Connected Vehicle Applications to Improve Infrastructure Safety and Durability

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16 Abstract

Connected autonomous vehicles have the potential to revolutionize the automotive industry by making transportation safer and more environmentally friendly. Despite early optimism, the timeline for widespread deployment of this novel technology continues to be pushed back. This is largely due to the difficulties in replacing human drivers with automated systems that rely on road and communication infrastructure, especially in rural applications where there is already less infrastructure and funding for needed investments will remain a challenge. Moreover, these challenges are greater for Maine and other northern and mountain states that experience seasonal snow and ice. This report discusses connected and autonomous vehicle technology and general applications but also emphasizes rural AV applications and challenges drawing on existing research and a number of case studies.

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List of Key Terms

AV – Autonomous Vehicle
BSM - Basic Safety Message
CAV - Connected Autonomous Vehicles
C-V2X - Cellular Vehicle-to-Everything
CSW - Curve Speed Warning
DSRC - Dedicated Short-Range Communication
FCC – Federal Communications Commission
HAV - High Automation Vehicles
OBU - On Board Unit
OEM - Original Equipment Manufacturers
RwD - Roadway departures
SAE – Society of Automotive Engineers
USDOT – United State Department of Transportation
V2I - Vehicles to Infrastructure
V2V - Vehicle to Vehicle
V2X - Vehicles to Other Road Users

Abstract

Connected autonomous vehicles have the potential to revolutionize the automotive industry by making transportation safer and more environmentally friendly. Despite early optimism, the timeline for widespread deployment of this novel technology continues to be pushed back. This is largely due to the difficulties in replacing human drivers with automated systems that rely on road and communication infrastructure, especially in rural applications where there is already less infrastructure and funding for needed investments will remain a challenge. Moreover, these challenges are greater for Maine and other northern and mountain states that experience seasonal snow and ice. This report discusses connected and autonomous vehicle technology and general applications but also emphasizes rural AV applications and challenges drawing on existing research and a number of case studies.

Chapter 1 Overview of Connected Autonomous Vehicle Applications

This report examines the federal and state regulation, research, and practice of connected and autonomous vehicle (CAV) applications and systems.

Connected autonomous vehicles (CAV) have the potential to revolutionize the automotive industry by making transportation safer and more environmentally friendly. The timeline of this novel technology in achieving this goal is however subject to debate. This timeline is set to be pushed back by many years as pioneers of autonomous vehicles have begun to cast doubt on their ability to completely replace human drivers (Chafkin, 2022). The reason often cited to undermine the ability of CAV is the inability of the system to maneuver “edge cases,” rural roads, weather conditions and many other scenarios. The difficulty of full automation (SAE level 4- 5) has pushed back the estimated commercial launch by at least 10 years (Chafkin, 2022).

Connected vehicle technology is more technically feasible in the near term but is also in a state of flux after a Nov 2020 ruling by the FCC to open the 5.9 GHz ‘Safety Band’ to cellular networks, which was previously reserved exclusively for transportation uses. This is a setback for research and pilots since most implementation projects have focused on DSRC technology. Other jurisdictions, such as the EU, Japan, and South Korea are still studying the potential of Cellular Vehicle-to-Everything (C-V2X) technology, whereas China is mandating the use of C-V2X on all roads.

CAV Technology Definitions

Autonomous vehicles (AVs) use sensors and computers to take over driving tasks from humans, ranging from adaptive cruise control to full automation under all conditions. The SAE defines the levels of automation on a scale of 0-5 in standard SAE J3016 (U.S. Department of Transportation & NHTSA, 2016) – see Table 1. Autonomous vehicles market penetration of various levels differs by make, model and vehicle trim level. Level 1 technologies are available in all new vehicles, with some premium vehicles having Level 2 and Level 3 features. High Automation Vehicles (HAV), Levels 4 and 5, are in development and may yet take a decade or more until generally available.

Table 1. Levels of Vehicle Automation (U.S. Department of Transportation & NHTSA, 2016)

SAE Automation Category	Vehicle Function	Example
Level 0	Human driver does everything.	Cruise control, automatic emergency breaking, forward collision warning, blind spot warning, lane departure warning
Level 1	An automated system in the vehicle can sometimes assist the human driver in conducting some parts of driving.	Adaptive cruise control, lane keeping assist, parking assist
Level 2	An automated system can conduct some parts of driving, while the human driver continues to monitor the driving environment and performs most of the driving.	Advanced Driver Assistance Systems (ADAS) or highway pilots: Tesla autopilot, Volvo pilot assist, Audi traffic jam pilot, Ford Blue Cruise
Level 3	An automated system can conduct some of the driving and monitor the driving environment in some instances, but the human driver must be ready to take back control if necessary.	Traffic jam chauffeur
Level 4	An automated system conducts the driving and monitors the driving environment, without human interference, but this level operates only in certain environments and conditions.	Local driverless taxi Pedal/steering wheel may or may not be installed
Level 5	The automated system performs all driving tasks, under all conditions that a human driver could.	Same as level 4, but the feature can drive everywhere in all conditions

Note: SAE is the Society of Automotive Engineers International, http://www.sae.org.

In contrast, Connected Vehicle (CV) technology refers to the applications that use constant transmission of data from one vehicle's On-Board Unit (OBU) to other vehicles (V2V), vehicles to infrastructure (V2I), and vehicles to other road users (V2X), such as pedestrians and motorcycles that are equipped with sensors and communications devices. CVs broadcast basic safety messages (BSM) about vehicle speed and trajectory using dedicated short-range communication (DSRC) or the 5G wireless cellular network. Infrastructure equipped with roadside communication units relates information about road geometry, traffic signal phasing, and unusual road conditions.

Vehicle and infrastructure connectivity augments and supports the autonomous vehicle ecosystem. It provides additional information about the surrounding driving environment, information already collected by other vehicle sensors, as well as new information that sensors cannot detect. For example – autonomous vehicle sensors can detect obstacles within visual range, but connected vehicles can alert vehicles to invisible or future conditions such as black ice, changing signal phase, accidents up ahead, and vehicle telematics in platoons.

CAV Applications Summary

CAV applications utilize new equipment along roadways and intersections, communication devices in vehicles, and new software and expertise in traffic management centers. These systems deliver new services and diverse benefits to drivers, businesses, and governments (The National Academies of Sciences, Engineering, and Medicine, n.d.). V2V and V2I software applications use data for a variety of applications that offer the benefits of:

- improving traffic data inputs to DOT operation centers,
- increasing the efficiency of traffic movements,
- changing traffic signal phasing to reduce time delays,
- reducing emissions from idling and driver behavior,
- generating driver warnings and driver suggestions to increase awareness of safety risks from other vehicles, and
- inform drivers of road and other infrastructure conditions.

The USDOT, through its Connected Vehicle Program, has conducted significant research and prototyping efforts in four major CV application areas: safety, mobility, environment, and road weather management (Garrett, 2021). They are summarized below.

Safety Applications

CV applications for safety can be used to reduce the incidence of accidents from a variety of driver-error-related causes by increasing situational awareness through driver advisories and warnings. They use V2V and V2I data communications to anonymous basic safety messages (BSM) that contain vehicle position, speed, and location data. The applications use this data to calculate risks of accidents that a driver alone may not be able to ascertain, such as cars up ahead suddenly braking due to icy road conditions. For the full benefits of these applications to be realized, each vehicle on the roadway should have CV communications and safety applications.

CV applications that utilize V2I communications to avoid traffic accidents include red light warnings, curve speed warnings, stop sign gap assist, railroad crossing violation warnings, spot weather impact warnings, oversize vehicle warnings, and reduced speed or work zone warnings. CV applications that utilize V2V communications to avoid collisions include emergency brake light warnings, forward collision warnings, intersection movement assist, blind spot, lane change warnings, do not pass warnings, and control loss warnings.

The applications listed below are from the USDOT Connected Vehicle program. Some applications are conceptual, and others have been piloted. Results of application testing are provided when available.

Curve Speed Warning application is designed to assist the driver to approach curves at safe speeds. Roadway departures (RwD) are a listed cause for 53% of all highway fatalities in 2016 in the US (National Highway Traffic Safety Administration, (n.d.)). Of these accidents, roadway or weather factors in 3% of cases, avoiding another potential crash in 13% of cases, and driving too fast for curves in 12% of cases. Conventional countermeasures for roadway departures include rumble strips, wide paved shoulders, additional signage at curves, speed feedback signage, median barriers, and the removal of sightline obstacles (U.S. Department of Transportation, 2018). The Curve Speed Warning (CSW) application can issue warnings if the vehicle is traveling too fast and is at risk of a roadway departure. The in-vehicle application receives geometric and weather information from a roadside unit and calculates speed thresholds for the specific vehicle. This application allows for more specification when considering variables such as the coefficient of friction and the curvature radius of defended lanes in multi-lane curved roads. Two-speed reduction warnings are generated by the in-vehicle application. There is potential for this application to be used for on-ramps and off-ramps, which are often located near bridges.

Spot Weather Impact Warning systems use information about weather conditions from road weather information systems, or directly from sensors in the road surface and in the air to detect hazardous conditions such as road icing, fog, or compact snow. A DSRC unit communicates these conditions to on-coming vehicles.

Oversize Vehicle Warning addresses the serious issue of bridge hits from vehicles that exceed the maximum clearance or width of bridges that can result in severe damage to the vehicles and their drivers, but also to the bridges themselves. In some cases, bridges, such as the I-95 bridge in Augusta Maine in 2017, must be closed for extended periods of time for structural investigation and replacement, which can cost the state millions of dollars and months of travel delay to local communities. Connected vehicle systems can be combined with these infrared sensors to detect and warn oversize vehicles if in violation of the maximum clearance for bridges. A current system used in Maine on the I-95/395 intersection uses sensors to detect the height of oncoming traffic and activates a number of flashing yellow lights to warn of an impending collision.

Reduced Speed/Work Zone Warning applications enhance driver warnings by broadcasting speed limit and lane change warnings to oncoming vehicles. The construction and repairs of bridges, which often can take months, require lane reduction and slower speeds to ensure the safety of workers and drivers. Current practices used to encourage slower speeds include signage, speed feedback signage, and doubling speed fines.

Red Light Violation Warning upgrades traffic signals to be able to communicate their signal phasing and timing (SPaT), geometric intersection description, and GPS data to allow vehicles to calculate whether they are able to travel through an intersection or are likely to violate a red light.

Stop Sign Gap Assist helps drivers at stop signs cross traffic lanes that do not have a 4 way stop sign or traffic control signal. The application uses either messages from other connected vehicles or sensors to estimate the position and travel speed of oncoming traffic to estimate a safe gap in traffic for crossing travel lanes.

