NCHRP 17-91
Assessing the Impacts of Automated Driving Systems (ADS) on the Future of Transportation Safety

Phase 4 Technical Memorandum

Documenting Proof of Concept Results Report

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Introduction

Quickly advancing automated driving system (ADS) technologies are expected to positively impact transportation safety in the coming years. ADS technologies have the potential to change multimodal highway and street planning, design, and operational policies and decisions. As a result, transportation agencies that traditionally plan, design, and operate roads with human drivers in mind will need to adapt related policies and decisions to account for ADS technologies. ADS will change safety in many ways, not only in crash severity and likelihood but also in the types of crashes that occur. Analysis of the impacts of ADS on safety, traffic flow, and other important considerations will depend on data sources that do not yet exist or were not designed to specifically examine the role of automation. To forecast safety impacts of ADS with limited data, it is important to understand the expected safety performance of the existing facility as well as the underlying ADS factors that are expected to influence safety, such as enabling technologies (e.g., sensors, communications), human-machine interaction, and vehicle-to-infrastructure interactions.

A framework was developed to help state and local agencies assess when their traditional safety-related processes and procedures may be affected and characterize the expected safety impacts of competing options. ADS (typically SAE levels 3 through 5 automation) includes many applications that are expected to impact safety, mobility, human factors, and environmental aspects of driving. The framework includes processes and procedures to assess the potential safety impacts of ADS applications under different contexts, timeframes, risks, and opportunities.

The framework is adaptable and provides flexibility to accommodate technology advances, policy changes, and varying requirements of different state and local agencies. The project team hosted a virtual summit through a three-part webinar series to engage a broad set of stakeholders and solicit their inputs to make the framework more robust. The purpose of the summit was to present the framework, discuss safety impacts of ADS on roadway planning design and operations, and gather feedback from the audience. For the webinar series, the target audience included both public (State Departments of Transportation (DOTs), Research Institutions, Standards Development Organizations (SDOs), etc.) and private (original equipment manufacturers (OEMs), technology companies, traffic control device manufacturers, etc.) entities in transportation. The project team used the feedback received from the stakeholders who attended the summit to update and refine the framework (Version 2).

To refine the framework further, a proof of concept (PoC) pilot of version 2 of the framework was completed with two state DOTs (Minnesota DOT (MnDOT) and Virginia DOT (VDOT)). A PoC offers an additional robust means of testing the framework for the purpose of validating its assumptions and elements. The goal of the PoC was to work directly with an agency at a specific locality to identify realistic scenarios of interest, determine the appropriate assumptions, collect available data, and assess the framework.

The PoC occurred over the course of a couple of months and provided enough time to identify scenarios of interest, collect available data, and work with the participating agency to confirm results and assumptions. For example, the project team first met with MnDOT to provide an overview of the framework, refine a scenario of interest, and request desired data to support the framework. MnDOT then provided data on the existing infrastructure and traffic operations and helped confirm assumptions based on knowledge of local conditions and behaviors. The project team applied the framework step by step to analyze safety impacts and what it all means for the agency. The results of each step were then socialized with the agency to validate assumptions and the analysis approach. As each step was discussed, feedback was documented and used to identify further refinements to the framework. This feedback will be used to finalize the safety assessment framework.

Framework Overview

The framework follows a 6-step process, displayed in Figure 1, that starts with characterizing the nature of ADS deployments within the area of interest (e.g., a jurisdiction or deployment region), described in terms of specific ADS applications. The ADS application chosen for a given area may depend on safety needs and goals of the region and what is available in the marketplace to address those needs. Step 2 involves estimating the expected market penetration rates of the ADS applications of interest to better estimate potential impacts. It also involves a thorough understanding of various functionalities of the ADS application and its dependencies. Deployment scenarios that describe when and where ADS will operate are developed in step 3 based on the operational design domain (ODD) defined for the application by the manufacturer. Once the deployment scenarios are described, step 4 defines safety goals and hypotheses related to that ADS and deployment scenario. For example, relationships between ADS technology performance and infrastructure elements. Step 5 then involves identifying data sources and data metrics to help evaluate the stated hypotheses. Analysis is conducted to derive insights from the data, e.g., isolating and modifying crash populations. Upon completion of the analysis, step 6 is to communicate the results and share the safety impact of the ADS application to support decision making.

