Connected and Autonomous Vehicle Technology: Determining the Impact on State DOT Maintenance Programs (2024)

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 1084

Connected and Autonomous Vehicle Technology

DETERMINING THE IMPACT ON STATE DOT MAINTENANCE PROGRAMS

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2024

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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NCHRP RESEARCH REPORT 1084

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FOREWORD

By Camille Crichton-Sumners
Staff Officer
Transportation Research Board

NCHRP Research Report 1084 provides an overview into how the implementation of connected and autonomous vehicle (CAV) technology will likely impact the state of practice for maintenance programs within state departments of transportation (DOTs). The report will be of interest to those responsible for intelligent transportation systems (ITS), transportation systems management and operations (TSMO) programs, maintenance of transportation assets, and practitioners interested in the deployment of CAV technologies within state DOT rights-of-way.

The transportation industry is examining how roadway appurtenances such as traffic control devices, markings, signals, guardrail, computing systems, communications infrastructure, and other permanent and temporary devices can be used to facilitate the operation of CAVs. The diffusion of CAV technologies impacts state transportation agencies, which often have constrained budgets and workforces. The quick pace of CAV technology obsolescence creates additional challenges as DOTs consider the implications of CAV implementation. In anticipation of CAVs, state DOTs need to identify gaps in knowledge and skills and prepare for the challenges of CAV implementation while maintaining the existing roadway system at an acceptable level of service.

Under NCHRP Project 14-42, Iowa State University was asked to estimate the impact of dynamic CAV technologies on roadway and TSMO asset maintenance programs. Among the findings, state DOTs are in the early stages of CAV technology implementation and lack significant experience with CAV asset maintenance. Additionally, many technologies have not been available for a sufficient amount of time, and as a result, the maintenance needs in many cases are unknown. Training and maintaining a skilled workforce is also challenging. Consequently, in many cases, state DOTs are temporarily contracting related work to third parties and piloting emerging technologies through public-private partnerships (PPP). CAVs will potentially lead to greater interconnectivity between systems, requiring additional skills and maintenance. In particular, significant changes are likely for pavement markings, roadside units, and vehicle-based on-board units as well as ITS and TSMO programs. A systems engineering approach will be beneficial for state DOTs as they consider resource allocation, system interoperability, and the potential for high-risk sudden failure of CAV technology once implemented.

Additional research is needed to develop guidance on proposed standards associated with roadway and TSMO asset maintenance for preventive, reactive, and emerging maintenance needs. *NCHRP Research Report 1084* provides a preliminary look at the state of practice related to CAV implementation and influencing factors for state DOT consideration. Additional deliverables, derived from NCHRP 14-42, are anticipated in the first quarter of 2024.

CONTENTS

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

SUMMARY

Connected and Autonomous Vehicle Technology: Determining the Impact on State DOT Maintenance Programs

Connected and autonomous vehicle (CAV) technologies have the potential to produce a number of safety, mobility, and environmental benefits for the users and operators of the nation's surface transportation system. Due to the rate of turnover in the existing vehicle fleet, however, infrastructure will need to be maintained for both human drivers and CAVs for some time. Additionally, uncertainty regarding CAV technology can make it difficult for agency managers to select and invest in assets supporting CAV deployment and to determine future workforce needs.

The aim of this study was to identify likely infrastructure maintenance needs due to the implementation of CAV technologies, develop guidance on measurable maintenance standards (if feasible) and the resources required to implement those standards, and assess any implications for workforce needs. Available maintenance information for key infrastructure assets identified in Phase I was collected from 39 state responses to a national survey and 18 follow-up interviews with states, municipalities, asset vendors, and maintenance contractors.

Key findings are summarized as follows:

- While no agencies were found to have mature practices or data concerning the maintenance of CAV assets, the information demonstrated that some level of CAV asset maintenance history would be available from most of the responding states within three to five years.
- CAVs are likely to impact a broad array of agency assets, contributing to a system that is more actively managed, interconnected, and in need of enhanced levels of maintenance. Three major asset types will especially impact transportation agencies in the next decade: pavement markings, which are likely to change with proposed updates to the *Manual on Uniform Traffic Control Devices* (MUTCD), roadside units (RSUs), and vehicle-based on-board units (OBUs), which have been supported by federal programs and grant opportunities enabling agencies to invest in these emerging asset types.
- The growth in CAV technology assets represents a natural extension of current intelligent transportation systems (ITS) and transportation systems management and operations (TSMO) programs in terms of the relationship between the needs and activities of field staff and back-office or traffic management center (TMC) staff. Like ITS and TSMO assets, CAV assets most benefit users and agencies when applied through a systems engineering process, may require a strong business case to elicit investment support from agency management, may struggle from a lack of operations and maintenance funding, and may represent a high risk of sudden failure to agencies that are used to investing in pavement and bridge assets.