Pedestrian in Signalized Crosswalk (PCW) Application uses crosswalks outfitted with DSRC units to communicate with vehicles that have an onboard unit to issue a warning that a pedestrian is present at the crosswalk. This application is particularly useful in cases where the visibility of the crosswalk signage or the pedestrian themselves may be difficult – low light, curves, or hills. These applications will communicate with all vehicles with OBUs in the vicinity, so cars down the queue who do not see the pedestrian can receive a warning.

Safety Benefits Related to Lane-Departure Accidents

Recent personal vehicle models include features such as Lane Departure Warning and Lane Keeping Assist Technologies that provide warnings of potential lane departures. It is estimated that advanced CAV technologies may reduce current US crash costs at least by $126 billion per year (not including pain and suffering damages, and other non-economic costs) and functional human-years lost by nearly 2 million per year (Li & Kockelman, 2018). Lane Departure Systems are estimated to prevent or mitigate 8% of all crashes and 30% of all road fatalities in the US. This is a very important technological intervention for reducing roadway fatalities. However, these systems are not always accurate, and the false identification and path corrections lead drivers to turn off these systems (McBride, *et al.,* 2014).

Lane departure systems can be supported by expanding shoulders and regularly painting lane markings so that exit lanes are not mistaken for travel through lanes. Furthermore, CV technology can include more scenarios where drivers are at risk of Roadway Departure (RwD) accidents such as high speeds approaching curves; spot weather hazards such as ice, flooding, or fog; and lane drop warnings. The USDOT's 2018 Report on Roadway Departure accidents recommends further research into road weather information, machine readable sign technology, identification of RwD-prone locations, and reconsidering geometric design of roads (U.S. Department of Transportation, 2018). Rahman et al., 2019 studied the safety benefits of arterials' crash risk under connected and automated vehicles and found that both connected vehicle (CV) and connected vehicle lower level of automation (CVLLA) significantly reduces segment crash risk compared to the base scenario. Connected vehicles also help in preventing not just primary accidents but are effective in reducing secondary crashes, which constitutes 20% of all crashes (Gaweesh et al., 2019).

Environment Applications

CAVs may change current vehicle configurations and designs. Extra components such as cameras, radars, Light Detection and Rangings (LiDARs), and communication modems will consume more energy and add curb weights. Additionally, CAVs can improve fuel efficiency through eco-driving strategies and vehicle platooning. If used, CAV can contribute to smoother traffic flow with fewer “stop and go” activities which will help reduce energy waste. However, the average speed on highways may rise, leading to a decreased fuel economy and people may choose to drive more as they can better use their time in vehicles on non-driving tasks. There are various studies on the environmental impact of CAVs, but there are no definitive answers currently (Wadud, 2016).

Eco-Approach at Signalized Intersections provides drivers with suggested speeds on approach and departure from intersections using information about signal timing and optimal driving profiles. The application tells a driver to start breaking for an upcoming red light using data from the traffic signal controller, before the driver sees the yellow light. Eco approach and departure applications can provide 5-10% fuel reduction benefits for an uncoordinated corridor. If a corridor is coordinated, the application can provide up to 13% fuel reduction benefits. In the Applications for the Environment: Real-Time Information Synthesis program 2009-2014 capstone report (United States Department of Transportation, 2016), 8% of the benefits were attributable to signal coordination while 5% were attributable to the eco approach and departure application.

Eco-Signal Timing attempts to minimize total delay for all vehicles at an intersection, which reduces fuel spent idling. Eco-Traffic Signal Timing applied to a signalized corridor that was well optimized provided a 5% fuel reduction benefit at full connected vehicle penetration.

Eco-Signal Priority allows transit and freight vehicles to request an extension of the green signal phase or a shorter red phase. Eco-Signal Priority application provided up to 2% fuel reduction benefits for transit vehicles. The Eco-Freight Signal Priority application provided up to 4% fuel reduction benefits for freight vehicles (AERIS, 2014). All eco-signal operation models showed up to an 11% decrease in CO_2 and fuel consumption at full connected vehicle penetration. The benefits decrease as volumes approach congested conditions because there isn’t much room for capacity improvement (AERIS, 2014).

Eco-Adaptive Cruise Control enables drivers to use cruise control with a setting that reduces acceleration and deceleration, given roadway geometry and surrounding vehicles, to reduce fuel consumption and emissions.

Eco-Smart Parking relays parking availability information to drivers to reduce time and emissions searching for parking in busy areas. Cities such as San Francisco have been using these applications.

Mobility and Traffic Management Applications

U.S. highway users wasted 6.9 billion hours stuck in traffic in 2014 (Texas Transportation Institute, JPO ITS, US DOT). During the height of COVID, traffic decreased significantly, and it is estimated that congestion cost drivers 3.4 billion hours in 2021, and 4.8 billion hours in 2022 (INRIX, 2021). CV technology can help drivers navigate the road more efficiently, as well as providing roadway information to operators to assist with traffic management that can reduce congestion, travel delays, and improve the overall mobility of our roadway. Corridors of V2I-enabled traffic signals can optimize traffic flow through the corridor and improve travel speed. By dynamically adjusting intersection controls to respond to traffic conditions, wait times can be reduced when compared to manually timed traffic controls (AERIS, 2014).

Multimodal Intelligent Traffic Signal System (MMITSS) uses Intelligent Traffic Signal System (I-SIG), Transit Signal Priority (TSP), Freight Signal Priority (FSP), Mobile Accessible Pedestrian Signal System (PEDSIG), and Emergency Vehicle Preemption (PREEMPT). The Anthem Arizona field test found that it effectively improved vehicle travel time, ranging from 6-27% improvement.

Intelligent Network Flow Optimization is a package of applications that will use connected vehicle information to increase roadway throughput, reduce crashes, and reduce fuel consumption.

Queue Warning aims to broadcast the formation of queues to nearby vehicles and to traffic management centers to allow for safe braking and lane changes.

Dynamic Speed Harmonization is intended to help drivers manage travel speeds in anticipation of road conditions up ahead, such as incidents, congestion, or poor weather conditions. The application uses information about road conditions to make recommendations on travel speed and travel lanes in a manner that is safer and decreases delays.

Cooperative Adaptive Cruise Control coordinates travel speeds in a platoon and enables the reduction in headways and the smoothing of traffic flow and increasing traffic throughput. This application is still under development and more work is needed to better understand technical feasibility and social acceptance.

Enable Advanced Traveler Information Systems envisions a dynamic traveler information system that utilizes data from public and private sources across multiple modes, providing personalized and predictive traveler information.

T-CONNECT application uses connected vehicle communications to increase the probability of completed transfers by sending transfer requests to vehicles across various modes.

Freight Advanced Traveler Information System (FRATIS) applications offer dynamic travel planning and minimize empty-load trips.

Smart Roadside Initiative comprises four applications that aim to streamline and digitize several functions of freight operations, such as universal commercial vehicle identification, electronic screening at weigh stations, wireless road inspections, and truck parking.

Durability Applications

The National Academies TRB Forum on AVs has listed infrastructure as one of the top ten research needs for autonomous and connected vehicles (Kortum & Norman, 2018). V2X systems can contribute to the durability of infrastructure by enhancing the winter maintenance systems and road infrastructure monitoring such as posted roads and bridge conditions. Connected autonomous vehicles can also improve the durability of road infrastructure through the reduction of road accidents. Blincoe et al., 2023 estimate that the cost of property damage which includes infrastructure damage from road crashes in the US was over $150 billion in 2019 alone. Recently, a fuel tanker accident caused the collapse of a bridge in Philadelphia which ultimately shortened the lifespan of the bridge (Alvarez, 2023). The expected reduction in accidents from CAVs will therefore improve the durability of road infrastructure such as signage, bus stops, bridges, and tunnels.

Road Weather Management Systems
The applications use data from vehicle to detect and forecast road, weather, and pavement conditions, to better support the road-weather management response.

Weather Data Environment (WxDE), Vehicle Data Translator (VDT) Integrated Modeling
WxDE, VDT, and Integrated Modeling for Road Weather Condition Prediction are systems that advance connected vehicle applications by enhancing their utilization of road weather data. Vehicle data translator combines and processes environmental and vehicle status data with ancillary weather data sources to create useful road, weather, and condition information. Vehicle data may use built-in or add-on sensors to capture information about vehicle velocity, rate of change of steering wheel, wiper and headlight status, anti-lock braking system, and traction controls system status, as well as external air temperature and pavement temperature. Weather station data, combined with vehicle data, can be used to predict conditions on particular road

segments, such as precipitation (rain, snow, ice, hail), pavement condition (dry, wet, snow, icy), and visibility (normal, low, fog, heavy rain, blowing snow, smoke).

Motorists Advisories and Warnings
The WxDE allows for road segment specific weather and road conditions to be estimated and predicted, and then shared with drivers in the area and those planning travel along those road segments, potentially up to 12 hours in advance. This could significantly improve driver's ability to change short and long-distance trips to avoid dangerous conditions and/or change travel plans to accommodate for slower travel.

Weather Responsive Traffic Management: Variable Speed Limits (VSL)
Data from the WxDE can be used to dynamically change posted speed limits. These systems can be paired with road works to ensure that driving speeds during inclement weather are safe for drivers and workers.

Enhanced Maintenance Decision Support Systems (EMDSS)
New data from connected vehicles will refine the current prototype of a MDSS to generate improved recommendations and road maintenance plans.

Bridge Infrastructure
Bridges are complex and expensive components of the road network that are designed to last for 50-100 years. The *Keeping our Bridges Safe* report by Maine DOT in 2014 highlights the need for bridge repairs in the state of Maine. This will require significant reconstruction and is an opportunity to consider road design for CAVs. The platooning of vehicles and trucks may change the structural loads on bridges, and either require new designs or regulations about spacing. Little research on this topic has been done to date.

Furthermore, DSRC sensors can be added to bridges to help HAVs and truck platoons safely navigate bridges. Embedded sensors could also be used to detect icing conditions on the deck. The installation of sensors and dynamic signage will require power and telecom equipment to support these systems and should be considered any time a bridge is being built or rehabilitated.

Chapter 2 Regulations, Guidelines and Standard Specifications

In the last 100 years, the federal government's mandate in the transportation sector has been to regulate the production, safety, and fuel economy of vehicles, whereas states have regulated driver licensing, built road infrastructure, and in the case of California and Section 177 states, including Maine, that also regulated vehicle GHG emissions. CAVs are showing the need for even greater coordination between federal and state jurisdictions and vehicle manufacturers as vehicles increasingly become responsible for more driving tasks. These autonomous functions are facilitated, if not actually required, by standardized infrastructure across states including such issues as consistent use of luminance, retro-reflectivity, and color when marking lanes. The paradigm shift to CAVs requires innovation and investment on the part of the private sector and a dramatic reorganization of the regulatory environment and the physical infrastructure, including communication networks, built *and maintained* by private companies and state and local governments.