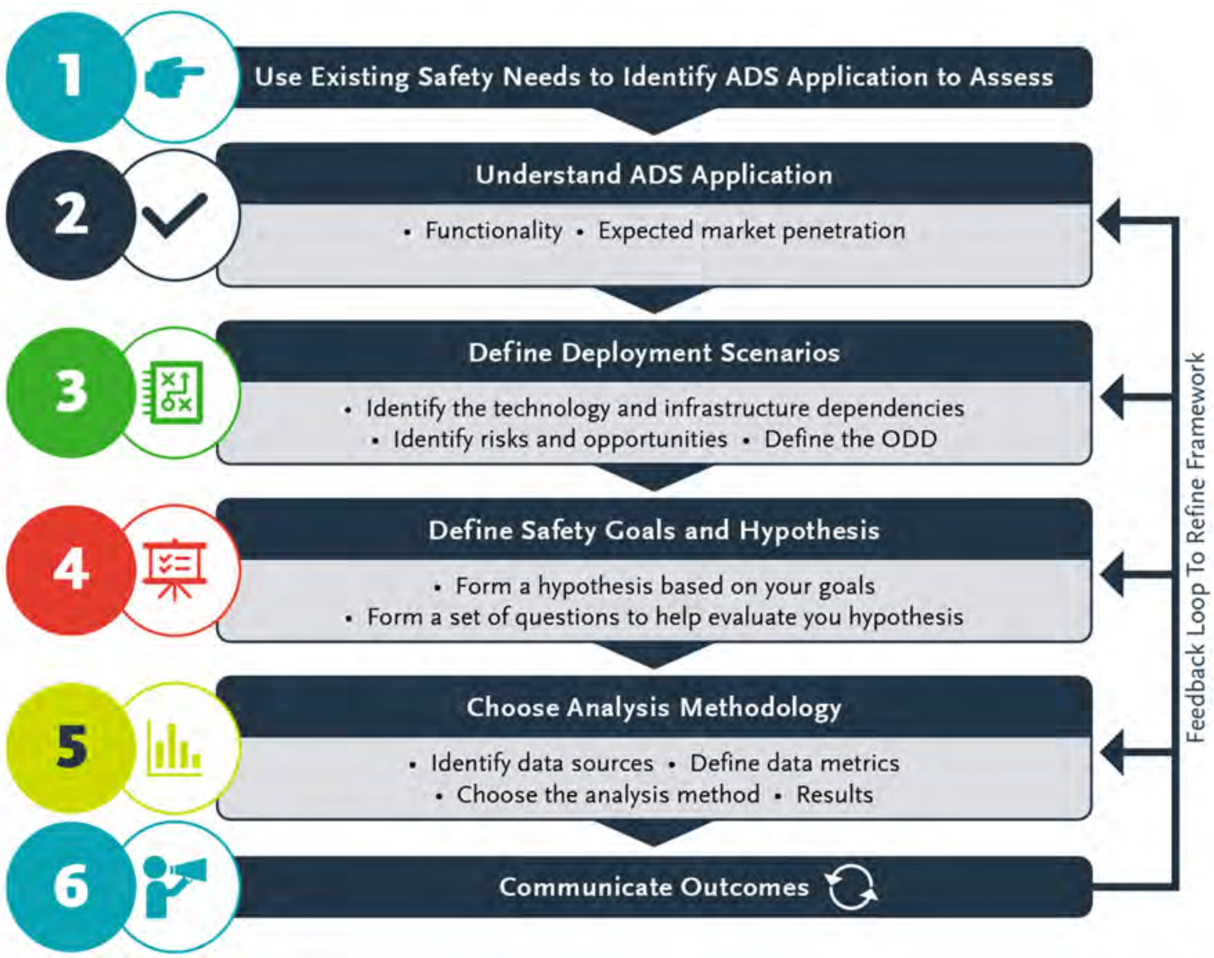


Figure 1. ADS Safety Assessment Framework

Each step of the framework is described in more detail below.

Step 1: Use Existing Safety Needs to Identify ADS Application to Assess

To identify and select ADS applications for safety analysis, infrastructure owners and operators (IOOs) may analyze different dimensions of their local transportation environment. These may include policy and regulations, local development, population densities, local service providers, infrastructure, safety and mobility needs, etc.

Step 2: Understand the ADS Application

The best source to understand the functionality of the ADS application is to go directly to the Original Equipment Manufacturers' (OEM) user manuals and online technology reviews. Individual ADS applications are unique, with disruption rates varying by location and transportation market segment. Estimating market penetration trends for an ADS application in specific deployment contexts can help assess the scale and timeframe of safety impacts in an area.

Step 3: Define Deployment Scenario

Deployment scenarios ground the analysis in theory but incorporate realistic timelines that represent potential technical solutions for the local context. These scenarios serve as the basis for identifying technology and infrastructure dependencies, risks, opportunities, and the ODD for the ADS application.

Step 4: Define Safety Goals and Hypothesis

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.

Step 5: Choose Analysis Methodology

This section describes how to identify appropriate data sources, define metrics and evaluation criteria, and select an appropriate evaluation method to test hypotheses developed in the previous step.

Step 6: Communicate Outcomes

The safety impacts can be used in the decision process to compare against other quantitative measures (e.g., costs, operational efficiency, environmental impacts) or qualitative measures (e.g., fairness, convenience, competitiveness).

Report Overview

This report summarizes the piloting efforts with two state DOTs namely MnDOT and VDOT. The report starts by providing an overview of each DOT's use case / scenario of interest and explains the data collection process. The subsequent sections describe how each step of the framework was applied to the use case / scenario and discusses in detail the data and analysis methodologies. This includes descriptions of the scenario, data, assumptions, methods, and results. The report ends with brief sections that identify challenges, lessons learned, potential refinements to the framework, and opportunities for future research. The project team will create the final framework based on feedback received during the pilots and comments from the Panel.

Technical Background

This section provides technical background needed for subsequent discussions.

- **Dynamic Driving Task (DDT):** Includes all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions (e.g., trip scheduling, selection of destinations and waypoints) and including (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).
- **Operational Design Domain (ODD):** Operating conditions under which a given driving automation system or feature is specifically designed to function, including, but not limited to, 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).
- **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 or by either resuming manual driving if the vehicle remains drivable, or by achieving a minimal risk condition if the vehicle is not drivable. For a level 4 or 5 ADS, the feature or ADS 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 towards a region of interest, then detecting the signals reflected back from objects within the field of view. Radar is a popular choice for Automated Vehicles (AVs) because they are relatively inexpensive and robust (Patole *et al.*, 2017).
- **Light Detection and Ranging (Lidar):** Lidar is a subset of radar and has been continually growing as a key enabling technology for AVs. Lidar allows for generations 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 – 1500 nm wavelengths) (Yole, 2015).
- **Communications**
  - **Vehicle-to-everything (V2X) Communication:** It is a compendium of V2X communications occurring over the dedicated short-range communications (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 Communications (DSRC):** The term “dedicated” refers to the fact that the U.S. Federal Communications Commission dedicated 75 MHz of licensed spectrum in the 5.9 GHz band for DSRC communication (Commission and others, 2002). Though recently part of the spectrum is now shared with unlicensed wi-fi users and the rest is shared simultaneously with Cellular technologies (discussed next). Communications in DSRC take 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 unique 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 very 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):** Cellular-V2X (C-V2X) is a wireless broadcast interface that permits a single platform for Vehicle-to-Vehicle (V2V), Vehicle-to-Network (V2N) and Vehicle-to-Infrastructure (V2I) communication. C-V2X can operate within a dedicated frequency band for low-latency use cases (5.9 GHz) or utilize more traditional connectivity channels (Qualcomm, 2019).

- **High Definition (HD) Maps:** These are types of maps that are particularly designed and made for self-driving cars and AV features operating at L3 and L4. These maps have extremely high precision (to the centimeter level). This is because the cars need very precise instructions on how to maneuver themselves, within a particular lane, along the route(Vardhan, 2017).

Pilot Descriptions

MnDOT - Rochester Automated Shuttle Pilot

MnDOT currently has many ADS planned 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 currently 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 team discussed state and local safety perspectives and have focused on three safety categories: 1) safety needs, 2) operational services (travel times/reliability services), and 3) multimodal (long ranged transit trips).

MnDOT also currently 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 IOO depends on community support.

MnDOT foresees early adoption of ADS technologies taking place at the mass transit level due to established ODDs and relative ease for public engagement when compared with private passenger vehicles. Furthermore, their strategic plan and their keen interest to use key performance indicators (KPIs) complements 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 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.

