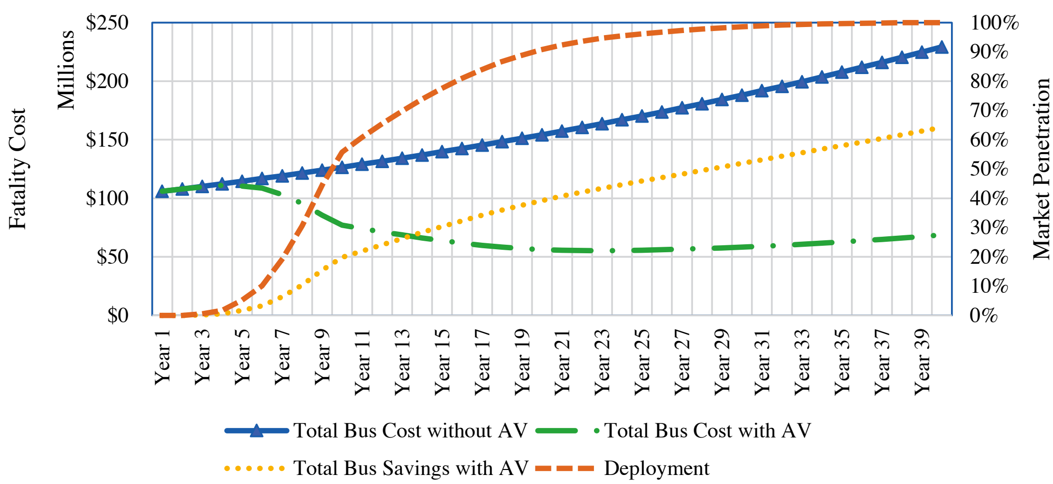


Figure 10. National monetary cost due to bus-related fatalities and savings due to crash reduction (Source: Booz Allen).

Table 11. National monetary costs and savings (millions) in bus fatalities by ADS market penetration.

Bus Fatality Costs	**Market Penetration**					
	0%	**20%**	**40%**	**60%**	**80%**	**100%**
Bus fatality cost without ADS	$3,541	$3,988	$4,149	$4,316	$4,766	$7,368
Bus fatality cost with ADS	$3,541	$3,450	$2,856	$2,479	$2,063	$2,210
Bus fatality savings with ADS	$0	$538	$1,290	$1,837	$2,702	$5,158

Table 12. Minnesota fatalities by vehicle type for year 2018 (Fatality Analysis Reporting System).

Body Type	Year 2018
Passenger cars	605
Light trucks	595
Large trucks	105
Motorcycles	143
Buses	7
Other/unknown	25

defined regional scale. The approach was applied to the state of Minnesota; Table 12 lists the Minnesota fatalities by vehicle type for the year 2018.

The example scenario in Figure 11 shows the monetary costs and savings due to bus-related fatalities and savings, respectively, over 40 years of ADS deployment to achieve 100% market penetration for the state of Minnesota, assuming a 2% growth rate.

Table 13 shows the monetary costs and savings in bus fatalities by various ADS market penetrations for the state of Minnesota. The baseline of seven bus-related fatalities in Table 12 is used to substitute the N_{Crash} as the total annual fatality-related crashes described in Equation 1.

The example above demonstrates that by using the same framework applied nationally, a study can be tailored for a specific geographic region to assess local impacts of monetary savings due to ADS deployment. The approach demonstrates that scope can be changed simply by using available local historical values corresponding to the N_{Crash}.

The N_{Crash} and CMF_{sev} can also be adjusted to assess the safety impacts of ADS deployment on subsets of vehicle collision types (e.g., rear-end, sideswipe, etc.). This detailed breakdown should be applied to improve crash analysis primarily when CMF values provide a breakdown at the collision type level.

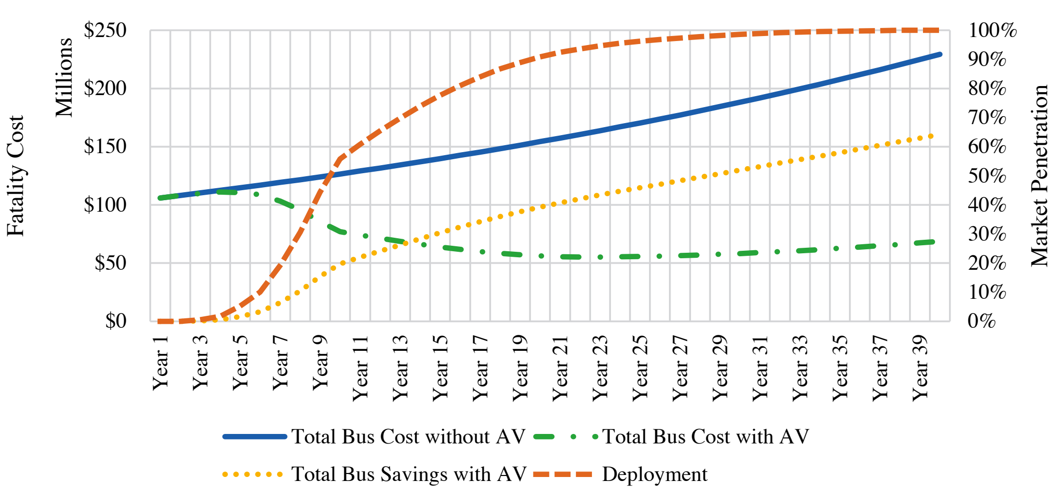


Figure 11. Minnesota monetary cost due to bus-related fatalities and savings due to crash reduction (Source: Booz Allen).

Table 13. Minnesota monetary costs and savings (millions) in bus fatalities by ADS market penetration.

Bus Fatality Costs	Market Penetration					
	0%	20%	40%	60%	80%	100%
Bus fatality cost without ADS	$105	$119	$124	$129	$142	$220
Bus fatality cost with ADS	$105	$103	$85	$74	$62	$66
Bus fatality savings with ADS	$0	$16	$38	$55	$81	$154

The expected safety performance results can be used with estimated investment costs to perform a benefit-cost analysis. As illustrated in the example application of this framework in Chapter 4 with ADS-equipped trucks (Levels 3 and 4), this can help to determine economic impacts of investment decisions or to compare various alternatives (e.g., compare different investment decisions). In a safety-focused benefit-cost analysis, the benefits, such as a decrease in crashes, are first converted to a monetary value based on average crash costs. The benefits could also include other factors such as operational and mobility, public health, and environmental impacts. The monetary benefits are compared with the costs associated with ADS implementation (e.g., infrastructure costs to enhance ADS performance or to expand the ODD, thereby expanding the benefits). ADS implementation costs could include costs associated with new infrastructure elements, upgrading infrastructure, and ongoing maintenance. For further information, refer to FHWA's *Highway Safety Benefit-Cost Analysis Guide* (Lawrence et al., 2018).

Further Socioeconomic Considerations

While safety benefits are the main focus of this document, ADS technologies, especially the Level 4 and Level 5 applications, have the potential to provide benefits to public health more broadly than just reduction in crashes. For example, these technologies are expected to have considerable socioeconomic impacts (travel, public health, and environmental) beyond just a reduction in crashes. ADS improves access to business districts and commercial and medical facilities for the elderly and people with disabilities. Once ADS technologies are deployed, induced demand would be served by these technologies, and induced travel would translate as more travel trips showing on the network. Induced demand is the demand that has not been previously accommodated by the network due to capacity, convenience, cost, safety, disability, or age constraints.

IOOs should be aware of the landscape of the socioeconomic factors that are affected by ADS features. Accordingly, this section discusses the approaches that IOOs need to consider for identifying these socioeconomic impacts of ADS. However, the scope of the framework application in Chapter 4 focuses only on the safety benefits.

Induced Travel Trips

To calculate the socioeconomic impact of ADS technologies, IOOs need to estimate the induced travel trips triggered by ADS deployment. The induced travel trips may be considered as the degree to which mobility is improved and driving constraints are removed on the network. This translates into new additional travel trips that could be accommodated. A portion of these trips would be zero-occupancy trips, where the vehicle is empty while moving in the traffic heading to a passenger or even cruising waiting for a passenger. An estimate for the non-zero-occupancy induced trips could be calculated using the following equations:

$$\text{Induced travel trips}_{\text{Non\_Zero}} = \text{Base trip rate} \times \text{Trip rate impact} \times \text{Market size} \times 365 \text{ Days} \qquad \textbf{Eq. 4}$$

Equation 4 may need to be calculated for the different population groups:

- Persons with disabilities.
- Older adults.
- All other travelers.

The base trip rate is the average number of trips per person per day. The nationwide average base trip rate is 4.06 (US Census Bureau, 2012).

Planning departments within state and local agencies may be able to ascertain more accurate estimates of the base trip rate based on local travel behavior, car ownership, and demographics data.

The trip rate impact is the percentage increase in daily trips from the base trip rate. This factor expresses the ability for an intervention (i.e., ADS technology) to overcome challenges, such as accessibility, reliability (e.g., measured in buffer time), and affordability of transportation. A study by the Puget Sound Regional Council (Childress et al., 2014) estimated the trip rate impact of autonomous vehicles for all travelers in the Puget Sound region would be 4.88%. Planning departments within state and local agencies may be able to ascertain more accurate estimates of trip rate impact based on their local travel conditions, challenges, demographics, and ADS market penetration data.

The market size is the population within the deployment region that has the potential to benefit from the mobility benefits of the ADS technology. For example, the market size may be estimated as the population within the city limits for a central business district deployment. This estimate may be informed by the deployment geography and targeted demographics.

One approach to obtaining more accurate travel impact estimates is to segment the population based on how ADS provides mobility benefits. Persons with disabilities may benefit differently than a tourist or daily commuter. For example, the base trip rate for the population with disabilities is approximately 2.60 (Mattson, 2012). This population is likely to have a higher trip rate impact factor, evidenced by a separate study by researchers in Carnegie Mellon University that estimated the impact of autonomous vehicles on vehicle miles traveled among non-drivers, elderly drivers, and drivers with travel-restrictive medical conditions would be a 14% increase (Harper et al., 2016).

Estimating the zero-occupancy induced trips would be more challenging for IOO and planners. The zero-occupancy trips could be estimated as a percentage of the total non-zero-occupancy trips. However, this percentage would vary significantly depending on the nature of ADS feature deployment. For instance, if Level 4 ADS features are deployed as privately owned vehicles, the zero-occupancy trips percentage is anticipated to be much higher than that if the ADS features are deployed as shared robo-taxis, operated by ride-hailing companies.

Moreover, there are additional complexities to the estimation of the non-zero-occupancy trips that relate to the inexpensive operating costs of an electric ADS-operated vehicle. For instance, it would cost owners of an ADS-equipped vehicle about 50 cents per hour for their empty vehicle to cruise city-center streets at urban traffic speeds (Coxworth, 2019). That is much less expensive than paying to park at a metered area or in a lot. This could encourage privately owned noncommercial ADS-operated vehicles to add a significant number of zero-occupancy trips to the network. Dynamic pricing and congestion fee policy set by the planners are envisioned to play a pivotal role in dampening the percentage of zero-occupancy induced trips.

Economic Value of Trips

Estimates of the economic value of each non-zero-occupancy trip can be based on guidance from the Federal Emergency Management Agency, which assumes a delay time of half-day (12 hours) per trip to reflect the loss in productivity and spending for each trip that is not made (i.e., when the trip does not happen, the economy is less productive and there is less spending overall). Therefore, this analysis assumes that the loss of a trip is equal to a trip not taken—each having a similar impact on the overall economy. Since the value of time for local travel for personal and business purposes is $13.85 per hour in 2016 dollars, each new non-zero occupancy trip represents a gross benefit of approximately $166 (US DOT, 2017). The gross economic benefit per trip considers the growth and wealth creation that benefits everyone, not only the traveler (health providers, retail stores, transportation companies, etc.). Economic value may be expressed as a percentage of the gross domestic product.

The economic value of zero-occupancy trips is anticipated to comprise solely the vehicle operating costs and the network-induced congestion costs. Dynamic pricing and congestion fee policies envisioned by cities can be used to estimate the economic cost of zero-occupancy trips. No major economic benefits are expected from the zero-occupancy trips.

Economic Impact of ADS Due to Induced Demand

The economic impacts of ADS can be calculated as the result of subtracting the cost of the induced zero-occupancy trips from the benefits of the induced non-zero-occupancy trips. The benefits can be calculated as the product of the newly induced travel trips served by ADS and the economic value of each trip.

$$\textbf{Impact of ADS} = \textbf{Benefits of induced travel trips}_{\textbf{Non-Zero}} - \textbf{Cost of induced travel trips}_{\textbf{Zero}}$$

$$\textbf{Benefits of induced travel trips}_{\textbf{Non\_Zero}} = \textbf{Induced trips}_{\textbf{Non\_Zero}} \times \textbf{Economic value of trips}_{\textbf{Non-Zero}}$$

$$\textbf{Cost of induced travel trips}_{\textbf{Zero}} = \textbf{Induced travel trips}_{\textbf{Zero}} \times \textbf{Economic value of trips}_{\textbf{Zero}}$$

Environmental and Fuel Consumption Considerations. ADS technologies are envisioned to have positive environmental impacts on the transportation network. The main impacts expected are reduced fuel consumption rates and less greenhouse gas (GHG) emission. These environmental gains could be analyzed for their impacts in monetary values. GHG vehicle emissions savings are a direct function of fuel consumption reduction. Table 14 shows the average motor gasoline sale in thousand gallons per day nationally and for the states of Minnesota and Virginia.

To estimate the environmental savings due to the introduction of ADS into the traffic network, the following equation framework is proposed:

$$\textit{Environmental benefit} = FC_{Total} * FC_{Cost} * F_{Rd_{ADS}} + \sum_{GHG\_type} Em_{GHG} * FC_{Total} * F_{Rd\_ADS} * Cost_{GHG\_type} \qquad \textbf{Eq. 5}$$

where:

FC_{Total} = Fuel consumption (gallons)
FC_{Cost} = Fuel cost (USD per gallon)
Em_{GHG} = Emission by GHG type per fuel consumption (lbs per gallon)
$Cost_{GHG\_type}$ = Social cost of greenhouse gas by GHG type (USD per lbs)
F_{Rd_ADS} = Fuel reduction factor (decimal) due to deployment of ADS features

The framework can be decomposed into two parts where the first is the direct fuel consumption cost due to vehicle operations while the second is the indirect environmental impact cost due to GHG emissions. The types of GHG cost can be expanded based on the relevant GHG cost and emissions data available. Table 15 shows the estimated dollar cost per unit for gasoline and sample GHG emissions.

Table 14. Thousand gallons per day average petroleum sale (motor gasoline).

Location	2016	2017	2018	2019
United States	371,725.6	375,118.3	374,602.1	367,306.0
Minnesota	6,592.5	6,382.7	6,218.3	6,305.1
Virginia	9,674.7	9,444.5	9,168.0	8,909.1

Table 15. Gasoline and GHG environmental costs.[1,2,3]

Fuel/Emission	Per Units	Cost
Gasoline	Gallon—2019 dollar	$2.258
CO_2	Metric ton—2007 dollar	$12
NO_x	Metric ton—2007 dollar	$4,700

[1]https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=emm_epm0_pte_nus_dpg&f=a.
[2]https://www.eia.gov/electricity/annual/html/epa_a_02.html.
[3]https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references.

Table 16. GHG emissions per unit of distilled petroleum.

Emission	Per Unit	Per Unit Converted
NO_x	443.80 lb per MG[1]	443.8×10^{-3} lb per gallon
CO_2	8.89 kg per gallon	19.6 lb per gallon

[1]MG: thousand gallons.

Table 16 shows the estimated GHG emissions per unit of fuel consumption by internal combustion engines.

The F_{Rd_ADS} is the expected percentage of reduction in the fuel consumption due to ADS deployment. This factor would be very close to the percentage of the ADS-equipped vehicles within the fleet. ADS-equipped vehicles would be fully electric vehicles with no internal combustion engine. Therefore, they would have zero fuel consumption and zero tailpipe emission. IOOs should be aware that ADS-equipped vehicles still add environmental costs relevant to GHG emissions that accompany battery production. However, these costs are not relevant to the transportation network and are expected to be outweighed by the zero emissions of the ADS-equipped vehicles through their lifetime.

Step 6—Communicate Outcomes

The objective of the framework is to assist transportation agencies in quantifying the safety performance of ADS under various scenarios. The safety performance can be evaluated in concert with other quantitative measures (e.g., costs, operational efficiency, environmental impacts) or qualitative measures (e.g., equity, convenience, competitiveness) to inform the decision-making process. While the framework in this guide can help estimate the safety performance of ADS, the ability to use the results to inform decisions is ultimately the key. As such, there is a need to clearly and concisely communicate the analysis results to various audiences.

The framework can serve the needs of both technical and nontechnical audiences. These audiences may include OEMs, technical developers, IOOs, policymakers, community advocates, and regulatory staff. Identifying the proper audiences with which to share results is crucial to meeting policy, funding, and public perception goals. It is important to devise and employ targeted communication approaches and messaging to reach diverse audience groups effectively. Furthermore, within each group, the communications tools and methods must effectively educate and support the potential wide ranges of expertise and interest. For example, the various divisions within IOOs (e.g., transportation planners, highway designers, traffic engineers, and maintenance and operations groups) may be interested in different aspects of the analysis results. Regardless of the target audience and method of communication, engagement with communications experts is needed throughout the process. Once the appropriate audience groups are targeted and their specific messages are conceived, engaging stakeholders with continuous feedback loops will help effective communication achieve messaging goals. Communications feedback loops not only inform stakeholders using the International Association for Public Participation model (https://www.iap2.org/page/resources) but also empower them.

Communicating with public audiences such as community advocates is crucial to sway public perception on the safety of ADS. Key performance indicators (KPIs) should be selected to demonstrate the progression of education and familiarity with ADS as well as willingness to support it. KPIs can be useful metrics to demonstrate to a less technical audience and can be used to track engagement. Additionally, feedback loops allow real-time strategic and coordinated emergency communication based on input from the entire community. The following sections describe different considerations, methods, measures, and formats for presenting the results of safety analyses to convey the key details to technical and nontechnical audiences.

Below is a step-by-step approach to ensuring that communications are well thought out to maximize their effectiveness and likelihood of driving the desired outcomes.

Communications Goal and Target Objectives

The first step in any strategic communications strategy is to determine the overall goal and target objectives. In this case, the overall goal is to convey the results of the analysis conducted, but there may be multiple subsidiary objectives. For example, one objective might be to persuade certain audiences about potential benefits or refute perceived drawbacks. Transportation agencies likely have multiple target objectives, so it is critical to understand what those objectives are in order to determine the best ways to achieve them.

Stakeholder/Audience Analysis

To do so, the next step is to conduct a stakeholder analysis to identify the target audiences. For state and local agencies, there will be distinct audiences when communicating about ADS, with different—and potentially competing—needs and interests. These include select "internal" audiences, such as the policymakers and regulatory bodies elsewhere within the affected jurisdictions, as well as numerous external audiences including OEMs, IOOs, technology developers, and community members (residents and the business community).

Some of the more technical audiences, such as OEMs, technical developers, and IOO staff (planners, engineers, and analysts) involved with design, development, and deployment of ADS as well as those involved in transportation project planning, design, development, implementation, operations, and maintenance, may be interested in the following:

- Details of the analysis, including data sources, methods, and assumptions.
- Details of the results such as the change in the estimated number of crashes by crash type and severity for the various alternatives.

- Economic measures such as the benefit-cost ratio or cost effectiveness to support investment decisions.

While the technical audiences may have some degree of familiarity with ADS technology and/or quantitative safety measures (e.g., expected changes in crash frequency and severity), there are significant differences in the level of expertise and experience among these audiences. As such, it is important to clearly define the ADS technology of interest, including the capabilities and limitations. It may even be necessary to define the terms and components associated with the ADS. The results should also be prefaced with the specific goals, hypotheses, target crashes, and assumptions of the analysis. The assumptions should clearly indicate the ADS penetration rate and the specific ODD. All of these factors are critical to understanding and correctly interpreting the results.

Other audiences, such as policymakers, elected officials, community members and advocates from the residential and business communities, and the media, are equally if not more important in investment and policy decisions as technical audiences. Communicating with public audiences is crucial to swaying public perception on the safety of ADS. These audiences may be interested in the following:

- Lives saved, injuries prevented, crashes reduced.
- Return on investment.

Further, it is unlikely for this audience to be interested in the technical details of the ADS technologies and analysis methods. As such, there is a need to focus more on the safety performance (e.g., expected crashes reduced, injuries prevented, and lives saved). This audience will also be interested in the costs, including the cost to purchase a vehicle with the related ADS technology and the cost to improve or maintain the infrastructure to support the ADS within the ODD. It is also useful to show other scenarios such as how the costs and benefits would change if the ODD is expanded.

The stakeholder analysis is also useful in identifying potential champions who can help amplify the results and/or deliver them to audiences who might be more receptive to receiving them from an independent entity instead of from the transportation agency directly. For example, one target audience might be local elected officials, and they may be more likely to pay attention to the analysis results if they receive them from community advocates or hear about them from the media than they would if they received them directly from the transportation agency.

Once the stakeholder analysis is complete, it can be useful to revisit the goal and key objectives identified in the first step.

Key Themes and Messages, and Stakeholder-Message Mapping

With the stakeholder analysis in hand, the next two steps occur simultaneously: develop a suite of key themes and messages, and map those messages to the stakeholder analysis. Different themes or messages may be more relevant, topical, or persuasive to different audiences, so transportation agencies should take care to map out the best themes and messages for each stakeholder group.

Communications Plan

The final step is to build and implement the communications plan itself, which lays out the details for each of the different types of communications that will be conveyed. Just as different audiences may be more receptive to different messages, they will also likely have needs in terms of from *whom* they receive communications, *when* they receive communications, and even *how* they receive communications. For example, do they prefer to receive information directly from transportation agencies? Or from their constituents? Or from elected officials? Do they prefer information delivered in a formal or academic style? Or via a presentation? Or more informally via a one-on-one conversation? Is it important for certain audiences to receive the information *before* or *after* other audiences? Think critically about how the sequence and different potential rollout schedules might affect your target stakeholders.

Continuous feedback loops are critical. Make sure you are constantly in touch with your stakeholders to ensure they understand the message and that you know whether to adjust or adapt your messaging at any point to respond to (or better yet, to anticipate) any confusion, misgivings, or countervailing information.

CHAPTER 4

Direct Application of the Framework

Framework Proof of Concept with MnDOT—*Rochester Automated Shuttle Pilot*

Minnesota Department of Transportation (MnDOT) has many planned automated driving system (ADS) activities. Goals for MnDOT's ADS activities include understanding the infrastructure needs for scaled autonomous surface transportation and the effects of cold weather conditions on ADS technologies. MnDOT wants to understand the limitations of operating under cold conditions in an area with snow and ice during several months of the year and to encourage industry to understand these challenges as well. For example, MnDOT is halfway through a project on a 50-mile corridor of Highway 52 with the goal of mapping technologies to transportation challenges. The corridor runs through a highly heterogenous area, including urban, rural, and suburban sections of highway. The project team discussed state and local safety perspectives and has focused on three safety categories: (1) safety needs, (2) operational services (travel times/reliability services), and (3) multimodal (long-range transit trips).

MnDOT also has plans for multiple ADS pilots involving mass transit operations. Early-stage goals for ADS projects include introducing ADS technologies to the public and beginning a discourse of public engagement and education on emerging technologies in transportation. MnDOT has a particular emphasis on community engagement because investment and funding for the infrastructure owners and operators (IOOs) depend on community support.

MnDOT foresees early adoption of ADS technologies at the mass transit level due to established operational design domains (ODDs) and relative ease for public engagement when compared with private passenger vehicles. Furthermore, MnDOT's strategic plan and keen interest to use key performance indicators (KPIs) complement the intention of the framework.

One of the envisioned pilots is the Rochester Automated Shuttle Pilot. The pilot will consist of a low-speed, highly automated shuttle bus in downtown Rochester operated by First Transit. The goal of the project is to operate in an urban area for a year to gather lessons learned on automated vehicle (AV) operations in all weather conditions, educate the public on ADS technologies, and provide mobility solutions through an enhanced ADS transit service to the city of Rochester.

First Transit will operate the 12-passenger EasyMile EZ10 shuttle. The Level 4 shuttles will have no steering wheel or pedals and will travel between 12 and 15 mph for the duration of the route. A remote attendant will be on standby ready to take control as necessary. As shown in Figure 12, the proposed pilot route is a six-block by three-block circulator route that operates clockwise on 6th St. SE, 3rd Ave. SW, W Center St., and S Broadway Ave. It will connect the Mayo Clinic Hospital Methodist Campus with hotels, shops, restaurants, grocery stores, and parking lots with proposed stops, as shown in Figure 12.

Figure 12. Proposed route for the AV shuttle (Source: MnDOT).

The scope of the Rochester Autonomous Shuttle Pilot is to assess the expected impacts of the project on the future of transportation safety (which is consistent with the title and scope of NCHRP Project 17-91). The expected safety impacts (benefits or disbenefits) are defined by comparing the expected safety performance with the autonomous shuttle to the expected safety performance without the autonomous shuttle. The extent of the network for the analysis includes the street segments and intersections along the fixed transit route that may be impacted by the autonomous shuttle (e.g., mode shift from walking, biking, or driving to shuttle ridership). It is important to note that the intent of the Rochester Autonomous Shuttle Pilot is not to provide additional public transit or induce some type of mode shift; it is simply to test the AV shuttle in inclement weather and introduce the community to ADS technology. The following is a discussion of each step of the framework.

Step 1—Identify ADS Application(s) of Interest

The selected ADS application to include in the proof of concept is the MnDOT Autonomous Shuttle Pilot. The agency was mainly interested in introducing new transportation technologies to the public to gauge public perception. It was seen more as sowing seed for people to become comfortable and help set the foundation for future deployments. Other goals of this project are to understand the following:

- Are there safety benefits and what data can be used to analyze ADS deployments?
- How should KPI be defined to monitor ADS technology deployments and what is important to capture?
- Infrastructure needs—what needs to change, or what can be left alone?
- How can this be a benefit for mobility?
- What is the impact of winter weather on ADS applications, specifically the limitations of the technology operating under cold weather conditions, and how can industry be encouraged to understand these challenges as well?

The agency wants to understand and consider public expectations while evaluating ADS or other transportation technology deployments. Completing surveys to understand community perception and interest in engagement can better support investment for ADS. It is easier to engage the public in transit applications and for an autonomous transit system if the ODD is well known to most users. As a result, the agency chose to pilot a low-speed autonomous transit shuttle within the central business district of Rochester. This will help the agency understand how the public perceives the application, evaluate technical feasibility, and understand challenges and lessons learned for future deployments.

Step 2—Understand the ADS Application

The project team worked with MnDOT and the original equipment manufacturers (OEMs) to understand better the specific technology. To understand the functionality of the ADS, the project team identified the specific technology components and sensor suite. The team reviewed the OEMs' user manuals and online documentation to define the functionality of the technology and identify technology and infrastructure dependencies. To understand the expected market, the team made assumptions on transit ridership (based on discussions with MnDOT) and plans for the autonomous shuttle (e.g., route, number and capacity of shuttles, number and location of stops, transit schedule, and rider fare). This was used to estimate a hypothetical market for the service, including the number of potential riders and hypothetical mode shift from walking, biking, or driving in the surrounding area. To understand potential changes to the expected market over time, the team worked with MnDOT to identify any plans for expanding the service in the future or for increasing ridership/mode shift over time. This will be crucial to assessing the scale and timeframe of safety impacts in the area. It is important to note that MnDOT and its partners in the ADS shuttle pilot are not anticipating a mode shift, and the intent of the pilot is not to enhance shuttle service. However, the NCHRP Project 17-91 team developed this hypothetical mode shift scenario to demonstrate how the framework could be used to assess related impacts. For any assumptions, the team has documented potential upper and lower bounds for use in scenario planning or sensitivity analysis.