Federal agencies such as the USDOT and FHWA have researched and developed connected vehicle applications, and are being tested and implemented, most notably in the Connected Vehicle Pilot Program in Tampa, New York City and Wyoming. The AASHTO "SPaT" (Signal Phase and Timing) Challenge is encouraging every state to implement a connected vehicle pilot. Several companies have partnered with State DOTs to create connected corridors, such as Panasonic and Colorado DOT for the I70 corridor (Colorado Department of Transportation, (n.d.)).

This chapter summarizes recent changes in regulations, policies, and guideline reports, as well as investments and testing of new applications and technologies at the federal and state level, with a focus on initiatives and topics of importance to New England. Recommendations on how the governments can adapt to and implement new mobility technologies are discussed in Chapter 5.

2.1 Federal Regulations, Policies and Guidelines

Researchers have recommended that the federal government should support the advancement of connected vehicles by coordinating and unifying the regulatory environment, including appropriate standards for liability, security, and data privacy (Fagnant & Kockelman, 2015). The NHTSA has issued several guideline reports for HAVs, but legislation has been delayed. The House of Representatives passed the SELF DRIVE Act in 2017 and the Senate introduced the AV START Act, but neither bill has been enacted.

Disagreements on the scope of the legislation have stalled progress on federal legislation and include concerns about changes to federal and state regulation of driver registration and licensing, the number of HAV vehicles permitted for on-road testing, cybersecurity requirements, and data privacy.

There are several regulatory issues for connected vehicle technology, such as a mandate to install CV equipment on all new vehicles, as well as the preservation of the 5.9GHz wireless band for transportation safety applications. Furthermore, connected vehicle technologies will change how DOTs deliver and finance transportation infrastructure and may require a fundamental change from infrastructure to mobility providers.

National Highway Traffic Safety Administration (NHTSA)

The USDOT's National Highway Traffic Safety Administration (NHTSA) is responsible for regulating the safety of HAVs and CAVs, as per the National Traffic and Motor Vehicle Act of 1966 ("Safety Act"). It also ensures that regulators and the industry are developing the technology in a clear and coordinated regulatory environment (Trimble et al., 2018).
Starting in 2016, the NHTSA began releasing annual reports providing policy guidance for autonomous and connected vehicles. The latest report - Ensuring American Leadership in Automated Vehicle Technologies was released in 2020 which seeks to ensure consistent approaches to AV technology by various states (National Science and Technology Council & United States Department of Transportation, 2020). Previous reports include performance guidance for HAVs, a model state policy, a review of current regulatory tools, suggestions for modern regulatory tools, reducing policy uncertainty, and outlining a process for working with the USDOT. The NHTSA in September 2017 released version 2 of A Vision for Safety which serves as voluntary and technical assistance to states on issues related to CAV. Using the interactive tool, the public can view information about the operation status of the testing, vehicles being tested, and the company in charge of the AV technology. In addition, information about States and companies involved in technologies related to AV can be found using the tracking tool.

AV TEST Initiative

The NHTSA launched the Automated Vehicle Transparency and Engagement for Safe Testing (AV TEST) Initiative in June 2020 in close collaboration with states and stakeholders in the driving automotive industry. The goal of such initiative is to increase transparency and access to information related to Connected Autonomous Vehicles. The initiative also provides opportunities for industries to showcase their advances in the move towards driverless automobiles. As of May 2023, 116 AV-related projects were listed on the AV TEST initiative website. 71 of these projects were active, 38 were completed and 7 were inactive. In terms of the activity type, 99 of these projects were testing autonomous vehicles, 10 of them involved the demonstration of AV technology and the remaining 7 involved commercial use. The vehicle types involved in the testing were dominated by shuttles (57) followed by cars (29) while bus (1) was the least among the 10 categories of vehicles being tested. The testing was mostly done on streets (43) and highways (14) with only one on rural roads.

Federal Highway Administration

The FHWA is focusing on different applications and situations in which the deployment of connectivity will provide benefits to transportation systems. They conducted tests of truck platooning and work zone speed management on I-95 express lanes in Virginia in 2018. FHWA launched WZDx to start the voluntary adoption of basic work zones through a collaboration between USDOT, producers, and data users. Version 4.0 of WZDx which was launched in December 2021 allows data producers to publish new feeds for smart work zone device data as well as non-work zone road restrictions. This version also allows the reporting of depreciated properties for them to be removed (U.S. Department of Transportation, 2023). FHWA has partnered with the automotive industry to examine concepts that are aimed at improving traffic flow through intersections. The initial test suggests traffic at intersections can be reduced through cooperative automation on signalized arterials (U.S. Department of Transportation, 2023). In February 2023, the Federal Highway Administration launched version 1 of Concept of Operations for transportation agencies which describes likely ADS use cases and how they can safely, equitably, and efficiently be integrated with the overall transportation system.

American Association of State Highway and Transportation Officials (AASHTO)

AASHTO commissioned a report "Connected/Automated Vehicle Roadmap", which was updated in 2018 (NCHRP 20-102, 2018). The document provides a detailed description and cost of research projects under the themes of institutions and policy, infrastructure design and operations, planning and modal applications. AASHTO also coordinates with the NCHRP's research program.

AASHTO is also accelerating the adoption of DSRC through its Signal Phase and Timing (SPaT) challenge, an interesting initiative to quickly start the adoption of connected vehicle technologies. SPaT encourages each state to install DSRC sensors in a corridor of at least 20 traffic signals. These can create knowledge within DOT about the potential applications, but also about the data management needs – what kind of data is collected and transmitted to vehicles, what are data storage and privacy and cybersecurity requirements, and what additional personal and skills sets are required.

American Association of Motor Vehicle Administrators (AAMVA)

The AAMVA assisted member states to prepare and adapt to regulatory changes. AAMVA was a key stakeholder in the development of the NHTSA model state policy in the 2016 HAV policy guidance report. AAMVA's vision of Safe Drivers, Safe Vehicles, Secure Identities, Saving Lives is at the core of AAMVA's operations. AAMVA works with standing committees to develop standards, best practices and guidelines for agency operations, customer service, and management to support service delivery and optimal agency operations.

National Conference of State Legislatures (NCSL)

The NCSL provides a searchable database and map of all C/HAV state legislation (National Conference of State Legislatures, 2020). According to the National Conference of State Legislatures (NCSL), 29 states and the District of Columbia have enacted AV legislation and governors from 11 states have issued AV-related executive orders as of February 21, 2020.

Standards and Specifications

There are many standards and specifications that guide the development of CAV technologies across the globe. These standards contribute significantly to the state of CAV technology. Most of these standards have been developed by the Society of Automotive Engineers (SAE) and the Institute of Electrical and Electronics Engineers (IEEE).

3GPP Cellular Vehicle-to-Everything (C-V2X) or Long-Term Evolution V2X (LTE-V2X) Standard

Through efforts under 3rd Generation Partnership Project (3GPP) standards organization, the Cellular Vehicle-to-Everything (C-V2X) standard was defined in 2016 with the goal of standardizing V2X capabilities integrated with LTE. C-V2X and DSRC are competing technologies and research results can be found that favor DSRC and others that favor C-V2X. C-V2X standardized the use of Cooperative-ITS (C-ITS) short-range technology referred to as 3GPP LTE V2X PC5 (or LTE side-link). These Peer-to-Peer (P2P) connections enable low-latency and high-reliability communication between links that are within communication range. Range can vary on a number of environmental factors for both technologies including Line of Sight, weather, and interference from other devices. LTE side-link and DSRC (IEEE 802.11p) both operate in the 5.9 GHz wireless radio frequency, though with incompatible modulation schemes (DSRC uses Orthogonal Frequency Division Multiplexing (OFDM), while PC5 uses Single Carrier Frequency Division Multiplexing (SC-FDM). The applications that are enabled through each technology are essentially the same. While DSRC has been deployed by traffic authorities in cities throughout the U.S. over the past decade, vehicle OEMs have only deployed a small number of vehicles equipped with DSRC. Now, as C-V2X equipment becomes more readily available, vehicle OEMs and traffic authorities are weighing the value of both technologies before deciding on which to use.

SAE J2735 Dedicated Short Range Communication (DSRC) Message Set Dictionary

This standard establishes the information and encoding/decoding format that is communicated between connected vehicles and infrastructure devices. This ensures interoperability for CVs at the application level and enables applications such as forward collision warning, emergency vehicle alerts, and traveler information messages.

SAE J2945/1 On-board Minimum Performance Requirements for V2V Safety Communications

This SAE standard sets the minimum performance requirements and the standard features for Over-The-Air (OTA) communication. This provides interoperability at the interface level for CVs and infrastructure devices.

IEEE 1609.3-2016 Standard for Wireless Access in Vehicular Environments

Networking Services is an IEEE standard which defines the network and transport layer services. These services include routing and addressing and work together to provide secure Wireless Access in Vehicular Environments (WAVE) data exchanges. Additionally, IEEE 1609.3 defines Wave Short Messages, enabling IPv6 over an efficient WAVE specific interface that can be directly supported by end applications. The Management Information Base (MIB) is also defined for the WAVE protocol stack.

ISO/SAE 21434 Standard for “Road Vehicles – Cybersecurity”

The ISO/SAE is developing a global standard for cybersecurity development of automotive systems. The key objectives are to define common terminology and key aspects of cybersecurity such that companies applying the standard can demonstrate responsible handling of automotive system development and cyber-threat prevention, ensuring security was adequately considered. The European Union (EU) is creating an EU Cyber Security Regulation in parallel with this standard and, in coordination with the United Nations Economic Commission for Europe (UNECE), is preparing a certification for a "Cyber Security Management System" (CSMS) as part of a task force on cybersecurity and OTA issues under a working party for automated/autonomous and connected vehicles (GRVA). This standard is currently under commenting and review. The ISO/SAE 21434 standard was made available on SAE’s website in 2021.

SAE J3061 Cybersecurity Guidebook for Cyber-Physical Vehicle Systems

While not a standard, it is guidance that establishes a comprehensive and systematic process and recommendations for designing cybersecurity into the cyber-physical vehicle system including product design, validation, deployment, and communication tasks. This guidance covers the complete lifecycle process to ensure cybersecurity is built into the design and carried throughout product development and includes monitoring and incident handling in the field, along with addressing vulnerabilities in service and operation.