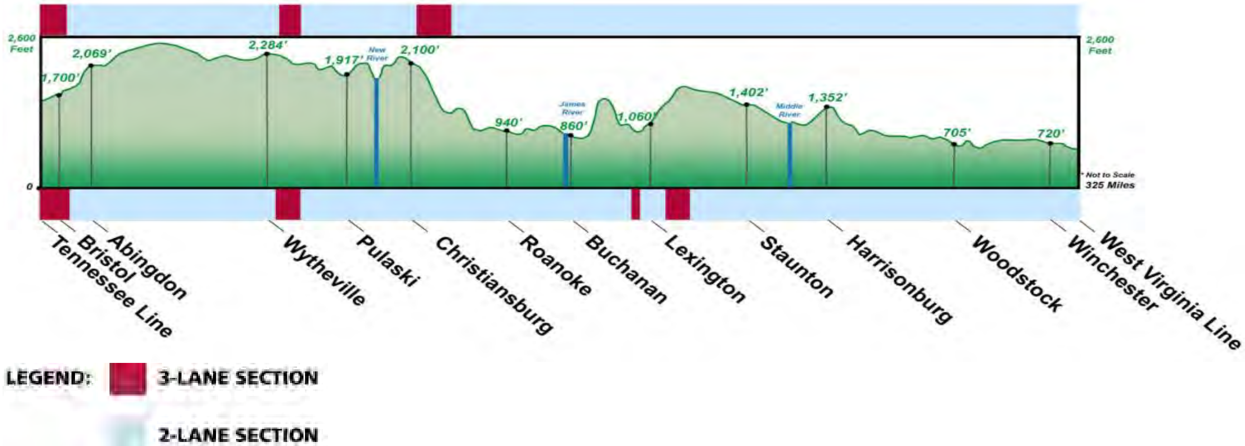
First Transit will operate the 12-passenger EasyMile EZ10 shuttle. The level 4 shuttles will have no steering wheel or pedals and will travel between 12 and 15 mph for the duration of the route. A remote attendant will be on standby ready to take control as necessary. As shown in Figure 2, the proposed pilot route is a 6-block by 3-block circulator route that operates clockwise on 6th St SE, 3rd Avenue SW, W Center St, and S Broadway. It will connect the Mayo Clinic Hospital

Methodist Campus with hotels, shops, restaurants, grocery stores, and parking lots with proposed stops shown in Figure 2.

Figure 2 Proposed Route for the AV Shuttle (Source: MnDOT)

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 3) is concerning as one truck is equivalent to as many as four passenger vehicles in terms of length. The annual average daily traffic (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 value jump significantly to 59,700 to 90,000 vehicles per day.



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

Figure 3. Elevation along the I-81 Corridor

Figure 4. Trucks Along the I-81 Corridor (VDOT Traffic Monitoring System)

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 these crashes involve heavy trucks. This is the highest percentage for any interstate in Virginia. This results in unpredictable travel delay and impacts on-time performance of both heavy commercial vehicle 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 their I-81 corridor improvement program. The expected safety impacts (benefits or disbenefits) are defined by comparing the expected safety performance with ADS 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 based on time for which roads are closed to clear incidents, delayed freight deliveries, fuel costs and increased emissions.

Data Collection Process

The project team identified the right points of contact and setup a series of meetings to help communicate the needs of the PoC, describe the steps involved in the framework, gather available data, and document feedback from the agencies. To be efficient and make good use of each agency's time, the project team compiled and documented as many details and data as possible based on information that is publicly available on the ADS project and scenario prior to these meetings. This helped focus the discussion on data gaps and facilitate feedback on the framework steps. To help with this process the project team developed a short 2-page data collection plan describing relevant information for testing the framework in the context of the Autonomous Shuttle Pilot scenario. The team worked with MnDOT and other stakeholders to obtain as much information as possible related to the questions presented in Table 1.

Table 1. Data Collection Cheat Sheet

FRAMEWORK STEPS	DATA NEEDS
Step 1: Select ADS application of Interest	• What factors are likely to influence ADS deployments? E.g. Target crash type to reduce, local needs, demographics, current infrastructure, regulation and policy, weather conditions, etc. • What ADS applications are you currently piloting or going to pilot?
Step 2: Understand the ADS application	• What are the expected functions of the ADS applications? • Have you estimated expected market penetration? • What market penetration is desired for impacts to manifest? • When do you anticipate these ADS applications will be deployed in your jurisdiction?
Step 3: Define Deployment Scenarios	• What is the anticipated operational design domain? • What infrastructure characteristics within the ODD may influence performance for the ADS applications? • What dependencies does the pilot have? • What are some of the anticipated risks and opportunities identified for your pilot? • Where is the pilot being conducted? • Have you made any assumptions for the pilot and if so, what are they?
Step 4: Define Safety Goals and Hypothesis	• What safety goals or targets have been defined for the pilot? • Are there other goals identified for this pilot? • How do ADS deployments potentially influence organizational goals, ranging from high level strategic goals to detailed performance targets?
Step 5: Choose Analysis Methodology	• What data sets are being captured, or being planned to be captured, that may help answer hypotheses about ADS safety impacts? • Has the team defined metrics to assess impacts? If so, what metrics are they? • Will the pilot team be willing to share data for framework analysis? Where data is sensitive, are there ways to aggregate or anonymize data while still providing insights? • Can we request data sets that are not collected specifically for ADS but will be useful for the framework, e.g., more granular State safety data not available through public databases? • What type of insights will the team find useful when evaluating or assessing the pilot?
Step 6: Communicate Outcomes	• Who are your key stakeholders? • What is your usual medium of communication? • How often do you communicate with these stakeholders?

Based on the methods described in the next section, the data required to support more detailed analysis include crash, roadway, and traffic data for the study area.

Pilot 1: Rochester AV Shuttle Analysis with MnDOT

The scope of the first pilot is to assess the expected impacts of the Rochester Autonomous Shuttle Project on the future of transportation safety (which is consistent with the title and scope of this NCHRP project). 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 streets segments and intersections along the fixed transit route that may be impacted by the autonomous shuttle (e.g., mode shift from walking, biking, driving to shuttle ridership). It is important to note that the intent of the Rochester AV 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 PoC is the MnDOT Autonomous Shuttle Pilot Project. The agency was mainly interested in introducing new transportation technologies to the public to gauge public perception. It was seen more as a sowing seed for people to become comfortable and help set the foundation for future deployments. Some of the other goals around this project are to understand:

- 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's important to capture?
- Infrastructure needs -- what needs to change, or what can be left alone?
- How can this be a benefit for mobility?
- Understand the impact of winter weather on ADS applications, specifically the limitations of the technology operating under these cold weather conditions and encourage industry to understand these challenges as well.

The agency wants to understand public expectations and take it into account while evaluating an ADS or other transportation technology deployments. Completing surveys to better 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 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, Minnesota. This will help them understand how public receive the application, evaluate technical feasibility, understand challenges and lessons learned for future deployments.

Step 2: Understand the ADS application

The project team worked with MnDOT and the OEMs to better understand the specific technology. To understand the functionality of the ADS, the project team identified the specific technology components and sensor suite. The team then reviewed the OEM's 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), 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 then 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 their 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 17-91 project team developed this hypothetical mode shift scenario to demonstrate how the framework could be used to assess related impacts. For any assumptions, the team have documented potential upper and lower bounds for use in scenario planning or sensitivity analysis.