To further understanding of the expected market and potential changes over time, the team looked to other similar deployment examples throughout the United States, including those shown in Table 17.

Step 3—Define Deployment Scenarios

In this step, the project team worked with MnDOT to estimate the penetration rate, define the ODD, and identify limitations of the ADS. The penetration rate is speculative and could follow diverse scenarios since it hinges on several interrelated factors. As such, the team assumed different rates for use in scenario planning or sensitivity analysis. The assumed rates coincide with different scenarios for factors such as reliability of technology, regulatory challenges, consumer acceptance, and willingness to pay. For the ODD, the team worked with MnDOT to define the spatial and temporal extent of crashes that could be impacted by the ADS. The spatial extent includes the fixed route along which the autonomous shuttle will operate. A more extensive analysis could include the surrounding network from which the autonomous shuttle could attract ridership and result in mode shifts. The team requested data and results from existing travel demand, origin-destination, and other planning-level models relevant to this analysis. The temporal extent considered ODD factors such as speed range, weather, and time of day. Some risks and opportunities are described below. A subset of these was explored based on available data.

Below are some potential risks.

- Challenges for first responders include disabling, accessing, or moving low-speed shuttles; directing traffic; and signaling right of way.
- At low market penetration rates, low-speed shuttles could emerge and contribute to new crash types. For example, traditional nonautomated vehicles following shuttles could experience increased risk for rear-end crashes because of the shuttle's slower speed. Shuttles could result in

Table 17. ADS deployment examples in the United States.

Operators	Location	Service Area
Local Motors— Olli, IBM	National Harbor, MD	City streets
EasyMile EZ10	Arlington, TX	Private compound
Navya	Ann Arbor, MI	Campus streets
EasyMile EZ10	MnDOT	Private compound
EasyMile/CCTA	San Ramon, CA	City streets
EasyMile/Transdev	Gainesville, FL	City streets
Optimus Ride	Boston, MA; South Weymouth, MA	City streets
May Mobility and Quicken Loans	Detroit, MI	City streets
EasyMile/Transdev	Babcock Ranch, FL	Private compound

more aggressive and frequent lane-change maneuvers by the following nonautomated vehicles. This could increase the crash risk for the aggregate traffic stream.

- Shuttles will operate in dense areas, with a high likelihood of significant interactions with pedestrians, bikes, and other motor vehicles.
- Access to vehicle and safety data is limited.

The following are potential opportunities.

- Positive disruption to urban areas may result from increased mobility and reduced congestion.
- Common method to introduce AV technologies to the public may help open the door for more ADS technologies.
- Slow speed mitigates many safety concerns and allows for less sophisticated and costly sensors because stopping distances are shorter.
- Controlled environments, low speed, fewer regulatory constraints, and fixed routes allow easy testing and deployment.
- Crashes with pedestrians may be reduced (e.g., sensors on shuttles can perceive at-fault pedestrians better than drivers, particularly in unexpected scenarios; however, there is not enough data to statistically prove that these sensors are better than human drivers in most scenarios).
- Low-cost public transportation option may be due to a reduction in labor costs and a reduction in capital and operational costs associated with smaller, lower-capacity vehicles.

Step 4—Define Safety Goals and Hypothesis

The project team worked with MnDOT to document the overall goals of the proof of concept and define specific safety-related hypotheses. Based on initial discussions, one goal of the autonomous shuttle deployment is to introduce ADS technologies to the public. While the overarching goal is not related to safety, there is an opportunity to explore several hypotheses related to safety. For example, one hypothesis may be that the autonomous shuttle will improve safety in the area by reducing crash frequency and severity compared to existing conditions or compared to a similar scenario using traditional transit bus. The following are more detailed questions related to the hypothesis regarding crash types, crash severity levels, infrastructure, and data.

- How will the frequency of certain crash types change in relation to safety? It is anticipated that crashes involving transit vehicles will decrease with the deployment of low-speed shuttles. There is a potential to reduce other vehicle-, pedestrian-, and bicycle-related crashes if these modes shift to the shuttle, which would remove them from the segments and intersections along the route.
- How will the severity of certain crash types change? It is anticipated that crash severity would decrease with the use of low-speed shuttles. These shuttles drive at lower speeds and are autonomous, which could reduce crash severity levels.
- How will the frequency of other crash types change (e.g., those not involving shuttles)? With the deployment of low-speed shuttles, there is potential for other crash types to change and possibly increase. Low-speed shuttles might contribute to aggressive driving and evasive moves by other drivers, thus contributing to crashes. The deployment could also draw more pedestrians from surrounding areas, which could increase exposure at certain intersections.
- How will the autonomous shuttles respond to dynamic conditions (e.g., weather, work zones, and roadway lighting)?
- How will safety change if the ODD is expanded and/or infrastructure improvements are made? If the shuttles can operate in additional conditions, then there is the potential to expand the safety benefits.
- How will crash contributing factors change? There is the potential to change factors related to road-user condition (e.g., distracted, impaired) and behavior (e.g., speeding) if these users shift to using the shuttles.

In defining the hypotheses and related questions, the team documented the expected deployment timeline, which could include multiple timeframes depending on the certainty in deployment and penetration rates.

Finally, the team demonstrated how to map these hypotheses and findings to plans, policies, and procedures. For example, the team attempted to answer questions such as, How do the expected safety-related benefits (or disbenefits) map to the state's Strategic Highway Safety Plan (SHSP), safety goals, and emphasis areas?

Step 5—Choose Analysis Methodology

In Step 5, the project team obtained data from appropriate data sources, defined metrics and evaluation criteria, and selected an appropriate evaluation method to test the hypotheses developed in the previous step. For the Autonomous Shuttle Pilot, the team followed the data collection plan and worked with MnDOT and other stakeholders to obtain crash, roadway, traffic, and other relevant data for the study area.

Data Sources

The study area includes the route(s) where the autonomous shuttle will operate as well as some areas of influence adjacent to the route(s). Other data of interest include transit ridership, pedestrian counts/activity, and origin-destination models. The following describes how the team collected these data elements, including the desired level of detail and source(s).

Crash Data

The desired crash data elements include the location, type, severity, date, time, and contributing factors (e.g., weather conditions, driver condition/behavior, etc.) related to the crash. The sources of information include MnDOT, City of Rochester, and local transit agencies.

Roadway Data

The desired roadway data elements include the number of lanes, lane and shoulder width/type, median width/type, presence of on-street parking, presence of bike lanes, presence of sidewalks, and posted speed limit. For intersections, the desired data elements include the number of legs, traffic control, presence of turn lanes, and presence of crosswalks and other pedestrian features. The sources of information include MnDOT, City of Rochester, and desktop data collection by the project team.

Traffic and Pedestrian Data

The desired traffic data elements include annual average daily traffic (AADT) or other measures of traffic exposure that could be used to estimate AADT for the segments within the study area. The desired pedestrian data elements include any pedestrian counts or major pedestrian generators within the study area that could be used to develop estimates of pedestrian exposure at various intersections. This would support certain crash prediction methods. The sources of information include MnDOT, City of Rochester, and Rochester-Olmsted Council of Governments (COG).

Transit Data

The desired transit data elements include routes, number of vehicles per route, ridership by route, number of stops, and boarding and alighting by stop. The sources of information include local transit agencies. This did not consider drop spots to make sure the pedestrians did not get dropped on one side of the road and had to cross a busy intersection.

Surrounding Land Use

The desired elements for surrounding land use include the zoning and types of businesses within and adjacent to the study area. The intent of this information is to identify potential origins and destinations of transit riders, pedestrians, and bicyclists. The sources of this information are online databases or datasets that the Rochester-Olmsted COG has compiled.

The team used the traditional datasets (crash, roadway, and traffic) to understand crash contributing factors and establish the baseline safety performance for existing and future conditions assuming the current (traditional) vehicle fleet. These data allowed the team to quantify and assess the safety performance of traditional vehicles and identify the conditions under which these crashes are occurring. These datasets also helped to quantify the number of crashes by type and severity that could be impacted by the autonomous shuttle under different deployment scenarios.

The project team used the following method for evaluating the safety impacts:

1. Used the *Highway Safety Manual* (HSM) Part C Predictive Method and associated safety analysis tools [e.g., Interactive Highway Safety Design Model (IHSDM)], to estimate the safety performance of existing and future conditions under the current vehicle fleet (traditional vehicles). Safety performance measures include the expected crash frequency by type and severity.
2. Estimated the safety performance of future conditions with autonomous shuttles in the vehicle fleet. This includes assumptions related to the penetration rate, mode shift, and ADS functionality as determined from previous tasks. For example, if there is a shift to autonomous shuttles from passenger vehicles, walking, or biking in the surrounding area, this will reduce the exposure that, in turn, will reduce the predicted crashes from the HSM Part C Predictive Method. The Part C Predictive Method does not, however, account for the potential mix of ADS applications in the vehicle fleet. As such, this step also involves assumptions about the potential impacts of autonomous shuttles on specific crash types. For example, estimating the percentage of crashes related to traditional transit vehicles per vehicle-mile can inform the predictions from the Part C Predictive Method. The team documented assumptions and explored the effects of different ranges of assumptions for use in scenario planning or sensitivity analysis.
3. Used the results from Steps 1 and 2 to estimate the expected impacts of autonomous shuttles based on underlying assumptions.

MnDOT provided crash data from 2016 through 2020 for the study area, including crashes along the shuttle loop and crashes along roads on the interior of the loop. Some of the variables in the crash data included severity, first harmful event, road condition, weather, and an indicator for intersection-related crashes. Table 18 displays the crash history along the shuttle loop by year and severity. The crash history includes crashes on segments and at intersections.

Table 18. Crash history along shuttle loop by year and severity.

Year	Serious Injury	Minor Injury	Possible Injury	Property Damage Only	Unknown Severity	Total
2016	0	6	10	57	3	76
2017	1	4	3	40	0	48
2018	1	5	5	45	0	56
2019	0	4	12	59	0	75
2020	1	3	2	27	0	33
Total	3	22	32	228	3	288

The project team obtained roadway data and surrounding area characteristics for the IHSDM analysis through a desktop data collection effort using Google Earth. Roadway information included alignment type, lane width, median width, median type, number of driveways, presence of on-street parking, and lighting. The number of schools, alcohol sales establishments, and bus stops within 1,000 feet of an intersection were also estimated using Google Earth.

In addition to the crash and roadway data, the project team obtained traffic data for the roadways along the shuttle loop and for the roadways that intersect the loop. MnDOT's Traffic Mapping Application (MnDOT, 2021) provided traffic volume data (AADT) for the majority of roadways. However, there are a few roads that intersect the shuttle loop that do not have AADT values. For those roads, the project team estimated AADT based on the features of the road and compared them against AADT values for similar roads and surrounding roads. Figure 13 displays the AADT values used in the analysis for roads in the study area. The shuttle route is displayed as a dashed red line in Figure 13.

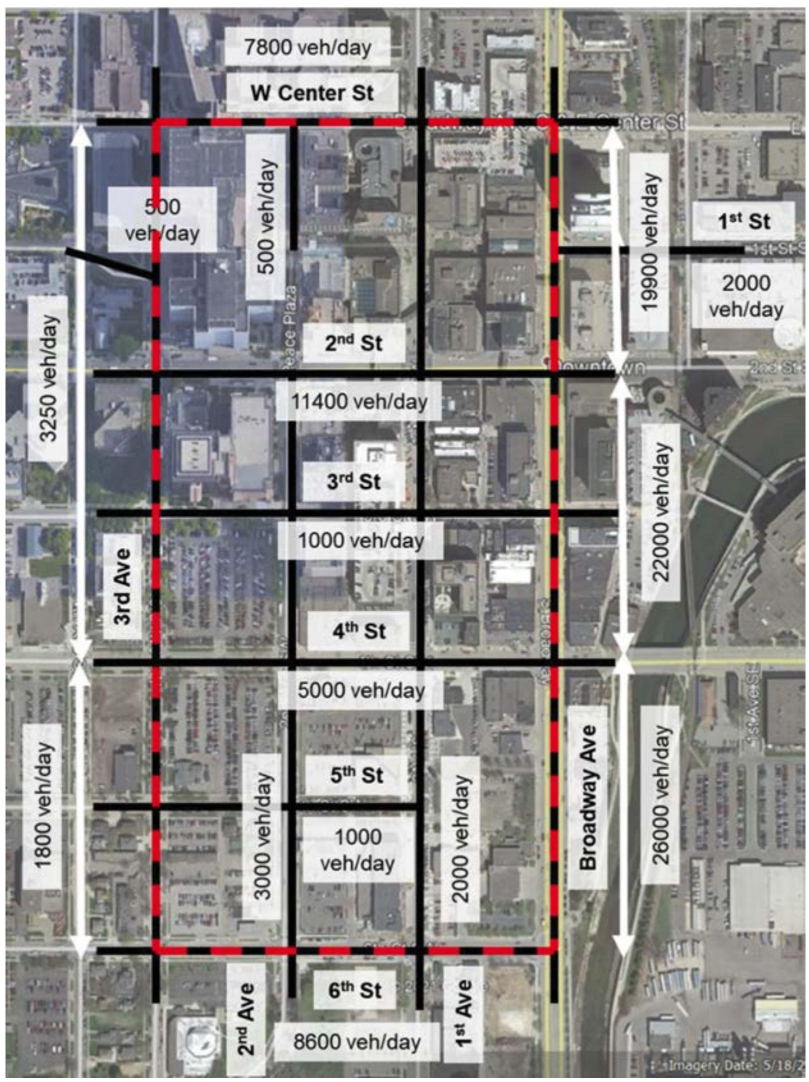


Figure 13. AADT values for each road in study area (Source: © 2021 Google modified by the authors).

Evaluation Method

The project team used the IHSDM Crash Prediction Module (CPM) to predict crashes along the shuttle loop for existing conditions, calculate the expected crashes using historical crash data, and predict crashes for two scenarios that involve a shuttle. The two scenarios are described below.

Scenario 1 includes adjusting pedestrian activity at the signalized intersections adjacent to the three shuttle stops. Pedestrian volumes are hypothetically expected to increase at the two signalized intersections directly adjacent to shuttle stops and decrease at all other intersections along the shuttle route. As noted, the shift in pedestrian activity is only hypothetical and does not reflect actual changes due to implementation of the shuttle. The project team assumed that technology does not limit functionality in adverse weather conditions, but this may not be a realistic assumption based on potential limitations of the current technology.

Scenario 2 includes adjusting AADT based on a potential mode shift from people using personal vehicles to using a shuttle. The project team assumed an AADT reduction of 7% on all roads along the shuttle route and along roads that intersect the shuttle route. The 7% reduction was based on the number of people that two of the current-style shuttles can accommodate when operating 12 hours per day. This reduction in AADT is only a hypothetical future scenario, assuming the shuttle pilot is successful and that there is a demand for more ADS shuttles to expand service. Again, the project team assumed that technology does not limit functionality in adverse weather conditions, which may not be a valid assumption.

First, the project team entered crash, roadway, and traffic data for the existing conditions into the IHSDM for each segment and intersection along the shuttle loop. Figure 14 displays the segments and intersections that form the shuttle loop as they appear in IHSDM. The intent of this image is to display how a network is viewed in IHSDM.

To run the analysis, the project team made assumptions about characteristics in the study area. First, driveways were classified as "minor commercial," and on-street parking was classified as "parallel, commercial/industrial/institutional." Additionally, all left-turn movements at signalized intersections were considered to be permissive. The project team estimated pedestrian crossing volumes at intersections based on the surrounding area characteristics and estimates of pedestrian volumes based on general level of pedestrian activity from the HSM. Figure 15 displays the estimates of existing pedestrian volumes at intersections in the study area.

For the first scenario, the project team adjusted the pedestrian activity based on the location of the shuttle stops and a hypothetical mode shift. Pedestrian activity at intersections directly next to a shuttle stop is expected to increase, while pedestrian activity at all other intersections is expected to decrease. Figure 16 displays the hypothetical pedestrian activity due to the presence of the shuttle.

Results

Using the data and assumptions, the project team entered the information into IHSDM to predict crash frequency along the shuttle loop for existing conditions and the hypothetical future scenarios. Table 19 displays the predicted crash frequency from IHSDM for the segments for the existing conditions. As shown in Table 19, there are a total of 5.1 predicted crashes per year, 1.5 predicted fatal plus injury crashes per year, and 3.6 predicted property damage only crashes on the four segments for the existing conditions. Broadway Ave. experiences the most predicted crashes compared to Center St., 6th St., and 3rd Ave.

Table 20 displays the predicted crash frequency from IHSDM for the intersections in the study area for the existing conditions. As shown in Table 20, there are a total of 43.4 predicted

Figure 14. Road network of the shuttle loop as it appears in IHSDM (Source: IHSDM project output).

Figure 15. Existing pedestrian activity at intersections in the study area (Source: © 2021 Google modified by the authors).

crashes per year, 16.3 predicted fatal plus injury crashes per year, and 27.2 predicted property damage only crashes at the 16 intersections in the study area for the existing conditions. The 2nd St. and Broadway Ave. intersection experiences the most predicted crashes (6.9 predicted crashes per year) compared to the other intersections, followed by the Broadway Ave. and 4th St. intersection (6.5 predicted crashes per year).

Using the predicted crashes and crash history for the existing conditions, the project team used IHSDM to calculate the expected crashes for the shuttle loop for the existing conditions. These results can be used to establish a baseline for comparison with proposed or hypothetical future scenarios and to identify locations where ADS technologies could have the largest impact.

Table 21 displays the expected crash frequency from IHSDM by segment for the existing conditions. The results in Table 21 indicate there are a total of 7.1 expected crashes per year, 1.8 expected fatal plus injury crashes per year, and 5.4 expected property damage only crashes on the four segments for the existing conditions. Broadway Ave. experiences the most predicted crashes compared to Center St., 6th St., and 3rd Ave.

Figure 16. Hypothetical pedestrian activity due to shuttle at intersections in the study area (Source: © 2021 Google modified by the authors).

Table 19. Predicted crashes for segments along the shuttle route from IHSDM for the existing conditions.

Location	Predicted Total Crash Frequency (crashes/yr)	Predicted Fatal + Injury Crash Frequency (crashes/yr)	Predicted Property Damage Only Crash Frequency (crashes/yr)
Segments	**5.1**	**1.5**	**3.6**
Center St.	0.7	0.2	0.5
Broadway Ave.	2.8	0.9	1.9
6th St.	0.7	0.2	0.5
3rd Ave.	0.9	0.2	0.7

Table 20. Predicted crashes for intersections along the shuttle route from IHSDM for the existing conditions.

Location	Predicted Total Crash Frequency (crashes/yr)	Predicted Fatal+Injury Crash Frequency (crashes/yr)	Predicted Property Damage Only Crash Frequency (crashes/yr)
Intersections	**43.4**	**16.3**	**27.2**
3rd Ave. and Center St.	2.1	0.8	1.3
Center St. and 2nd Ave.	0.7	0.4	0.3
Center St. and 1st Ave.	1.7	0.7	1.0
Center St. and Broadway Ave.	5.7	2.2	3.5
1st St. and Broadway Ave.	2.4	1.0	1.4
2nd St. and Broadway Ave.	6.9	2.7	4.2
3rd St. and Broadway Ave.	3.1	1.1	2.0
Broadway Ave. and 4th St.	6.5	2.5	4.1
Broadway Ave. and 6th St.	4.5	1.5	3.0
6th St. and 3rd Ave.	0.5	0.1	0.3
6th St. and 2nd Ave.	2.0	0.8	1.3
6th St. and 1st Ave.	1.7	0.6	1.2
3rd Ave. and 4th St.	1.7	0.6	1.1
3rd Ave. and 3rd St.	0.1	0.0	0.0
3rd Ave. and 2nd St.	3.4	1.2	2.3
1st St. and 3rd Ave.	0.4	0.1	0.2

Table 21. Expected crashes along shuttle route segments from IHSDM (existing conditions).

Location	Expected Total Crash Frequency (crashes/yr)	Expected Fatal and Injury Crash Frequency (crashes/yr)	Expected Property Damage Only Crash Frequency (crashes/yr)
Segments	**7.1**	**1.8**	**5.4**
Center St.	0.8	0.2	0.6
Broadway Ave.	4.9	1.2	3.8
6th St.	0.7	0.2	0.5
3rd Ave.	0.7	0.2	0.5

Table 22 displays the expected crash frequency from IHSDM by intersection for the existing conditions. There are a total of 38.6 expected crashes per year, 11.9 expected fatal plus injury crashes per year, and 26.6 expected property damage only crashes at the 16 intersections in the study area for the existing conditions. The 2nd St. and Broadway Ave. intersection experiences the most predicted crashes (9.5 expected crashes per year) compared to the other analyzed intersections, followed by the Broadway Ave. and 4th St. intersection (7.4 expected crashes per year).

The expected crashes from IHSDM can also be broken out by crash type for either a segment or an intersection. This information can be used to identify crash types with a high percentage of crashes and identify ADS that could positively impact those crash types. It can also help to identify areas of concern if ADS is expected to exacerbate certain crash types. For instance, if a given ADS technology is expected to reduce angle crashes and potentially increase rear-end crashes, then one could use this table to understand the potential net impacts. If angle crashes are highly represented and rear-end crashes are not, then this might be an acceptable tradeoff. However, if rear-end crashes are highly represented and angle crashes are not, then this might not provide desirable safety outcomes.

Table 23 displays the expected crash type distribution for segments in the study area by severity for the 5-year study period for the existing conditions. Table 23 indicates there are more

Table 22. Expected crashes for intersections along the shuttle route from IHSDM for the existing conditions.

Location	Expected Total Crash Frequency (crashes/yr)	Expected Fatal and Injury Crash Frequency (crashes/yr)	Expected Property Damage Only Crash Frequency (crashes/yr)
Intersections	**38.6**	**11.9**	**26.6**
3rd Ave. and Center St.	0.9	0.6	0.3
Center St. and 2nd Ave.	0.5	0.3	0.3
Center St. and 1st Ave.	1.0	0.5	0.5
Center St. and Broadway Ave.	4.6	1.5	3.2
1st St. and Broadway Ave.	2.0	0.6	1.4
2nd St. and Broadway Ave.	9.5	2.4	7.1
3rd St. and Broadway Ave.	1.6	0.5	1.0
Broadway Ave. and 4th St.	7.4	2.3	5.0
Broadway Ave. and 6th St.	5.2	1.1	4.0
6th St. and 3rd Ave.	0.2	0.1	0.1
6th St. and 2nd Ave.	1.2	0.5	0.8
6th St. and 1st Ave.	1.4	0.4	1.0
3rd Ave. and 4th St.	1.1	0.5	0.6
3rd Ave. and 3rd St.	0.1	0.0	0.0
3rd Ave. and 2nd St.	1.7	0.5	1.2
1st St. and 3rd Ave.	0.2	0.1	0.1

Table 23. Expected crash type distribution for segments for the 5-year study period for the existing conditions.

Crash Type	Fatal and Injury		Property Damage Only		Total	
	Crashes	%	Crashes	%	Crashes	%
Collision with animal	0.2	0.2	0.4	0.2	0.6	0.2
Collision with bicycle	0.4	0.5	0.0	0.0	0.4	0.2
Collision with fixed object	0.6	0.8	3.1	1.7	3.7	1.4
Collision with other object	0.0	0.0	0.2	0.1	0.2	0.1
Other single-vehicle collision	0.5	0.7	0.6	0.3	1.1	0.4
Collision with pedestrian	1.5	1.9	0.0	0.0	1.5	0.6
Total single-vehicle crashes	*3.2*	*4.2*	*4.3*	*2.4*	*7.5*	*2.9*
Angle collision	0.4	0.5	1.2	0.6	1.6	0.6
Driveway-related collision	0.9	1.2	1.9	1.0	2.8	1.1
Head-on collision	0.2	0.3	0.2	0.1	0.4	0.2
Other multivehicle collision	0.3	0.4	1.8	1.0	2.1	0.8
Rear-end collision	5.5	7.3	17.0	9.3	22.5	8.7
Sideswipe, opposite direction collision	0.2	0.2	0.3	0.2	0.5	0.2
Sideswipe, same direction collision	0.4	0.5	5.3	2.9	5.7	2.2
Total multiple-vehicle crashes	*7.9*	*10.4*	*27.6*	*15.1*	*35.5*	*13.7*
Total segment crashes	**11.1**	**14.6**	**31.9**	**17.4**	**43.0**	**16.6**

multiple-vehicle crashes along segments in the study area compared to single-vehicle collisions. Rear-end collisions are the crash type with the highest expected crash frequency (22.5 expected crashes for the 5-year study period) compared to the other crash types.

Table 24 displays the expected crash type distribution for intersections in the study area by severity for the 5-year study period for the existing conditions. As shown in Table 24, there are more multiple-vehicle crashes along segments in the study area compared to single-vehicle collisions. Rear-end collisions are the crash type with the highest expected crash frequency (84.5 expected crashes for the 5-year study period) compared to the other crash types.

After predicting crashes for the existing conditions, the project team analyzed the two scenarios using the IHSDM CPM to compare the change in predicted crashes between the existing conditions and the two scenarios to determine whether crashes are expected to increase or decrease. The two scenarios, previously described, are:

- **Scenario 1** includes adjusting pedestrian activity at the signalized intersections adjacent to the three shuttle stops.
- **Scenario 2** includes adjusting AADT based on a potential mode shift from people using personal vehicles to using a shuttle.

Table 24. Expected crash type distribution for intersections for the 5-year study period for the existing conditions.

Crash Type	Fatal and Injury		Property Damage Only		Total	
	Crashes	%	Crashes	%	Crashes	%
Collision with animal	0.0	0.0	0.0	0.0	0.0	0.0
Collision with bicycle	2.9	3.8	0.0	0.0	2.9	1.1
Collision with fixed object	2.1	2.8	7.6	4.2	9.8	3.8
Non-collision	0.5	0.6	0.3	0.1	0.8	0.3
Collision with other object	0.2	0.3	0.6	0.3	0.8	0.3
Other single-vehicle collision	0.2	0.2	0.5	0.2	0.6	0.2
Collision with parked vehicle	0.0	0.0	0.0	0.0	0.0	0.0
Collision with pedestrian	15.8	20.8	0.0	0.0	15.8	6.1
Total intersection single-vehicle crashes	*21.6*	*28.6*	*9.0*	*4.9*	*30.6*	*11.8*
Angle collision	15.7	20.7	39.3	21.5	55.0	21.3
Head-on collision	2.0	2.6	3.9	2.1	5.9	2.3
Other multivehicle collision	2.3	3.1	27.4	14.9	29.7	11.5
Rear-end collision	19.0	25.1	65.5	35.8	84.5	32.7
Sideswipe	4.0	5.3	6.0	3.3	10.0	3.9
Total intersection multivehicle crashes	*43.1*	*56.8*	*142.1*	*77.6*	*185.2*	*71.5*
Total intersection crashes	**64.7**	**85.4**	**151.1**	**82.6**	**215.8**	**83.4**

Table 25 displays a comparison of the predicted total crash frequency for the existing conditions, Scenario 1, and Scenario 2 for the segments along the shuttle route. Table 26 displays the predicted total crash frequencies for the intersections. Comparing the existing conditions and Scenario 1, the results indicate that predicted total crashes do not change for segments and do not change dramatically for intersections. However, there are slight changes in predicted crashes between the existing conditions and Scenario 1 at individual intersections (e.g., 3rd Avenue and Center Street intersection). In contrast to Scenario 1, the results for Scenario 2 indicate a 4% decrease in predicted segment crashes and a 7% decrease in predicted intersection crashes compared to the existing conditions.