IEEE ISTO and the Uptane Alliance

Under the Institute of Electrical and Electronics Engineers (IEEE) Industry Standards and Technology Organization (ISTO), the Uptane Alliance is working on completing a standard for protecting remote Software-Over-The-Air (SOTA) updates for automotive Electronic Control Units (ECU). This standardization effort will provide the necessary requirements and recommendations for suppliers, Original Equipment Manufacturers (OEM), and solution providers to deploy a secured software update process similar to the methods that are protecting updates for non-embedded computing platforms. Security measures similar to these may protect field-deployed equipment in the future.

The **SAE Recommended Practice J3016 (June 2018) "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles"** lays out the terms and operational domains for automated driving systems. This clarifies the six levels of driving assistance from a fully manually operated to a fully automated vehicle. These terms needed clarification due to the misuse of the various levels in marketing material. SAE Levels 1-2 (car controls gas, brake, and/or steering) always rely on a human driver and account for virtually all systems on the road today. Some self-driving systems are arguably capable of partial Level 3 (fully automated with human backup) or Level 4 (fully automated without human backup, does not work in all road conditions) but, because they rely on human oversight, are still considered Level 2. Level 5 is reserved for an Automated Driving System (ADS) that operates without any design-based restrictions such as time-of-day, weather conditions, or regional limitations. A Level 5 vehicle would not need to include manual vehicle controls such as a brake pedal or steering wheel. A Level 5 ADS would be capable of detecting road conditions that a human driver would deem "unsafe" such as dense fog, flowing water, and black ice and would achieve a minimal risk condition (such as pulling over to the side of the road) until the condition changes.

2.2 *Funding sources for ITS and CAV applications*

Most of the transportation funding available is dedicated to maintaining the existing infrastructure. Public agencies are seeking answers on how these technologies are affecting traditional revenue streams, the potential for new revenue streams, and continued support for legacy systems, transitions to new technologies, and the risks and rewards for investment planning.

Current Programs

RAISE

The Rebuilding American Infrastructure with Sustainability and Equity, or RAISE Discretionary Grant program, provides a unique opportunity for the DOT to invest in road, rail, transit, and port projects that promise to achieve national objectives. Previously known as the Better Utilizing Investments to Leverage Development (BUILD) and Transportation Investment Generating Economic Recovery (TIGER) Discretionary Grants, Congress has dedicated nearly $12.1 billion for fourteen rounds of National Infrastructure Investments to fund projects that have a significant local or regional impact.

ATVM (Advanced Technology Vehicles Manufacturing, ***Inflation Reduction Act (IRA),*** *2022-* 2028)

The Inflation Reduction Act (IRA) of 2022 invests in climate and energy, securing America's position as a world leader in domestic clean energy manufacturing, and putting the United States on a pathway to achieving a net-zero economy by 2050. The Loans Programs Office (LPO) through ATVM loan program provides loans for innovative and high-impact energy technologies that are yet to reach market acceptance and cannot secure loans from private lenders. The *Inflation Reduction Act* removed the $25 billion cap on the ATVM direct loan program and appropriated $3 billion for the cost of direct loans under ATVM. The funds will be available through September 30, 2028.

Advanced technology vehicles were originally defined as light-duty vehicles that meet or exceed a 25% improvement in fuel efficiency beyond a 2005 model year baseline of comparable vehicles; and/or ultra-efficient vehicles which achieve a fuel efficiency of 75 miles per gallon or equivalent using alternative fuels. The Bipartisan Infrastructure Law expanded the definition to include medium- and heavy-duty vehicles, locomotives, maritime vessels including offshore wind vessels, aviation, and hyperloop.

SLFRF (State and Local Fiscal Recovery Funds program, ***American Rescue Plan Act of* 2021**)

This program delivers $350 billion to state, local, and tribal governments across the country to support their response to and recovery from the COVID-19 public health emergency. Invest in water, sewer, and broadband infrastructure, making necessary investments to improve access to clean drinking water, to support vital wastewater and stormwater infrastructure, and to expand affordable access to broadband internet. The Coronavirus State Fiscal Recovery Funds (CSFRF) provides $195.3 billion to the 50 states and the District of Columbia, with $25.5 billion to be allocated equally to the 50 states and the District of Columbia.

BEAD (**Broadband Equity Access and Deployment) program**, Infrastructure Investment and Jobs Act (IIJA) 2021

This program will deliver $65 billion to help ensure that every American has access to reliable high-speed internet through a historic investment in broadband infrastructure deployment. The legislation will also help lower prices for internet service and help close the digital divide so that more Americans can afford internet access. States may request up to $5,000,000 in Initial

Planning Funds. Further, each State is eligible to receive a minimum initial allocation of $100,000,000 (inclusive of the Initial Planning Funds). Territories may request up to $1,250,000 of initial planning funds and are each eligible to receive an initial minimum allocation of $25,000,000. Remaining funds will be allocated to Eligible Entities based on the formulas provided in Section 60102(c)(1) and (c)(3) of the Infrastructure Act.

Chapter 3 CAV Applications - Costs, Benefits, and Lessons Learned

Making the right type of investment is essential to facilitate the adoption of autonomous vehicles for various states. Testing of autonomous vehicles will provide a means to identify the infrastructure gaps and the areas much needed for the successful deployment of CAVs. This session looks at planned CAVs as well as operational CAVs to inform strategic investment in CAVs. Figure 3 displays the planned and operational CAV deployments in the United States.

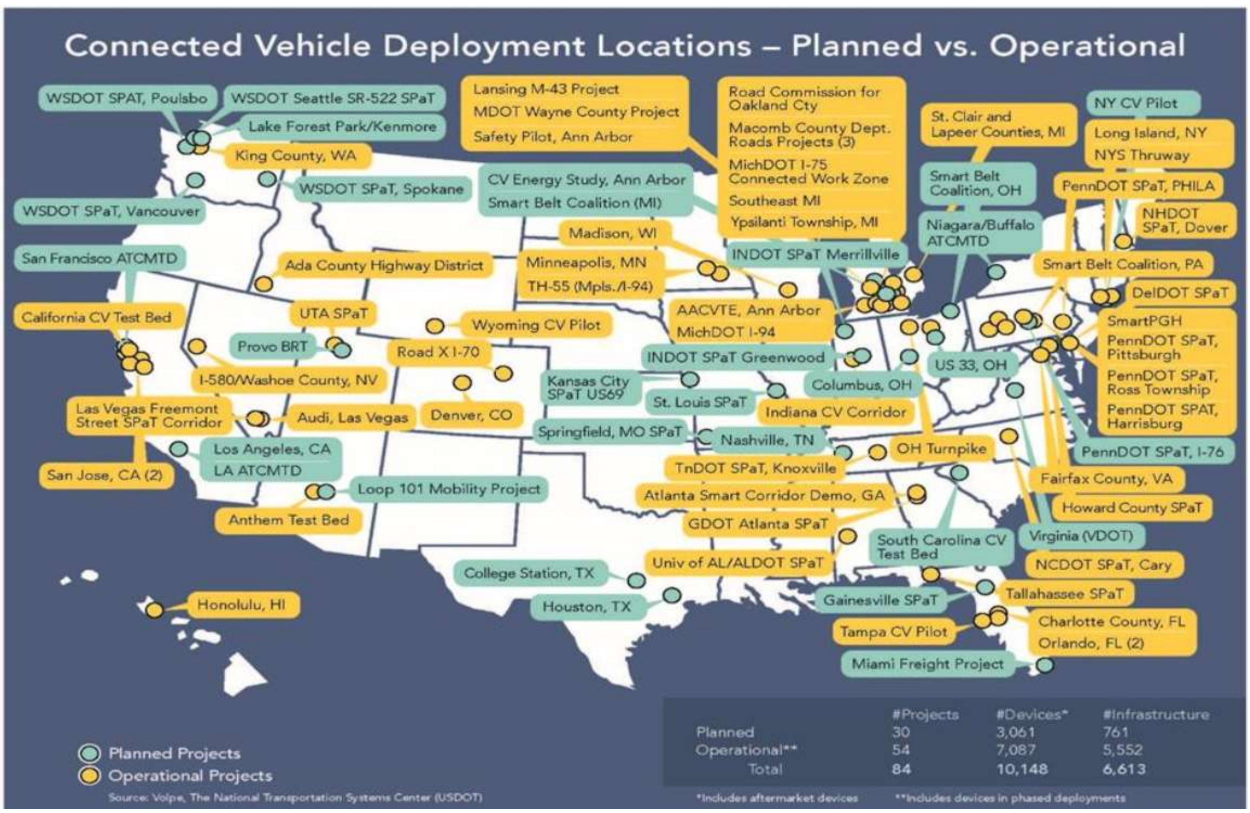

Figure 1. Connected Vehicle Deployment Locations- Planned vs. Operational (U.S. Department of Transportation, Intelligent Transportation Systems, 2019)

USDOT Connected Vehicle Program

The USDOT & FHWA have funded CV pilots in Tampa, New York City, and Wyoming. These projects apply USDOT research on CV application concepts into real-world settings and are some of the first instances of pilots allowing the measurement of the implementation costs and potential benefits from these applications.

Tampa Pilot Deployment

In Tampa, the chosen CV applications focus on improving the safety of drivers of personal vehicles, transit riders, and pedestrians. The 13 deployed applications include End of Ramp Deceleration Warning, Wrong-Way Entry Warning, and Probe Data Enabled Traffic Monitoring, among others. The pilot enrolled more than 1,000 private citizens to participate by installing a Human Machine Interface (HMI) in the vehicles' rear-view mirrors. The HMI uses Dedicated Short-Range Communications (DSRC) and was installed for both a treatment and control group the latter of which had the HMI disabled (Concas et al., 2021).

Safety applications such as curve speed warning and wrong-way entries work by alerting drivers of unsafe situations. Applications are effective if they correctly identify all or most dangerous situations and have a low rate of false positives that would confuse drivers, and eventually lead them to disregard the system. Forward Collision Warnings had a good rate of success identifying potential risk of collision. The Wrong-Way Entry system correctly identified 75% of true conflicts, but due to complex intersection design and turning movements, as well as GPS time lag, meant that the system generated false positives at a rate of 28%. Pedestrian and Streetcar Conflict Warnings did not have enough true conflict situations to allow the team to evaluate its effectiveness.

Three applications were deployed to improve traffic flow through signalized intersections in a busy arterial. Forward Collision Warning, Electronic Emergency Brake Light, and Intersection Movement Assist application issued 26 warnings classified as true positives, of which 8 were shown to drivers with the HMI enabled (i.e., treatment group). The conflict detection algorithm revealed that in two of these warnings the participants responded to the HMI message. It is estimated that the applications produced a 2.1% reduction in mean travel times, a 1.8% reduction in idle time, and a 1.8% reduction in queue length. A travel time index, measured as peak hour travel time divided by off-peak travel time, was reduced from 2.7 to 1.9.