To further our understanding of the expected market and potential changes over time, the team looked to other similar deployment examples throughout the U.S., including those shown in Table 2:

Table 2. ADS Deployment Examples in the US

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

Step 3: Define Deployment Scenarios

In this step, the 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 were explored based on available data.

Below are some potential risks:

- Challenges for first responders (e.g., 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 non-automated vehicles following shuttles could experience increased risk for rear-end crashes due to their slower speed. Shuttles could result in more aggressive and frequent lane-change maneuvers by the following non-automated vehicles. This could increase the crash risk for the aggregate traffic stream.
- Shuttles will operate in dense areas, with high likelihood of significant interactions between pedestrians, bikes, and other motor vehicles.
- Access to vehicle and safety data.

The following are potential opportunities:

- Positive disruption to urban areas by offering increased mobility and reduced congestion.
- Common method to introduce automated vehicle technologies to the public to help open the doors 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.
- May help to reduce crashes with pedestrians (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 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 team worked with MnDOT to document the overall goals of the PoC 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 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 involved 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 area 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 boardings and /alightings 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 us 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 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 which, in turn, will reduce the predicted crashes from the Highway Safety Manual 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 3 displays the crash history along the shuttle loop by year and severity. The crash history includes crashes on segments and at intersections.

Table 3. 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 desired roadway data and surrounding area characteristics necessary for the IHSDM analysis through a desktop data collection effort using Google Earth. Roadway information obtained 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 1000 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 which do not have AADT values. For those roads, the project team estimated AADT based on the features of the road and comparing them against AADT values for similar roads and surrounding roads. Figure 5 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 5.

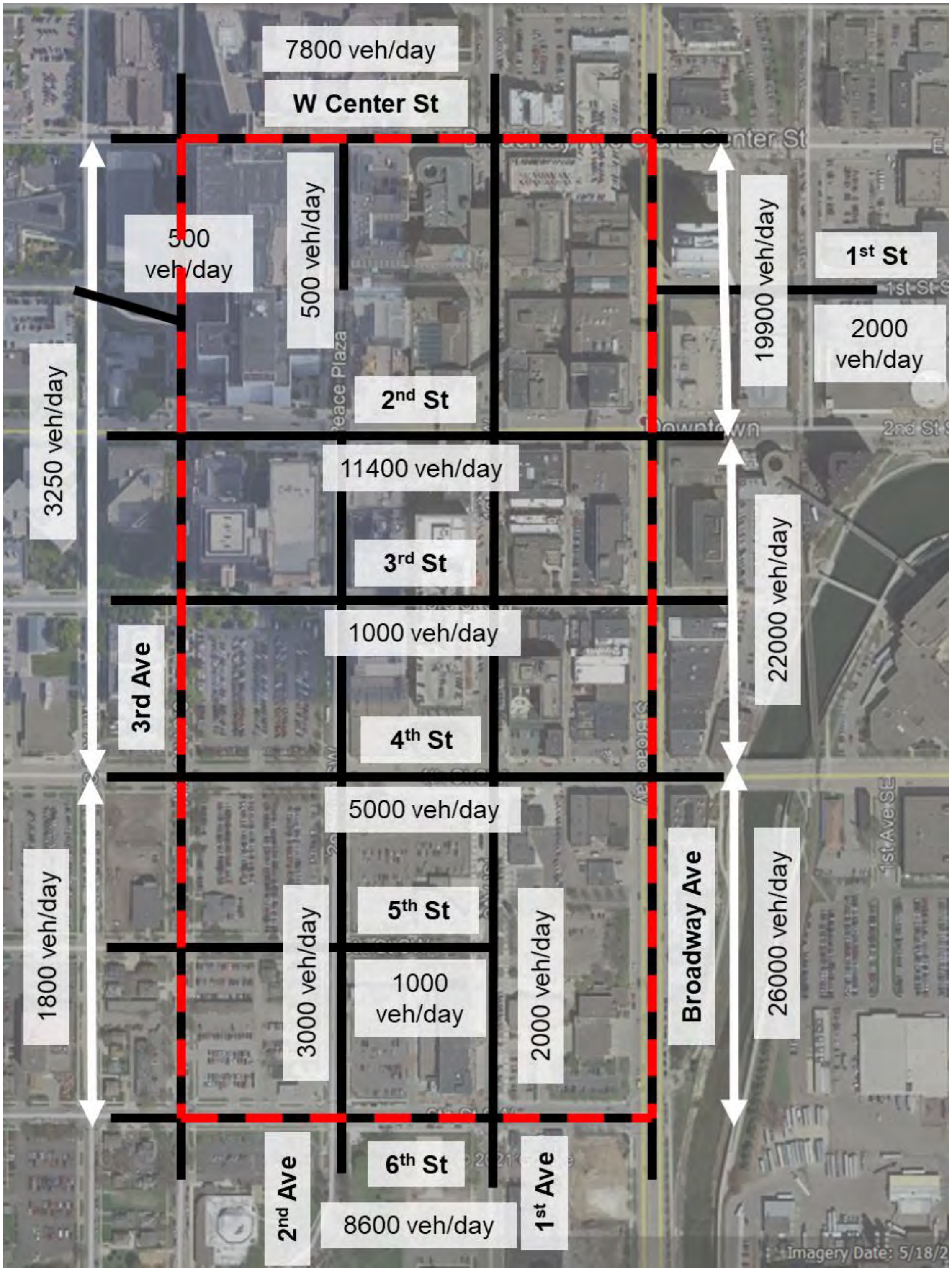


Figure 5. AADT Values for Each Road in Study Area.

Evaluation Method

The project team used the IHSDM Crash Prediction Module (CPM) to predict crashes along the shuttle loop for the existing conditions, calculate the expected crashes using existing 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 are not 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 seven percent on all roads along the shuttle route and along roads that intersect the shuttle route. The seven percent 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 6 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.