The project team compared the predicted crashes broken out by crash type. Table 27 displays the crash type distributions for segments for the existing conditions, Scenario 1, and Scenario 2. The results indicate a 19% decrease in total segment crashes between the existing conditions and Scenario 1 and a 33.5% decrease in total segment crashes between the existing conditions and Scenario 2.

Table 28 displays the crash type distributions for intersections for the existing conditions, Scenario 1, and Scenario 2. The results indicate a 5% increase in total intersection crashes between the existing conditions and Scenario 1 and a 3% decrease in total intersection crashes between the existing conditions and Scenario 2.

Table 25. Predicted total crash frequency for segments in the study area for existing conditions, Scenario 1, and Scenario 2.

Location	Predicted Total Crash Frequency (crashes/yr) for Existing Conditions	Predicted Total Crash Frequency (crashes/yr) for Scenario 1	Predicted Total Crash Frequency (crashes/yr) for Scenario 2
Segments	**5.1**	**5.1**	**4.9**
Center St.	0.7	0.7	0.7
Broadway Ave.	2.8	2.8	2.6
6th St.	0.7	0.7	0.7
3rd Ave.	0.9	0.9	0.9
% Crash reduction	—	—	**4%**

Table 26. Predicted total crash frequency for intersections in the study area for existing conditions, scenario 1, and scenario 2.

Location	Predicted Total Crash Frequency (crashes/yr) for Existing Conditions	Predicted Total Crash Frequency (crashes/yr) for Scenario 1	Predicted Total Crash Frequency (crashes/yr) for Scenario 2
Intersections	**43.4**	**43.4**	**40.2**
3rd Ave. and Center St.	2.1	2.0	2.0
Center St. and 2nd Ave.	0.7	0.7	0.6
Center St. and 1st Ave.	1.7	1.8	1.6
Center St. and Broadway Ave.	5.7	5.5	5.2
1st St. and Broadway Ave.	2.4	2.3	2.2
2nd St. and Broadway Ave.	6.9	7.1	6.3
3rd St. and Broadway Ave.	3.1	3.2	2.9
Broadway Ave. and 4th St.	6.5	6.4	6.0
Broadway Ave. and 6th St.	4.5	4.5	4.1
6th St. and 3rd Ave.	0.5	0.5	0.4
6th St. and 2nd Ave.	2.0	2.0	1.9
6th St. and 1st Ave.	1.7	1.8	1.6
3rd Ave. and 4th St.	1.7	1.9	1.7
3rd Ave. and 3rd St.	0.1	0.1	0.1
3rd Ave. and 2nd St.	3.4	3.3	3.3
1st St. and 3rd Ave.	0.4	0.3	0.3
% Crash reduction	**N/A**	**0%**	**7%**

Table 27. Predicted segment crash type distribution for the 5-year study period for the existing conditions, scenario 1, and scenario 2.

Crash Type	Total Expected Crashes for Existing Conditions (2021–2026)		Total Predicted Crashes for Scenario 1 (2021–2026)		Total Predicted Crashes for Scenario 2 (2021–2026)	
	Crashes	%	Crashes	%	Crashes	%
Collision with animal	0.6	1.4	0.7	2.3	0.7	2.4
Collision with bicycle	0.4	0.9	0.4	1.3	0.4	1.4
Collision with fixed object	3.7	8.6	4.0	12.9	3.9	13.6
Collision with other object	0.2	0.5	0.2	0.6	0.2	0.7
Other single-vehicle collision	1.1	2.6	1.2	3.9	1.2	4.2
Collision with pedestrian	1.5	3.5	1.5	4.8	1.3	4.5
Total single-vehicle crashes	*7.5*	*17.4*	*8.0*	*25.7*	*7.6*	*26.6*
Angle collision	1.6	3.7	1.1	3.5	1.0	3.5
Driveway-related collision	2.8	6.5	3.6	11.6	3.3	11.5
Head-on collision	0.4	0.9	0.3	1.0	0.2	0.7
Other multivehicle collision	2.1	4.9	1.2	3.9	1.1	3.8
Rear-end collision	22.5	52.3	13.1	42.1	11.9	41.6
Sideswipe, opposite direction collision	0.5	1.2	0.4	1.3	0.4	1.4
Sideswipe, same direction collision	5.7	13.3	3.4	10.9	3.1	10.8
Total multiple-vehicle crashes	*35.5*	*82.6*	*23.1*	*74.3*	*21.0*	*73.4*
Total arterial segment crashes	**43.0**	—	**31.1**	—	**28.6**	—
% Change in crashes	—	—	**–19%**	—	**–33.5%**	—

Step 6—Communicate Outcomes

For this step, the team worked with MnDOT and its stakeholders to discuss how the results of the analysis could be used in the decision process and options for presenting the results to different audiences. Specifically, the team discussed options for communicating results to technical and nontechnical audiences and how MnDOT might approach a typical project to devise and employ targeted communication and messaging effectively to reach diverse audience groups.

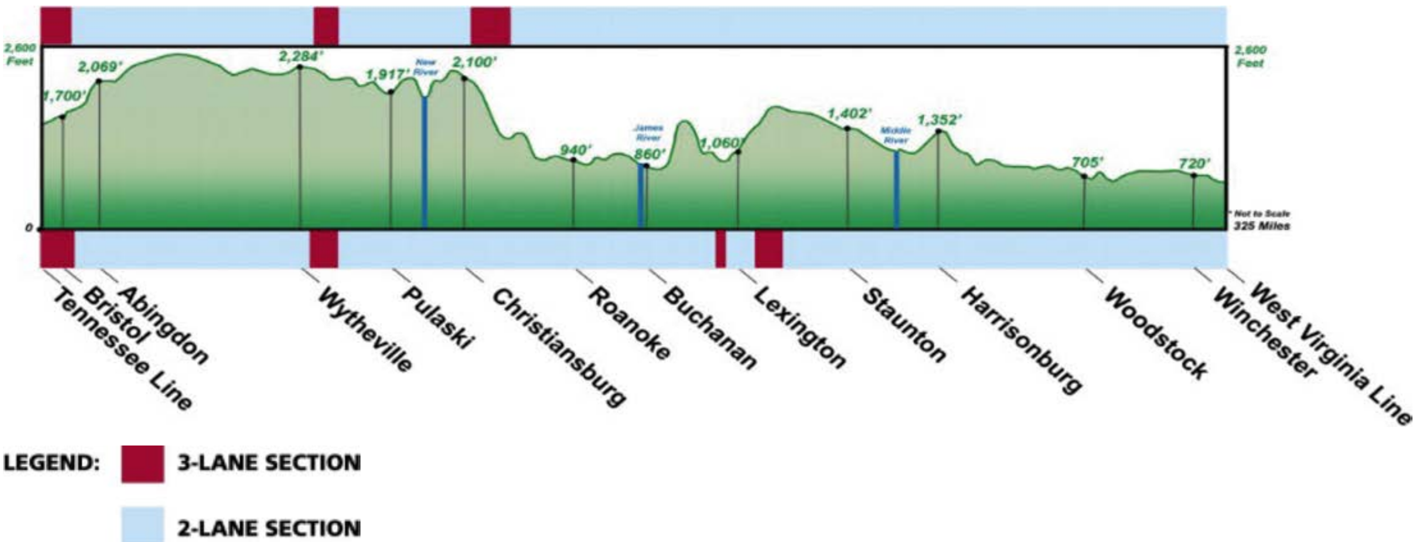
As demonstrated from the analysis and results, the framework can be used to estimate a change in crash frequency for various scenarios associated with an AV shuttle. These results can be linked to SHSPs and other safety-related plans or policies. Many SHSPs contain emphasis areas as well as strategies the state can use to accomplish crash-reduction targets in each emphasis area. By supporting the implementation of ADS technologies, such as ADS-equipped shuttles, states can help achieve the crash-reduction goals laid out in their safety plans.

Table 28. Predicted intersection crash type distribution for the 5-year study period for the existing conditions, scenario 1, and scenario 2.

Crash Type	Total Expected Crashes for Existing Conditions (2021–2026)		Total Predicted Crashes for Scenario 1 (2021–2026)		Total Predicted Crashes for Scenario 2 (2021–2026)	
	Crashes	%	Crashes	%	Crashes	%
Collision with animal	0.0	0.0	0.1	0.0	0.1	0.0
Collision with bicycle	2.9	1.3	2.9	1.3	2.7	1.3
Collision with fixed object	9.8	4.5	10.1	4.5	9.5	4.5
Non-collision	0.8	0.3	0.8	0.4	0.8	0.4
Collision with other object	0.8	0.4	0.9	0.4	0.8	0.4
Other single-vehicle collision	0.6	0.3	0.8	0.4	0.8	0.4
Collision with parked vehicle	0.0	0.0	0.0	0.0	0.0	0.0
Collision with pedestrian	15.8	7.3	15.7	6.9	15.3	7.4
Total intersection single-vehicle crashes	*30.6*	*14.2*	*31.3*	*13.8*	*29.9*	*14.3*
Angle collision	55.0	25.5	67.2	29.7	62.0	29.7
Head-on collision	5.9	2.7	6.5	2.9	5.9	2.8
Other multivehicle collision	29.7	13.8	26.7	11.8	24.3	11.7
Rear-end collision	84.5	39.2	82.1	36.2	74.7	35.8
Sideswipe	10.0	4.6	12.7	5.6	11.7	5.6
Total intersection multiple-vehicle crashes	*185.1*	*85.8*	*195.1*	*86.2*	*178.7*	*85.7*
Total intersection crashes	**215.8**	—	**226.4**	—	**208.6**	—
% Change in crashes	—	—	**5%**	—	**–3%**	—

Framework Proof of Concept with Virginia Department of Transportation (VDOT)—ADS-Equipped Trucks Along I-81 (VDOT, 2021)

The I-81 corridor serves as a critical north-south backbone of the East Coast's freight network. It is vital to the efficient movement of goods through the state of Virginia. It connects with five other interstates and traverses 21 cities and towns, 13 counties, and 25 colleges and universities between the West Virginia and Tennessee borders. More than 30% of all trucks and nearly 50% of the state's value of goods are transported along this corridor (AASHTO, 2021). I-81 has the highest per capita truck volume in Virginia. The high percentage of trucks and steep terrain (Figure 17) are concerning as one truck is equivalent to as many as four passenger vehicles in terms of length (Figure 18). The AADT volume along I-81 ranged from 38,600 to 66,700 vehicles per day in 2016. If these numbers are converted to passenger-car equivalents, the AADT values jump significantly to 59,700 to 90,000 vehicles per day.



Source: I-81 Corridor Improvement Plan, VDOT, December 2018

Figure 17. Elevation along the I-81 corridor (Source: VDOT).

As a result, the I-81 corridor is beset by significant safety and reliability issues. There are more than 2,000 vehicle crashes every year, and 26% of those crashes involve heavy trucks. This is the highest percentage for any interstate in Virginia. This results in unpredictable travel delay and affects on-time performance of both heavy commercial vehicles and passenger vehicles. I-81 for the most part has two lanes in each direction; when one lane is blocked, there is a 65% reduction in capacity (VDOT, 2021). Factors that contribute to long crash clearance times include lack of capacity, the rolling terrain, lack of reliable detour routes, and the constrained configuration.

Given this background, VDOT wanted to explore a scenario where ADS-equipped trucks and vehicles with forward collision avoidance are deployed along the I-81 corridor as part of the I-81 corridor improvement program. The expected safety impacts (benefits or disbenefits) are defined by comparing the expected safety performance with ADS-equipped trucks and vehicles with forward collision avoidance to the existing crash history along the study corridor. The extent of the study corridor for analysis includes I-81 from milepost 110 to milepost 150, which represents an area north of Roanoke (with higher urban volumes and congestion) to south of Christiansburg (with mountainous terrain, steep grades, and truck climbing lanes). Additionally, truck crashes also cost the state in terms of time when roads are closed to clear incidents, delayed freight deliveries, fuel costs, and increased emissions.

Figure 18. Truck along an interstate corridor in Virginia (Source: VHB).

Step 1—Identify ADS Application(s) of Interest

The selected applications included in the proof of concept are ADS-equipped trucks and vehicles with forward collision avoidance. The project team worked with VDOT to select a route in Virginia that could potentially benefit from various ADS technologies and, in particular, ADS technologies related to trucks. The team sought to identify a route with high truck volumes and select ADS applications that directly impact crashes involving trucks. VDOT indicated that this route is also heavily congested and has rolling to mountainous terrain. The steep grades influence vehicle speeds, particularly for heavy vehicles, and, when combined with heavy congestion, can lead to safety concerns. The results from this analysis can help inform strategic plans such as Virginia's SHSP and Long-Range Plan, which has a 2045 horizon year.

Step 2—Understand the ADS Application

Application Description

ADS-equipped trucks operate without the need for a driver on a predefined set of roads or geographic area and within a specified ODD. Depending on the level of automation, either a driver or the ADS is the fallback for the dynamic driving task. The ADS automatically collects and processes data from onboard sensors and handles the vehicle-to-vehicle (V2V) communications, if available, to perceive the surroundings (such as relevant signage, roadway markings, and nearby obstacles) and identify the appropriate action to perform the driving task.

ADS-equipped trucks in global freight operations are expected to dramatically increase soon. Trucks haul nearly 71% of U.S. freight, with a market size of $740 billion per year (Viscelli, 2018). Automated trucks could double the productivity of long-haul trucking, while reducing energy costs. Experts agree that trucks are great candidates for automation due to high proportions of uninterrupted highway driving. Additionally, demand for ADS-equipped trucking benefits vastly outpaces autonomous passenger cars due to high return on investment (ROI) on vehicles and increased industry efficiency.

Expected Market

Allied Market Research valued the global self-driving truck market at $1 billion for 2020, and it is expected to reach up to $1.7 billion by 2025 with a compound annual growth rate (CAGR) of 10.4% over the 5 years (Chandani and Baul, 2018). North America is expected to account for the majority of the self-driving truck market share, but the Asia Pacific region will likely exhibit the highest CAGR, 14.7%. The top market driving factors will be rising environmental concerns, traffic congestion, road safety, and security.

Table 29 lists a few examples of ADS-equipped trucks that are commercially deployed or being tested.

Table 29. ADS-equipped truck examples.

Provider	Details
Michelin	Partnered with the startup Einride to develop a Level 4 autonomous driving feature designed to haul up to 16 metric tons at speeds up to 50 mph for over 125 miles.
Otto	In 2018, Otto performed one of the world's first shipments by a self-driving truck. The pilot was a demonstration of Otto's exit-to-exit approach, where the driver does the difficult task of getting the truck to the highway where the ADS takes over. Once the truck was on the highway, the driver was not even in the driver's seat (Walker, 2019).

Step 3—Define Deployment Scenarios

Operational Design Domain

Table 30 summarizes the anticipated ODD elements of ADS-equipped trucks for two different predicted timelines, the short term (next 5 years) and the medium term (next 5 to 10 years). In addition, the table outlines the major deployment specifications envisioned for the ADS applications that are expected to impact its safety assessment. The deployment elements are also provided for the two identified timelines. Based on discussions with VDOT, one of the most appealing capabilities of ADS-equipped trucks is the ability to operate in mixed traffic. In an earlier study, VDOT examined the potential for truck-only lanes on I-81 and concluded that this type of infrastructure would be cost-prohibitive (VDOT, 2007).

Table 31 provides a summary of the technology specifications and key infrastructure needs pertinent to the envisioned ADS-equipped trucks.

Stage of Technology Development

Generation (Gen I)

Gen I is the first version of the ADS-equipped truck sensor package and the underlying computational algorithms for processing the data. Typically, this package embraces the needed combination of sensors such as forward-facing cameras, radar, ultrasonic sensors, laser scanners,

Table 30. ADS-equipped trucks deployment scenarios of interest.

Operational Design Domain Level	Timeline	Additional Deployment Context
• Freeways (both urban and rural). • Operating only in clear and good weather condition (e.g., no rain, snow, etc.).	Short term (high disruption).	• Conditional automation (Level 3) where driver is fall back for dynamic driving task. • Cooperative adaptive cruise control. • Long-line haul between cities. • Drivers will be necessary, but vehicle will maintain acceleration, braking, and lane assist. • Operating in mixed traffic. • Operating on well-marked roads and well-maintained signage roads.
• Freeways (both urban and rural). • All +4-lane divided highways (urban and rural). • Navigate through interchanges and ramps. • Navigate through signals.	Medium term (high disruption).	• Operating in mixed traffic. • Level 4 automation ADS application where ADS is responsible for the dynamic driving task fallback and achieving appropriate minimal risk conditions. • Potential for remote piloting. • The driver drives the truck to the freeway and then the driverless feature takes over. • Hand-off trailers between human-driven trucks and ADS-equipped trucks near the exits of the interstate highway system at ADS-equipped truck ports. • Vehicle-to-everything (V2X) communications. • Operating on well-marked and well-maintained signage roads.

Table 31. ADS-equipped trucks key infrastructure requirements.

Expected Timeline	Vehicle Type	Sensor Package	Key Infrastructure Requirements	
			Digital	Physical
Short term (High disruption).	Heavy-duty.	Gen I.	• V2V communications. • Global positioning system (GPS). • High-definition (HD) maps. • Weather data. • Infrastructure data. • Work zone alerts.	• Clear lane markings. • Visible signage. • Highly detectable traffic control device.
Medium term (High disruption).	Heavy-duty.	Gen II.	• V2X communications. • GPS. • HD maps. • Weather data. • Infrastructure data. • Work zone alerts. • 5G and dedicated short-range communication.	• Lane markings visible. • Visible signage. • Highly detectable traffic control device. • ADS-equipped truck port.

and inertial measurement units (gyroscopes and accelerometers) with *a priori* digital maps (lane-level detail). This package will not have a good object detection capability in low-visibility conditions, limiting the ODD to certain conditions (e.g., light rain, no snow, good lane markings).

Similarly, the underlying perception algorithms for processing data can handle the basic computations for the proper functionality of the ADS-equipped truck feature within the ODD and deployment context. These algorithms are at early development and may have more errors than later, more mature technology, leading to lower safety performance and/or lower percentage of time operating in automated mode (high disengagement rate). Sensors and computation algorithms used at this stage are commercially available and currently operate in certain vehicles.

Second Generation (Gen II)

Gen II is a more advanced stage of technology than first-generation models or systems. In addition to the sensor types included in Gen II, this generation embraces high-fidelity lidar sensors and an onboard unit (OBU). All Gen II sensors are newer, more advanced, and accurate and have a longer perception range than the Gen I sensors. A key feature of the Gen II sensor package is providing layers of redundancy to one another. The perception algorithms frequently cross-check the data from different sensors to ensure that no object is left undetected and to eliminate false positives.

This sensor package manifests as a mature sensor fusion technology that is able to combine the sensing capabilities of multiple sensors, resulting in more reliable and robust perception with a broad sensing scope. To this end, the underlying perception algorithms for processing the data are more advanced and are capable of performing complex sensor fusion calculations enabling the operation in an expanded ODD and deployment context. Another envisioned key feature of this generation of sensors is integrating V2V and vehicle-to-infrastructure (V2I) communication within the vehicles through the OBU. This would provide opportunities for the vehicle to receive real-time dynamic data for weather, work zones, and traffic. The new advanced sensor suite will allow trucks to operate effectively on more road types, such as four-lane divided highways, in more severe weather, and on roadways with imperfect lane markings and signage.

Table 32 provides a qualitative assessment of the technology state of the different sensor package generations. The table highlights the key functional and technical differences between the two generations as well as the operational atmospheric conditions.

Infrastructure Needs and Impacts

The features will assist the driver navigating a highway. The sensors on board the vehicle need to detect infrastructure elements, such as lane markings, barriers, and signs, to determine proper heading and speed. The infrastructure requirements for this feature are largely driven by challenges in human factors, connectivity, and limits to ADS perception technology.

To increase functionality and efficiency of ADS-equipped truck features, ADS-equipped truck ports (ATPs) may need to be constructed near interstates. At ATPs, drivers operating locally can swap trailers to automated tractors optimized for highway driving. Likewise, highway-optimized trucks can swap trailers to human-driven trucks for last mile and urban delivery where driverless operations are more complex (Figure 19).

The feature uses more advanced technologies compared to existing platooning technologies, including radar, cameras, and dedicated short-range communication, which may have challenges perceiving certain aspects of infrastructure. Vision is predominantly used to detect lane markings and signage; therefore, it is important that they are as machine readable as possible.

Table 32. Scenario technological specifications of ADS-equipped trucks.

Scenario	Scenario Technology State Comparison		
	Qualitative Assessment of Technology State	Operational and Atmospheric Conditions	Key Functional and Technical Differences
Gen I	• Higher-priced vehicles. • Less sophisticated algorithms, making driverless mode active less often. • Communication with other vehicles.	• Weather: clear, wind.	• V2V communications.
Gen II	• Lower-priced vehicles. • More sophisticated algorithms, making driverless mode active more often. • Communication with vehicles and roadway infrastructure.	• Weather: clear, wind, rain.	• Lidar. • V2X communications.

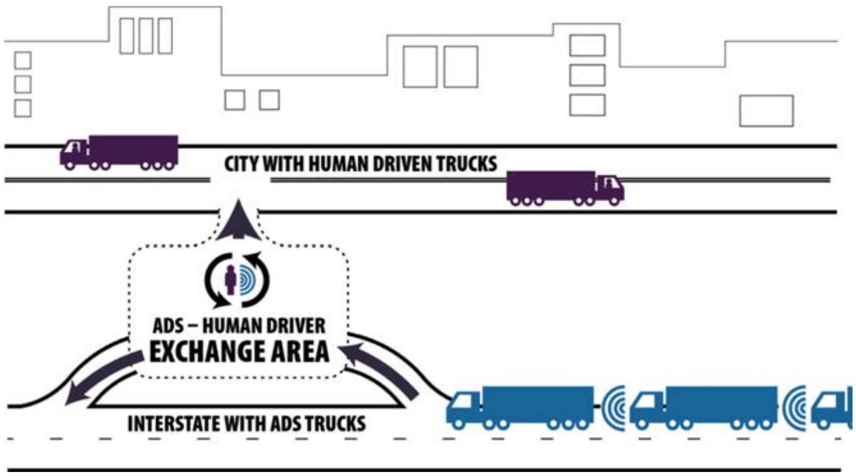


Figure 19. What an ADS-equipped truck port could look like (Source: Adopted from Viscelli, 2018).

Cameras are an important part of perceiving the road structure and signage and classifying objects. Cameras do not perform well in precipitation and fog and are dependent on ambient light to detect infrastructure components. Therefore, AV deployment of ADS applications will benefit from efforts to make infrastructure more easily perceived by machine vision in a variety of lighting and weather conditions, such as lane markings that are wider, higher contrast, more retroreflective, and well maintained.

Risk Assessment

Risks

- A major risk is navigating the "machine-to-human handover," when the technology requests to hand back control to the human. Since it is irresponsible for the technology to simply signal to the human, "Here, you take over," it is evident there must be a transition time following the handover request for the human driver to regain proper situational awareness.
- Relatively low numbers of units are sold by truck manufacturers (Viscelli, 2018).
- Lateral wandering of ADS-equipped trucks is much narrower than for human-driven trucks. Pavement fatigue in turn increases the risk of hydroplaning (Zhou et al., 2019).
- Labor opposition due to job loss.
- Training needs on ADS and ATP use.

Opportunities

- ADS-equipped truck driving is a promising technology that could bring great benefits to society and road users. In fact, the wide benefits achieved by self-driving trucks (e.g., increased hours of operations and road capacity) are expected to be the main reason for expanding the market of this feature more rapidly than other features for passenger cars.
- Unlike with cars, there is already high demand for ADS-equipped trucks. Because of the labor savings of autonomy and because trucks are bought as business decisions thoroughly evaluated by fleets, ROI on ADS-equipped trucks is expected to be high (Viscelli, 2018). In 2013, Moran Stanley estimated that ADS-equipped trucks would provide $168 billion in savings.
- Implementing ATPs will provide a host of benefits to both industry and drivers that are at risk from automation. ATPs can be built in strategic locations near interstate exits and truck

parking lots outside congested urban areas. ATPs not only allow trailer switching, but also provide driver facilities and refueling and charging stations. ATPs could facilitate off-peak deliveries to reduce road congestion and cut down on the coordination between shippers and carriers. Efficiency could be greatly enhanced through a ride-sharing style service that matches drivers and freight through an app with real-time pricing, keeping wages and work opportunity high (Viscelli, 2018).

- In the future, many trucks with ADS capabilities will likely be electric. In the United States, the transportation sector is responsible for almost 30% of annual GHG emissions (US EPA, 2019). Battery electric vehicles (BEV), however, have been shown to reduce overall GHG emissions and pollution relative to vehicles with an internal combustion engine and could greatly reduce the need for oil (Delucchi et al., 2014; Lattanzio and Clark, 2020). Transferring emissions from the tailpipe to power-generating plants also further centralizes total emissions in the power production sector where measures such as carbon capture and sequestration and a cleaner fuel mix could contribute to reduced overall emissions. Additionally, BEV engines are inherently more energy efficient than internal combustion engines and can increase energy efficiency further by making use of "energy recovery" technology where breaking and unaccelerated motion act to recharge the battery (Delucchi et al., 2014; Manzetti and Mariasiu, 2015). Also, this feature eliminates the need for a highly skilled driver in following trucks, which could bring shipping costs down when platooning is deployed at a large scale.
- ADS-equipped trucks could positively impact other road users by offering safety benefits when applied at a large scale by reducing or eliminating truck driver errors, at least for the portion of the trip that is operated by the ADS-equipped truck.
- ADS-equipped trucks will provide significant safety benefits due to changes in operating hours and reduction of human error. ADS-equipped trucks will likely operate during off-peak hours, reducing traffic congestion and its associated crashes due to fewer interactions with passenger vehicles. ADS-equipped trucks will help reduce driver fatigue and human errors, which are associated with 94% of serious crashes (NHTSA, 2019).

Step 4—Define Safety Goals and Hypothesis

For the deployment scenario of ADS-equipped trucks, the goal is to reduce the frequency and severity of truck-involved crashes through the use of ADS-equipped trucks (SAE Levels 3 and 4) and supporting infrastructure. The overall hypothesis is that ADS-equipped trucks will improve safety on I-81 by reducing truck-involved crashes during non-adverse weather conditions. The expected change in the number and percentage of truck-involved crashes will depend on market penetration and the ability of the technology to mitigate certain crash types and events, which are explored in the analysis.

The questions to evaluate the overall hypothesis are listed below and relate to crash types, crash severity levels, infrastructure, and data.

1. How will the frequency of truck-related crashes change? It is anticipated that ADS-equipped trucks will impact the frequency of truck-related and truck-involved crashes.
2. How will the severity of truck-related crashes change? ADS-equipped trucks will traverse roads differently than human-driven trucks (e.g., different speeds, ability to stay within lane, etc.). The different driving behavior could alter the severity of truck-involved crashes.
3. How will the frequency of non-truck-related crashes change? While it is anticipated that the frequency of truck-related crashes will decrease, the frequency of non-truck-involved crashes could also change. For example, if truck-involved maneuvers contribute to other vehicle crashes, and ADS-equipped trucks can avoid or reduce these types of maneuvers, then there

is the potential to reduce crashes in which the truck is not one of the vehicles involved in the crash. Conversely, if ADS-equipped trucks can detect and react to situations faster than human-driven vehicles, this could lead to a potential increase in rear-end crashes, particularly if the large trucks limit forward sight distance for following vehicles. This leads to a follow-up question: How can forward collision avoidance in passenger cars mitigate this potential risk?