New York City Pilot Deployment

In New York City, the pilot aimed to improve safety for travelers and pedestrians, deploying 15 CV applications including: Red Light Violation Warning, Curve Speed Compliance, Reduced Speed/Work Zone Warning, and Pedestrian in Signalized Crosswalk Warning. The pilot program installed Aftermarket Safety Device units into vehicles from various DOT and other city agencies (FHWA-JPO-18-715, 2021).

Results of the pilot include a reduction in speed limit violations by 47.7 per 1000 events (i.e., 5%) compared to the control group, and a reduction in the speed at curve entry of approximately 8.8 mph. There was an extra 0.427 m/s deceleration from the drivers on average after being issued work zone warnings. This finding suggests that comparing before and after the implementation period, both injury and PDO rear-end crashes decreased by 5.3% and 9.4%, respectively, and both injury and PDO side-swipe crashes decreased by 1.5% and 15%.

WYDOT CV Pilot Deployment Results

In Wyoming, the state DOT piloted 5 CV applications aimed at improving freight and passenger car driver safety along I-80. These included Forward Collision Warning, Infrastructure to Vehicle Situational Awareness, Work Zone Warning, and Spot Weather Impact Warning. The pilot deployed 75 roadside DSRC units and instrumented 400 fleet vehicles with On-Board Units DSRC enabled devices. The WYDOT 511 traveler information system was also included to communicate with drivers (FHWA-JPO-20-829, 2020).

During a testing period from January 2021 to April 2022, the number of road condition reports during unique severe weather events increased from a baseline of 4.3 to 16.9, and the coverage of the road condition messages added one region, bringing the total to 6.4 sections. The refresh time of road condition reports reduced from a baseline of 3.9 to 3.2 hours. On average about 90% of Traveler Information Messages were received by at least one vehicle with an OBU on I-80. While speed limit compliance during mixed condition storms increased by ~4-5%, overall speed compliance was reduced by 11.3% in all weather conditions. No crashes involving a connected vehicle were reported to WYDOT during the period from December 2020 through February 2022. While the pilot found there to be some benefits for truck fleets to receive more road conditions warnings, the uncertain technological and financial sustainability of the project put its future continuation in question. WYDOT did not continue the use of DSRC OBUs after July 2022 due to the FCC ruling that allocated the majority of the 5.9GHz band to cellular technology.

State-led CAV Applications

Hawaii Connected Vehicle Pilot Project

Hawaii CV pilot project is developed in the heart of downtown Honolulu and integrated by 34 intersections. This project used V2X units that are connected to the corridor’s traffic lights, and a traffic software program administered by HDOT (Hawaii Department of Transportation). This project focuses on developing real-time traffic mobility and safety applications, analysis of traffic data and optimization of the performance of the traffic system. Examples of these applications include CV system control, red light violations, pedestrian and cyclist collisions, emergency vehicle warnings, traffic signal priorities, and arterial wide speed harmonization (Hawaii Department of Transportation, 2020).

Columbus Connected Vehicle Pilot Project

Columbus's CV pilot project is a new project deployed in the context of the smart Columbus city founded by the USDOT. This project was launched in July 2020 in USA's Columbus city (Smart Columbus, 2021). The goal of this project is expected to enhance safety and mobility for vehicle operators, improve pedestrian safety in school zones, and provide sources of high-quality data for traffic management and safety purposes. This project began at the end of 2019 and ended in July of 2020. The operation and installation of RSUs was finished in February 2020, and status monitoring of the RSU network was completed in March 2021. Under the Columbus project, more than 113 RSUs and up to 1800 OBUs have been mounted on top of private, emergency transit, and freight vehicles with other CVs equipment installed at intersections, school zones and bus stops (Phil, 2018). 12 V2V or V2I applications were tested under this project, such as traffic signal priority and emergency vehicle preemption, red-light violation warnings applications, and speed reduction alerts. Communications in this project was done using DSRC, Satellite, Backhaul and WIFI.

Connected Vehicle Pooled Fund Study

The Transportation Pooled Fund Program is led by the University of Virginia and provides technical and administrative support to states and local governments, each providing $25-50K (Transportation Pooled Fund, 2023). The program has commissioned a number of reports and guidance documents on the topics of adapting traffic management centers to a connected vehicle environment as well as best practices for surveying and mapping roadways and intersections for connected vehicle applications. An updated Connected Intersection MAP creation guidance report, written by Athey Creek Consultants, LLC and Synesis Partners, LLC., was released in May 2022. Participation in the fund includes 23 states and 2 federal agencies:

- AZ, AK, AL, CA, CT, DE, FL, GA, ID, IL, MD, MI, MN, MS, NH, NJ, OH, PA, TN, TX, UT, VA, WI, FHWA, Transport Canada. (Transportation Pooled Fund, 2023)

Smart Belt Coalition

The coalition is a three-state effort between Pennsylvania, Michigan, and Ohio's state agencies and academic institutions to test CV/AV technologies in a cross-border corridor. Research output to date includes a strategic plan for applications in work zones, traffic incident management, and commercial freight truck platooning (Smart Belt Coalition, 2017).

North/West Passage Coalition

The seven-state Transportation Pooled Fund between Idaho, Minnesota, Montana, North and South Dakota, Washington, and Wyoming DOTs was created to address operational disruptions to commercial freight travel along I-90 and I-94 due to weather conditions (North/West Passage, 2023). The coalition includes an operations and a freight taskforce, and issues annual progress reports on research. The project will expand on the success of the Wyoming USDOT Connected Vehicle Pilot for applications such as truck platooning, work zone traveler information, rural 511 alert systems, plow cameras, and other weather tracking practices.

I-95 Corridor Coalition

The coalition held a Connected and Automated Vehicle Workshop in 2018 (Transportation Pooled Fund, 2023). The forum discussed barriers to CV/AV implementation including public mistrust, institutional factors, funding, law enforcement, operator, and vehicle licensing. Priorities for the coalition include a regional working group to stay up to date on latest developments, better training for staff, improving understanding of data interoperability, and pursuing regional funding.

Colorado I-70 Connected Corridor

Starting in 2017, CoDOT has deployed V2X roadside units along 90 miles of I-70 from Golden to Vail, as well as V2X onboard radios in at least 2,500 vehicles. A key component of the project is the development of an operations and application platform where CoDOT can collect, interpret, and analyze connected vehicle data to improve the transportation system, and also create and send messages to vehicles in real-time so drivers can avoid crashes, hazards, or congestion. As of 2022, CoDOT has issued several RFP for RSU installation as part of the implementation of this project.

Autonomous Vehicles Testing in Rural Applications

ADS for Rural America Pilot, Iowa

Autonomous vehicles were tested on rural roads in Iowa (NHTSA, 2023) using Ford Transit for shuttle services. The ADS For Rural America project, which was funded through a $7 million grant from the U.S. Department of Transportation and $400,000 from the Iowa DOT, tested automated vehicles on rural roads from fall 2021 to summer 2023. It made 80 trips on a 47-mile loop through Iowa City, Hills, Riverside, and Kalona. The testing which was spearheaded by researchers at the Driving Safety Research Institute at the University of Iowa in partnership with Iowa Department of Transportation, AutonomouStuff, and Mandli Communications used four vehicles and 32 participants. The pilot had 3410 (85%) miles in autonomous mode out of the 3989 miles recorded. The participants expressed increased trust in the automated vehicles after riding compared to the levels of trust before riding. The study also observed increased belief in the reliability of autonomous driving after riding the shuttle. The autonomous systems disengaged on many occasions and the reason for the disengagements included; decreases in speed limits not recognized by the system, stopping at traffic lights, vehicles passing in no passing zone, exiting a highway, inappropriate transit brakes, approaching blind hill, too much traffic for merge, turning right from highway, traveling too fast for a curve, an object like carcass or tires located on the roadway, transit crosses the centerline, an abrupt lane change, and aggressive cornering on on-ramp (Iowa Driving Safety Research Institute, 2023).

Yellowstone National Park (TEDDY) and Wright Brothers National Memorial (CASSI) Shuttle Pilots

The Federal Lands Transportation Program in partnership with the Federal Highway Administration funded autonomous shuttle pilots at Yellowstone National Park and Wright Brothers National Memorial (Cregger et al*.,* 2022). The first is The Electric Driverless Demonstration in Yellowstone (TEDDY) operated from June 2021 to August 2021. This was operated by Beep on a 1.6-mile loop with 4 stops and a 1.5-mile loop with 3 stops using two Local Motors Olli shuttles. The second of the two pilots is the Connected Autonomous Shuttle Supporting Innovation (CASSI) pilot operated at the Wright Brothers National Memorial from April to July 2021 with a single EasyMile EZ10 Gen 3 shuttle by Transdev. The two pilots together served more than 13,400 riders on over 3,300 trips (Cregger et al*.,* 2022*)*. In terms of rider experience, 78.7% strongly agreed to having a good experience using the shuttle while only 2.3% strongly disagreed with having a good experience with the shuttle use. The majority (71%) of the riders indicated that they felt very safe riding the shuttle while 1% felt very unsafe after riding the shuttle. Some factors that affected the pilot included roadside vegetation which had to be cleared 2 feet from the shoulder since swaying vegetation near roadway triggers sensors of the shuttle. Pedestrian and car movement at parking lots was also a challenge to the autonomous shuttle. One of the key lessons from the Yellowstone National Park pilot is the need to emphasize accessibility and user friendliness in relation to the design and operation of autonomous vehicles. The lessons learned from these pilots relate to contracting, planning, communications, technology, evaluation, and accessibility.

Lessons learned from the Rural America Pilot, TEDDY, and CASSI Demonstrations

1. **Training and communication are imperative**
   a. Clearly define the roles for all team members.
   b. On-site staff should be trained to troubleshoot simpler issues.
   c. Close communication with technology providers is essential.

d. Safety drivers need to have extensive experience and be intimately familiar with the operational design domain.

2. **Conservative automation behavior is the norm**
   a. To have a vehicle drive autonomously at 65 mph in live traffic is a big deal. It took a lot of testing to raise it from the initial 50 mph max speed.
   b. Automation behavior is conservative for good reason (i.e., safety), but this means the vehicle is often very slow to start moving from stop signs and railroad crossings (at times to the frustration of drivers behind).
   c. Automation does not adapt to poor weather conditions.
   d. Icy weather impacts sensor performance and can essentially blind the LiDAR.