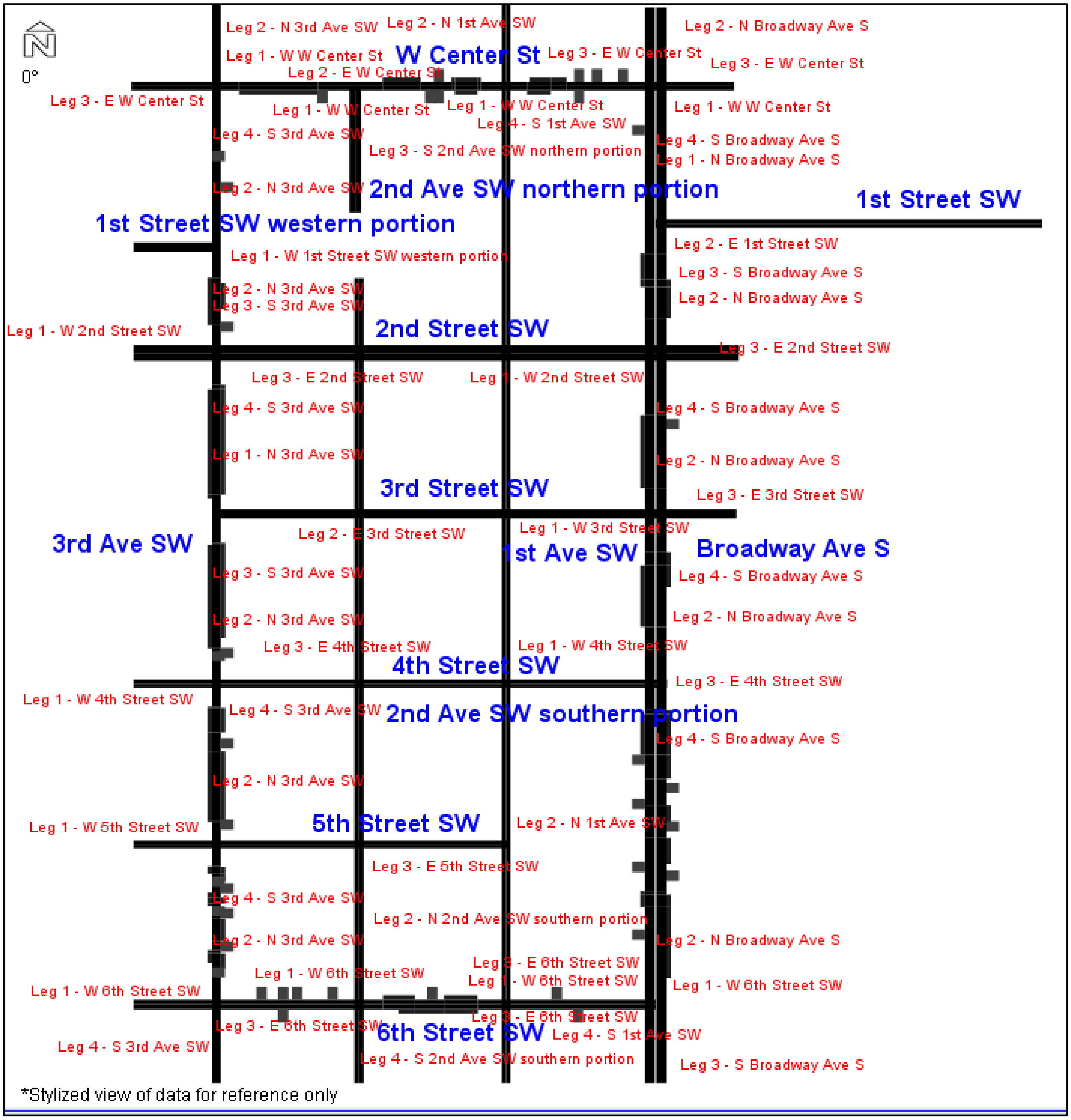


Figure 6. Road Network of the Shuttle Loop as it Appears in IHSDM

In order 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 7 displays the estimates of existing pedestrian volumes at intersections in the study area.

Figure 7. Existing Pedestrian Activity at Intersections in the Study Area.

For the first scenario, the project team adjusted the existing 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 are expected to decrease. Figure 8 displays the hypothetical pedestrian activity due to the presence of the shuttle.

Figure 8. Hypothetical Pedestrian Activity Due to Shuttle at Intersections in the Study Area.

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 4 displays the predicted crash frequency from IHSDM for the segments for the existing conditions. As shown in Table 4, 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 Avenue experiences the most predicted crashes compared to Center Street, 6th Street, and 3rd Avenue.

Table 4. 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 Street	0.7	0.2	0.5
Broadway Avenue	2.8	0.9	1.9
6th Street	0.7	0.2	0.5
3rd Avenue	0.9	0.2	0.7

Table 5 displays the predicted crash frequency from IHSDM for the intersections in the study area for the existing conditions. As shown in Table 5, there are a total of 43.4 predicted 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 Street and Broadway Avenue intersection experiences the most predicted crashes (6.9 predicted crashes per year) compared to the other intersections, followed by the Broadway Avenue and 4th Street intersection (6.5 predicted crashes per year).

Table 5. 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 Avenue and Center Street	2.1	0.8	1.3
Center Street and 2nd Avenue	0.7	0.4	0.3
Center Street and 1st Avenue	1.7	0.7	1.0
Center Street and Broadway Avenue	5.7	2.2	3.5
1st Street and Broadway Avenue	2.4	1.0	1.4
2nd Street and Broadway Avenue	6.9	2.7	4.2
3rd Street and Broadway Avenue	3.1	1.1	2.0
Broadway Avenue and 4th Street	6.5	2.5	4.1
Broadway Avenue and 6th Street	4.5	1.5	3.0
6th Street and 3rd Avenue	0.5	0.1	0.3
6th Street and 2nd Avenue	2.0	0.8	1.3
6th Street and 1st Avenue	1.7	0.6	1.2
3rd Avenue and 4th Street	1.7	0.6	1.1
3rd Avenue and 3rd Street	0.1	0.0	0.0
3rd Avenue and 2nd Street	3.4	1.2	2.3
1st Street and 3rd Avenue	0.4	0.1	0.2

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 6 displays the expected crash frequency from IHSDM by segment for the existing conditions. The results in Table 6 indicate there are a total of 7.1 expected crashes per year, 1.8

expected fatal plus injury crashes per year, and 3.6 expected property damage only crashes on the four segments for the existing conditions. Broadway Avenue experiences the most predicted crashes compared to Center Street, 6th Street, and 3rd Avenue.

Table 6. 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 Street	0.8	0.2	0.6
Broadway Ave	4.9	1.2	3.8
6th Street	0.7	0.2	0.5
3rd Avenue	0.7	0.2	0.5

Table 7 displays the expected crash frequency from IHSDM by intersection for the existing conditions. As shown in Table 7, 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 Street and Broadway Avenue intersection experiences the most predicted crashes (9.5 expected crashes per year) compared to the other analyzed intersections, followed by Broadway Avenue and 4th Street intersection (7.4 expected crashes per year).