4. Will safety of ADS-equipped trucks change if the ODD is extended in which ADS-equipped trucks can operate? For example, the anticipated ODD for ADS-equipped trucks is currently higher classifications of roads (e.g., interstates, freeways, etc.).

In summary, through the deployment of ADS-equipped trucks, it is hypothesized that the frequency and severity of truck-related crashes will be reduced by 5–10%. The hypothesized reduction can be based on previous research or crash reduction goals of a specific agency. While this provides an overview of potential safety impacts, it is important to perform a crash sequencing exercise to think through the contributing factors and precipitating events that lead to a crash. The following are a few examples related to truck-involved crashes along the interstate.

1. Run-off-road:
    a) Driver of truck is distracted, falls asleep, or is otherwise inattentive and the vehicle drifts off the road.
    b) Driver of truck is fully attentive and adverse weather contributes to driver losing control or incorrectly navigating and the vehicle leaves the road.
    c) Driver of truck is fully attentive and sudden congestion leads to an evasive maneuver whereby the driver attempts to avoid the back of queue and the vehicle leaves the road.
2. Rear-end:
    a) Driver of truck is distracted, falls asleep, or is otherwise inattentive and the truck rear-ends another vehicle.
    b) Driver of truck is fully attentive and adverse weather contributes to limited stopping distance whereby the driver is not able to stop or slow and the truck rear-ends another vehicle.
    c) Driver of truck is fully attentive and sudden congestion leads to unanticipated braking whereby the driver attempts to stop, but the truck rear-ends another vehicle.

From the anticipated capabilities of ADS-equipped trucks and the above crash sequencing, the project team identified specific opportunities for ADS-equipped trucks to mitigate crashes. For example, ADS-equipped trucks are not expected to operate in adverse conditions, so there is limited potential to mitigate crashes related to sequence 1b; however, ADS-equipped trucks are expected to provide opportunities to mitigate crashes related to sequence 1a and 1c. Similarly, ADS-equipped trucks are not expected to mitigate crashes related to sequence 2b but are expected to mitigate crashes related to sequence 2a and 2c. A similar exercise could be completed for forward collision avoidance in passenger cars. The analyses in Step 5 explore the specific crashes that could be mitigated by ADS-equipped trucks and forward collision avoidance in passenger cars.

Step 5—Choose Analysis Methodology

Data Sources

VDOT provided historical crash data from 2014 through 2020 for Virginia. Variables in the crash data included severity, collision type, road surface condition, weather, and an indicator for truck-related crashes. The project team filtered the data to include crashes in the study area along I-81 from milepost 110 to milepost 150. Table 33 displays a summary of the crashes that occurred along the study corridor by year and severity, Table 34 displays the crashes by collision type, and Table 35 displays the crashes by weather condition when the crash occurred. As shown in the tables, crashes are generally increasing throughout the study period with a dip in 2020. Rear-end crashes are the most prevalent type for total crashes, which is consistent with the

Table 33. Crashes along I-81 from milepost 110 to 150 by year and severity (2014–2020).

Year	Fatal Injury	Suspected Serious Injury	Suspected Minor Injury	Possible Injury	Property Damage Only	Total
2014	1	20	53	7	282	363
2015	2	17	62	10	327	418
2016	4	22	67	11	370	474
2017	5	21	67	12	363	468
2018	3	25	82	17	468	595
2019	4	16	86	7	447	560
2020	7	15	49	10	319	400
Total	**26**	**136**	**466**	**74**	**2,576**	**3,278**

Table 34. Crashes along I-81 from milepost 110 to 150 by collision type (2014–2020).

Collision Type	Total Crashes	Total Truck-Involved Crashes	Truck-Involved Fatal Crashes	Truck-Involved Injury Crashes	Truck-Involved PDO Crashes
Rear end	1,246	330	7	96	227
Angle	156	90	3	23	64
Head on	4	1	0	1	0
Sideswipe—same direction	512	362	0	67	295
Sideswipe—opposite direction	4	2	0	0	2
Fixed object in road	22	2	0	0	2
Non-collision	53	16	0	5	11
Fixed object—off road	859	142	4	32	106
Deer	363	20	0	3	17
Other animal	28	2	0	0	2
Pedestrian	1	1	0	1	0
Backed into	10	7	0	0	7
Other	20	4	7	0	4
Total	**3,278**	**979**	**14**	**228**	**737**

Note: PDO = property damage only.

Table 35. Crashes along I-81 from milepost 110 to 150 by weather condition (2014–2020).

Weather Condition	Total Crashes	Total Truck-Involved Crashes
No adverse condition (clear/cloudy)	2,492	763
Fog	19	7
Mist	36	9
Rain	510	136
Snow	162	51
Sleet/hail	57	13
Other	1	0
Severe crosswinds	1	0
Total	**3,278**	**979**

input from VDOT and the recurring congestion issues. Rear-end crashes are the second most prevalent type for truck-involved crashes, second only to sideswipe, same-direction crashes. In total, 979 crashes (30% of total crashes along the study corridor) involved a large truck, and 330 rear-end crashes (26% of rear-end crashes along the study corridor) involved a large truck. The majority of total crashes and crashes involving a large truck occurred during no adverse weather conditions (76% of total crashes and 78% of large-truck-involved crashes), which is followed by crashes occurring during rain (16% of total crashes and 14% of truck-involved crashes).

Evaluation Method

The project team used the study corridor crash data to analyze two scenarios related to the number of trucks with ADS capabilities and the number of passenger vehicles with forward collision avoidance. The hypothetical scenarios are:

- **Scenario 1:** Various percentages of ADS-equipped trucks (5, 25, and 50%) in the fleet with no passenger vehicles equipped with forward collision avoidance. This scenario is expected to impact crashes that involve large trucks as the at-fault vehicle.
- **Scenario 2:** Various percentages of ADS trucks (5, 25, and 50%) in the fleet with various percentages of passenger vehicles equipped with forward collision avoidance (5, 25, and 50%). This scenario is expected to impact rear-end crashes that involve passenger cars and large trucks where the passenger car is the trailing vehicle. This scenario is expected to build on the crash reduction in Scenario 1 to include a reduction in rear-end crashes due to passenger vehicles with forward collision avoidance. According to FMCSA (2020), from 2016 to 2018, 78.5% of large trucks in rear-end fatal crashes with passenger vehicles occurred when the passenger vehicle rear-ended a large truck; 57.1% of large trucks in rear-end injury crashes with passenger vehicles occurred when the passenger vehicle rear-ended a large truck; and 45.3% of large trucks in rear-end property damage only crashes with passenger vehicles occurred when the passenger vehicle rear-ended a large truck.

The various percentages serve as a sensitivity analysis to explore assumptions related to penetration rates and probabilities that a truck is autonomous and, if it is autonomous, that the autonomous feature is activated and functions properly. Similarly, this serves as a sensitivity analysis to explore assumptions related to penetration rates and probabilities that a passenger vehicle is equipped with forward collision avoidance, and if it is equipped, that the feature is activated and functioning properly.

Crash reductions were calculated for the scenarios using the equation below. The change in crashes is calculated by subtracting the crashes ADS-equipped vehicles can impact from the total number of crashes for the given years. The following equation shows the change in crashes as a percent change, where a positive percent change indicates a safety benefit, and a negative change indicates an increase in crashes.

$$\text{Percent crash reduction} = \left[1 - \left(\frac{(\mathit{Total\ crashes}) - (\mathit{Crashes\ impacted\ by\ ADS\ feature})}{(\mathit{Total\ crashes})}\right)\right] \times 100$$

Eq. 6

Results

Scenario 1

The project team filtered the crash data to contain only crashes that involved a large truck and only crashes that occurred during clear or cloudy conditions (i.e., no adverse weather conditions). Those crashes were used to estimate the number of potential crashes reduced or eliminated due to various percentages of ADS-equipped trucks in the fleet and no change to passenger vehicles, as shown in Table 36. Table 36 assumes that all ADS features are 100% effective all of the time for the conditions of interest (i.e., truck-related crashes in non-adverse weather conditions). However, it may be more realistic to assume an effectiveness less than 100% to account for ADS features that may not mitigate certain crashes.

Results indicate that the greater the percentage of ADS-equipped trucks along the study corridor, the greater the potential reduction of truck-involved crashes during no adverse weather conditions and the greater the potential reduction in the percentage of total crashes. Five percent of ADS-equipped trucks in the fleet result in an expected 1% total crash reduction; 25% of ADS-equipped trucks in the fleet result in an expected 6% total crash reduction; 50% of ADS-equipped trucks in the fleet result in an expected 12% total crash reduction. These results can be used to identify potential safety benefits of ADS-equipped trucks for various penetration rates and as the expected number of trucks with ADS capabilities increases over time.

While total crashes may decrease with the onset of ADS-equipped trucks in the vehicle fleet, specific crash types may increase with the use of ADS features, such as rear-end crashes (Petrovic

Table 36. Truck-involved crash reduction by severity for various percentages of ADS-equipped trucks during no adverse weather conditions (2014–2020).

% ADS-Equipped Large Trucks	Fatal Injury Truck-Involved Crashes	Suspected Serious Injury Truck-Involved Crashes	Suspected Minor Injury Truck-Involved Crashes	Possible Injury Truck-Involved Crashes	Property Damage Only Truck-Involved Crashes	Potential Truck-Involved Crashes Reduced	% Total Crashes Reduced
5	1	2	6	1	29	38	1
25	3	9	28	5	146	191	6
50	7	19	56	10	292	382	12

Table 37. Rear-end truck-involved crashes increase when passenger vehicle rear-ends a large truck by severity for various percentages of ADS-equipped trucks during no adverse weather conditions (2014–2020).

% ADS-Equipped Large Trucks	Fatal Injury Truck-Involved Rear-End Crashes	Suspected Serious Injury Truck-Involved Rear-End Crashes	Suspected Minor Injury Truck-Involved Rear-End Crashes	Possible Injury Truck-Involved Rear-End Crashes	Property Damage Only Truck-Involved Rear-End Crashes	Expected Increase in Truck-Involved Rear-End Crashes	% Total Crashes Increased
5	0.1	0.1	0.3	0.0	1.1	2	0.1
25	0.4	0.7	1.7	0.2	5.3	8	0.3
50	0.7	1.3	3.5	0.5	10.5	17	0.5

et al., 2020). Table 37 displays a potential increase in truck-involved rear-end crashes due to ADS-equipped trucks in the fleet, assuming a 27% increase in rear-end crashes when ADS-equipped trucks are in the fleet. This increase includes rear-end truck-involved crashes where the passenger vehicle rear-ends a large truck. As previously mentioned, 78.5% of fatal rear-end crashes involving a large truck occur when passenger vehicles rear-end a large truck; 57.1% of injury rear-end crashes involving a large truck occur when passenger vehicles rear-end a large truck; and 45.3% of property damage only rear-end crashes involving a large truck occur when passenger vehicles rear-end a large truck.

Five percent of ADS-equipped trucks in the fleet result in an expected 0.1% increase in total crashes; 25% of ADS-equipped trucks in the fleet result in an expected 0.3% increase in total crashes; 50% of ADS-equipped trucks in the fleet result in an expected 0.5% increase in total crashes.

Scenario 2

The project team also analyzed the crash data to estimate potential crash reductions due to both ADS-equipped trucks in the fleet (Scenario 1) and passenger vehicles with forward collision avoidance. Table 38 shows the estimated number of truck-involved rear-end and run-off-road crashes reduced or eliminated due to various percentages of passenger vehicles with forward collision avoidance along the study corridor during no adverse weather conditions. These numbers include rear-end crashes where a passenger vehicle rear-ends a large truck. Run-off-road

Table 38. Rear-end crash reduction where passenger vehicle rear-ends a large truck by severity for various percentages of passenger vehicles with forward collision avoidance during no adverse weather conditions (2014–2020).

% Passenger Vehicles with Forward Collision Avoidance	Fatal Injury Truck-Involved Rear-End Crashes	Suspected Serious Injury Truck-Involved Rear-End Crashes	Suspected Minor Injury Truck-Involved Rear-End Crashes	Possible Injury Truck-Involved Rear-End Crashes	Property Damage Only Truck-Involved Rear-End Crashes	Expected Decrease in Truck-Involved Rear-End Crashes
5	0.3	0.5	1.3	0.2	3.9	6.2
25	1.4	2.4	6.4	0.9	19.7	30.8
50	2.7	4.9	12.8	1.7	39.5	61.6

Table 39. Crash reduction by severity for various percentages of ADS-equipped trucks and passenger vehicles with forward collision avoidance during no adverse weather conditions (2014–2020).

% ADS-Equipped Large Trucks	% Passenger Vehicles with Forward Collision Avoidance	Fatal Injury Crashes	Suspected Serious Injury Crashes	Suspected Minor Injury Crashes	Possible Injury Crashes	Property Damage Only Crashes	Total Crashes	% Total Crashes Along Study Corridor Reduced
5	5	0.9	2.2	6.5	1.1	32.0	42.7	1
	25	1.9	4.1	11.6	1.8	47.8	67.3	2
	50	3.3	6.6	18.1	2.6	67.6	98.1	3
25	5	3.2	9.1	27.3	4.7	144.4	188.7	6
	25	4.3	11.0	32.4	5.4	160.2	213.3	7
	50	5.6	13.4	38.9	6.2	179.9	244.1	7
50	5	6.0	17.7	53.3	9.2	284.9	371.2	11
	25	7.1	19.6	58.5	9.9	300.7	395.8	12
	50	8.5	22.0	64.9	10.8	320.4	426.6	13

crashes that could be the result of drivers trying to avoid a rear-end crash with a truck should be included, but this level of detail is not readily available in the current data (i.e., no information that a passenger car was following a large truck before the vehicle left the road). If that information was available, the research team would have included run-off-road crashes from 7 a.m. to 7 p.m. along I-81 between milepost 140 and 150, which represent common congested conditions in the Roanoke area.

The estimated reduction in truck-involved rear-end crashes due to passenger vehicles with forward collision avoidance (Table 38) is combined with the estimated crash reduction due to ADS-equipped large trucks in the fleet (Table 36) and the estimated rear-end crash increase (Table 37), as shown in Table 39. Results indicate that as the percentage of ADS-equipped trucks and passenger vehicles with forward collision avoidance in the fleet increases, the greater the estimated total crash reduction along the study corridor. These results can be used to quantify potential safety benefits of ADS-equipped trucks and vehicles with forward collision avoidance and quantify how the safety benefits change as more vehicles on the road have ADS capabilities.

Step 6—Communicate Outcomes

The analysis supports the goals and hypotheses of the safety impacts of ADS-equipped trucks and vehicles with forward collision avoidance. Through the framework process and analysis of the data, the results indicated that truck-involved crashes and rear-end crashes are expected to decrease in frequency with the deployment of ADS-equipped trucks and vehicles with forward collision avoidance. Additionally, safety is expected to continue to improve if the extent of the ODD expands in which ADS-equipped trucks and vehicles with forward collision avoidance can operate.

However, to test the hypothesis and related questions, assumptions were made to estimate the safety impacts of ADS-equipped trucks. Regarding the ODD facility conditions, the technology requires dedicated or separated trucking lanes. However, these lanes are not readily found in existing road networks or explicitly identified in road databases. The analysis assumed that the road network for the facilities of interest had dedicated, separated trucking lanes. Another assumption relates to the condition of pavement markings needed for the operation of ADS-equipped trucks. At present, pavement markings need to be in excellent condition. The analysis was performed under the assumption that the roadways included in the analysis had pavement markings in excellent condition. The roadway databases used for the ADS-equipped truck analysis do not have information about pavement marking condition, which is typical for these databases.

CHAPTER 5

Conclusion

This report provides practitioners (e.g., transportation infrastructure owners, safety agencies, and ADS manufacturers) with a safety assessment framework to use in safety planning, design, operational, and investment decisions on multimodal infrastructure. The framework accounts for multiple timelines and is developed so that it can be easily applied by practitioners through a series of successive steps.

The first step is identifying the ADS feature that agencies would like to assess. The second step is to understand different aspects of the ADS feature such as functionality and expected market penetration rates. The third step is to envision the possible deployment scenarios for the feature. This step builds on data and information shared by car manufacturers and technology companies regarding the operational design domain (ODD) of the feature and the possible timelines of deployment. As part of defining the deployment scenarios, it is important to understand the technology and its infrastructure dependencies, which helps to recognize the associated risks and opportunities. With the scenarios identified, the fourth step is to define safety goals and the associated hypothesis. The fifth step involves the identification of data sources and metrics to help evaluate the stated hypothesis. The analysis method is also chosen during this step to derive insights from the data. Upon completion of the analysis, the results are interpreted to understand the safety impact of the ADS feature and to inform related decisions.

The report shows the practical application of the framework by summarizing the results of a proof-of-concept study that involved piloting the framework in partnership with two state departments of transportation. One study evaluated a low-speed shuttle scenario in Minnesota, and the other evaluated the potential deployment of ADS-equipped trucks in Virginia's I-81 corridor.

Appendix B demonstrates how the framework could be applied for three additional ADS applications, namely, conditional traffic jam assist, highway truck platooning, and fleet-operated automated driverless vehicles. The framework is applied for two different planning horizons: the short term (0–5 years) and the medium term (5–10 years). It is worth mentioning that four of the five features discussed are envisioned to follow a high-disruption scenario and the numbers in Chapter 4 reflect this assumption. Though this seems to be a reasonable assumption for some jurisdictions, it may not be the same for others. ADS adoption will likely be uneven, both geographically and temporally, and different jurisdictions may experience different disruption levels. Therefore, it is recommended that practitioners review their jurisdictional and institutional goals and policies to identify the possible level of disruption based on the factors mentioned in Chapter 3 (customer acceptance, willingness to pay, policy and regulation, and willingness to share).

The infrastructure owners and operators should be aware that their infrastructure condition and investment plans are a key factor for expanding the ODD defined by vehicle manufacturers in the short term. For instance, investing in the infrastructure to maximize the portions of the network that are with good pavement, marking, and signage conditions would maximize the ODD of the fleet-operated automated driverless vehicles in the near term, which would translate into saving more lives in the near term. However, as they invest in the key infrastructure elements to enable a particular scenario or deployment level, they need to be aware that car manufacturers are regularly upgrading their technologies. The manufacturer's goal is providing a driverless vehicle that is capable of navigating the roads with minimal reliance on upgrades to infrastructure, typically, capable of navigating roads with adequate infrastructure (roads that can be navigated by human drivers).

State and local agencies should be aware that ADS-equipped vehicles, particularly the Level 4 and Level 5, generate massive amounts of high-resolution data that can be applied in various aspects of the vehicle's operation (safety research, safety assessment, etc.). Collaboration and data sharing between different car manufacturers could provide better opportunities for enhancing safety. However, driverless car manufacturers or startups are not willing to share data nor collaborate, mainly because of the proprietary nature of ADS development and relevant intellectual property. There is also little data sharing between developers and regulators or researchers.

State and local agencies looking to accommodate ADS features on their roads should consider the landscape of the driverless vehicles industry. They will have to consider what level of information to be mandated for disclosure or sharing by the manufacturers and what are the possible ways to audit the reported data without compromising the intellectual property of the manufacturer. For example, California, by law, mandates all companies that are actively testing Level 4 driverless vehicles on California public roads to disclose the number of miles driven and the frequency in which human safety drivers were forced to take control of their autonomous vehicles (Autonomous Vehicle Disengagement Reports). Manufacturers are also required to provide the California Department of Motor Vehicles with Traffic Collision Involving an Autonomous Vehicle (form OL 316) within 10 days after the collision (Autonomous Vehicle Collision Reports). Once these driverless vehicles are commercially deployed at wide scale, these reports could provide valuable data for refining the framework results.

The framework presented in this report was developed considering three aspects: usability (e.g., is the framework intuitive and approachable by the target audience), practicality (e.g., does the framework allow agencies to assess current questions), and data availability (e.g., do current data capabilities limit the application of the framework). This framework was refined throughout the course of this project based on feedback from stakeholder engagement (obtained in research Phase 3) and the proof-of-concept pilots (obtained in research Phase 4).

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APPENDIX A

Factors Considered for Estimating ADS Market Penetration

Deployment Pattern

Forecasting the timeline for penetration of automated driving system (ADS) technologies is significantly complicated by the rapidly emerging nature of ADS development, as well as the flood of information and hype created by individual automakers/developers, each contending with market and shareholder pressures to accelerate their timeline to market. Based on the literature review, technology innovations generally follow a predictable S-curve deployment pattern, as illustrated in Figure A-1. As the figure shows, the deployment pattern follows the following phases: development, testing, approval, commercial release, product improvement, market expansion, differentiation, maturation, and eventually saturation and decline (Litman, 2019). ADS technology will probably follow this pattern.

Cost

According to previous studies on ADS cost and market penetration, about 24% of consumers would be willing to pay an additional $4,000 for an ADS feature, while 17% would be willing to pay more than $5,000 for a fully automated vehicle (AV) (Mosquet et al., 2015). The surveyed consumers indicated a lack of clear preference toward a specific feature. However, the consumers expressed a more intense level of interest in ADSs compared to electric vehicles (EVs) prior to their deployment, providing an indication of a more rapid and prevalent ADS deployment compared to the slow EV deployment. Depending on the ADS feature, the price after launch is expected to decrease by a compound annual rate of about 4% to 10% due to original equipment manufacturers (OEMs) benefiting from the economies of scale of the ADS market.

Public Acceptance

Public acceptance of ADSs is an essential factor to consider in conjunction with the willingness to pay and could be a barrier for expanding the market of ADS features. While many studies (AAA, 2019; Hewitt et al., 2019) documented a lower intention for drivers to use ADS features, the majority of these studies confirmed that this attitude was specific toward full and higher levels of automation (Level 4/Level 5). Additionally, a recent study (Penmetsa et al., 2019) reported that as the public interacts with ADSs, their acceptance and perception toward the technology are more likely to be positive. In this study, respondents interacting directly with ADSs reported significantly higher expectations of the benefits of ADSs than those not interacting with ADSs. In fact, the study recommended that policymakers should provide opportunities for the public to have interaction experience with ADSs.

Figure A-1. Innovative technology deployment trend (Source: Adapted from Litman, 2019).

Fleet Turnover Rates

Studies have shown that consumers who are willing to pay more than $5,000 will be the primary customers for ADS features and will move the ADS market forward in the early stages of ADS features deployment (Mosquet et al., 2015). Since OEMs will later benefit from the ADS market economies of scale and based on the consumer willingness to pay survey, it is expected that the ADS market (partially and fully AV) will blossom until it reaches a penetration rate of around 29% over the next 10 to 15 years. The number of cars and light trucks expected to be on U.S. roads in 2030 and 2035 is about 290 million and 300 million vehicles (https://news.nationalgeographic.com/2017/09/electric-cars-replace-gasoline-engines-2040/), respectively, and the projected annual sales of the U.S. car market would be about 17 million vehicles. Extrapolating from these figures, this could take anywhere from 58 to 60 years during the period from 2030 to 2035 for the entire fleet to turn over to become automated. Another study anticipates that ADS technologies would normally require 3 to 5 decades to penetrate 90% of vehicle fleets (https://www.vtpi.org/avip.pdf).

Policy and Regulation

The timeframe for AV deployment will depend not only on technology readiness, but on regulatory activities at various levels of government and in countless jurisdictions around the nation; the response of the insurance industry in terms of shifting liability; initial cost of the technology; and, of course, infrastructure dependencies.

Some ADS features are commercially available and deployed in vehicles that are certified to operate on the road by customers (such as autopilot); policy barriers should be minimal for these ADS features. Other features, however, are not yet commercially available (such as conditional automated highway drive) or have been deployed only as a proof of concept (such as platooning). Some of these features might face policy or regulation barriers on either the federal or state levels before being made available for commercial use. It is worth noting that a major influence on the deployment rates is the pace of modernizing existing federal regulations and standards to be more flexible, responsive, and technology-neutral for accommodating the rapid pace of innovations in ADS. Specifically, major changes are needed for safety standards at the federal level to accommodate the development, testing, and sale of certain ADS features within specific Level 4 and Level 5 vehicle design. The different paces at which these regulatory challenges will be addressed would result in different deployment timelines and rates.

Proportion of Shared HAVs in the Fleet

According to several articles documenting automaker announcements regarding the timeline for introducing highly automated vehicles (HAVs; Levels 4 and 5) (http://www.businessinsider.com/google-apple-tesla-race-todevelop-self-driving-cars-by-2020-2016-4/; https://www.cbinsights.com/research/autonomous-driverless-vehicles-corporations-list/), the first phase of deploying these vehicles will probably occur from 2020 to 2021. During the early deployment stages of HAVs, the car manufacturers will primarily target transportation network companies (TNCs) with large fleets. Large-fleet companies will be able to afford the HAV at early deployment and will be the key players for expanding the HAV market. In an early response to these facts, automakers and TNCs have been forging corporate coalitions to reserve a decent share of what is expected to be a multibillion-dollar market by 2030. For instance, in 2017, Volvo announced a 3-year deal to supply up to 24,000 robo-taxis to Uber, with the vehicle shipment expected to start during 2019. On the other hand, Lyft began partnering with General Motors earlier in 2016 to develop HAVs. Lyft pursued further collaboration by making two separate pacts in 2017 with Ford and Waymo, respectively, for collaboration on HAVs.

Accordingly, the market of TNCs and shared mobility is expected to grow rapidly, with the introduction of HAVs reaching $173.15 billion by 2030 with shared mobility services contributing to 65.31% (Frost and Sullivan, 2018). These cascade trends and partnerships are expected to reshape the transportation sector and trigger a disruptive change to the transportation industry, probably the largest ever in transportation history. For instance, by 2030 the traditional process for buying or renting a car could be replaced by a subscription system operated by TNCs and fleet managers. These systems would offer a variety of ride-hailing plans covering the different types of subscriber trips (e.g., work, errands, recreational). Discount would be offered for subscribers affiliated with the TNC on long-term agreements to a level that makes the cost per mile traveled using these services much cheaper and convenient than the cost and satisfaction per mile traveling using private cars. Assuming these scenarios, parking lots are expected to shrink across the United States and gradually be replaced with electric charging stations.

Proportion of Total VMT

Many studies suggest that automating the dynamic driving task would make traveling more convenient and travelers would be capable of making better use of their time, which will eventually increase the vehicle miles traveled (VMT). ADS-equipped vehicles are likely to increase total VMT. Some researchers estimate that the VMT will increase between 15% and 59% (Soteropoulos et al., 2019). Also, annual mileage tends to decline as the vehicles age. For example, 2001 vehicles averaged approximately 15,000 miles their first year, 10,000 miles their 10th year, and 5,000 miles their 15th year, so vehicles older than 10 years represent about 50% of the vehicle fleet, but only about 20% of vehicle mileage (Oak Ridge National Laboratory, 2012; Litman, 2015). Therefore, from a planning perspective, it is also imperative to have an estimate for the anticipated contribution of ADS to the total VMT in addition to estimating the envisioned ADS market penetration.

APPENDIX B

Additional Example Scenarios

This appendix provides analytical examples for applying the framework to three prominent ADS features that are envisioned, namely, conditional traffic jam assist, highway platooning, and fleet-operated automated driving system–dedicated vehicle (ADS-DV). The following subsections apply the framework steps described in Chapter 3 to assess the safety impacts of the ADS features.