3. **Automation behaviors don't adapt well to rural roads**
   a. The vehicle travels at the speed limit programmed into the HD map, regardless of approaching a blind corner or hill. Virtual speed limits must be added to the HD map to slow the vehicle down at these specific locations.
   b. On a narrow gravel road, humans drive near the center to avoid the edge of the road, where there can be looser gravel and steep drop-offs (unless approaching another vehicle or blind hill/corner, then they move over). The automation is currently being fine-tuned to reflect the way humans drive on gravel roads.
   c. The vehicle may not be able to classify all objects and has slowed for (e.g., water spray from a lawn sprinkler, dust clouds on gravel roads).

4. **Camera-based approach to identify traffic signals has its pros and cons:**
   a. Pros: Cameras allow you to pick up the state of signal heads without any changes to physical infrastructure.
   b. Cons: There is a potential to pick up the wrong signal head from an adjacent lane, and the view can be blocked if behind a tall vehicle or near sharp elevation changes. The vehicle's sensors may not "see" far enough to safely turn onto a highway where traffic is moving at 55+ mph.

5. **Lessons learned related to contracting**
   a. Seek additional technical expertise on new technologies during the contracting phase to build context and details into the contract.
   b. Strongly and clearly identify data needs and formats in solicitation documents.
   c. Consider the various contract mechanisms available and how the choice of a particular approach will affect how a project is executed and managed.
   d. Understand expectations of the pilot technology and impacts to services and partner obligations.
   e. Ensure that replacement parts are readily available, and that maintenance staff can quickly address technology malfunctions.

f. Identify all funding obligation processes early and maintain open communication until approved.

6. **Lessons learned related to planning**
   a. To the extent possible, maintain consistent staffing from all project partners throughout the pilot period. In cases where staffing changes are required, consider how documentation and training procedures can assist with providing continuity.
   b. Identify staff, stakeholders, and subject matter experts early on and include them in all stages of planning and contracting.
   c. Make timelines clear and build in buffer time to allow for unexpected delays.
   d. Gather information needed to understand environmental and operational conditions early in the process and ask for additional clarification where needed.
   e. Look for opportunities to reduce redundancy in planning documents and clearly convey expectations in terms of what they should include.
   f. Involve all subcontractors during the planning process.
   g. Establish a plan for on-site oversight throughout the project period.
   h. Develop a plan for service interruptions.

7. **Lessons learned related to communications**
   a. Involve communications staff at all levels early on.
   b. Have dedicated project staff on the ground during the pilot project.
   c. Develop a thorough communications plan that addresses all items related to the project scope.

8. **Lessons learned related to technology**
   a. Understand the level of maturity of the technology and expect disruptions caused by environmental conditions and technical malfunctions.
   b. Plan for additional landscape maintenance activities.
   c. Place charging infrastructure close to the shuttle route.
   d. Plan for redundancies in obtaining and transferring data.
   e. Expect disruptions caused by environmental conditions and plan for additional landscape maintenance activities.

9. **Lessons learned related to accessibility**
   a. Require the use of robust accessibility equipment with a good supply chain for replacement parts.
   b. Use the shuttle’s kneeling function for elderly riders and others who may need it.
   c. Design accessibility infrastructure in initial planning stages with input from all partners.

DriveOhio Rural Automated Driving Systems

The USDOT awarded the state of Ohio a $ 7.5 million ADS demonstration grant. The project which began in January 2023 will show how automated and connected semi-trucks and passenger vehicles that are being tested separately could increase safety for drivers, passengers, and other road users in rural areas. This project promises to be the most comprehensive testing yet to be done in rural areas. The first of the two Automated vehicles deployment in Southeast Ohio includes three passenger vehicles equipped with AutonomouStuff - a leading supplier of software and engineering services for the advancement of robotics and autonomy systems- technology traveling on divided highways and rural two-lane roads in Athens and Vinton counties. The first deployment will also include truck Platooning in central Ohio. The program is expected to test the safe operation of automated trucks and Ford Transit vans on a mix of rural routes with hilly terrain, twisting roads, a variety of tree canopies and limited internet connectivity. The Federal Motor Carrier Safety Administration (FMCSA) will collect, analyze, and report the data which will be used by the USDOT to improve safety and benefit rural regions across the nation. The lessons learned will be shared with other stakeholders to safely integrate ADS technologies across the U.S., especially in rural areas (DriveOhio, 2023)

goMARTI Shuttle- Minnesota Autonomous Rural Transit Initiative

goMARTI is a self-driving shuttle pilot sponsored by Minnesota DOT in partnership with the City of Grand Rapids, The PLUM Catalyst, May Mobility, Department of Iron Range Resources & Rehabilitation, Itasca County, Via, University of Minnesota, Arrowhead Transit, and Mobility Mania who have a shared goal of increasing accessibility and transportation options for residents and visitors in Grand Rapids, Minnesota. The 18-month pilot program will cover nearly 17 miles and close to 70 pickup and drop-off points using a fleet of five mobility vehicles. Three of the five vehicles are wheelchair accessible which ensures the elderly as well as people with disabilities are able to patronize the free, on-demand rides provided by the pilot program. All the vehicles have people behind the steer who monitor the van and take over whenever the autonomous mode is disengaged. The drivers also help people with disabilities get into the van. The pilot intends to advance and inform the operation of automated vehicle technology in rural and winter conditions. The pilot program will provide real-world automated vehicle experiences to the local community as a means of educating them about autonomous vehicles, providing accessible mobility for people with transportation challenges, and unearthing the economic development this innovative pilot brings (goMarti.com).

CAV Pilots in New England

Connecticut

CTDOT is a supporting member of the Connected Vehicle Pooled Fund Study. As part of CTDOT's official entry into the SPaT Challenge 2021, CTDOT will be upgrading the non-highway portion of U.S. Route 5/15 (Berlin Turnpike), which by 2023 will allow it to begin testing V2I applications such traffic signal priority, adaptive signal control and automatic traffic signal performance measures (ATSPM). CTDOT and its assembled team, including the Federal Transit Administration (FTA), Center for Transportation and the Environment (CTE), New Flyer Industries, Robotic Research, Inc., University of Connecticut, and the Capital Region Council of Governments (CRCOG), will be working collaboratively to advance a first in the nation, state-of-the-art, pilot project that tests the performance and operation of full size, automated, and battery electric buses (BEB) in revenue service on the CTfastrak BRT over the next few years.

Maine

The State of Maine introduced Bill ME H 135 ("Smart City Technology"), on January 16, 2019, to provide funding through Maine Technology Institute to invest in smart and connected infrastructure, technology, and capacity. Maine DOT is installing dual DSRC/5G roadside units (RSU) at traffic lights – 101 traffic signals in 2020 were installed with funding from Build Grant. The rest of the 804 traffic signals across the state will be upgraded at a rate of 40 /year (mobility report). This effort will yield an estimated 20% reduction in crashes (p12 BUILD Grant application, Appendix B of Mobility Report). Applications of new traffic signals include priority signals for emergency vehicles, freight, and transit. Coordinated Traffic Signal Corridor in Augusta is under development.

Massachusetts

SPaT Challenge participation locations are on Route 9 from Worcester to Wellesley with DSRC V2I devices to improve traffic signal performance (NETC, 2018). The city of Somerville has partnered with WSP and Audi to upgrade traffic signals in Union Square with CV RSUs (WSP USA, 2017). Audi is testing in-vehicle equipment that will use SPaT data from traffic signals to estimate optimal driving approaches to red and green lights.

New Hampshire

NHDOT is supporting the efforts in Dover, NH to implement various signal controller platforms to test V2I strategies (Klasen, 2018). NHDOT is collaborating with neighboring states in a regional approach to CAV planning and deployment through the NE Compass software platform (NHDOT, 2018). NHDOT is a supporting member of the Connected Vehicle Pooled Fund Study.

Rhode Island

The Rhode Island Transportation Innovation Partnership (TRIP) was formed in 2017 (Rhode Island Department of Transportation, 2023). RIDOT launched an Autonomous Shuttle Pilot Project "Little Roady" on May 15, 2019, which provided free transit rides in Providence, RI for one year (Rhode Island Department of Transportation, 2023).

Vermont

There are no known planned or implemented participation in the AASHTO SPaT challenge or other CV pilot, as of June 2023.

Chapter 4 Research and Deployment Issues

Significant barriers to CV & AV applications include the substantial cost of equipment installation and maintenance, differing communication technologies and capabilities of DSRC vs 5G, low percentage of vehicles equipped with CV sensors, and the need for better, less energy-intensive on-board and connected artificial intelligence capabilities. Additionally, there is a need for rules and protocols to safeguard the massive amount of sensitive data generated. Industry and governments need to develop numerous standards to regulate CV & AV applications to ensure safety and reliability. There are some issues that need to be resolved for Avs, such as who bears the legal responsibilities of the AVs, what the course of action will be if the AV controller is hacked, and others.

National Cooperative Highway Research Program (NCHRP)

The **NCHRP Project 20-102** "Impacts of Connected Vehicles and Automated Vehicles on State and Local Transportation Agencies" supports a broad research program for CAVs and has the following goals:

> (1) identify critical issues associated with connected vehicles and automated vehicles that state and local transportation agencies and AASHTO will face,
> (2) conduct research to address those issues, and
> (3) conduct related technology transfer and information exchange activities.

The project contains dozens of sub-projects that each explore specific research and policy goals related to the implementation of V2X across the US. The following past and ongoing NCHRP research projects related to CAV research and implementation are listed below and further summarized in Appendix A.