Table 7. 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 Avenue and Center Street	0.9	0.6	0.3
Center Street and 2nd Avenue	0.5	0.3	0.3
Center Street and 1st Avenue	1.0	0.5	0.5
Center Street and Broadway Ave	4.6	1.5	3.2
1st Street and Broadway Ave	2.0	0.6	1.4
2nd Street and Broadway Ave	9.5	2.4	7.1
3rd Street and Broadway Ave	1.6	0.5	1.0
Broadway Avenue and 4th St	7.4	2.3	5.0
Broadway Avenue and 6th St	5.2	1.1	4.0
6th Street and 3rd Avenue	0.2	0.1	0.1
6th Street and 2nd Avenue	1.2	0.5	0.8
6th Street and 1st Avenue	1.4	0.4	1.0
3rd Avenue and 4th Street	1.1	0.5	0.6
3rd Avenue and 3rd Street	0.1	0.0	0.0
3rd Avenue and 2nd Street	1.7	0.5	1.2
1st Street and 3rd Avenue	0.2	0.1	0.1

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 are 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 8 displays the expected crash type distribution for segments in the study area by severity for the five year study period for the existing conditions. As shown in Table 8, 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 (22.5 expected crashes for the five year study period) compared to the other crash types.

Table 8. Expected Crash Type Distribution for Segments for the Five 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 Multi-vehicle 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**

Table 9 displays the expected crash type distribution for intersections in the study area by severity for the five year study period for the existing conditions. As shown in

Table 9, 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 five year study period) compared to the other crash types.

Table 9. Expected Crash Type Distribution for Intersections for the Five-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 Intersec. 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 Multi-vehicle 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 Multiple Vehicle 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**

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 if crashes are expected to increase or decrease. The two scenarios, previously described, include:

- **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 10 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, and Table 11 displays the predicted total crash frequencies for the intersections. The results indicate that predicted total crashes for all segments and intersections do not change dramatically between the existing conditions and Scenario 1. 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 nine percent decrease in predicted total crash frequency compared to the existing conditions.

Table 10. 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 Street	0.7	0.7	0.7
Broadway Avenue	2.8	2.8	2.6
6th Street	0.7	0.7	0.7
3rd Avenue	0.9	0.9	0.9
% Crash Reduction		-	**4%**

Table 11. 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 Avenue and Center Street	2.1	2.0	2.0
Center Street and 2nd Avenue	0.7	0.7	0.6
Center Street and 1st Avenue	1.7	1.8	1.6
Center Street and Broadway Avenue	5.7	5.5	5.2
1st Street and Broadway Avenue	2.4	2.3	2.2
2nd Street and Broadway Avenue	6.9	7.1	6.3
3rd Street and Broadway Avenue	3.1	3.2	2.9
Broadway Avenue and 4th Street	6.5	6.4	6.0
Broadway Avenue and 6th Street	4.5	4.5	4.1
6th Street and 3rd Avenue	0.5	0.5	0.4
6th Street and 2nd Avenue	2.0	2.0	1.9
6th Street and 1st Avenue	1.7	1.8	1.6
3rd Avenue and 4th Street	1.7	1.9	1.7
3rd Avenue and 3rd Street	0.1	0.1	0.1
3rd Avenue and 2nd Street	3.4	3.3	3.3
1st Street and 3rd Avenue	0.4	0.3	0.3
% Crash Reduction	**N/A**	**0%**	**7%**

The project team then compared the predicted crashes broken out by crash type. *Table* 12 displays the crash type distributions for segments for the existing conditions, Scenario 1, and Scenario 2. The results indicate a 19 percent decrease in total segment crashes between the existing conditions and Scenario 1 and a 33.5 percent decrease in total segment crashes between the existing conditions and Scenario 2.

Table 12. Predicted Segment Crash Type Distribution for the Five 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 Multi-vehicle 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%**	--

Table 13 displays the crash type distributions for intersections for the existing conditions, Scenario 1, and Scenario 2. The results indicate a five percent increase in total intersection crashes between the existing conditions and Scenario 1 and a three percent decrease in total intersection crashes between the existing conditions and Scenario 2.

Table 13. Predicted Intersection Crash Type Distribution for the Five 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 Multi-vehicle 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%**	--

Step 6: Communicate Outcomes

For this step, the team worked with MnDOT and their 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 non-technical audiences and how MnDOT might approach a typical project to devise and employ targeted communication and messaging to effectively 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 shuttles, states can help achieve the crash reduction goals laid out in their safety plans.

Pilot 2: ADS Equipped Trucks Along I-81 with VDOT

The scope this pilot is to assess the expected impacts of ADS trucks and vehicles with forward collision avoidance on the future of transportation safety for a study corridor along I-81 in Virginia. The expected safety impacts (benefits or disbenefits) are defined by comparing the expected safety performance with ADS 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. The following is a discussion of each step of the framework.

Step 1: Identify ADS application(s) of Interest

The selected application included in the proof of concept are ADS trucks and vehicles with forward collision avoidance. Our 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 then 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 to inform Strategic Plans such as Virginia's Strategic Highway Safety Plan (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 of 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 system is the fallback for the dynamic driving task. The ADS automatically collects and processes data from onboard sensors and handles the 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 is expected to reach up to $1.7 billion by 2025 with a CAGR of 10.4% over the five years (Chandani & 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 Figure 9.

Figure 9. Key Impacting Factors for Global Self-driving Trucking Market (Allied Market Research 2018)

Table 14 lists a few examples of the existing ADS-equipped trucks that are commercially deployed or being tested.

Table 14: 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, they performed one of the world's first shipment 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 system takes over. Once the truck was on the highway, the driver wasn't even in the driver's seat (Jon, 2019).

Step 3: Define Deployment Scenarios

Operational Design Domain

Table 15 summarizes the anticipated ODD elements of ADS-equipped trucks for two different predicted timelines, the short term (next five years) and the medium term (next five to ten 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. Based on 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 15: ADS-equipped Trucks Deployment Scenarios of Interest

Operation 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 (L3) where driver is fall back for DDT • Cooperative ACC • 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 • L4 Automation ADS application where ADS is responsible for the DDT 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 (ATP). • V2X communications • Operating on well-marked and well-maintained signage roads

Table 16 provides a summary of the technology specifications and key infrastructure needs pertinent to the envisioned ADS-equipped trucks.

Table 16: ADS-equipped trucks Key Infrastructure Requirements

Expected Timeline	Vehicle Type	Sensor Package	Key Infrastructure Requirements	
			Digital	Physical
Short Term o 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 TCD
Medium Term o High Disruption	Heavy-duty	Gen-II	• V2X Communications • GPS • HD Maps • Weather Data • Infrastructure Data • Work Zone Alerts • 5G and DSR Communication	• Lane Markings Visible • Visible Signage • Highly Detectable TCD • ATP

Stage of Technology Development

Generation (Gen I)

This is the first version of ADS-equipped trucks sensors 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, 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 data can handle the basic computations needed for the proper functionality of the ADS-equipped truck feature within the ODD and deployment context. These algorithms are at early development and still, 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)

Of a more advanced stage of technology than first-generation models or systems. In addition to the sensor types included in Gen II, this generation would embrace high-fidelity lidar sensors and an On-Board Unit (OBU). An 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. 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 sensors 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 itself 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 table 4). Another envisioned key feature of this generation of sensors is integrating V2V and 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 17 provide 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.