ADS Feature: Conditional Traffic Jam Assist

Understanding the ADS Feature

Feature Description

Level 3 conditional traffic jam assist (TJA) is a subsystem of adaptive cruise control (ACC) with extended lane-keeping assist functionality. The types of sensors needed by this feature and the feature's operating settings vary significantly depending on the offering manufacturer. However, the core of the different TJA systems operates on the same concept. Typically, the automated vehicle (AV) uses onboard sensors such as cameras, radars, and lidars to identify slow-moving traffic; once slow traffic is identified (less than 35 mph), the TJA engages. The AV then locks on to the vehicles in front within the same lane and handles the driving task such that the TJA-equipped AV stays about 3 seconds behind the vehicle ahead of it.

AVs equipped with TJA can assume certain steering tasks over a speed range up to 35 mph on roads that are in good condition, as long as the traffic is moving slowly. The system uses the AV sensors to guide the vehicle by making gentle steering movements within system limits and orients itself to lane markings, roadside structures, and other vehicles on the road. For this feature, a human operator is the fallback for the dynamic driving task. When TJA operates beyond its operational design domain (ODD) or system limits (see "Operational Design Domains" in Chapter 3 for details), such as when the traffic speed is above 35 mph; lane markings are not clear; or there is a sharp curve ahead, inclement weather, or poor lighting, the driver must assume driving tasks again. If the driver does not, the system warns the driver in several stages, and as a final measure, it would engage an emergency assist, bringing the car to a safe stop. TJA performance can be affected by inclement weather, poor lighting, and poor infrastructure conditions.

Expected Market

The Level 3 TJA was supposed to launch in the United States starting in 2019. A few years earlier, Audi announced the inclusion of a Traffic Jam Pilot driver-assist technical feature in the 2019 Audi A8 luxury sedan. Although Audi might be able to make this commitment to the European automotive market, Audi could not offer the feature in any of the 2019 U.S. models, primarily due to legislative barriers and some infrastructure challenges. The main infrastructure obstacle is the discrepancy among U.S. states in lane markings, signage, traffic signals, and road configuration. For instance, pavement markings, particularly skip lines, vary in width and length among states, making it difficult to develop a reliable system that is able to function accurately across the entire United States.

As this feature will be offered at the Level 3 automation level, drivers engaged in road jams are no longer required to keep their hands on the steering wheel or continuously monitor the vehicle and the road. They must only be alert and prepared to take over the task of driving when the system prompts them to do so. Unlike previous AV features offered (Tesla Autopilot, Cadillac Super Cruise, or Nissan Pro Pilot) where drivers are instructed to watch the road, this one does not require this. This raises concerns about whether the driver would be able to react promptly to the situation and take full control of the vehicle. Expectations of full and complete attentiveness of the driver in this model are unlikely. Hence, insurance companies might offer higher-than-average premiums for these vehicles. Audi mentioned concerns with the lack of clear federal regulations for autonomous driving technology and the absence of comprehensive federal standards. Audi believes state regulations make it impossible to sell these products nationwide. Several car manufacturers (Volvo, Ford, and Google, among others) expected the safety and policy concerns associated with Level 3 automation and decided to skip it and jump directly to Level 4 and Level 5 automation. In fact, Ford announced in 2018 that the company is finalizing its own TJA; however, Ford has offered no timeline for the debut, which is expected to be on a Level 4 vehicle.

Recently, Ford began investigating stepping back to the Level 3 automation, with the aid of cameras and other systems that can ensure drivers are paying attention at the wheel (Martinez, 2019). Researchers and drivers may argue that coupling the Level 3 features operation with the driver's continuous attention is contradicting the SAE definition (SAE, 2018) for Level 3 automation, where the driver is not required to be attentive to the driving task once the ADS is in control.

In this regard, the market of the Level 3 does not seem to be promising for expanding the deployment of ADS features. Specifically, all ADS features expected to launch on U.S. roads at Level 3 automation are susceptible to safety, policy, and regulations barriers. Although the policy and regulations barriers hold in the subsequent automation levels (4 and 5), it is anticipated that resolving these issues can be easier for highly automated vehicles (HAVs) (Levels 4 and 5). Further, the global TJA market (all automation levels) was estimated at $1.08 billion in 2016 and is expected to reach over $48 billion by 2026 (BIS Research, 2017). The baseline status of the automation market implies that the growth of the TJA market is likely to occur mainly at automation Level 2 until HAVs (Levels 4 and 5) are offered for commercial deployment. On the basis of these facts, and extrapolating from the forecasted market size for the Level 3, 4, and 5 vehicles until 2030 (McKinsey & Company, 2016; Frost and Sullivan, 2018), the project team projected the deployment scenarios for this feature to follow a low disruption pattern.

Table B-1 lists a few examples of the TJA features that are commercially deployed. According to currently available information, none of the car manufacturers offered their TJA feature as pure Level 3 in the feature's description in the user manual. In 2019, Audi reverted to promoting its TJA as a subsystem of ACC. For all of these features, car manufacturers are obligating drivers to stay 100% attentive to the roadway and to ensure that these features are operating within their specified ODD.

Anticipated Deployment Scenario

Operational Design Domain

Table B-2 summarizes the anticipated ODD elements of the conditional TJA. As discussed earlier, the ODD elements are predicted for two timelines, the short term (next 5 years) and

Table B-1. Examples of commercially deployed TJA features (Source: Mays, 2019).

Car Manufacturer	Traffic Jam Assist Feature
Audi	The closest production car to that reality was to be the new Audi A8, equipped with the new Traffic Jam Pilot feature capable of navigating highway gridlock while the driver performs secondary tasks (not relevant to driving), but regulatory hurdles forced Audi to sideline the system for US shoppers, at least for now. Currently, Audi is offering its TJA as a subsystem of the ACC. TJA can assume certain steering tasks over a speed range up to 35 mph on roads that are in good condition, as long as the traffic is moving slowly. The base ACC system accelerates and brakes to keep the vehicles at the desired distance from the vehicle ahead.
BMW	BMW's ACC that operates all the way to a stop goes by Active Cruise Control with Stop & Go™. One step beyond that, Active Lane Keeping Assist with Side Collision Avoidance constitutes hands-on, lane-centering steering that can work down to a stop in certain traffic conditions. Finally, Extended Traffic Jam Assistant (ETJA) is a new feature available on the redesigned 3 Series and X5 plus the new 8 Series and X7. ETJA enables hands-free driving at low speeds on divided highways as long as the driver is paying attention, something the car intuits with a driver-facing camera.
Mazda	Mazda Radar Cruise Control with Stop and Go. The redesigned Mazda 3 has a TJA system with low-speed lane-centering steering, but Mazda did not offer the feature in the US market for 2019.
Acura	Depending on the car, AcuraWatch includes a Lane-Keeping Assist System, ACC with Low-Speed Follow, or both. Meanwhile, the RLX and RLX Sport Hybrid add TJA that incorporates lane-centering steering down to a stop.

the medium term (next 5 to 10 years). In addition, the table outlines the major deployment specifications envisioned for the feature that are expected to affect the safety assessment of the feature. The deployment elements are also provided for the two timelines.

Table B-3 provides a summary of the technology specifications and key infrastructure needs pertinent to the envisioned TJA scenarios.

As shown in Table B-3, the vehicle is expected to rely on different generations of sensor packages during the different planning horizons. Typically, Gen I is envisioned to persist during the short-term planning horizon while Gen II of the sensor package is expected to take over during the medium-term planning horizon. A detailed description of each of the anticipated scenarios, in terms of technology and infrastructure needs, follows.

Stage of Technology Development

- *First Generation (Gen I):* This is the first version of TJA technology and sensor package and their underlying computational algorithms for processing the data. Typically, this package embraces the needed combination of sensors such as forward-facing cameras, radar, ultrasonic sensors, laser scanners, and inertial measurement unit (gyroscopes and accelerometers) with *a priori* digital maps (lane-level detail). This package will not have a good object detection capability in low-visibility conditions, limiting the ODD to certain conditions (e.g., light rain, no snow, good lane markings).
- Similarly, the underlying perception algorithms for processing the data are primitive and are capable of handling the basic computations needed for the proper functionality of the TJA feature within the ODD and specified deployment context.

Table B-2. TJA L3 deployment scenarios of interest.

Timeline	Operational Design Domain Level	Additional Deployment Context
Short term (low disruption) • **Market share = 2%** • **Fleet share = 1%** • **VHT share = 1%**	• Urban and rural highways (divided). • Intrastate and freeways (between urban or rural areas). • Operating only in traffic conditions where traffic speed is below 35 mph. • Operating only in clear and good weather condition (e.g., no rain, snow, etc.).	• This is a conditional automation Level 3 feature where the driver is the fallback for the dynamic driving task (DDT). • Operating with mixed traffic. • Operating in stop-and-go traffic at headway of about 3 seconds (2 to 4). • No lane changes. • Not operating on off- or on-ramps. • Not operating on horizontal curves. • Not operating near intersections (signalized or stop controlled).
Medium term (low disruption) • **Market share = 6%** • **Fleet share = 3%** • **VHT share = 4%**	• In addition to the short-term ODD elements: ○ Urban one-way arterial streets. ○ Urban and rural multilane arterial streets (divided). ○ Operating in traffic conditions where traffic speed is below 50 mph. ○ Could operate in light and moderate rain conditions.	• This is a conditional automation Level 3 feature where the driver is the fallback for the DDT. • Operating with mixed traffic. • Operating in stop-and-go traffic at headway of about 3 seconds (2 to 4). • Can perform simple lane change maneuvers. • Could navigate through work zones. • Could operate on off- or on-ramps. • Could operate on horizontal curves. • Could navigate through intersections.

Table B-3. Sensor specifications and infrastructure requirements of TJA scenarios.

Planning Horizon	Vehicle Type	Sensor Package	Key Infrastructure Requirements	
			Digital	Physical
Short term **(low disruption)**	Light duty.	Gen I.	Global Positioning System (GPS)-relevant infrastructure.	• Pavement markings in excellent condition. • Signage in excellent or good condition. • Highway median barriers.
Medium term **(low disruption)**	Light duty.	Gen II.	• GPS-relevant infrastructure. • Vehicle-to-vehicle (V2V)- and vehicle-to-everything (V2X)-relevant infrastructure. • Weather data. • Work zone data. • Dynamic traffic data.	• Lane and pavement markings in excellent condition. • Signage in excellent or good condition.

- These algorithms are in early development and may have more errors than later, more mature technology, leading to lower safety performance and/or lower percentage of time operating in autonomous mode (high disengagement rate). Sensors and computation algorithms used at this stage are commercially available and currently operate in certain vehicles.
- *Second Generation (Gen II):* Gen II is of a more advanced stage of technology than first-generation models or systems. In addition to the sensor types included in Gen I, this generation embraces high-fidelity lidar sensors and a vehicle onboard unit (OBU). All Gen II sensors are newer, more advanced, accurate, and have longer perception range than the Gen I sensors. A key feature of the Gen II sensor package is providing layers of redundancy to one another. The perception algorithms frequently cross-check the data from different sensors to improve the chance that no object is left undetected and to eliminate false positives.
- This sensor package manifests as a mature sensor fusion technology that is able to combine the sensing capabilities of multiple sensors, resulting in more reliable and robust perception with a broad sensing scope. To this end, the underlying perception algorithms for processing the data are more advanced and are capable of performing complex sensor fusion calculations, enabling the operation in expanded ODD and deployment context (check).
- Another envisioned key feature of this generation of sensors is integrating V2V and vehicle-to-infrastructure (V2I) communication within the vehicles through the OBU. This would provide opportunities for the vehicle to receive real-time dynamic data for weather, work zones, and traffic.

Table B-4 provides a qualitative assessment of the technology state of the different sensor package generations. The table highlights the key functional and technical differences between the two generations as well as the operational atmospheric conditions.

Infrastructure Needs and Impacts

- *Short-Term Planning Horizon:* From the infrastructure perspective, the short-term planning scenario for this feature has some key limitations, such as depending on surrounding vehicles and having clear roadway edges. There are also potential challenges around changes to the roadway and being unable to navigate work zones, horizontal curves, broken-down

Table B-4. Scenario technological specifications of traffic jam assist.

Sensor Package	Scenario Technology State Comparison		
	Qualitative Assessment of Technology State	Operational Atmospheric Conditions	Key Functional and Technical Differences
Gen I	• Lower-priced vehicles. • Less sophisticated algorithms, making driverless mode active less often.	Weather: clear, wind.	All Gen I features are offered in the Gen II package with enhanced capabilities.
Gen II	• Higher-priced vehicles. • More sophisticated algorithms, making driverless mode active more often. • Communication with vehicles and roadway infrastructure.	Weather: clear, wind, light, and moderate rain conditions.	• Lidar. • V2X communications. • V2V communications.

vehicles, or poor weather conditions. The dependence on surrounding cars to help navigate (i.e., the requirement to have a car in front and cars to the side) decreases the dependence on sensors for lane detection. Still, the Level 3 feature must detect the lanes and roadway edge based on lines, barriers, guard rails, or other markings. To improve functionality of these systems, infrastructure owners and operators (IOOs) may wish to inventory and maintain clear roadway edges and lane assignments.

- *Medium-Term Planning Horizon:* Digital infrastructure pertaining to connectivity plays an integral role in expanding the capabilities of this feature. The feature may benefit from real-time message updates for weather, traffic, and other changing conditions. In heavily congested areas, IOOs may consider investments for connectivity. Additionally, connectivity such as V2I communications could provide vital information to the vehicle, such as work zones and stopped vehicles. For example, roadside equipment in Virginia's connected corridors along portions of I-66, I-495, U.S. 7, U.S. 29, and U.S. 50 provides data flows for live transmission of incidents, weather, work zone, and variable and dynamic message signs that may benefit Level 3 features.

Risk Assessment

Risks

- The major risk for this feature resides in the known challenges for ensuring a safe transition of the DDT task from machine to human. One such concern is the poor understanding of how much time and context a human driver needs to regain control and proper situational awareness. Another challenge is monitoring driver state. These challenges impose extra safety and liability risks at the Level 3 automation—compared to all other levels of automation—due to human factors. The conservative approach implemented by OEMs so far for handling these challenges is promoting the feature as a hybrid automation of Level 2 and Level 3. In these hybrid automation levels, the human driver is liable at all times, including when the ADS is handling the DDT.
- Another concern with the implementation of ADS features (Level 3 and Level 4) is the expected degradation of some driving skills—depending on the ADS feature—due to reliance on automation and lack of exposure to DDT. Skill degradation is not limited to psychomotor skills (i.e., those pertaining to performing maneuvers), but also include decision-making skills.
- A potential risk envisioned with the deployment of TJA is that it is not expected to have one uniform TJA system in place across all OEMs and car models. Therefore, drivers may need to take caution when using a new ADS-equipped vehicle and becoming familiar with the machine-user interface and operation specifications of the new TJA system. For instance, not all TJA systems would use the same headway when following a leading vehicle. A driver familiar with one system could fail to react safely for a request-for-control takeover by another system. This failure may not only be due to the difference in default operation specifications but could be attributed to human factors related to different machine-user interfaces for control takeover requests. States could consider updating their theoretical content for state driving handbooks to educate new applicants and ADS users about these issues. Similarly, TJA systems may also not work properly in certain weather conditions like heavy rain or fog, if there is mud or snow on the sensors, or if roads are slippery. Drivers should be fully aware of the limitations of the system and capable to interact with the machine interface efficiently.
- At low market penetration rates, TJA systems could contribute to new crash types since they may have negative safety impacts on the nearby traditional, nonautomated vehicles. For example:
  - Traditional nonautomated vehicles following TJA-equipped vehicles could experience increased risk for rear-end crashes at low penetration rates.

– At low penetration rates, TJA-equipped vehicles could result in more aggressive and frequent lane-change maneuvers by following, nonautomated vehicles. This could increase the crash risk for sideswipe crashes and other crashes in the aggregate traffic stream due to disruptions in traffic flow.

Opportunities

- TJA has the potential to reduce the number of crashes, such as rear-end collisions, occurring on congested roads due to human driver fatigue. TJA is a subsystem of ACC with extended lane-keeping assist functionality. Therefore, these technologies also have the potential to decrease crashes occurring on congested roads pertaining to lane-change maneuvers. Overall, these technologies are envisioned to improve safety on roads during congested traffic conditions.
- TJA is among the ADS features that provide massive opportunities for better fuel savings and longer vehicle life. Automating the vehicle in congested conditions improves the vehicle's fuel economy and motor lifetime. Recipients of funding from the U.S. Department of Energy's NEXTCAR Program are commercializing these types of technologies (ARPA-E, 2020).
- With increased market share, TJA-equipped vehicles provide the potential for implementing innovative eco-driving and speed harmonization techniques when such vehicles are connected (supporting V2V or V2I communication systems). More sophisticated eco-driving and speed harmonization techniques could be considered, such as geofencing of a cordon that may be scalable and movable.

Goals and Hypothesis

For the TJA deployment scenario, the safety objectives and hypothesis for how procedures and processes can influence these outcomes in future deployments are formulated in terms of a goal and hypotheses. The goal of TJA is to reduce the frequency and severity of crashes across a transportation agency's system (e.g., state of California or city of Charlotte) through the adoption of TJA features (SAE Level 3) and supporting infrastructure.

The overall hypothesis is that *TJA will improve safety on urban divided streets across a state by reducing rear-end crashes within 3 to 5 years*. The expected change in the number and percentage of rear-end crashes will depend on market penetration, which is explored in the analysis. The questions to evaluate this hypothesis are listed below and relate to crash types, crash severity levels, infrastructure, and data.

1. How will the frequency of certain types of crashes (e.g., rear-end crashes due to human error, including driver fatigue, inattention, and inebriation) change in relation to safety?
2. How will the severity of certain crash types change? While it is anticipated most crashes affected would be property damage only (PDO), the feature could reduce the severity of crashes that do occur (e.g., reducing possible injury crashes to PDO crashes).
3. Will safety change if the ODD is extended in which TJA features can operate? For example, it is hypothesized that TJA features do not perform well on facilities with poor pavement markings, and there is an opportunity to further improve safety through infrastructure investments in lane markings (application of new markings and maintenance of existing markings).
4. Will safety and deployment of TJA features change if work zone data are shared that improve the safety performance of the ADS and make it easier for manufacturers to deploy the technology ubiquitously?

In summary, through the deployment of TJA, it is hypothesized that certain crash types will be reduced, crash severity will lessen, infrastructure improvements will help advance and extend the deployment and use of TJA, and data sharing can help improve safety performance. However, certain crash types might increase (e.g., sideswipe crashes).

While this provides an overview of potential safety impacts, it is important to perform a crash sequencing exercise to think through the contributing factors and precipitating events that lead to a crash. The following are a few examples related to TJA:

1. Rear-end:
   a. Congested conditions cause vehicle 1 to stop. Driver of vehicle 2 is distracted, falls asleep, or is otherwise inattentive. Vehicle 2 rear-ends vehicle 1.
   b. Congested conditions cause vehicle 1 to stop. Driver of vehicle 2 is fully attentive but following too closely whereby vehicle 2 is not able to stop in time. Vehicle 2 rear-ends vehicle 1.
   c. Congested conditions cause vehicle 1 to stop. Driver of vehicle 2 is fully attentive and adverse weather contributes to limited stopping distance whereby vehicle 2 is not able to stop or slow. Vehicle 2 rear-ends vehicle 1.
2. Sideswipe:
   a. Driver of vehicle 1 is distracted, falls asleep, or is otherwise inattentive. Vehicle 2 is traveling in the same direction in the adjacent lane to vehicle 1. Vehicle 1 drifts into the adjacent lane and sideswipes vehicle 2.
   b. Vehicle 1 is equipped with TJA. Vehicle 2 is not equipped with TJA and is following vehicle 1. Vehicle 3 is traveling in the same direction in the adjacent lane to vehicle 1 and vehicle 2. Driver of vehicle 2 becomes inpatient with steady speed of vehicle 1. Driver of vehicle 2 abruptly changes lanes to pass vehicle 1 and does not see vehicle 3 in the blind spot. Vehicle 2 sideswipes vehicle 3.

From the anticipated capabilities of vehicles equipped with TJA and the above crash sequencing, the project team identified specific opportunities for TJA to mitigate crashes. For example, TJA is not expected to operate in adverse conditions, so there is limited potential to mitigate crashes related to sequence 1c; however, TJA is expected to provide opportunities to mitigate crashes related to sequence 1a and 1b. TJA could also contribute to (or be associated with) crashes related to sequence 2b.

Method of Analysis

Components of the Analysis

To estimate the safety effects of TJA, an analysis to quantify its impacts needs to be performed using crash data and the types of crashes TJA is expected to influence. As previously described, the ODD includes divided roadways in urban environments. TJA can only operate in clear weather conditions (clear or windy) for the short-term timeline and in clear (clear or windy) with moderate rain weather conditions on roads with well-maintained lane markings. Also, TJA can operate in conditions where there is a lead vehicle and operating speeds are a maximum of 35 mph. Therefore, the focus facility type is defined as all urban divided roads with any speed limit, with the assumption that the feature and resulting safety impact are relevant only during congested conditions (e.g., peak time periods). Congested conditions are assumed to occur from 6:00 to 9:00 a.m. and 4:00 to 7:00 p.m.

TJA will potentially affect only certain crash types. The main crash type expected to decrease is rear-end crashes. This is due to the ability of TJA to keep a safe distance between it and the vehicle in front and brake when needed. Differently, sideswipe crashes could potentially increase. The rationale is that if a vehicle using TJA is maintaining a safe following distance or traveling at a slower speed, a trailing vehicle might see it as an opportunity to switch lanes and increase the potential for a sideswipe crash.

While only certain crash types are expected to change, all crash severity levels are expected to be affected by TJA. Related PDO crashes could be eliminated, and crashes of higher severity levels could decrease in severity. A summary of the components of the analysis is shown in Table B-5.

Table B-5. Components of the analysis.

Component	Description
Functional classification.	Freeways and expressways.
	Arterials.
	Major and minor collectors.
Area type.	Urban.
Speed conditions.	Any speed limit, congested conditions (weekdays 6:00 to 9:00 a.m. and 4:00 to 7:00 p.m.).
Number of lanes and road configuration.	Multilane, divided.
	One or more lanes, one-way.
Weather conditions.	Clear, wind, moderate rain.
Crash types.	Rear-end, sideswipe.
Crash severity level.	All severity levels.

To estimate the safety benefits or disbenefits of TJA, technical assumptions about the scenario were made in analyzing crash data. An "optimistic scenario" is assumed where there is a maximum crash reduction. The scenario assumes a low disruption of vehicles with TJA, for example, a certain percentage of vehicles with the feature within 5 years.

Other technical assumptions relate to the crashes that are expected to be affected by TJA. It is assumed that TJA will not eliminate all rear-end crashes in the ODD described above where the trailing vehicle is ADS equipped and the feature is activated. The assumption is that TJA will eliminate only a certain percentage of crashes where the trailing vehicle is ADS equipped and the feature is activated. Varying penetration and activation rates are assumed to account for different scenarios and number of vehicles equipped with TJA. ADS-equipped vehicles may also be involved in other crash types when the driver takes control (e.g., sideswipe crashes when a driver changes lanes).

The expected timeframe for achieving success depends on the expected timeline for deployment and penetration rates of ADS-equipped vehicles. In this scenario, the expected timeline is assumed to pertain to short-term planning, which is a fast uptake (3 to 5 years).

Analysis Methods

Data Sources. The main source of crash and roadway data used to estimate the potential effect of TJA on safety was the Highway Safety Information System (HSIS). The HSIS dataset consists of crash and roadway data from seven states and one city (California, Washington, Minnesota, Illinois, Ohio, North Carolina, Maine, and Charlotte). The data can be requested online and can be requested for specific states and variables needed. For this analysis, data for Charlotte were obtained because of its urbanization, availability of variables, and availability of supplemental datasets that can be merged with HSIS data. The raw HSIS data consist of roadway, crash, vehicle, and occupant files that can be merged. Data include information about the roadway (number of lanes, divided or undivided, speed limit, etc.), crash (day, light condition, weather, contributory factor, etc.), vehicle (vehicle type, etc.), and occupant (age, condition, etc.).

Roadway data from Connect NCDOT (Road Characteristics Arcs; https://connect.ncdot.gov/resources/gis/Pages/GIS-Data-Layers.aspx) were used to supplement the HSIS roadway data and provide additional variables for analysis, including road functional class. Other supplemental data included census information from Charlotte's Open Data Portal (https://data.charlottenc.gov/). These data include household income information. The census data can be used to estimate the prevalence of ADS features based on median household income in an area. However, to do so, assumptions need to be made about income and the associated possibility of owning an ADS-equipped vehicle. Both supplemental databases were merged with the HSIS roadway and crash data.

Define Metrics. The primary metric for assessing the safety impact of TJA is the change in crashes by frequency and severity. In particular, the change in crashes is based on crashes of interest for the deployment scenario and crashes that TJA has the potential to impact, described in the "Components of the Analysis" section.

The crashes of interest are identified by categorizing and filtering the crashes based on variables selected to identify crashes with the potential for TJA to reduce. Most were identified in the "Components of the Analysis" section, which identified several variables that can be used to filter based on the ODD and deployment context. Crash types include rear-end and sideswipe. The weather conditions need to be clear or windy for the short-term timeline and clear, windy, or moderate rain for the medium-term timeline. Other conditions that need to be considered if information is available include visible lane markings (maintained and clear of snow or debris) and visible signage (high retroreflectivity). If this information is not readily available, then assumptions need to be made based on local knowledge, judgment, or a sample of data. In this case, lane marking and signage condition information is not available in the Charlotte database, and assumptions are made with respect to those factors.

Evaluation Method. It is important to select an appropriate method to test the hypothesis and related questions based on the available data. This evaluation uses crash history and identifies the crashes that could potentially be affected by TJA. The evaluation estimates crash reduction by frequency and severity. Table B-6 lists the categories of crashes used to estimate the impact of TJA.

Table B-6. Crash types and severity levels to estimate TJA impact.

Category	Crash Type	Crash Severity
1	Rear-end	PDO.
2	Rear-end	Possible injury.
3	Rear-end	Suspected minor injury.
4	Rear-end	Fatal and suspected serious injury.
5	Sideswipe	PDO.
6	Sideswipe	Possible injury.
7	Sideswipe	Suspected minor injury.
8	Sideswipe	Fatal and suspected serious injury.

A sensitivity analysis is used to explore various assumptions related to penetration rates and probabilities that the trailing vehicle has TJA, has it activated, and it functions properly.

The change in crashes is calculated by subtracting the crashes TJA can reduce or increase from the total number of crashes for the given years. This is repeated for each crash type and severity level. The following equation shows the change in crashes as a percent change, where a positive percent change indicates a safety benefit, and a negative change indicates an increase in crashes.

$$\text{Percent change in crashes} = \left[1 - \left(\frac{(\textit{Total crashes}) - (\textit{Crashes impacted by ADS feature})}{(\textit{Total crashes})}\right)\right] \times 100$$

Eq. 7

Results

HSIS crash and roadway data were merged with road data from Connect NCDOT and census data from Charlotte's Open Data Portal to identify crashes that could be impacted by TJA for 6 years (2012–2017). First, total crashes on the road types of interest were identified. Next, crash types that could specifically be impacted by use of TJA were identified.

The total crashes were categorized based on the variables of interest and filters listed in Table B-6. Three different scenarios for categorizing the Charlotte crash data were used for the analysis to identify the crashes that could potentially be affected by the use of TJA. The scenarios include:

1. Urban, multilane, divided roadways (non-freeways and expressways) during peak periods.
2. Urban, one-way roadways (non-freeways and expressways) during peak periods.
3. Divided, multilane freeways and expressways during peak periods.