Projects Underway

0. **NCHRP Project 14-42** Determining the Impact of Connected and Automated Vehicle Technology on State DOT Maintenance Programs
1. **NCHRP Project 20-102(16**) Impacts of Connected, Automated Vehicle Technologies on Traffic Incident Management Response
2. **TCRP B-47** Impact of Transformational Technologies on Underserved Populations
3. **NCHRP 20-102(29)** Incorporating New Mobility Options into Travel Demand Forecasting and Modeling
4. **NCHRP 23-15** Guidance on Risks Related to Emerging and Disruptive Transportation Technologies
5. **NCHRP 20-102(34)** Toolbox for Navigating the Land-Use Impacts of the Automated Vehicle Ecosystem
6. **NCHRP 08-119** Data Integration, Sharing, and Management for Transportation Planning and Traffic Operations
7. **NCHRP Project 20-102 (24)** Infrastructure Enablers for Connected and Automated Vehicles and Shared Mobility--Near-Term and Mid-Term

Completed Projects

0. **NCHRP Project 20-24 (98)** Connected/Automated Vehicle Research Roadmap for AASHTO
1. **NCHRP Project 20-102 (19)** Update AASHTO's Connected Vehicle/Automated Vehicle Research Roadmap
2. **NCHRP Project 20-102(03)** Challenges to CV and AV Application in Truck Freight Operations
3. **NCHRP Project 20-102(08)** Dedicating Lanes for Priority or Exclusive Use by CVs and AVs
4. **NCHRP 03-101** Costs and Benefits of Public-Sector Deployment of Vehicle to Infrastructure Technologies
5. **NCHRP Report 845** Advancing Automated and Connected Vehicles: Policy and Planning Strategies for State and Local Transportation Agencies
6. **NCHRP Project 03-127** Cybersecurity of Traffic Management Systems
7. **NCHRP 20-102(01**) Policy and Planning Actions to Internalize Societal Impacts of CV and AV Systems into Market Decisions

8. **NCHRP Project 20-102(02**) Impacts of Regulations and Policies on CV and AV Technology Introduction in Transit Operations
9. **NCHRP 20-102(06)** Road Markings for Machine Vision
10. **NCHRP 20-102(07)** Implications of Automation for Motor Vehicle Codes
11. **NCHRP 20-102(09)** Updating Regional Transportation Planning and Modeling Tools to Address Impacts of Connected and Automated Vehicles
12. **NCHRP 20-102(11)** Mobility-on-Demand and Automated Driving Systems: A Framework for Public-Sector Assessment.
13. **NCHRP 20-102(12)** Business Models to Facilitate Deployment of CV Infrastructure to Support AV Operations
14. **NCHRP 20-102(15)** Impacts of Connected and Automated Vehicle Technologies on the Highway Infrastructure
15. **NCHRP 17-91** Assessing the Impacts of Automated Driving Systems (ADS) on the Future of Transportation Safety
16. **NCHRP 20-102(19) B** Updated Research Roadmap for NCHRP 20-102, Impacts of Connected Vehicles and Automated Vehicles on State and Local Transportation Agencies
17. **NCHRP 20-102(22)** State and Local Impacts of Automated Freight Transportation Systems
18. **NCHRP 20-102(26)** Dynamic Curbside Management: Keeping Pace with New and Emerging Mobility and Technology in the Public Right of Way
19. **NCHRP 20-102(27)** Realistic Timing Estimates for Automated Vehicle Implementation
20. **NCHRP Project 20-102(28)** Preparing Transportation Agencies for Connected and Automated Vehicles in Work Zones
21. **NCHRP 20-102(28)** Preparing Transportation Agencies for Connected and Automated Vehicles in Work Zones
22. **NCHRP 08-120** Initiating the Systems Engineering Process for Rural Connected Vehicle Corridors

DSRC vs. 5G

There are two competing methods of wirelessly transmitting messages between vehicles and infrastructure. The first, DSRC, uses a dedicated 5.9GHz communication band to relay information and warnings in the system. DSRC has a range of about 1000 meters and a low message transmission latency of 0.02 seconds. One essential component of this system is the standard Basic Safety Message (BSM). DSRC may be better suited for safety applications that require system communication to be low-latency (fast) and reliable (no blackouts).

5G is a new generation of wireless communications networks that provide high-speed and high-volume data transmissions via cellular networks. The 5G network is only available in major urban areas and will take several years to reach rural communities and mountainous locations. Reliance on the private sector may leave many parts of rural states without 5G coverage and will require state agencies to invest and plan for more power and broadband technology in regions with poor internet access and power lines. Further issues with this nascent technology include the reliability and security of data transmission across an ecosystem of vehicles, wireless carriers, and road-side units.

CVs need to be able to communicate with other vehicles and the roadway infrastructure. The NHTSA issued a proposed rulemaking that mandated all new vehicles be equipped with DSRC capabilities by 2023. However, the proposal was abandoned in December 2019 due to the Federal Communications Commission's (FCC) expansion of the 5.9 GHz band (called the safety band by the USDOT) for non-transportation related applications, called Cellular Vehicle-to-Everything (C-V2X) in November 2020. The FCC issued a ruling in favor of opening the band in 2020. The USDOT opposed the ruling because it renders decades of research and millions of funding dollars useless, but the approval of the request for Waiver of 5.9 GHz band ruled to permit initial deployment of C-V2X on April 24, 2023. This decision was welcomed by both the USDOT and the Intelligent Transportation Society of America (ITSA). The European Union (EU) has approved DSRC for vehicle-to-vehicle application and cellular networks for the transfer of data to and from centralized traffic management centers. Japan and South Korea are still considering between the two, and China is not only choosing C-V2X, but is mandating the development of C-V2X on all roads (5G America, 2021).

Some proponents of the system say that there is a need for redundancy of CV/AV systems, and that combining the long-range communications of cellular networks with roadside DSRC can improve the function and possible applications. C-V2X networks and CV applications will need years of research and investment to reach most locations and populated areas. In the meantime, DOTs choosing roadside units that use both C-V2X and DSRC carry additional costs compared to DSRC only units and may need to wait several years for robust applications of C-V2X.

Data Management and Cybersecurity

NCHRP 03-127 documents the existing security standards for CAV technology as well as recommendations for best practices to be used in the U.S. This document helps state and local agencies address cybersecurity risks in current transportation systems and those posed by the integration of Connected and Autonomous Vehicles (CAVs). Southwest Research Institute (SwRI) also researched cybersecurity weakness in TMS which is included in the report. This was also intended to help safeguard the security of over 400,000 Traffic Signal Systems across the United States.

The developing Operational Technology (OT) cybersecurity area has drawn its initial inspiration from the Information Technology (IT) cybersecurity sector. Although OT security focuses on the protection of the device and the users, IT security is primarily concerned with protecting information. The latter attempts to strike a compromise between providing connectivity and control while ensuring physical safety and operations, whereas the former is data centric. Although OT security prioritizes prevention, IT prioritizes incident detection and response. Similar to Industrial Control System (ICS) networks, TMS utilizes a large number of low-technology field sensors. Particularly with the development and use of CAV, these basic field devices are becoming more linked and powerful.

Rural Applications of Connected Autonomous Vehicles

Rural communities have a greater need for new transportation options due to the need to travel longer distances for basic services such as grocery and health care. Public transit and ridesharing services are also more challenging in rural areas due to less frequent trips and longer distances (von Mörner, M. 2019). In addition to often limited transit services in rural areas, traffic safety is lower in rural areas compared to urban areas. In 2020, the risk of dying in a vehicular crash was 62% higher on a rural road compared to an urban road for the same trip length. Major contributing factors include simpler roadway infrastructure, more limited emergency medical services, and risky behaviors like not wearing a seatbelt, impaired driving, speeding, and distracted driving (Governors Highway Safety Association, 2023). Approximately 45% of fatal crashes in the U.S. occurred in rural areas in 2019 where only 19% of the population live (Stewart, 2021).

CAVs that are able to provide new options for the transportation of humans and freight could help address many non-financial challenges to transportation faced in rural areas. Rural transportation can be made safer with the use of some connected vehicles applications such as lane departure warning, lane keeping assist, and lane centering assist. About 52% of all crashes in rural areas in the US were single vehicle crashes, which usually involve vehicles running off the road. This can be reduced with CAV applications that help keep vehicles in their lane. Roadway departure crashes which constitute the majority of crashes in rural areas caused $72 billion in economic costs and $314 billion in comprehensive costs in 2019 to the US economy (Blincoe et al., 2023*)*. About 95% of crashes are associated with human error which can be moderated with CAVs (Brown, 2017; Wu et al., 2021).

Using CAVs will not only increase access to goods and services like education, healthcare, and finance by providing more transportation alternatives for people to travel to urban areas and access these services, it may also lead to increased profitability for firms because of eliminated driver costs and reduced risk of collision (Prevedouros & Alghamdi, 2022). Using CAV for delivery can also allow rural residents, including the elderly or physically limited who do not wish to or are unable to drive, to meet their needs more reliably for goods such as groceries while remaining in their homes. Deliveries can also benefit more from CAVs since the liability and risk in transporting goods is lower than in transporting people. Some transport companies like Airbus, WAYMO, NURO, Volkswagen, and recently Cruise, have successfully deployed autonomous vehicles for delivery purposes which adds to the feasibility of using this technology for delivering goods in rural areas (Pisarov & Mester, 2021). There is also a high potential for using autonomous mobility in last-mile delivery (Yoo & Chankov, 2018).

Airbus released a prototype of an autonomous helicopter in July 2020 named VSR700 which had its first test drive in the south of France. The helicopter designed to operate alongside other shipborne naval assets allows ships to explore their surroundings using sensors from the autonomous helicopter. Waymo produced Waymo One and Waymo Via which refer to driverless cars and trucks respectively. The car, which is primarily tested in Phoenix, Arizona via a mobile application, has over 10 million miles of experience. Volkswagen's autonomous vehicle which is called SEDRIC was first exhibited in 2017 at the Geneva Motor Show. SEDRIC operates on voice commands telling the car where you would like to go, and which route you would like to take. Nuro's self-driving mini car is designed to transport goods from store to buyers and run other errands as the user may want. This fully automated vehicle will primarily help the elderly by reducing the severity of transportation challenges that usually result from driving cessation (Strogatz et al., 2020). Cruise started autonomous rides to its employees in 2017 and currently has close to 400 fleet of autonomous vehicles primarily in San Francisco and Phoenix. Cruise has partnered with Walmart to deliver thousands of Walmart orders in the Phoenix area (Cruise, 2023).

Connected vehicles, but without autonomous driving, can also be useful in reducing secondary crashes in rural areas by alerting upcoming drivers in advance (Yang et al., 2017). According to Tedesco et al. (1994), the chance of having another crash can be six times higher than it would be in the absence of an earlier crash. The likelihood of a secondary crash can rise by 2.8% if the previous crash remains on the road for an extra minute (Owens et al., 2009). The frequency of secondary crashes also increases the danger of crashes for drivers and delays the arrival of incident responders at crash sites. According to estimates from O'Laughlin et al. (2002) and Owens et al. (2010), these secondary crashes contributed to about 20% of all collisions and 18% of fatalities on US freeways. Additionally, according to Sarker et al. (2017), secondary crashes were responsible for up to 50% of the traffic in urban areas. Motorists who receive alerts via CAV applications will be more cautious and approach queues carefully, reducing the risk of secondary crashes.

The drawback to using CAVs in rural areas is the cost of vehicle ownership and the need to upgrade road and communications infrastructure. The average rural household spent about 15% of their income on vehicle purchase and maintenance in 2020 (BLS Consumer Expenditure Survey, 2021). 46% of vehicle expenses were on purchase of vehicles, while gasoline and insurance each accounted for 30% of the operational expenses but considering that autonomous vehicles have higher initial costs (Fagnant & Kockelman, 2015), many rural households might not be able to afford this newer technology. However, different ownership structures for CAVs, such as shared vehicles, may reduce the upfront cost of CAVs. This will also help ensure that the vehicles get regular maintenance and software updates that they require to operate safely. Operating an autonomous transit service can also ensure people in rural areas get access to autonomous vehicles at lower per-user costs. An analysis of the present autonomous vehicle (AV) testing landscape in the United States found that 57 out of 116 (49%) testing initiatives were centered around shuttles. This suggests a greater inclination toward utilizing autonomous vehicles for public transportation services rather than personal vehicles. How this might evolve in a rural setting is not known as most of the applications and research have been focused on urban areas.