Table 17: 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

Infrastructure Needs and Impacts

The features will assist the driver navigating a highway. The sensors onboard the vehicle will 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, ATP 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 10: What an ADS-equipped truck port could look like (Viscelli, 2018).

Figure 10: What an ADS-equipped truck port could look like (Viscelli, 2018)

The feature uses more advanced technologies, compared to existing platooning technologies, including Radar, cameras, and DSRC, 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. 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 period of 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 finer than human driven trucks. This could increase pavement cracking and fatigue. Pavement fatigue in turn increases the risk of hydroplaning (Zhou et al., 2019).
- Labor opposition due to job loss.
- Training needs on ADS systems 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. Due to the labor savings of autonomy and that trucks are bought as business decisions thoroughly evaluated by fleets, ROI on ADS-equipped trucks is expected to be very 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 put at risk from automation. ATPs can be built in strategic locations near interstate exits and truck parking lots outside of congested urban areas. ATPs would 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 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 U.S., 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 our need for oil (Delucchi et al., 2014; Lattanzio & 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 (CCS) 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 & 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 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 remove 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 Level 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 percent of truck-involved crashes will depend on market penetration and the ability of the technology to mitigate certain crash types and events, which is 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 reduce, 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 to 10 percent. 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 vehicle drifts off the road.
   b. Driver of truck is fully attentive and adverse weather contributes to driver losing control or incorrectly navigating and vehicle leaves the road.
   c. Driver of truck is fully attentive and sudden congestion leads to an evasive maneuver where 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 truck rear-ends another vehicle.
   b. Driver of truck is fully attentive and adverse weather contributes to limited stopping distance where driver is not able to stop or slow and truck rear-ends another vehicle.
   c. Driver of truck is fully attentive and sudden congestion leads to unanticipated braking where the driver attempts to stop but truck rear-ends another vehicle.

Based on the anticipated capabilities of ADS-equipped trucks and the above crash sequencing, the research 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 18 displays a summary of the crashes that occurred along the study corridor by year and severity, Table 19 displays the crashes by collision type, and Table 20 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 crash type for total crashes, which is consistent with the input from VDOT and the recurring congestion issues. Rear-end crashes are the second most prevalent crash type for truck-involved crashes, second only to sideswipe same direction crashes. In total, 979 crashes (30 percent of total crashes along the study corridor) involved a large truck, and 330 rear-end crashes (26 percent 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 percent of total crashes and 78 percent of large truck-involved crashes), which is followed by crashes occurring during rain (16 percent of total crashes and 14 percent of truck-involved crashes).

Table 18. 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**	**2576**	**3278**

Table 19. 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	1246	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
Ped	1	1	0	1	0
Backed Into	10	7	0	0	7
Other	20	4	7	0	4
Total	**3278**	**979**	**14**	**228**	**737**

Table 20. 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)	2492	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	**3278**	**979**

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 number of passenger vehicles with forward collision avoidance. The hypothetical scenarios include:

- **Scenario 1:** Various percentages of ADS trucks (5, 25, and 50 percent) 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 percent) in the fleet with various percentages of passenger vehicles equipped with forward collision avoidance (5, 25, and 50 percent). 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 percent of large trucks in rear-end fatal crashes with passenger vehicles occurred when the passenger vehicle rear-ended a large truck; 57.1 percent of large trucks in rear-end injury crashes with passenger vehicles occurred when the passenger vehicle rear-ended a large truck; and 45.3 percent 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 various 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 various 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.

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

Results

Scenario 1

The project team filtered the crash data to only contain crashes that involved a large truck and only contain crashes that occurred during clear or cloudy conditions (i.e., no adverse weather conditions). Those crashes were then used to estimate the number of potential crashes reduced or eliminated due to various percentages of ADS trucks in the fleet and no change to passenger vehicles, shown in

Table 21.

Table 21 assumes that all ADS features are 100 percent 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 percent to account for ADS features that may not mitigate certain crashes.

Table 21. Truck-Involved Crash Reduction by Severity for Various Percentages of ADS Trucks During No Adverse Weather Conditions (2014-2020).

% ADS 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%

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 percent of total crashes. Five percent ADS trucks in the fleet result in an expected 1 percent total crash reduction; 25 percent ADS trucks in the fleet result in an expected 6 percent total crash reduction; 50 percent ADS trucks in the fleet result in an expected 12 percent total crash reduction. These results can be used to identify potential safety benefits of ADS trucks for various penetration rates and as the expected number of trucks with ADS capabilities increase 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 et al., 2020).

Table 22 displays a potential increase in truck-involved rear-end crashes due to ADS-equipped trucks in the fleet assuming a 27 percent increase in rear-end crashes when ADS 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 percent of fatal rear-end crashes involving a large truck occur when passenger vehicles rear-end a large truck; 57.1 percent of injury rear-end crashes involving a large truck occur when passenger vehicles rear-end a large truck; and 45.3 percent of property damage only rear-end crashes involving a large truck occur when passenger vehicles rear-end a large truck.

Five percent ADS trucks in the fleet result in an expected 0.1 percent increase in total crashes; 25 percent ADS trucks in the fleet result in an expected 0.5 percent increase in total crashes; 50 percent ADS trucks in the fleet result in an expected 1 percent increase in total crashes.

Table 22. Rear-End Truck-Involved Crash Increase When Passenger Vehicle Rear-Ends a Large Truck by Severity for Various Percentages of ADS Trucks During No Adverse Weather Conditions (2014-2020).

% ADS 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%

Scenario 2

The project team also analyzed the crash data to estimate potential crash reductions due to both ADS trucks in the fleet (Scenario 1) and passenger vehicles with forward collision avoidance.

Table 23 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. It was desired to also include run-off-road crashes that could be the result of drivers trying to avoid a rear-end crash with a truck, 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 7AM to 7PM along I-81 between milepost 140 and 150, which represent common congested conditions in the Roanoke area.

Table 23. 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

The estimated reduction in truck-involved rear-end crashes due to passenger vehicles with forward collision avoidance (

Table 23) are then combined with the estimated crash reduction due to ADS large trucks in the fleet (

Table 21) and the estimated rear-end crash increase (

Table 22), shown in Table 24. Results indicate that as the percentage of ADS trucks and passenger vehicles with forward collision avoidance in the fleet increase, the greater the estimated total crash reduction along the study corridor. These results can be used to quantify potential safety benefits of ADS trucks and vehicles with forward collision avoidance and quantify how the safety benefits change as more vehicles on the road have ADS capabilities.

Table 24. Crash Reduction by Severity for Various Percentages of ADS Trucks and Passenger Vehicles with Forward Collision Avoidance During No Adverse Weather Conditions (2014-2020).