Total Crashes on All Road Types

Table C-1 through Table C-5 in Appendix C display crash statistics for all crashes in Charlotte (on all road types). The crashes are separated by severity level (Table C-1), crash type (Table C-2), weather condition (Table C-3), speed limit (Table C-4), and speed limit and weather condition combined (Table C-5).

Urban, Multilane, Divided Roadways (Non-freeways and Expressways) During Peak Periods

The total crashes were categorized to identify those that TJA has the potential to impact. The first categorization included separating out urban, multilane, divided roads (non-freeways and expressways) during congested conditions (weekday peak periods). It also included crashes occurring during clear or windy weather conditions, all non-clear and non-windy weather conditions, and rain weather conditions. Table B-7 displays total crashes by severity level on these roadways. Table B-8 includes only rear-end crashes on these roads of interest, and Table B-9 includes only sideswipe crashes on these roads of interest.

Urban, One-Way Roadways (Non-freeways and Expressways) During Peak Periods

The second categorization of the total crashes separated out urban, one-way roads (non-freeways and expressways) during congested conditions (weekday peak periods). It also included crashes occurring during clear or windy weather conditions, all non-clear and non-windy weather conditions, and rain weather conditions. Table B-10 displays total crashes by severity level on these roadways. Table B-11 includes only rear-end crashes on these roads of interest. Table B-12 includes only sideswipe crashes on these roads of interest.

Table B-7. Total crashes on urban, multilane, divided roadways during peak periods (2012–2017).

Severity Level	Number of Crashes in Clear Weather Conditions	Number of Crashes in Other Weather Conditions	Number of Crashes in Rain Weather Conditions
Blank	2	1	1
PDO	2,890	404	371
Possible injury	1,172	152	146
Suspected minor injury	176	20	19
Fatal and suspected serious injury	16	5	4
Total	4,256	582	541

Table B-8. Rear-end crashes on urban, multilane, divided roadways during peak periods (2012–2017).

Severity Level	Number of Crashes in Clear Weather Conditions	Number of Crashes in Other Weather Conditions	Number of Crashes in Rain Weather Conditions
Blank	2	1	1
PDO	1,537	250	235
Possible injury	783	111	108
Suspected minor injury	84	9	9
Fatal and suspected serious injury	6	1	1
Total	2,412	372	354

Table B-9. Sideswipe crashes on urban, multilane, divided roadways during peak periods (2012–2017).

Severity Level	Number of Crashes in Clear Weather Conditions	Number of Crashes in Other Weather Conditions	Number of Crashes in Rain Weather Conditions
Blank	0	0	0
PDO	740	69	67
Possible injury	128	13	12
Suspected minor injury	8	0	0
Fatal and suspected serious injury	2	0	0
Total	878	82	79

Table B-10. Total crashes on urban, one-way roadways during peak periods (2012–2017).

Severity Level	Number of Crashes in Clear Weather Conditions	Number of Crashes in Other Weather Conditions	Number of Crashes in Rain Weather Conditions
Blank	0	0	0
PDO	13	1	1
Possible injury	2	0	0
Suspected minor injury	0	0	0
Fatal and suspected serious injury	0	0	0
Total	15	1	1

Table B-11. Rear-end crashes on urban, one-way roadways during peak periods (2012–2017).

Severity Level	Number of Crashes in Clear Weather Conditions	Number of Crashes in Other Weather Conditions	Number of Crashes in Rain Weather Conditions
Blank	0	0	0
PDO	2	0	0
Possible injury	2	0	0
Suspected minor injury	0	0	0
Fatal and suspected serious injury	0	0	0
Total	4	0	0

Table B-12. Sideswipe crashes on urban, one-way roadways during peak periods (2012–2017).

Severity Level	Number of Crashes in Clear Weather Conditions	Number of Crashes in Other Weather Conditions	Number of Crashes in Rain Weather Conditions
Blank	0	0	0
PDO	7	1	1
Possible injury	0	0	0
Suspected minor injury	0	0	0
Fatal and suspected serious injury	0	0	0
Total	7	1	1

Table B-13. Total crashes on urban, divided, multilane freeways and expressways during peak periods (2012–2017).

Severity Level	Number of Crashes in Clear Weather Conditions	Number of Crashes in Other Weather Conditions	Number of Crashes in Rain Weather Conditions
Blank	0	0	0
PDO	416	48	44
Possible injury	199	29	29
Suspected minor injury	14	1	1
Fatal and suspected serious injury	0	0	0
Total	629	78	74

Divided, Multilane Freeways and Expressways During Peak Periods

The third categorization of the total crashes included separating out urban, divided, multilane freeways and expressways during congested conditions (weekday peak periods) (Tables B-13, B-14, and B-15). It also included crashes occurring during clear or windy weather conditions, all non-clear and non-windy weather conditions, and rain weather conditions.

Impact of TJA

The crashes with potential for impact from TJA were further reduced to estimate a quantifiable number of crashes impacted. The potential reduction in crashes is based on the vehicle miles traveled (VMT) share described in the deployment scenarios. The VMT shares for different timelines of TJA are:

Short-term (low disruption) VMT share = 1%

Medium-term (low disruption) VMT share = 4%

Table B-14. Rear-end crashes on urban, divided, multilane freeways and expressways during peak periods (2012–2017).

Severity Level	Number of Crashes in Clear Weather Conditions	Number of Crashes in Other Weather Conditions	Number of Crashes in Rain Weather Conditions
Blank	0	0	0
PDO	286	27	29
Possible injury	167	19	19
Suspected minor injury	10	0	0
Fatal and suspected serious injury	0	0	0
Total	463	46	48

Table B-15. Sideswipe crashes on urban, divided, multilane freeways and expressways during peak periods (2012–2017).

Severity Level	Number of Crashes in Clear Weather Conditions	Number of Crashes in Other Weather Conditions	Number of Crashes in Rain Weather Conditions
Blank	0	0	0
PDO	95	7	6
Possible injury	16	2	2
Suspected minor injury	1	0	0
Fatal and suspected serious injury	0	0	0
Total	112	9	8

In addition to the percentage of VMT share shown above, other percentages of VMT share were used as a sensitivity analysis to account for two variants: (1) vehicles that have the ADS but not engaged, and (2) vehicles that have the ADS available and engaged but it does not operate as intended. Given the wide range of projections for market penetration, 50% of the VMT shares (listed above) were assumed as the values for the sensitivity analysis, listed below. This helps to show the relative difference in results if only half of the expected market penetration is achieved.

Short-term VMT share for sensitivity analysis = 0.5%

Medium-term VMT share for sensitivity analysis = 2%

The following sections display the short- and medium-term impact of TJA.

Rear-End Crashes Short-Term Timeline. The ODD for the short-term timeline includes urban, divided highways and freeways, where traffic speed is below 35 mph and weather conditions are clear or windy. The potential crashes impacted per year are then reduced using the VMT percentages for different sensitivities. Table B-16 and Table B-17 show the expected reduction in crashes per year by severity for the short-term timeline.

The percent crash reduction with respect to average total crashes per year is calculated below using a VMT share of 0.5%.

$$\text{Percent crash reduction per year} = \left(1 - \frac{23{,}975 - 2.396}{23{,}975}\right) \times 100 = 0.01\%$$

The percent crash reduction with respect to average total crashes per year is calculated below using a VMT share of 1%.

$$\text{Percent crash reduction per year} = \left(1 - \frac{23{,}975 - 4.792}{23{,}975}\right) \times 100 = 0.02\%$$

Rear-End Crashes Medium-Term Timeline. The ODD for the medium-term timeline includes all elements from the short-term timeline with the addition of one-way roadways and including crashes during rain (Tables B-18 and B-19).

Table B-16. Crashes impacted for short-term timeline.

Severity	Total Crashes on All Roads and in All Weather Conditions (2012–2017)	Rear-End Crashes on Urban, Multilane, Divided Roadways during Peak Periods in Clear and Windy Weather Conditions (2012–2017)	Rear-End Crashes on Urban, Divided, Multilane Freeways and Expressways during Peak Periods in Clear and Windy Weather Conditions (2012–2017)	Total Potential Crashes Impacted (2012–2017)	Total Potential Crashes Impacted per Year
Blank	28	2	0	2	0.333
PDO	94,526	1,537	286	1,823	303.833
Possible injury	38,608	783	167	950	158.333
Suspected minor injury	9,796	84	10	94	15.667
Fatal and suspected serious injury	892	6	0	6	1
Total	143,850	2,412	463	2,875	479.167

Table B-17. Crash reduction for short-term timeline.

Severity	Crashes Reduced per Year (0.5% VMT Share)	Crashes Reduced per Year (1% VMT Share)
Blank	0.002	0.003
PDO	1.519	3.038
Possible injury	0.792	1.583
Suspected minor injury	0.078	0.157
Fatal and suspected serious injury	0.005	0.010
Total	2.396	4.792

Table B-18. Crashes impacted for medium-term timeline.

Severity	Total Crashes on All Roads in All Weather Conditions (2012–2017)	Rear-End Crashes on Urban, Multilane, Divided Roadways during Peak Periods in Clear, Windy, and Rainy Weather Conditions (2012–2017)	Rear-End Crashes on Urban, One-Way Roadways during Peak Periods in Clear, Windy, and Rainy Weather Conditions (2012–2017)	Rear-End Crashes on Urban, Divided, Multilane Freeways and Expressways during Peak Period in Clear, Windy, and Rainy Weather Conditions (2012–2017)	Total Crashes impacted (2012–2017)	Total Crashes Impacted per Year
Blank	28	3	0	0	3	1
PDO	94,526	1,772	2	315	2,089	348
Possible injury	38,608	891	2	186	1,079	180
Suspected minor injury	9,796	93	0	10	103	17
Fatal and suspected serious injury	892	7	0	0	7	1
Total	143,850	2,766	4	511	3,281	547

Table B-19. Crash reduction for medium-term timeline.

Severity	Crashes Reduced per Year (2% VMT Share)	Crashes Reduced per Year (4% VMT Share)
Blank	0.010	0.020
PDO	6.963	13.927
Possible injury	3.597	7.193
Suspected minor injury	0.343	0.687
Fatal and suspected serious injury	0.023	0.047
Total	10.937	21.873

The percent crash reduction with respect to average total crashes per year is calculated below using a VMT share of 2%.

$$\text{Percent crash reduction per year} = \left(1 - \frac{23{,}975 - 10.94}{23{,}975}\right) \times 100 = 0.046\%$$

The percent crash reduction with respect to average total crashes per year is calculated below using a VMT share of 4%.

$$\text{Percent crash reduction per year} = \left(1 - \frac{23{,}975 - 21.87}{23{,}975}\right) \times 100 = 0.091\%$$

Sideswipe Crashes. As previously mentioned, other crash types might be impacted by TJA, such as sideswipe crashes. Sideswipe crashes might increase due to a situation when a vehicle with TJA enabled is following a car in front at a safe distance and an adjacent vehicle sees the gap as an opportunity to switch lanes, causing a sideswipe crash; however, there is a lack of research on this topic. As a point of reference, Table B-20 displays total sideswipe crashes during the study period, 2012 through 2017. This could serve as a point of reference for estimating the relative magnitude of an increase in sideswipe crashes for different assumptions related to percent increase.

Interpreting the Results

Table B-21 displays a summary of the results for the potential crash reduction of rear-end crashes in comparison to total crashes for different sensitivities of VMT share. The percent crash reduction increases from the short-term to the medium-term timelines as the ODD is expanded to include more facility types and environmental conditions.

There is also the potential for TJA to impact sideswipe crashes. However, it is not known exactly how. Table B-20 displays the historical sideswipe crashes in the applicable ODD as

Table B-20. Sideswipe crashes potentially impacted by TJA.

Severity	Sideswipe Crashes on Urban, Multilane, Divided Roadways during Peak Periods (2012–2017) in Clear Weather Conditions	Sideswipe Crashes on Urban, One-Way Roadways during Peak Periods (2012–2017) in Clear Weather Conditions	Sideswipe Crashes on Urban, Divided, Multilane Freeways and Expressways during Peak Periods (2012–2017) in Clear Weather Conditions	Total Crashes Potentially Impacted per Year
Blank	0	0	0	0
PDO	740	7	95	140
Possible injury	128	0	16	24
Suspected minor injury	8	0	1	2
Fatal and suspected serious injury	1	0	0	0
Total	877	7	112	166

Table B-21. Summary of results for rear-end crashes.

Timeline	VMT Share	Crash Reduction
Short-term	0.5%	0.01%
	1%	0.02%
Medium-term	2%	0.046%
	4%	0.091%

a point of reference. These numbers might increase due to conditional traffic jam assist. The increase in crashes due to TJA is from the potential of other non-ADS-equipped vehicles colliding with the ADS-equipped vehicle. However, there is also potential for sideswipe crashes to decrease that were caused by the ADS-equipped vehicle if they also have a lane-keeping assist feature.

Agencies can use the results to estimate the potential reduction in crashes. The following example displays rate reduction for a given agency. An agency is considering infrastructure improvements that will allow use of TJA in additional areas. Based on historical data, there are 30,000 rear-end crashes in a particular area that has 102,000 million VMT. The calculated crash rate is 0.3 rear-end crashes per million VMT or 30 rear-end crashes per 100 million VMT. Using the short- and medium-term VMT shares, the reductions in crash rates and new crash rates are calculated and shown in Table B-22. Assuming a medium-term VMT share of 4%, there will be an expected reduction of 1 crash for every 100 million VMT. An agency could perform a more detailed benefit-cost analysis to compare these benefits with the cost to upgrade or maintain infrastructure as part of the decision process.

Communicate Outcomes

Through the framework and analysis, the results indicated how the frequency and severity of certain crash types are expected to change. If the ODD is extended so TJA can operate on different facilities or in different environmental conditions, and if data are shared to improve ADS performance, safety will likely change by reducing crash frequency and severity. As the timeline expands and VMT share increases, the percent crash reduction is expected to be greater.

Table B-22. Example of crash reduction.

	Reduction in Rate (Crashes per 100 million VMT)	New Rate (Crashes per 100 million VMT)
Short-term:		
• **VMT share = 0.5%**	0.2	29.85
• **VMT share = 1%**	0.3	29.70
Medium-term:		
• **VMT share = 2%**	0.6	29.40
• **VMT share = 4%**	1.2	28.8

However, assumptions were made to perform the analysis. The analysis and results could change slightly as the technology landscape changes, the ODD (or extent of the ODD) expands, and more and better data are available. Two assumptions relate to lane marking and sign conditions. The ODD describes the need for visible lane markings clear of snow or debris and visible signage with high retroreflectivity. That information is not available in the dataset used and not available in typical crash or roadway databases. Because of this, the analysis assumed the lane marking and signage conditions are visible and clear.

Another assumption relates to an element in the ODD stating that operating speeds need to be below 35 mph for TJA is operate. The speed of vehicles before a crash is typically not known and not reported on crash records. To create conditions where speeds are less than 35 mph, only crashes occurring during peak periods during the week were used in the analysis. This would hopefully create conditions in which TJA could operate.

One last assumption used in the analysis relates to the environmental conditions. The medium-term timeline allows TJA to operate in moderate rain conditions. Crash records do not separate out the level of rain; rather, they only indicate if it was raining or not. The rain variable was used to represent moderate rain conditions.

ADS Feature: Highway Platooning (Level 2–Level 4)

Understanding the ADS Feature

Feature Description

In addition to autonomous driving capability scenarios, long- and short-haul freight operations have the opportunity to further increase savings, productivity, and energy efficiency through platooning. Platooning is defined as linking two or more trucks in a convoy using automated driving assistance technologies and with connectivity between vehicles (Figure B-1). This feature can be an advanced cooperative ACC that automates lateral and longitudinal vehicle control of heavy-duty vehicles on a highway. Platooning may include maintaining a formation of vehicles with very short following distances. The feature uses advanced driver assistance system (ADAS) features such as cooperative ACC to maintain short following distances with multiple heavy-duty vehicles. This scenario focuses on highly automated vehicles fitted with second-generation technologies. In addition to providing benefits to the driver, commercial operator, and environment, platooning operations can support capacity management goals. If technology continues to advance, sensor costs fall, and policy adapts, a fruitful system of ADS-equipped trucks deploying platooning features can be achieved.

Expected Market

A key feature of many scenarios of self-driving truck implementation, platooning is expected to experience market growth. Allied Market Research (2019) valued the global truck platooning

Figure B-1. Automated truck and highway platooning scenario (Source: Adopted from Viscelli, 2018).

market at $501 million in 2017 and projected it to grow to $4.6 billion by 2025 with a compound annual growth rate (CAGR) of 32.4%. North America currently represents, and will likely continue to represent, the highest share of the global platooning market, though the Latin America, Middle East, and Africa region expects to have the highest CAGR. The study segments the market based on technology, platooning type, communication technology, and region. Technologically, the market is classified into groups such as ACC, blind spot warning, global positioning system (GPS), forward collision warning, and lane-keeping assist. Platooning type can be split into driver-assistive truck platooning and ADS-equipped truck platooning. Finally, communication type can be divided into vehicle to vehicle (V2V}, vehicle to infrastructure (V2I), and vehicle to everything (V2X).

Policy may be the key driver for the truck platooning market, both in favorable regulation for platoons and new emissions standards that require a decrease in fuel consumption. The production of fully ADS-equipped trucks and the increase in fleet size represent the greatest opportunities for growth in the market. However, the high cost of autonomous technologies and rising security and privacy concerns may limit the speed of adoption and overall growth of truck platooning.

Research and pilot studies have been taking place regularly in Europe since 2016. Through regulatory changes and truck manufacturing, the European Union hopes to introduce platooning technologies into the marketplace in 2022.

Table B-23 lists a few examples of the ADS-equipped trucks and/or highway platooning models that are commercially deployed or being tested.

Anticipated Deployment Scenario

Operational Design Domain

Table B-24 summarizes the anticipated ODD elements of the ADS-equipped trucks and highway platooning features. The ODD elements are predicted for two timelines, the short-term (next 5 years) and the medium-term (next 5 to 10 years). In addition, the table outlines the major deployment specifications envisioned for the two features that are expected to impact their safety assessment. The deployment elements are also provided for the two timelines.

Table B-23. Highway platooning examples.

Peloton	PlatoonPro Truck Platooning utilizes V2V communications and radar-based active braking systems, combined with vehicle control algorithms. Peloton can link pairs of heavy trucks for connected driving.
DAF	The EcoTwin uses Wi-Fi-P, radar, and cameras to allow multiple connected trucks to drive close together. Driving inputs are taken from the lead truck, allowing the convoy of vehicles to simultaneously accelerate, brake, and steer.
Iveco	Iveco participated in the world's first truck platooning challenge using two trucks from Brussels to Rotterdam.
MAN Truck and Bus	The company completed a successful pilot where two professional drivers drove electronically linked trucks on the Autobahn for 35,000 test kilometers over 7 months.
Volvo	Volvo, FedEx, and the North Carolina Turnpike Authority used ADAS to test the first public highway platooning showcase in the United States using three Volvo VNL tractors.
Tesla	The Semi is an electric Class 8 semi-trailer truck with a stated goal to provide auto pilot and based platooning capabilities using radar and cameras led by a truck with a driver.

Table B-24. Highway platooning deployment scenarios of interest.

Operational Design Domain Level	Timeline	Additional Deployment Context
Self-driving features of ADS-equipped trucks can be supplemented with platooning capabilities to further increase benefits.		
• **Freeways (both urban and rural).** • **Dedicated lanes.** • **Navigate through interchanges and ramps.**	Short-term (high disruption).	• The lead truck in a platoon has a driver who must take control as needed. Following trucks use the platooning feature to follow the leader. • Platoons of two to three trucks. • V2V communication. • Following trucks are Level 3; lead trucks can be Level 2 or Level 3. • Operating on well-marked roads with well-maintained signs.
• **Freeways (both urban and rural).** • **All +4-lane divided highways (urban and rural).** • **Mixed traffic.** • **Navigate through interchanges and ramps.**	Medium-term (high disruption).	• The lead truck and following trucks can be driverless. • Platoons of three or more trucks. • V2X communications. • All trucks in platoon are Level 4. • Operating on well-marked roads with well-maintained signs.

Table B-25 provides a summary of the technology specifications and key infrastructure needs pertinent to the envisioned highway platooning scenarios.

Stage of Technology Development

- *First Generation (Gen I):* This is the first version of ADS-equipped trucks sensor package and their underlying computational algorithms for processing the data. Typically, this package embraces the needed combination of sensors such as forward-facing cameras, radar, ultrasonic sensors, laser scanners, and inertial measurement units (gyroscopes and accelerometers) with *a priori* digital maps (lane-level detail). This package will not have a good object detection capability in low-visibility conditions, limiting the ODD to certain conditions (e.g., light rain, no snow, good lane markings).

  Similarly, the underlying perception algorithms for processing data are capable of handling the basic computations for the proper functionality of the ADS-equipped truck feature within the ODD and deployment context specified in Tables B-24 and B-25. These algorithms are at early development and may have more errors than later, more mature technology, leading to lower safety performance and/or lower percentage of time operating in autonomous mode (high disengagement rate). Sensors and computation algorithms used at this stage are commercially available and currently operate in certain vehicles.
- *Second Generation (Gen II):* Gen II is a more advanced stage of technology than first-generation models or systems. In addition to the sensor types included in Gen II, this generation embraces high-fidelity lidar sensors and an OBU. All Gen II sensors are newer, more advanced, accurate, and have longer perception range than the Gen I sensors. A key feature of the Gen II sensor package is providing layers of redundancy to one another. The perception algorithms frequently cross-check the data from different sensors to ensure that no object is left undetected and to eliminate false positives.

Table B-25. Highway platooning key infrastructure requirements.

Expected Timeline	Vehicle Type	Sensor Package	Key Infrastructure Requirements	
			Digital	Physical
Short-term **High disruption**	Heavy-duty.	Gen I.	• V2V communications. • GPS. • HD maps. • Weather data. • Infrastructure data. • Work zone alerts.	• Clear lane markings. • Visible signage. • Highly detectable traffic control device.
Medium-term **High disruption**	Heavy-duty.	Gen II.	• V2X communication. • GPS. • HD maps. • Weather data. • Infrastructure data. • Work zone alerts. • 5G and dedicated short-range communication.	• Lane markings. • Visible signage. • Highly detectable traffic control device.

- This sensor package manifests as mature sensor fusion technology that is able to combine the sensing capabilities of multiple sensors, resulting in more reliable and robust perception with a broad sensing scope. To this end, the underlying perception algorithms for processing the data are more advanced and are capable of performing complex sensor fusion calculations enabling the operation in an expanded ODD and deployment context. Another envisioned key feature of this generation of sensors is integrating V2V and V2I communication within the vehicles through the OBU. This provides opportunities for the vehicle to receive real-time dynamic data for weather, work zones, and traffic. The new advanced sensor suite allows trucks to operate effectively on more road types, such as four-lane divided highways, in more severe weather, and on roadways with imperfect lane markings and signage. Table B-26 provides a qualitative assessment of the technology state of the different sensor package generations. The table highlights the key functional and technical differences between the two generations as well as the operational atmospheric conditions.

Infrastructure Needs and Impacts

The features assist the driver navigating a highway, and when in platooning mode, the follower vehicle maintains a headway and lateral alignment. The sensors on board the vehicle need to detect infrastructure elements, such as lane markings, barriers, and signs, to determine proper heading and speed. The infrastructure requirements for this feature are largely driven by challenges in human factors, connectivity, and limits to ADS perception technology.

To increase functionality and efficiency of autonomous and platooning truck features, ADS-equipped truck ports (ATPs) may need to be constructed near interstates. At ATPs, drivers

Table B-26. Scenario technological specifications of highway platooning.

Scenario	Scenario Technology State Comparison		
	Qualitative Assessment of Technology State	Operational and Atmospheric Conditions	Key Functional and Technical Differences
• **Gen I**	• Smaller platoons. • ODD exclusively on freeways. • Communications with other trucks.	Weather: clear, wind.	• V2V communications. • Two- to three-vehicle platoons.
• **Gen II**	• Larger platoons. • ODD expanded to divided highways. • Communications with vehicles and roadway infrastructure.	Weather: clear, wind, rain.	• Lidar. • V2X communications. • Platoons of three or more vehicles.

operating locally can swap trailers to autonomous tractors optimized for highway driving. Likewise, highway-optimized trucks can swap trailers to human-driven trucks for last-mile and urban delivery where driverless operations are more complex.

In platooning, the leader vehicle's responsibilities differ from those of the follower vehicle. For the rear vehicle, the radar and camera are critical for measuring distances, and connectivity provides information about the lead vehicle's future speed, which is critical for maintaining the headway and lateral position. Look-ahead information about traffic disruptions, such as congestion or emergency vehicles, can help improve coordination between vehicles in a platoon.

Connectivity can provide additional information that improves freight operations and safety in targeted areas. For example, along Wyoming roadways over 6,000 ft in elevation, wind gusts exceed 65 mph and crash rates are three to five times as high in winter than in summer. The Wyoming DOT pilot is developing applications that use V2I and V2V connectivity to support a range of services from advisories including roadside alerts, parking notifications, and dynamic travel guidance to help reduce the number of blow-over and adverse weather incidents in the corridor to improve safety and reduce incident-related delays. Partially automated platooning features could benefit from these types of applications.

Risk Assessment

Risks

- A major risk is navigating the "machine-to-human handover," when the machine driver requests to hand back control to the human. Since it is irresponsible for the machine driver to simply signal to the human "Here, you take over," it is evident there must be a period of time following the handover request for the human driver to regain proper situational awareness.
- At present, ADS and platooning features are variable in trucks. With no standard on how the ADS feature performs, which sensors it includes, or in what circumstances they can platoon,

a driver may not be familiar with more than one machine-user interface and may fail to react safely in a request for control takeover initiated by the ADS.
- The occupant injury risks in truck platooning are different from risks in single-passenger vehicle crashes. Structural adequacy, vehicle stability, and occupant risk are the main criteria when evaluating roadside infrastructures.
- ADS-equipped truck features and platoons may contribute to new crash types. Though rear-end crashes may become less frequent, large trucks moving closely together may promote different driving behavior when on mixed roads, increasing human-driven lane change risk for drivers next to platoons.
- Platoon length, speed, and intraplatoon gaps may vary over trips. In real traffic conditions, fuel reductions may not be observed because speeds and convoy gaps will vary due to interactions and disruptions with other vehicles (Ramezani et al., 2018).
- Daimler, the German automotive corporation, recently said it would "reassess its view on platooning." Daimler tested platooning for several years in the United States and determined that benefits were "less than expected." Even in perfect driving conditions, fuel savings were low and diminished further when the convoy becomes disconnected and trucks must accelerate to reconnect. Because of this, Daimler determined that in U.S. long-distance applications, analysis showed no business case (Lopez, 2019).
- Relatively low numbers of units are sold by truck manufacturers (Viscelli, 2018).
- Roadway infrastructure, such as bridges, may not be able to handle the higher weight concentration that platoons create (Grant, 2018).
- Lateral wandering of AV platoons is much narrower than that of human-driven trucks, increasing pavement cracking and rutting. Pavement fatigue in turn increases the risk of hydroplaning (Zhou et al., 2019).
- Labor may be opposed due to job loss.
- Training is needed on ADS and ATP use.