Another potential hindrance to the adoption of CAV is the lack of infrastructure in rural areas to support autonomous vehicles. CAVs require properly marked roads and adequate signages to safely operate but many roads in rural America have road markings that are discontinuous and varying making it difficult for CAV applications on such roads. Most rural roads have curvature or steep grades limiting the line of sight of autonomous vehicles. Governments and organizations will have to embark on large-scale upgrades of rural roads before deploying CAVs which can impose a cost burden on rural areas (Yuyan Liu *et al* 2019). One of the key upgrades required to deploy CAVs in rural areas is the use of 6-inch-wide markings instead of 4-inch-wide as part of proposed changes to national standards. Six-inch-wide markings are more visible to machines. A six-inch-wide waterborne marking costs $ 0.15 per foot compared to $0.10 per foot of a 4-inch-wide marking, which results in an extra $264 per mile of single edge (Paul Carlson and Jason Wagner, 2012). The state of Michigan spent $200,000 and $450,000 for 6-inch lane markings and dotted line extensions respectively on its freeways in the year 2021. This was part of a restriping project to enhance machine vision.

Given the significant upgrade in infrastructure that rural communities will need before successfully deploying CAV, various low-cost alternatives have been proposed. Karaaslan et al., (2021) studied how V2I communication to infrastructure can continue in areas with limited wireless communication infrastructure and found that reading vehicular information from smart Road Signs would be a low-cost solution in various V2I applications. This involves using machine-readable traffic signs which can be read by machine vision. Information like MapData, traveler information messages and red-light violation warnings can be sent to vehicles with the help of smart signs. Using smart signs will increase the security of posted information and reduce data breaches since traffic information will be posted and managed by government authorities. Another alternative to deploying AVs on unpaved roads without line markings will be the use of high-precision digital maps and Global Navigation Satellite Systems (GNSS) technology like GPS. A new technology known as Maplite, which is developed by researchers at MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) could potentially allow autonomous vehicles to be deployed onto country roads. These vehicles will use GPS data and sensors to navigate roads instead of relying on 3D maps as is currently used by most autonomous vehicles (MIT News, 2018).

Readiness of rural roads for connected and autonomous vehicles applications

This section examines the readiness of rural roads for the implementation of connected vehicles in these areas. Rural road infrastructure can be divided into physical infrastructure, Traffic control devices, and TSMO and ITS infrastructure. The physical infrastructure has to do with pavements, bridges, and culverts while the traffic control devices have to do with anything that helps regulate traffic on the road, ranging from pavement markings to roadside barriers. The TSMO and ITS infrastructure consider roadway technological equipment that will be used to ensure there is efficient communication within the CAV atmosphere. Two workshops were held on July 17, 2019, and July 18, 2019, in Grand Rapids, MI and Orlando, FL respectively, to assess the infrastructure readiness of various state roads for AV. The responses from the over 100 participants revealed a very low readiness level of infrastructure to support AV.

Incomplete maintenance plans for AV infrastructure makes it difficult to maintain pavement markings. This has resulted in poor roads and pavement conditions that are not conducive for the deployment of CAVs in rural areas. The responses from the various stakeholders also indicate the signage and stripping of many roads are not ready for CAVs to be deployed, given that most basic CAV features like lane departure warnings will require visible markings and signages. The changing technology related to AV infrastructure makes it difficult for Infrastructure Owner-Operators (IOOs) to keep up with the flux in AV technology.

Connected and Autonomous Vehicle Applications to People with Disabilities

An estimated 1.3 billion people, representing 16% of the world's population, experience significant disabilities. People with disabilities find inaccessible and unaffordable transportation 15 times more difficult than those without disabilities (World Health Organization, 2023). In the United States alone, there are over 25 million people who report experiencing travel limitations due to a disability, one-third of whom assert that they do not leave their homes as a result of these limitations (United States Bureau of Transportation Statistics, 2018). Autonomous vehicles can be used to support the transportation needs of people with disabilities and improve their access to goods and services as well as reduce their dependence on other people for travel needs. AVs could allow a 14% increase in travel for people with conditions that prevent them from driving (Harper et al., 2016)

The successful use of autonomous vehicles by people with disabilities will involve not just getting the technology right but making sure it is accepted by the disabled community (Park & Nojoumian, 2022). Kassens-Noor et al., (2021) found that in general, 46% of respondents with special needs would like to ride AVs given the opportunity. In relation to the attitudes of individuals about CAVs, Miller et al., (2022) studied the acceptability of shared autonomous vehicles among people with mobility and communications needs and found that respondents expressed higher levels (mean= 2.98) of positive emotions (Proud, Excited, Interested) than negative emotions (Afraid, Upset, Nervous). A Study in Germany by Gössling et al., (2023) also revealed openness to the use of autonomous transport services for most people aged 65 and above. The openness to use autonomous vehicles was also accompanied by a high willingness to pay for the technology.

To increase the acceptability of AVs by people with disabilities, the design of AVs must address the perceptions, needs, and concerns of people with special needs in relation to AVs. In addition, state laws that discriminate against ownership of AVs on the basis of disability will have to be eliminated or modified and sections of Part 37 of the Americans with Disabilities Act relevant to AV technology will have to be extended (Fink et al., 2021). Policies related to CAVs will have to be drafted with the equity implications of the policy in mind. Access and inclusion policies should be designed to help those who have been historically underserved by transportation infrastructure, such as people with disabilities (Wu et al., 2021). AV policies will also have to include multimodal transportation policies that will enhance and extend access to non-private AV means of transportation such as Shared Autonomous Vehicles (SAV). The acceptability of autonomous vehicles can be stimulated by designing the vehicles to meet the safety and security needs of the public, the need for autonomy by riders, the need for simulation, and the need for meaning (Detjen et al., 2021). The acceptability of CAV can be enhanced by the prioritization and allocation of resources and policies relating to marketing, education, subsidization, and infrastructure development to enhance public acceptance of CAV (Yuen et al., 2020).

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Appendix A NCHRP research projects that are relevant to CAV applications

Project Number	Project Title	Effective Start Date	Completion Date
Completed			
NCHRP 20-24(98)	Connected/Automated Vehicle Research Roadmap for AASHTO	6/25/2014	6/24/2015
NCHRP 20-102(19)	Update AASHTO's Connected Vehicle/Automated Vehicle Research Roadmap	3/13/2018	3/12/2020
NCHRP 20-102(03)	Challenges to CV and AV Application in Truck Freight Operations	10/15/2015	1/31/2017
NCHRP 20-102(08)	Dedicating Lanes for Priority or Exclusive Use by CVs and AVs	8/9/2016	4/15/2018
NCHRP 03-101	Costs and Benefits of Public-Sector Deployment of Vehicle to Infrastructure Technologies	5/6/2011	5/5/2015
NCHRP Report 845	Advancing Automated and Connected Vehicles: Policy and Planning Strategies for State and Local Transportation Agencies		
NCHRP Project 03-127	Cybersecurity of Traffic Management Systems	8/16/2017	10/15/2019
NCHRP 20-102(01)	Policy and Planning Actions to Internalize Societal Impacts of	11/03/2015	5/2/2017

	CV and AV Systems into Market Decisions		
NCHRP 20-102(02)	Impacts of Regulations and Policies on CV and AV Technology Introduction in Transit Operations	1/4/2016	5/15/2017
NCHRP 20-102(06)	Road Markings for Machine Vision	7/13/2016	8/12/2018
NCHRP 20-102(07)	Implications of Automation for Motor Vehicle Codes	11/14/2016	2/13/2018
NCHRP 20-102(09)	Updating Regional Transportation Planning and Modeling Tools to Address Impacts of Connected and Automated Vehicles	9/7/2016	6/30/2018
NCHRP 20-102(11)	Mobility-on-Demand and Automated Driving Systems: A Framework for Public-Sector Assessment	5/17/2018	9/15/2020
NCHRP 20-102(12)	Business Models to Facilitate Deployment of CV Infrastructure to Support AV Operations	7/11/2017	7/15/2020
NCHRP 20-102(15)	Impacts of Connected and Automated Vehicle Technologies on the Highway Infrastructure	5/24/2018	2/23/2020
NCHRP 17-91	Assessing the Impacts of Automated Driving Systems (ADS) on the Future of Transportation Safety	5/24/2019	11/23/2021

NCHRP 20-102(19)B	Updated Research Roadmap for NCHRP 20-102, Impacts of Connected Vehicles and Automated Vehicles on State and Local Transportation Agencies	1/21/2020	6/30/2022
NCHRP 20-102(22)	State and Local Impacts of Automated Freight Transportation Systems	9/16/2019	4/30/2022
NCHRP 20-102(26)	Dynamic Curbside Management: Keeping Pace with New and Emerging Mobility and Technology in the Public Right of Way	2/16/2021	5/15/2022
NCHRP 20-102(27)	Realistic Timing Estimates for Automated Vehicle Implementation	6/29/2021	9/29/2022
NCHRP 20-102(28)	Preparing Transportation Agencies for Connected and Automated Vehicles in Work Zones	10/21/2020	7/21/2022
NCHRP 08-120	Initiating the Systems Engineering Process for Rural Connected Vehicle Corridors	8/1/2019	1/31/2021
Underway			
NCHRP 14-42	Determining the Impact of Connected and Automated Vehicle Technology on State DOT Maintenance Programs	4/8/2019	12/21/2023
NCHRP 20-102(16)	Impacts of Connected, Automated Vehicle Technologies on Traffic Incident Management Response	2/7/2022	9/8/2023

TCRP B-47	Impact of Transformational Technologies on Underserved Populations	11/5/2019	3/31/2023
NCHRP 20-102(29)	Incorporating New Mobility Options into Travel Demand Forecasting and Modeling	8/22/2022	12/22/2023
NCHRP 23-15	Guidance on Risks Related to Emerging and Disruptive Transportation Technologies	10/01/2021	6/30/2023
NCHRP 20-102(34)	Toolbox for Navigating the Land-Use Impacts of the Automated Vehicle Ecosystem	10/26/2022	8/26/2024
NCHRP 08-119	Data Integration, Sharing, and Management for Transportation Planning and Traffic Operations	9/16/2019	5/31/2023