% ADS 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%

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 analyzing 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.

Challenges and Lessons Learned

When the proof-of-concept phase was started the world was in the middle of the Covid-19 pandemic. With most teams working from home, many of the ADS pilot projects slated for 2020 were put on hold and deferred to mid-late 2021. Furthermore, testing during pandemic traffic conditions wouldn't provide real world testing experience and data needed to evaluate the functionality and impact of ADS applications. Thus, the first challenge was trying to find active ADS pilots with the potential to generate data. Though agencies deferred the actual pilots, the planning for the pilot was already complete. This meant data and information on what the agencies intended to test was readily available and could be used as a base for piloting the framework. To make up for the lack of data, informed assumptions (input from agencies and other stakeholders) were made and substitute data such as connected vehicle and ADAS data from the Insurance Institute of Highway Safety were used for the analysis.

Second, not all ADS pilots are evaluating the safety aspect of the application. Some are evaluating the technology; some are evaluating how the application is received by the public; and some are focused on creating more public awareness of the technology. There are no specific safety functionalities or scenarios that get tested. For example, the MnDOT low speed shuttle has its main goal to create awareness among the public of ADS and to gauge public perception. The analysis methodology needs to account for this and tweak the scenario as necessary to focus on evaluating safety impacts of the pilot in transportation. This can be done by making informed assumptions (input from agencies and other stakeholders). For example, the goal of the low-speed shuttle pilot was assumed to be that of improving transit options for people in the downtown area and thus to reduce congestion and crashes on the central business district.

Third state and local agencies are very busy with day-to-day operations and don't always have the bandwidth to help pilot the framework. As a result, scheduling meetings with the agencies can take a long time. It is best to start the PoC pilot as early as possible and to create brief summary documents for easy communications. For example, a 2-pager was developed during the data collection phase and shared with the state agencies. The short document helped the agency come prepared for the meeting and helped the analysis team obtain all necessary insights to carry on with the analysis process.

Lastly, besides technical challenges in developing ADS functions for complex situations (workzones) new methods for evaluating functionality and safety are necessary. The method should help assess benefits and identify potential weaknesses. Classical methods for evaluation usually require extensive testing that is time, resource, and budget consuming. Therefore, the classical methods are less feasible and don't help IOOs in decision making. Informed assumptions backed by a strong and diverse stakeholder engagement can provide greater confidence in analyzing scenarios that lack real-time data.

Potential Refinements to the Framework

Based on piloting the framework with both MnDOT and VDOT the following updates were identified to help refine the framework further:

- Step 1 – Recommend adding a public engagement activity to better understand public opinion / perception / preference. Public opinion should play a larger role in the ADS selection process.
    - Stakeholder engagement throughout the process can be beneficial

- Step 1 - Emphasize the importance of setting goals based on the agency's current safety challenges and needs or the local ecosystem
- Step 1 – Add mobility as a factor to be a specific component of mobility or a standalone factor.
- Step 1 – Indicate that policy could include regulatory issues.
- Consider how parking ties into ADS features. This could be incorporated into planning-level questions or long-term planning.
- Step 4 – Hypotheses may be more specific to the specific technologies.
- Step 4 – Questions to test the hypothesis could be elaborated to discuss targeted collision types and ancillary types.
- Consider including a discussion of crash sequencing and explain how to include this as part of the framework.
- Recommend including a feedback loop through steps 3-5 so that the framework can be adapted as new information becomes available and technology advances
- The framework must emphasize an iterative approach as goals/questions/hypotheses /design approaches can change throughout the project
    - Enable a process for continual updates to the framework based on lessons learned
- The framework should enable agencies to evaluate all modes of transportation and to evaluate safety impacts
    - Add analysis steps, goals, and hypotheses for all modes of transportation (bikes, pedestrians, private vehicles, transit)
- Recommend including a high-level framework to evaluate socio-economic impact of the preferred ADS application
- In addition to considering benefits to ADS, the team should consider the potential safety impacts (benefits) for non-ADS (human-driven vehicles)
    - Recommend that the framework allows for state and local agencies to consider impacts on other vulnerable road users (pedestrians, bikes, etc.)
- Consider simplifying the language and process where necessary so different program offices can use the framework
- Step 6 – Recommend adding a communications strategy framework. The framework should include considerations for the message/theme/takeaway (i.e., what is the message to be communicated) for the final report or method of documenting the results of the analysis.

Opportunities for Future Research

There are numerous opportunities for future research with respect to quantifying the expected safety impacts of ADS. The following are select opportunities with respect to the framework based on the PoC:

- **Evaluate the safe effectiveness of ADS deployments**: rigorous safety evaluations include the study of crash-based performance measures over several years and typically at multiple locations. These types of studies will help to refine the assumptions used in the framework.
- **Evaluate non-crash-based measures for ADS deployments**: While ADS deployments are relatively new, there are opportunities to track and evaluate non-crash-based measures (e.g., conflicts, speeds, erratic maneuvers, etc.) to help understand the potential long-term safety impacts. There is not a direct established link between safety surrogate measures and crashes, but these measures can help to identify potential concerns that could lead to future safety issues. They also provide an opportunity to be more proactive and responsive to safety needs than waiting for several years of crash data.

- **Track ADS deployments**: Related to the previous two opportunities, there is a need to track and document the details of ADS deployments. Without good records of where, when, and what was implemented, it is very difficult to perform a reliable before-after analysis of any strategy. This may include collecting and saving performance measures before the ADS deployment so they are available for future use (e.g., operating speeds, conflicts, traffic volumes, pedestrian and bicycle counts, etc.).
- **Refine crash prediction models**: Currently, the Highway Safety Manual provides a predictive method to estimate the frequency and severity of crashes based on the design and operations of the facility of interest. For existing facilities, the method can incorporate the historical crashes as part of the prediction. While ADS deployments will presumably affect predictions from these predictive methods, the challenge is that these methods were developed based on historical data representing traditional vehicles. As such, there is a need to update these methods to reflect a mixed fleet (i.e., one with both ADS-equipped and traditional vehicles). This may be a longer-term opportunity because at present, it would be difficult to update the predictive methods to reflect different deployment scenarios without the luxury of historical data that represent ADS-equipped vehicles.
- **Understand fundamental relationships between the driver, vehicle, roadway, and technology**: There is a wealth of research on the traditional relationships between the driver, vehicle, and roadway but there is a new factor to include in these relationships—ADS. There is an opportunity to expand our current understanding of the traditional relationships using simulation, modeling, visualizations, and case studies as ADS becomes more prevalent.
- **Calibrate HSM models:** There is an opportunity to calibrate HSM models over time in different States/jurisdictions to account for different penetration rates of ADS. These differences in penetration rates can be due to differences in socioeconomics as well as general adoption and acceptance by public agencies and the public at large.

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