Opportunities

- Truck platooning is a promising technology that could bring great benefits to society and road users. In fact, the wide benefits achieved by self-driving trucks and highway platooning (e.g., safety, energy savings, road capacity) are expected to be the main reason for expanding the market of this feature more rapidly than other features for passenger cars.
- Unlike cars, there is already high demand for ADS-equipped trucks. Because of the labor savings of autonomy and because trucks are bought as business decisions thoroughly evaluated by fleets, return on investment on ADS-equipped trucks is expected to be high (Viscelli, 2018). In 2013, Moran Stanley estimated that ADS-equipped trucks would provide $168 billion in savings (Viscelli, 2018).
- Implementing ATPs will provide a host of benefits to both industry and drivers at risk from automation. ATPs can be built in strategic locations near interstate exits and truck parking lots outside congested urban areas. ATPs not only allow for trailer switching, but also provide driver facilities and refueling and charging stations. ATPs could facilitate off-peak deliveries to reduce road congestion and cut down on the coordination between shippers and carriers. Efficiency could be greatly enhanced through a ridesharing-style service that matches drivers and freight through an app with real-time pricing, keeping wages and work opportunity high (Viscelli, 2018).
- Platooning is expected to reduce the air resistance within a traveling fleet, which can translate to significant savings in fuel consumption by the fleet. The added advantage of reducing aerodynamic drag can reduce the maximum fuel consumption of trucks by between 6.5% and 21% (Ramezani et al., 2018) and induce fuel reductions of entire fleets up to 43% (Eilbert et al., 2019).

- In the future, many trucks with ADS and platooning capabilities will likely be electric. In the United States, the transportation sector is responsible for almost 30% of annual greenhouse gas (GHG) emissions (US EPA, 2019). Battery electric vehicles (BEV), however, have been shown to reduce overall GHG emissions and pollution relative to vehicles with an internal combustion engine and could greatly reduce our need for oil (Notter et al., 2010; Delucchi et al., 2014). Transferring emissions from the tailpipe to power-generating plants also further centralizes total emissions in the power production sector where measures such as carbon capture and sequestration and a cleaner fuel mix could contribute to reduced overall emissions. Additionally, BEV engines are inherently more energy efficient than internal combustion engines (Messagie, 2017) and can increase energy efficiency further by making use of "energy recovery" technology where breaking and unaccelerated motion act to recharge the battery (Delucchi et al., 2014; Manzetti and Mariasiu, 2015). Also, this feature eliminates the need for a highly skilled driver in following trucks, which could bring shipping costs down when platooning is deployed at a large scale.
- ADS-equipped trucks and platooning could positively affect other road users by providing increased capacity for the road (reducing gaps between vehicles). Self-driving and platooning also offer safety benefits when applied at a large scale by eliminating truck drivers' induced errors.
- Roadside barriers have proven to produce low risk of injury to platooning truck occupants given failure.

Goals and Hypothesis

For the deployment scenario of highway truck platooning, the goal is to reduce the frequency and severity of truck-involved crashes on truck-route corridors through use of highway truck platooning (SAE Level 4) and supporting infrastructure.

The overall hypothesis is that highway truck platooning will improve safety on interstates, freeways, and other divided highways with four or more lanes by reducing truck-involved crashes. The expected change in the number and percentage of truck-involved crashes will depend on market penetration, which is explored in the analysis. The questions to evaluate this hypothesis are listed below and relate to crash types, crash severity levels, infrastructure, and data.

1. How will the frequency of crashes change? It is anticipated that highway truck platooning will change the frequency of all crashes. While it is anticipated that truck-related or truck-involved crashes would decrease, other types of crashes might increase, such as crashes in the vicinity of interchanges where merging or diverging maneuvers occur.
2. How will the severity of truck-involved crashes change? It is anticipated that the severity of truck-related and truck-involved crashes would decrease. It is also anticipated that the severity of other crashes would remain the same as the speed, angle of impact, and other factors related to severity are expected to remain the same.
3. How will the number of trucks on interstates and highways change and, in turn, impact the number of crashes? While overall it is anticipated that highway truck platooning would reduce crash frequency and severity by removing human error, it is also anticipated that truck volume will increase with the deployment of highway truck platooning due to trailing trucks not needing humans present in the trucks. This could alter the crash frequency due to the increase in truck traffic.
4. Will the safety and deployment of highway truck platooning change if the ODD is extended in which highway truck platooning can operate? The current ODD for the short- and medium-term timelines includes certain weather conditions and certain infrastructure conditions. If the ODD is extended, it is anticipated that more crashes could be impacted by the deployment of highway truck platooning.

In summary, through the deployment of highway truck platooning, it is hypothesized that the frequency and severity of truck-involved and truck-related crashes will decrease. While other crash types such as merging and diverging actions at interchanges may increase, it is expected that the severity distribution will remain the same. While this provides an overview of potential safety impacts, it is important to perform a crash sequencing exercise to think through the contributing factors and precipitating events that lead to a crash. The following are a few examples related to truck platooning along the interstate:

1. Run-off-road:
   a. Driver of truck is distracted, falls asleep, or is otherwise inattentive and the vehicle drifts off the road.
   b. Driver of truck is fully attentive and adverse weather contributes to the driver losing control or incorrectly navigating and the vehicle leaves the road.
   c. Driver of truck is fully attentive and sudden congestion leads to an evasive maneuver whereby the driver attempts to avoid the back of queue and the vehicle leaves the road.
2. Rear-end:
   a. Driver of truck is distracted, falls asleep, or is otherwise inattentive and the truck rear-ends another vehicle.
   b. Driver of truck is fully attentive and adverse weather contributes to limited stopping distance whereby the driver is not able to stop or slow and the truck rear-ends another vehicle.
   c. Driver of truck is fully attentive and sudden congestion leads to unanticipated braking whereby the driver attempts to stop, but the truck rear-ends another vehicle.

From the anticipated capabilities of ADS-supported truck platooning and the above crash sequencing, the project team identified specific opportunities for this ADS application to mitigate crashes. For example, ADS-supported truck platooning is not expected to operate in adverse conditions, so there is limited potential to mitigate crashes related to sequence 1b; however, ADS-supported truck platooning is expected to provide opportunities to mitigate crashes related to sequence 1a and 1c. Similarly, ADS-supported truck platooning is not expected to mitigate crashes related to sequence 2b but is expected to mitigate crashes related to sequence 2a and 2c.

Methods of Analysis

Components of the Analysis. To estimate the safety effects of highway truck platooning, an analysis is needed to quantify the potential impacts by using crash data and the types of crashes platooning is expected to influence. The ODD of highway truck platooning is separated by facilities and traffic features in which they can operate in short- and medium-term timelines. For both timelines, highway truck platooning can operate on interstates and freeways and can navigate through interchanges and ramps. However, highway truck platooning can operate only in dedicated, separated trucking lanes for the short-term timeline but can operate in traditional lanes with mixed traffic during the medium-term timeline. Because of the lack of dedicated truck lanes in transportation networks and lack of data, dedicated lanes cannot be filtered out, and it is assumed that the ODD for the short-term timeline includes interstates and freeways. Highway truck platooning can also operate on urban and rural divided highways with four or more lanes, in addition to interstates and freeways, in the medium-term timeline.

Highway truck platooning is anticipated to only operate during certain weather conditions. In the short term, it is anticipated that platooning will operate in clear and windy weather conditions (e.g., no rail, snow, ice, etc.). In the medium term, it is anticipated that platooning will operate in clear, windy, and rain weather conditions.

Truck-involved crashes are crashes where at least one vehicle involved, per the police record, is a truck. While truck-involved crashes are the main crash type impacted, there is the potential to impact crashes with no trucks indicated on police records [e.g., truck-related action contributed to crashes involving other vehicle(s) on the road], which are referred to as truck-related crashes. However, in this analysis, only truck-involved crashes are assessed because of the lack of information from police reports to determine whether crashes are truck-related. It is anticipated that all crash severity levels will be impacted by highway truck platooning.

A summary of the components of the analysis is shown in Table B-27.

It is assumed that highway truck platooning will not eliminate all truck-involved crashes in the ODD described above. The assumption is that platooning will eliminate only a certain percentage of crashes because not all trucks will be equipped with the ability to platoon, and if a truck is able to platoon, there is the possibility that it is not used or does not operate as intended.

It is assumed that highway truck platooning will also have an impact on merging and diverging actions in the vicinity of ramps and interchanges, potentially causing an increase in crash frequency. The analysis related to this identifies whether a vehicle maneuver was either "merge" or "diverge" but does not show a potential crash reduction due to lack of information on exactly how these crash types will be impacted.

The expected timeline for achieving success depends on the expected timeline for deployment and penetration rates of platooning trucks. In this scenario, the timeline is assumed to pertain to short- and medium-term planning, which is a high disruption.

Analysis Methods

Data Sources. The sources of crash, roadway, and traffic data to analyze the impact of highway truck platooning are similar to those of ADS-equipped trucks due to similar ODDs, distribution, and VMT share. The data from HSIS include crash, roadway, and traffic data from Illinois and Ohio. The data were merged to identify crashes that could be impacted by highway truck platooning. Illinois data are from 2006 to 2010, and the Ohio data are from 2010 to 2015. These merged data were used in the analysis described below.

Define Metrics. The metrics are also similar to those of ADS-equipped trucks due to similar ODDs, disruption, and VMT share. The primary metric for assessing the safety impact of highway truck platooning is the change in crash frequency and severity.

Table B-27. Components of the analysis.

Component	Description
Functional classification, lanes, and road configuration.	Interstates and freeways (short- and medium-term).
	All other functional classifications that are divided with four or more lanes (medium-term).
Area type.	Urban and rural.
Speed conditions.	Any speed limit.
Weather conditions.	Clear, wind (short-term).
	Clear, wind, rain (medium-term).
Crash types.	Truck-involved.
	Merge and diverge vehicle maneuvers in vicinity of interchanges.
Crash severity level.	All severity levels.
Traffic conditions.	Dedicated lanes (short-term).
	Mixed (medium-term).

Evaluation Method. The impact method is also similar to that of ADS-equipped trucks. The evaluation uses crash history and identifies the crashes that could potentially be affected by the use of ADS-equipped trucks. The evaluation also includes a sensitivity analysis to explore assumptions related to penetration rates as well as probabilities that trucks are platooning and that the feature is activated and functions properly.

Results

Crash Reduction Due to Highway Truck Platooning. The impact of highway truck platooning is similar to that of ADS-equipped trucks due to their similar ODDs, distribution, and VMT share. However, the ADS-equipped trucks analysis does not include the potential crash increase due to merging and diverging. Based on the ADS-equipped truck analysis, Table B-28 displays the percent reduction in total truck-involved crashes per year for various sensitivities of VMT share in the short- and medium-term timelines.

Crash Increase Due to Highway Truck Platooning. While some crashes are expected to decrease, as shown previously, there is potential for other types of crashes to increase. Crashes related to merging and diverging maneuvers at ramps can potentially increase. Vehicles merging or diverging from a ramp to the main line might have difficulty merging into or out of traffic if a truck platoon is driving past the ramp or interchange. The following sections discuss crashes that could increase due to highway truck platooning; however, no analysis was performed due to the lack of information on how highway truck platooning will impact vehicles merging or diverging to or from ramps and the mainline.

Illinois data were used to identify the number of crashes involving merging or diverging maneuvers. The Illinois data were selected because of the availability of crash codes for vehicle maneuver and the explicit indication of a vehicle merging or diverging. Table B-27 shows the ODD (same as for the ADS-equipped truck analysis), indicating the filters for roadway types and weather conditions for both the short- and medium-term timelines. Table B-29 displays average total crashes per year for the short-term timeline for all crashes and truck-involved crashes by severity level when a vehicle maneuver in the crash was “merge” or “diverge.” Table B-30 displays average total crashes per year for the medium-term timeline for all crashes and truck-involved crashes by severity level when a vehicle maneuver in the crash was “merge” or “diverge.”

While the average crashes per year where vehicle maneuvers were “merge” or “diverge,” it is unknown how highway truck platooning will affect these numbers. It is anticipated that crashes involving merging or diverging maneuvers could increase because of highway truck platooning.

Interpreting the Results

Agencies can use the results to estimate the potential reduction in crashes. The following example displays rate reduction for a given agency. The agency is considering converting its truck

Table B-28. Components of the analysis.

Timeline	VMT Share	Percent Reduction in Total Truck-Involved Crashes per Year
Short term	5%	0.135%
	10%	0.271%
Medium term	11%	0.471%
	22%	0.941%

Table B-29. Crashes with merging or diverging vehicles for short-term timeline.

Severity Level	Total Crashes per Year in Clear and Windy Weather Conditions with Vehicle Maneuver of Merge or Diverge on Interstates and Freeways	Truck-Involved Crashes per Year in Clear and Windy Weather Conditions with Vehicle Maneuver of Merge or Diverge on Interstates and Freeways
PDO	530	285
Possible injury	18	7
Suspected minor injury	33	15
Fatal and suspected serious injury	11	3
Total	591	310

fleet to be automated and able to drive in platoons or improving infrastructure to allow highway truck platooning (e.g., constructing truck-only lanes or truck-bypass lanes). Based on historical data, there are 5,000 heavy-truck-involved crashes in an area with 2,000 million heavy-truck miles traveled. The calculated crash rate is 250 crashes per 100 million heavy-truck miles traveled. Using the short-term and medium-term VMT share, the calculated reduction in crash rates is in Table B-31. Assuming a short-term VMT share of 5%, a reduction of 12.5 crashes is expected for every 100 million heavy-truck miles traveled. An agency could perform a simple or more detailed benefit-cost analysis to compare these benefits with the cost of converting a truck fleet or the cost of infrastructure improvements or maintenance as part of the decision process.

Communicate Outcomes

The analysis supports the goals and hypotheses of the safety impacts of highway truck platooning. The results determined that truck-involved crashes would decrease in frequency and severity with the deployment of highway truck platooning. There is the possibility that crashes at interchanges and ramps would change; however, that could not be verified.

Table B-30. Crashes with merging or diverging vehicles for medium-term timeline.

Severity Level	Total Crashes per Year in Clear, Windy, and Rain Weather Conditions with Vehicle Maneuver of Merge or Diverge on Interstates, Freeways, and Divided Roads with 4 or More Lanes	Truck-Involved Crashes per Year in Clear, Windy, and Rain Weather Conditions with Vehicle Maneuver of Merge or Diverge on Interstates, Freeways, and Divided Roads with 4 or More Lanes
PDO	971	385
Possible injury	47	12
Suspected minor injury	61	20
Fatal and suspected serious injury	21	5
Total	1,100	422

Table B-31. Example of crash reduction.

	Reduction in Rate (Crashes per 100 Million Heavy-Truck Miles Traveled)	New Rate (Crashes per 100 Million Heavy-Truck Miles Traveled)
Short term:		
• **VMT share = 5%**	12.5	237.5
• **VMT share = 10%**	25.0	225.0
Medium term:		
• **VMT share = 11%**	27.5	222.5
• **VMT share = 22%**	55.0	195.0

Assumptions were made regarding facility conditions. Roads need to be well marked and well maintained for highway truck platooning to operate. This information is not readily available in the data used and is not available in most roadway databases. Therefore, it had to be assumed that the roadways were well marked and well maintained.

The ODDs of ADS-equipped trucks and highway truck platooning were similar. Therefore, it was assumed that truck-involved crash reduction would be the same. Crashes around interchanges and ramps could be different from those of ADS-equipped trucks, but that could not be determined with the available data and information about highway truck platooning.

ADS Feature: Level 4 Fleet-Operated Automated Driving System–Dedicated Vehicle (ADS-DV)

Understanding the ADS Feature

Feature Description. Level 4 fleet-operated ADS-DVs are driverless vehicles anticipated to be operated primarily by transportation network companies. This ADS feature allows the vehicle to operate without the need for a driver on a predefined set of roads or geographic area and within the specified ODD. The ADS automatically collects and processes data from onboard sensors and handles the V2V communications to perceive the surroundings, as well as obstacles and relevant signage, and identify the appropriate navigation trajectories. Fleet-operated ADS-DVs are capable of navigating through the identified trajectories safely with no human input. For this feature, the ADS is responsible for the DDT fallbacks and for achieving a minimal risk condition. Fleet-operated ADS-DVs that are designed to also accommodate operation by a driver (whether conventional or remote) may allow a user to perform the DDT fallback if they choose to do so. However, a Level 4 need not be designed to allow a user to perform DDT fallback and, indeed, may be designed to disallow (SAE, 2018).

For instance, consider a scenario where a fleet-operated ADS-DV, which handles the entire DDT within a geo-fenced area, experiences severe weather conditions that are beyond its ODD. In response, the fleet-operated ADS-DV should handle the DDT fallback and achieve a minimal risk condition that could include turning on the hazard flashers, maneuvering the vehicle to the road shoulder and parking it, and automatically summoning emergency assistance, which concludes the fallback response. However, if a driver was allowed to handle the DDT fallback and accepted risk, the ADS-DV may simply continue driving manually instead of achieving a minimal risk condition.

For noticeable benefits from Level 4 fleet-operated ADS-DVs, it is imperative that they operate as electric vehicles for many reasons. First, vehicle miles traveled are expected to increase drastically for this level of automation if they are operated as shared vehicles. If fleet-operated ADS-DVs are offered as gasoline engines, their operational costs will outweigh the benefits of shared mobility. Additionally, the environmental impacts would make them an unpopular option and, for AVs to operate safely, vehicle sensors and components must be maintained in good condition and operate with high levels of reliability. This is difficult to maintain in an internal fuel combustion environment, where there is a need to maintain all components of the engine in a reliable manner. Overall, it is much easier and more reliable to maintain the fleet-operated ADS-DV sensors and components functioning well in a drive-by-wire environment compared to an internal combustion engine.

OEMs are aware of these facts, and to facilitate the commoditization of their offered products, they are offering them as electric vehicles. Major cities are concerned with the potentially negative implications of increased shared gasoline vehicles and have started scheduling a future ban for fuel combustion engines (Boffey, 2019; Evarts, 2019). This trend is expected to intensify with a successful commercial deployment of Level 4 fleet-operated ADS-DVs, assuming there is public acceptance to support this engagement.

Expected Market. In December 2018, Waymo officially launched its commercial fleet-operated ADS-DV service in the suburbs of Phoenix (Hawkins, 2019b). During early deployment stages of fleet-operated ADS-DV, the car manufacturers will primarily target transportation network companies (TNCs) with large fleets. Large-fleet companies will be able to afford the HAV at early deployment and will be the key players for expanding the HAV market. In an early response to these facts, automakers and TNCs have been forging corporate coalitions to reserve a decent share of what is expected to be a multibillion-dollar market by 2030. For instance, in 2017, Volvo announced a 3-year deal to supply up to 24,000 ADS-DV to Uber, and the vehicle shipment was expected to start by the end of 2019. On the other hand, Lyft began partnering with General Motors earlier in 2016 for development of HAVs. Lyft pursued further collaboration by making two separate pacts in 2017 with Ford and Waymo, respectively, for collaboration on fleet-operated ADS-DVs.

Accordingly, the market of TNCs and shared mobility is expected to grow rapidly with the introduction of fleet-operated ADS-DVs reaching $173.15 billion by 2030, with shared mobility services contributing to 65.31% (Frost and Sullivan, 2018). These cascade trends and partnerships are expected to reshape the transportation sector and trigger a disruptive change to the transportation industry, probably the largest in transportation history. For instance, by 2030 the traditional processes for buying and renting cars could be replaced by a subscription system operated by TNCs and fleet managers. These systems would offer a variety of ride-hailing plans covering the different types of subscriber trips (e.g., work, errands, recreational). Discounts would be offered for subscribers affiliated with the TNC on long-term agreements to a level that makes the cost per mile traveled using these services much cheaper and more convenient than the cost and satisfaction per mile traveled using private cars. Assuming these scenarios, parking lots are expected to shrink across the United States and gradually be replaced with electric charging stations.

Cities are partnering on tests of a variety of fleet-operated ADS-DV technologies, including retrofitted autos, and shuttles and innovative types of vehicles like conveyors (small, cart-sized AVs that travel on sidewalks). The ODD for testing of these pilots can take place on private roads and planned environments, such as technology parks and college campuses, or public roads and city streets. AV pilots take many forms but can be categorized into two main groups: (a) HAVs for TNCs and (b) low-speed shuttles. The next subsections review some of the pilots conducted and ongoing and outline the lessons learned from some of these pilots (Table B-32).

Anticipated Deployment Scenario

Operational Design Domain. This scenario assumes that fleet-operated ADS-DV deployments will initially limit coverage only to certain trips within a geographic boundary. The ODD is

Table B-32. Recent AV pilot programs.

Operators	Location	Description
Waymo	Phoenix, AZ	Waymo launched an Early Rider program in early 2017, allowing select Phoenix residents to request rides in their automated minivans. Waymo engineers have now moved to the backseat as of November 2017 (Barr, 2018).
Cruise/GM	San Francisco, CA	In 2017, Cruise launched its pilot, "Cruise Anywhere," a shared AV (SAV) service for its employees to use for preselected destinations in San Francisco. Cruise intended to launch a commercial SAV offering in 2019 (Felton, 2018).
Nuro and Kroger Foods	Scottsdale, AZ	As of August 2018, Nuro is running its grocery delivery pilot using Toyota Priuses and intended to start delivery with its specialized R1 vehicle in fall 2018. The R1 is designed to exclusively have space for delivery goods, without any passengers (Nuro, 2018).
NuTonomy and Aptiv	Boston, MA	NuTonomy has been testing its vehicles in the Seaport neighborhood of Boston since 2017, and in June 2018, the vehicles were approved for testing citywide. NuTonomy is required to submit quarterly update reports to the city of Boston (Locklear, 2018).
Uber	Pittsburgh, PA; Tempe, AZ (ended)	In September 2016, Uber began a SAV pilot in Pittsburgh, and was the first SAV service in the United States to serve passengers selected from the public. However, testing stopped in both cities after the high-profile crash and death in Tempe, Arizona, in 2018. While Uber is banned from testing in Arizona, it began testing SAVs in "manual mode" with a specialist in control at all times in Pittsburgh (Bliss, 2018; Rogers, 2018).
Voyage	The Villages, FL	Voyage operates SAV pilots at The Villages retirement community in Central Florida. Service launched in Florida in 2018 (Corder, 2018).
Ford/ Domino's	Ann Arbor, MI; Miami, FL	A Ford Fusion hybrid began delivering pizzas with test driver in Ann Arbor in 2018 and plans were announced for Miami (Marakby, 2018).
Voyage	The Villages, San Jose, CA	Voyage operates SAV pilots at The Villages retirement community in San Jose. It has operated in San Jose since 2017 (Cameron, 2017).

assumed to be geographically bounded, and the designated route network for the fleet-operated ADS-DV does not use all roads and intersections within the road network (e.g., highways, school zones). As an illustrative example of an early deployment geographic region, consider Chandler, Arizona. This ODD includes signalized intersections, stop signs, pedestrian crosswalks, bike lanes, multilane roads, and speed limits up to 45 mph. It does not include some roads, including those over 45 mph and temporary traffic zones. The infrastructure in this ODD is well suited to early deployment, including modern and well-maintained signage and markings, good sight distance, minimal grade and curvature, and wide lanes.

Table B-33 summarizes the anticipated ODD elements of the fleet-operated ADS-DV feature. The ODD elements are predicted for two timelines: the short term (next 5 years) and the medium term (next 5 to 10 years). In addition, the table outlines the major deployment specifications envisioned for the two features that are expected to impact their safety assessment. The deployment elements are also provided for the two timelines.

Table B-33. Fleet-operated ADS-DV deployment scenarios of interest.

Operational Design Domain Level	Timeline	Additional Deployment Context
• **Suburban geofenced area.** • **All streets and intersections within a typical suburb such as Chandler, Arizona, that are fulfilling an ODD model set by the manufacturer.** ○ **Operating on well-marked roads with well-maintained signs.** ○ **Operating only in clear and good weather condition (e.g., no rain, snow, etc.).** ○ **Speed can reach up to 45 mph.**	Short term • Market share = 10% • Fleet share = 7% • VHT share = 10%	• Level 4 automation ADS feature where ADS is responsible for the DDT fallback and achieving appropriate minimal risk conditions. • Operating predominantly as fleet-operated ADS-DVs operated by transportation network companies. • Increased willingness for vehicle sharing. • Decreased vehicle ownership. • Navigating among other road users, including passenger vehicles, commercial vehicles, transit vehicles, and vulnerable road users. • Navigating among special vehicles, such as emergency vehicles, school buses, and mail delivery vehicles. • Highly visible signalized intersections with backer plates. • Road surface conditions in very good condition (Pavement Condition Index, 2019)[1] with minimal road damage (e.g., cracking, rutting, raveling, potholes). • Road surface is dry and not covered by snow or ice. • Road markings are in good condition.[2] • Cannot navigate temporary traffic zones (e.g., work zones, school zones). • Sidewalks rarely traversed by pedestrians. • Limited VRU interactions, mostly traveling within designated areas (e.g., crosswalks and bike lanes). • Can operate in any sky condition,[3] with the exception of conditions that cause sun glare.[4]

[1] Very good state of repair is defined as 80–89.9 Pavement Condition Index (PCI).
[2] Refer to NCHRP Project 20-102(06) for more details on road markings for machine vision (Pike et al., 2018).
[3] The National Weather Service provides a scale of sky conditions by percent of opaque cloud cover.
[4] Sun glare occurs if the sun is within a specified angular distance between the driver's line of sight and the sun. For a 40-year-old driver, this angular distance is 19° and for a 60-year-old driver it is 25°. For early deployments, 25° is assumed. This would exclude travel in the direction of the sunrise and sunset while the sun is below this angle.

Table B-33. (Continued).

Operational Design Domain Level	Timeline	Additional Deployment Context
		• Illuminance is brighter than twilight (AMS Glossary of Meteorology, 2018; NOAO, 2019).[5] • No rain, snow, sleet, freezing rain, hail, or more than gale force winds (NOAA, 2019).[6]

• **Suburban and urban geofenced area.**
• **All streets and intersections within a suburb or a central business district that are fulfilling an ODD model set by the car manufacturer.**
  ○ **Operating on well-marked roads with well-maintained signs.**
  ○ **Operating in good and clear weather conditions but could operate in mild and light rain conditions.**
  ○ **Speed could reach up to 50 mph.**
	Medium term
	• Market share = 30%
	• Fleet share = 14%
	• VHT share = 22%
		• Level 4 automation ADS feature where ADS is responsible for the DDT fallback and achieving appropriate minimal risk conditions.
		• Operating predominantly as fleet-operated ADS-DVs operated by TNC.
		• Increased willingness for vehicle sharing.
		• Decreased vehicle ownership.
		• Sidewalks are frequently traversed by pedestrians.
		• Frequent pedestrian interaction with the vehicle.
		• Up to moderate rain, but no snow, sleet, freezing rain, or hail.[7]

Table B-34 provides a summary of the technology specifications and key infrastructure needs pertinent to the envisioned fleet-operated ADS-DV scenarios.

First Generation (Gen I): This is the first version of sensors and technology package and the underlying computational algorithms for processing the data needed for full autonomy. Typically, this package embraces all needed combinations of sensors such as forward-facing cameras, radars, ultrasonic sensors, lidars, and inertial measurement units (gyroscopes and accelerometers) with *a priori* HD maps. This package will not have a good object detection capability in low-visibility conditions, limiting the ODD to certain conditions (e.g., good and clear weather condition, good lane markings).

Similarly, the underlying perception algorithms for processing the data are at early stages and are capable of handling the basic computations for reaching full autonomy within the ODD and deployment context specified in Table B-34. These algorithms are in early development and may have more errors than later, more mature technology, leading to lower percentage of time operating in autonomous mode (high disengagement rate). Sensors and computation algorithms used at this stage are commercially available and currently operate in certain vehicles (Hawkins, 2019a).

[5] Twilight may be defined multiple ways. The National Optical Astronomy Observatory has developed a scale for illuminance, or intensity of visible light, which is measured in Lux. Twilight is illuminance greater than 10.8 Lux. The American Meteorological Society describes civil twilight as when the sun is 6 degrees below the horizon, http://glossary.ametsoc.org/wiki.
[6] Beaufort Wind Scale, including World Meteorological Organization Classification.
[7] Moderate rain is defined as up to 0.3 inch per hour (0.76 cm/hr), according to the American Meteorological Society, Glossary of Meteorology, 2019, http://glossary.ametsoc.org/wiki.

Table B-34. Sensor specifications and infrastructure requirements of fleet-operated ADS-DV scenarios.

<table>
<tr><th rowspan="2">Expected Timeline</th><th rowspan="2">Vehicle Type</th><th rowspan="2">Sensor Package</th><th colspan="2">Key Infrastructure Requirements</th></tr>
<tr><th>Digital</th><th>Physical</th></tr>
<tr><td>Short term

High disruption.</td><td>Light duty.</td><td>Gen I.</td><td>GPS-relevant infrastructure.</td><td>• Pavement markings in excellent condition.
• Signage in excellent or good condition.
• Parking infrastructure with charging infrastructure.</td></tr>
<tr><td>Medium term

High disruption.</td><td>Light duty.</td><td>Gen II.</td><td>• GPS-relevant infrastructure.
• V2V- and V2X-relevant infrastructure.
• Weather data.
• Work zone data.
• Dynamic traffic data.</td><td>• Lane and pavement markings in excellent condition.
• Signage in excellent or good condition.
• Curbside management.
• Parking infrastructure with charging infrastructure.</td></tr>
</table>

Second Generation (Gen II): Gen II is a more advanced stage of technology than first-generation models or systems. In addition to the sensor types included in Gen I, this generation embraces a vehicle OBU for handling V2X communications. All Gen II sensors are newer, more advanced, more accurate, and have longer perception range than the Gen I sensors. Assuming a high-disruption scenario would occur, the development curve for these technologies could follow Moore's Law in computer chips. For instance, it is possible that every 18 months, resolution doubles and the price drops by half for the lidar sensor—the most important and expensive sensor in the package (Bloomberg, 2019).

The supporting HD maps for this generation have better accuracy and include more reliable dynamic layers—updating in real time—for different traffic conditions, such as work zones and crashes. A key feature of the Gen II sensor package is providing layers of redundancy to one another. The perception algorithms frequently cross-check the data from different sensors to increase the chances that no object is left undetected and to eliminate false positives.

This sensor package manifests as mature sensor fusion technology able to combine the sensing capabilities of multiple sensors, resulting in more reliable and robust perception with a broad sensing scope. To this end, the underlying perception algorithms for processing the data are more advanced and capable of performing complex sensor fusion calculations and applying artificial intelligence algorithms in real time. Another envisioned key feature of this generation of sensors is integrating V2V and V2I communication within the vehicles through the OBU. This provides opportunities for the vehicle to receive real-time dynamic data for weather, work zones, and traffic.

Risk Assessment

Risks

- There is a lack of standardization in vehicles and among service providers.
- At low market penetration rates, fleet-operated ADS-DVs could emerge and contribute to new crash types. Specifically, at low penetration rates, traditional nonautomated vehicles following fleet-operated ADS-DV could experience increased risk for rear-end crashes.

- Another concern with the implementation of fleet-operated ADS-DVs could be the expected degradation of some driving skills—depending on the ADS feature—due to reliance on automation and lack of exposure to DDT. Skill degradation is not limited to psychomotor skills—those pertaining to performing maneuvers—but also include decision-making skills (Miller and Parasuraman, 2007). At higher market penetration of fleet-operated ADS-DVs (Level 4 ADS features), state agencies may consider enacting legislation that necessitates the reassessment of driving skills for those relying on fleet-operated ADS-DVs for prolonged time with no exposure to driving.
- Interacting with first responders may present challenges. Typically, first responders need to be trained on new procedures for interacting with these vehicles, particularly during emergency situations. First responders may need to disable, access, or move low-speed shuttles, direct traffic (e.g., signaling right of way), and identify ADS-related hazards. At early stages of deployment, these procedures are expected to vary between manufacturers, and having a plan for these interactions can help address this risk.
- Traffic congestion may occur near curbsides and zones specified for loading, pick-up, and dropping.
- Fleet-operated ADS-DVs have the potential to reduce public transport and other mode shares (bicycles and pedestrians).
- Major investment in electrification infrastructure is needed. Battery limitations in fleet-operated ADS-DV—they are envisioned to operate as electric vehicles—produce range anxiety and limit operational capacity.
- Until the technology is fully mature, and ADS-DVs reach high market penetration values, it is speculated that these vehicles will keep moving slower than an average human driver. This would cause increased traffic congestion, especially during rush hours, and could result in more aggressive and frequent lane-change maneuvers (e.g., nonautomated vehicles passing slow-moving robo-taxis).

Opportunities

- The high-tech vision system has the potential to outperform human drivers in detecting potential safety issues. Unlike distracted or drunk drivers, fleet-operated ADS-DVs operate at their maximum ability. Therefore, they are likely to reduce crash frequency and severity. This would translate into enhanced pedestrian safety at pedestrian crossings and crosswalks. In fact, there is a concern that some pedestrians could exploit this benefit and "harass," or at least illegally hinder, fleet-operated ADS-DVs.
- Reduced traffic violations may have an aggregate positive impact on traffic safety. There is the potential to redirect law enforcement efforts toward the enforcement of pedestrian and bicyclist laws and related behaviors.
- The value of time or travel time may be reduced due to fleet-operated ADS-DVs, because of the increased comfort, reduced stress, and increased productivity while traveling as a passenger instead of as a driver (e.g., Childress et al., 2015).
- The need for parking spots (on-street and off-street) may be reduced.
- Curbs may be reinvented curbs by changing some on-street parking to pick-up, drop-off, transit stops, or commercial use during the different time of the day.
- The infrastructure necessary to price the curb dynamically and collect revenues needs development (for instance, by installing smart meters that display current prices, accept payments, and notify servers if they are occupied).
- Fleet-operated ADS-DVs are the among ADS features that provide massive opportunities for better fuel saving and longer vehicle life. Since these vehicles are envisioned to operate as electric vehicles, major reductions in GHG emissions and fuel consumption are expected to occur simultaneously with their deployment. Also, automating the vehicle in congested

conditions improves the vehicle's energy efficiency and motor lifetime. Funding recipients of the DOE NEXTCAR program are commercializing these types of technologies (ARPA-E, 2020). Additionally, smart eco-routing algorithms could be integrated with these vehicles, such that they are capable of finding faster routes to their destinations, drive more efficiently, and consume less fuel.

- With increased market share, fleet-operated ADS-DVs provide potential for implementing innovative eco-driving and speed harmonization techniques, when such vehicles are connected (supporting V2V or V2I communication systems). More sophisticated eco-driving and speed harmonization techniques could be considered, such as geofencing a cordon that may be scalable and movable.

Goals and Hypothesis. For the fleet-operated ADS-DV deployment scenario, the goal is to reduce the frequency and severity of crashes involving on-demand and demand response mobility services in controlled environments and urban centers through use of fleet-operated ADS-DVs (SAE Level 3 and Level 4) and supporting infrastructure.

The overall hypothesis is that *fleet-operated ADS-DVs will improve safety in controlled environments and urban areas by reducing the frequency and severity of crashes involving demand response and on-demand mobility vehicles within 3 to 5 years.* The expected change in the number and percentage of crashes involving demand response and on-demand mobility vehicles will depend on market penetration, which is explored in the analysis. The questions related to the hypothesis are listed below and relate to crash types, crash severity levels, infrastructure, and data.

1. How will the frequency of crashes involving on-demand mobility vehicles change in relation to safety? It is anticipated that crashes involving on-demand mobility service vehicles will decrease with the deployment of fleet-operated ADS-DVs by removing human error from the vehicles.
2. How will the severity of crashes involving on-demand mobility vehicles change in relation to safety?
3. How will the frequency of crashes involving on-demand mobility service vehicles (traditional human-operated vehicles) change in relation to safety? There is the potential for road users to change travel modes from driving their own vehicles to using fleet-operated ADS-DVs. Therefore, this switch would impact crashes involving regular user-owned vehicles.
4. Will the safety and deployment of fleet-operated ADS-DVs change if the ODD is expanded and/or infrastructure improvements are made? The current ODD for fleet-operated ADS-DVs includes certain road types, environmental conditions, and infrastructure conditions (e.g., pavement markings in excellent conditions, electric vehicle charging stations, V2X-related infrastructure). If fleet-operated ADS-DVs can operate in additional conditions, then there is potential to expand the safety benefits.
5. Will frequency and severity of pedestrian- and bicycle-related crashes change with the deployment of fleet-operated ADS-DVs? It is anticipated that pedestrian crashes will decrease in frequency and severity. This is due to the deployment of fleet-operated ADS-DVs (i.e., removing human error from the vehicles) in controlled and urban environments where pedestrians are typically present.

In summary, through the deployment of fleet-operated ADS-DVs, it is hypothesized that the frequency and severity of crashes involving demand response vehicles, on-demand mobility vehicles, and individual-owned vehicles, including pedestrian- and bicycle-related crashes, will be reduced. While this provides an overview of potential safety impacts, it is important to perform a crash sequencing exercise to think through the contributing factors and precipitating events that lead to a crash. The following are a few examples related to ADS-DVs:

1. Rear-end:
   a. Congested conditions cause vehicle 1 to stop. Driver of vehicle 2 (a fleet-operated vehicle) is distracted, falls asleep, or is otherwise inattentive. Vehicle 2 rear-ends vehicle 1.
2. Right-angle:
   a. Driver of vehicle 1 (a fleet-operated vehicle) stops at a stop-controlled approach of a two-way stop-controlled intersection. Vehicle 2 is traveling on the uncontrolled approach. Driver of vehicle 1 does not see vehicle 2 because of sun glare. Vehicle 1 proceeds through the intersection. Vehicle 2 collides with vehicle 1.
3. Run-off-road:
   a. Driver of vehicle 1 (a fleet-operated vehicle) is distracted, falls asleep, or is otherwise inattentive and the vehicle drifts off the road.
   b. Driver of vehicle 1 (a fleet-operated vehicle) is fully attentive and adverse weather contributes to driver losing control or incorrectly navigating and the vehicle leaves the road.

From the anticipated capabilities of ADS-DVs and the above crash sequencing, the research team identified specific opportunities for this ADS application to mitigate crashes. For example, ADS-DVs are not expected to operate in adverse conditions, so there is limited potential to mitigate crashes related to sequence 3b; however, ADS-DVs are expected to provide opportunities to mitigate crashes related to sequence 1a, 2a, and 3a among others.

Methods of Analysis

Components of the Analysis

To estimate the safety effects of fleet-operated ADS-DV, an analysis is needed to quantify the potential safety impacts using crash data and the types of crashes fleet-operated ADS-DVs are expected to influence, including the operating environments of the expected deployment. The ODD of fleet-operated ADS-DVs is separated by area type, speed conditions, environmental conditions, and traffic features.

For the short- and medium-term timelines, fleet-operated ADS-DVs can operate only in suburban geofenced areas. However, fleet-operated ADS-DVs in the medium-term timeline can also operate in urban geofenced areas. While there are some pilot projects of ADS-DV in urban areas, these services are not available as fully automated options and are not expected to be available on a larger scale in the short term. The streets and intersections in the short-term timeline are similar to those in suburban areas, where speeds can reach up to 45 mph. The streets and intersections in the medium-term timeline are similar to those of suburban areas and central business districts, and speeds can reach up to 50 mph. To operate in these area types, the roadways must have well-marked and well-maintained signs and pavement markings in excellent conditions for both the short- and medium-term timelines.

Fleet-operated ADS-DVs are anticipated to only operate in clear weather conditions for the short-term timeline. This includes no rain, snow, or ice. Fleet-operated ADS-DVs can similarly only operate in clear weather conditions in the medium-term timeline; however, they can also operate in light or mild rain conditions.

Fleet-operated ADS-DVs are expected to affect specific crash types and crashes with specific types of vehicles. The crash types typically include those relating to the types of vehicles fleet-operated ADS-DVs will replace. These include crashes with on-demand mobility service vehicles, demand response vehicles, and privately owned vehicles where users switched travel modes to fleet-operated ADS-DVs. The use of fleet-operated ADS-DVs will also potentially affect crashes where the crash contributing factor relates to driver behavior (e.g., speeding) or condition (e.g., distraction, impaired) due to the removal of human error from the driving scenario with the use of fleet-operated ADS-DVs.

A summary of the components of the analysis is shown in Table B-35.

It is assumed that fleet-operated ADS-DVs will not eliminate all crashes, including pedestrian and bicycle crashes, where the vehicles involved are vehicles that fleet-operated ADS-DVs are expected to replace. The assumption is that they will eliminate only a certain percentage of crashes because there remains the potential for road-user error or technology failure for fleet-operated ADS-DVs. The expected timeline for achieving success depends on the timeline for deployment and penetration rates of fleet-operated ADS-DVs. In this scenario, the expected timeline is assumed to pertain to a high disruption of fleet-operated ADS-DVs.

Analysis Methods

Data Sources

The source of crash data used to estimate the effect of fleet-operated ADS-DVs on safety is the National Transit Database (NTD). The NTD, provided by the U.S. Department of Transportation Federal Transit Administration (FTA), offers crash information related to transit vehicles. Transit agencies in urban areas (850 transit providers) report financial and operating information to the FTA, where it is compiled and offered to the public. Some of the information available includes agency, transit mode, location (city and state), directional route miles, passenger miles traveled, events, collisions, fatalities, and injuries.

By law, California mandates all companies that are actively testing Level 4 driverless vehicles on California public roads to disclose the number of miles driven and the frequency in which human safety drivers were forced to take control of their autonomous vehicles (Autonomous Vehicle Disengagement Reports). Manufacturers are also required to provide the California Department of Motor Vehicles with Traffic Collision Involving an Autonomous Vehicle report (form OL 316) within 10 days after the collision (Autonomous Vehicle Collision Reports). These reports could provide valuable data for refining the framework results, once these driverless vehicles are commercially deployed at wide scale.

Table B-35. Components of the analysis.

Component	Description
Functional classification, lanes, and road configuration.	All streets and intersections within area type.
Area type.	Suburban geofenced area.
	Urban geofenced area.
Operating speed.	Up to 45 mph (short term).
	Up to 50 mph (medium term).
Weather conditions.	Clear (short term).
	Clear and mild and light rain (medium term).
Crash types.	On-demand mobility service vehicles.
	Transit vehicles.
	Privately owned vehicles.
	Pedestrian and bicycle.
Crash severity level.	All severity levels.

Define Metrics

The primary metric for assessing the safety impact of fleet-operated ADS-DVs is the change in crashes by frequency. While the change in crashes should be based on the crashes of interest for the deployment scenario, the NTD data are not sufficiently detailed to categorize and filter crashes based on area type, infrastructure conditions, speed requirements, and weather conditions. Therefore, the data were filtered based on passenger miles traveled and mode. The passenger miles traveled were required to be greater than 0 miles to ensure availability of a normalization parameter for the crashes. As mentioned, the data were also filtered by mode. The modes included from the NTD used in the analysis are demand response (including taxi), jitney, and vanpool.

Evaluation Method

It is important to test the hypothesis and related questions based on the available data. The evaluation uses crash history and identifies the crashes that could potentially be affected by fleet-operated ADS-DVs. The evaluation estimates crash reduction by frequency. Table B-36 lists the categories of crashes used to estimate the safety impact of fleet-operated ADS-DVs.

For the analysis, the collisions are normalized using the passenger miles traveled to obtain a rate (i.e., collision, fatality, or injury rate), shown in the following equation per 100 million passenger miles traveled.

$$Rate = \frac{\dfrac{number\ of\ events}{passenger\ miles\ traveled}}{100{,}000{,}000\, miles}$$

Using the normalized numbers, the estimated reductions in related events (collisions with vehicle, pedestrian, or bicyclist) were calculated based on the percentage of VMT share represented by the fleet-operated ADS-DVs. For example, rates calculated using the above equation were multiplied by the VMT share, shown in the equation below.

$$Reduction = rate \times VMT\ share$$

A sensitivity analysis is used to explore various assumptions related to penetration rates and probabilities that a vehicle is a fleet-operated ADS-DV and the technology functions properly.

Table B-36. Crash types and severity levels to estimate fleet-operated ADS-DV impact.

Category	Event Type or Severity
1	Collision with vehicle.
2	Collision with person.
3	Total events (including collisions and non-collisions).
4	Fatalities—bicyclist.
5	Fatalities—pedestrian.
6	Total fatalities.
7	Injuries—bicyclist.
8	Injuries—pedestrians.
9	Total injuries.

Results

Statistics

Table B-37 through Table B-39 display crash statistics for the NTD data for 2008 to 2018. The crashes are separated by events and collisions, fatalities, and injuries, respectively.

Impact of Fleet-Operated ADS-DVs

The potential crash rate reduction is based on the VMT share described in the deployment scenarios. The VMT shares for the different timelines of fleet-operated ADS-DVs are listed below.

Short-term (high disruption) VMT share = 10%

Medium-term (high disruption) VMT share = 22%

In addition to the percentage of VMT share shown above, other percentages of VMT share were used as a sensitivity analysis to account for fleet-operated ADS-DVs that do not have the autonomous feature engaged or for situations when the technology fails. Given the wide range of projections for market penetration, 50% of the VMT share (listed above) were assumed as the values for the sensitivity analysis, listed below. This helps to show the relative difference in results if only half of the expected market penetration is achieved.

Table B-37. Number of collisions and collision rate.

Collision Type	Number of Collisions	Collisions per 100 Million Passenger Miles Traveled
Collision with vehicle	6,200	26.74
Collision with person	463	2.00
Total collisions and non-collisions	16,456	70.97

Table B-38. Number of fatalities and fatality rate.

Fatality Type	Number of Fatalities	Fatalities per 100 Million Passenger Miles Traveled
Fatalities—bicyclist	0	0.00
Fatalities—pedestrians	9	0.04
Fatalities total	92	0.40

Table B-39. Number of injuries and injury rate.

Injury Type	Number of Injuries	Injuries per 100 Million Passenger Miles Traveled
Injuries—bicyclist	138	0.60
Injuries—pedestrians	334	1.44
Injuries total	19,272	83.11

Short-term VMT share for sensitivity analysis = 5%

Medium-term VMT share for the sensitivity analysis = 11%

The estimated reductions for total collisions, fatalities, and injuries were calculated using the method previously described, where the rate is multiplied by the VMT share. The analysis considered pedestrian and bicyclist fatalities and injuries separately as well as collision with person. However, the data for "collision with person" did not distinguish between collision with a bicyclist and collision with a pedestrian. The analysis assumed collision with a person refers to both a bicyclist and pedestrian. Table B-40 displays the reduction in rates for the short-term timeline due to the deployment of fleet-operated ADS-DVs. Table B-41 displays the reduction in rates for the medium-term timeline due to the deployment of fleet-operated ADS-DVs. In both tables, the rate reduction is shown in terms of events per 100 million passenger miles traveled.

Interpreting the Results

The reductions in Table B-40 and Table B-41 indicate that events involving demand response—taxis, jitney, and vanpool vehicles, which are used as surrogates for fleet-operated ADS-DVs—are expected to decrease with the deployment of fleet-operated ADS-DVs. As time progresses from the short-term to medium-term timeline, a greater reduction is expected.

Agencies can use the results to estimate the potential reduction in events. The following example displays rate reduction for a given agency. The agency is considering conversion of a fleet of traditional, driver-operated, demand-response vehicles to fleet-operated ADS-DVs. Based on historical data, there are 80 events involving the traditional, driver-operated, demand-response vehicles on routes with an associated 97,249,449 passenger miles traveled. The calculated event rate is 82.26 events per 100 million passenger miles traveled. Using the short- and medium-term VMT share, the reduction in crash rate and new crash rates are calculated, as shown in Table B-42. Assuming a short-term VMT share of 5%, the expected reduction is 4 events for

Table B-40. Crash rate reduction for the short-term timeline.

Collision/Fatality/Injury Type	Rate Reduced (5% VMT Share) (Events per 100 Million Passenger Miles Traveled)	Rate Reduced (10% VMT Share) (Events per 100 Million Passenger Miles Traveled)
Collision with vehicle	1.34	2.67
Collision with person	0.10	0.20
Total collisions and non-collisions	3.55	7.10
Fatalities—bicyclist	0.00	0.00
Fatalities—pedestrians	0.002	0.00
Fatalities total	0.02	0.04
Injuries—bicyclist	0.03	0.06
Injuries—pedestrians	0.07	0.14
Injuries total	4.16	8.31

Table B-41. Crash rate reduction for the medium-term timeline.

Collision/Fatality/Injury Type	Rate Reduced (11% VMT Share) (Events per 100 Million Passenger Miles Traveled)	Rate Reduced (22% VMT Share) (Events per 100 Million Passenger Miles Traveled)
Collision with vehicle	2.94	5.88
Collision with person	0.22	0.44
Total collisions and non-collisions	7.81	15.61
Fatalities—bicyclist	0.00	0.00
Fatalities—pedestrians	0.004	0.01
Fatalities total	0.04	0.09
Injuries—bicyclist	0.07	0.13
Injuries—pedestrians	0.16	0.32
Injuries total	9.14	18.29

every 100 million passenger miles traveled. An agency could perform a simple or more detailed benefit-cost analysis to compare these benefits with the cost to convert the vehicle fleet as part of the decision process.

Communicate Outcomes

Through the framework and analysis, the results demonstrate how rates are expected to decrease. Specifically, fleet-operated ADS-DVs are expected to reduce crashes. If the ODD is extended so fleet-operated ADS-DVs can operate in different areas, different facilities, or different environmental conditions, a further reduction in crashes would be expected. However, this could not be verified in the analysis because of the limited variables available in the dataset.

Assumptions were made to perform the analysis. As previously mentioned, the exact elements from the ODD (e.g., area type and weather) could not be filtered or separated. For example, fleet-operated ADS-DVs can only operate in specific area types. The crashes could not be separated by only those occurring in specific locations. Therefore, the analysis assumed the crashes were occurring in locations where fleet-operated ADS-DVs would operate.

Table B-42. Example of crash reduction.

	Reduction in Rate (Events per 100 Million Passenger Miles Traveled)	New Rate (Events per 100 Million Passenger Miles Traveled)
Short term:		
• **VMT share = 5%**	4.11	78.15
• **VMT share = 10%**	8.23	74.04
Medium term:		
• **VMT share = 11%**	9.05	73.21
• **VMT share = 22%**	18.10	64.16

Another assumption used in the analysis relates to the environmental conditions. Fleet-operated ADS-DVs can only operate in clear and windy weather conditions for the short-term timeline and in weather conditions consisting of no heavy rain or snow for the medium-term timeline. However, the weather conditions for the crashes in the NTD are unknown. The analysis assumed that the crashes occurred in weather conditions in which fleet-operated ADS-DVs can operate in the short- and medium-term timelines.

Other elements of fleet-operated ADS-DVs that were assumed to be present in the data for the short- and medium-term timelines include well-marked and well-maintained roads, parking infrastructure with electric vehicle charging stations, and GPS-relevant infrastructure.

APPENDIX C

Reference Crash Data for Traffic Jam Assist

Table C-1. Total crashes on all roads by severity level (2012–2017).

Severity Level	Number of Crashes
Blank	28
Property damage only	94,526
Possible injury	38,608
Suspected minor injury	9,796
Fatal and suspected serious injury	892
Total	143,850

Table C-2. Total crashes on all roads by crash type (2012–2017).

Crash Type	Number of Crashes
Unknown	114
Non-collision	
1. Ran off road right	7,614
2. Ran off road left	3,890
3. Ran off road straight ahead	573
4. Jackknife	96
5. Overturn/rollover	385
6. Crossed centerline/median	309
7. Downhill runaway	9
8. Cargo/equipment loss or shift	13
9. Fire/explosion	9
10. Immersion	5

(continued on next page)

Table C-2. (Continued).

Crash Type	Number of Crashes
11. Equipment failure (tires, brakes, etc.)	60
12. Separation of units	22
13. Other non-collision	443
Collision of motor vehicle with	
14. Pedestrian	1,936
15. Pedal cyclist	625
16. Railroad train, engine	20
17. Animal	1,507
18. Movable object	503
19. Fixed object	1,428
Collision of two or more motor vehicles	
20. Parked motor vehicle	4,455
21. Rear-end, slow or stop	50,171
22. Rear-end, turn	1,402
23. Left turn, same roadways	12,695
24. Left turn, different roadways	11,239
25. Right turn, same roadways	1,770
26. Right turn, different roadways	4,178
27. Head-on	1,372
28. Sideswipe, same direction	17,295
29. Sideswipe, opposite direction	1,822
30. Angle	11,270
31. Backing up	3,843
32. Other collision with vehicle	2,257
33. Tree	77
34. Utility pole (with or without light)	104
35. Luminaire pole non-breakaway	6
36. Luminaire pole breakaway	9
37. Official highway sign non-breakaway	7
38. Official highway sign breakaway	10
39. Overhead sign support	0
40. Commercial sign	0
41. Guardrail end on shoulder	3
42. Guardrail face on shoulder	19
43. Guardrail end on median	1
44. Guardrail face on median	5

Table C-2. (Continued).

Crash Type	Number of Crashes
45. Shoulder barrier end (non-guardrail)	2
46. Shoulder barrier face (non-guardrail)	4
47. Median barrier end (non-guardrail)	11
48. Median barrier face (non-guardrail)	23
49. Bridge rail end	0
50. Bridge rail face	5
51. Overhead part underpass	2
52. Pier on shoulder of underpass	0
53. Pier in median of underpass	0
54. Abutment of underpass	0
55. Traffic island curb or median	30
56. Catch basin or culvert on shoulder	0
57. Catch basin or culvert on median	1
58. Ditch	4
59. Embankment	4
60. Mailbox	44
61. Fence or fence post	22
62. Construction barrier	2
63. Crash cushion	2
64. Other fixed object	112
99. Blank	11
Total	143,850

Table C-3. Total crashes on all roads by weather condition (2012–2017).

Weather Condition	Number of Crashes
Blowing sand, dirt, snow	5
Clear	104,002
Cloudy	23,974
Fog, smog, smoke	306
Other	190
Rain	14,324
Severe crosswinds	15
Sleet, hail, freezing rain/drizzle	453
Snow	581
Total	143,850

Table C-4. Total crashes on all roads by speed limit (2012–2017).

Speed Limit (mph)	Number of Crashes
25	13,821
30	4,965
35	67,954
40	5,200
45	44,068
50	445
55	6,589
60	205
65	603
Total	143,850

Table C-5. Total crashes by speed limit and weather condition (2012–2017).

Weather Condition	Speed Limit (mph)									Total
	25	30	35	40	45	50	55	60	65	
Blowing sand, dirt, snow	0	0	1	1	3	0	0	0	0	5
Clear	10,314	3,610	49,353	3,687	31,653	317	4,540	142	386	104,002
Cloudy	2,168	856	11,298	971	7,352	69	1,126	31	103	23,974
Fog, smog, smoke	20	7	156	7	98	1	14	0	3	306
Other	42	8	107	3	25	0	4	1	0	190
Rain	1,194	449	6,542	502	4,627	43	847	29	91	14,324
Severe crosswinds	0	1	10	0	3	0	1	0	0	15
Sleet, hail, freezing rain/drizzle	30	10	206	12	137	7	39	1	11	453
Snow	53	24	281	17	170	8	18	1	9	581
Grand total	13,821	4,965	67,954	5,200	44,068	445	6,589	205	603	143,850

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GHSA	Governors Highway Safety Association
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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