- During the project, instability in national technology and communication standards led to the functional obsolescence of some of the CAV assets studied. State agencies must therefore be cautious as they consider their future investments in CAV assets; the potential growth in the knowledge, skills, and abilities of the agency's workforce must be balanced against the risk of technology deployment costs with limited public benefit.

Among the most significant findings of the research was that states are acting in anticipation of CAVs, but with significant limitations in the knowledge, skills, and abilities of their workforces. Agencies addressed that gap temporarily by contracting work to third parties such as universities, vendors, consultants, and contractors. Public-private partnership (PPP) relationships also represented an effective method to pilot emerging technologies. However, long-term adverse outcomes could result if the agency deploying the technology does not retain the knowledge gained during deployment.

Because agencies were in earlier stages of implementation than expected during this project, none of the agencies or maintenance contractors interviewed had significant experience with CAV asset maintenance. As a result, maintenance standards and best practices were not sufficiently mature for documentation. Further activities will ideally include the following:

- Identify several states or agencies that have deployed one or more of the assets investigated in this project (such as pavement markings or RSUs) to gather focused performance and cost information. This group of agencies would include those that have conducted widespread implementation of the asset(s) or that have several years of experience with the asset(s). For the agencies, develop a database with a structure that allows performance data to be tracked (historical information if available and an additional two years of data) and develop initial performance and cost estimates using this information.
- Conduct focus groups with asset vendors to develop initial performance estimates. Many agencies indicated that they used vendor contractors for maintenance due to the newness and uncertainty of the technologies. While some limited information was obtained from vendors, contacting vendors was not within the scope of the original work because it was expected that agency implementation of the assets would be more mature.

CHAPTER 1

Introduction

1.1 Background

Connected and autonomous vehicle (CAV) technologies hold the potential to produce a number of safety, mobility, and environmental benefits for the users and operators of the nation's surface transportation system. The benefits of CAVs are expected to be wide-ranging and apply not only to roadway users but also to transportation agencies. These benefits include reduced crashes, improved mobility, lower emissions, and a reduced need to construct roadway infrastructure (fostered by mobility improvements).

However, even with fully autonomous capabilities, the advent of a fully integrated CAV system is not expected to come online for at least 20 years due to turnover in the existing vehicle fleet. As a result, infrastructure will need to be maintained for human drivers as well as CAVs for some time.

Additionally, uncertainty in CAV technology poses challenges. When agencies invest too early in assets for CAV technologies, and then the associated technology changes, many resources spent in acquisition, changes to maintenance practices, and workforce investments may be wasted. Uncertainty about CAV technology can make it difficult for agency managers to select and invest in assets to support CAV deployment and to determine the focus for future workforce needs.

The need for a dual system coupled with uncertainty about the future of CAV technology creates an additional maintenance burden for agencies that already have a constrained workforce and tight budgets. Additionally, changing maintenance needs will likely require a different set of workforce skills than is currently available in most transportation agencies.

1.2 Project Objectives

The objectives of this project were to (1) identify likely maintenance needs due to CAV technologies, (2) develop guidance on measurable standards and resource implications, and (3) assess any workforce implications.

Phase I entailed the following:

- Literature review, which summarized the known timeline for implementation of CAV technology, infrastructure elements that state and local agencies have implemented for CAVs, and any known maintenance or workforce implications (see Chapter 2).
- Survey of agencies to identify state-of-the-practice for the CAV assets that have been implemented (see Chapter 3).
- Stakeholder interviews with 10 agencies to fill in the gaps (see Chapters 4 through 13).

- Summary of available information and identification of gaps to develop performance measures in Phase II (see Chapter 2).
- Recommendations for assets to be included in Phase II (see Chapter 2).

Once Phase I commenced, it was evident that agencies' implementation of CAV technologies was not as mature as expected. The researchers found that the projected move to fully autonomous vehicles was slowed due to technology and policy challenges as well as the COVID-19 pandemic, which altered the focus of many state agencies at least for the short term. As a result, the original objective of developing performance measures for several assets was not feasible. The focus of Phase II became gathering as much maintenance information as was available for the selected assets. Phase II then consisted of the following:

- Conduct additional interviews with agency representatives,
- Conduct interviews with maintenance contractors,
- Collect information from asset vendors,
- Summarize available information about maintenance for each selected asset, and
- Final report and implementation.

1.3 CAV Technologies

A connected vehicle (CV) has internal technologies that allow communications to external systems such as other vehicles or the roadway infrastructure through advanced wireless communication technology (Arseneau 2018). Communication technologies such as connected, dedicated short-range communication (DSRC), cellular, or automotive long-term evolution (LTE) allow vehicles to communicate with the driver, other vehicles [vehicle-to-vehicle (V2V) applications], the roadway [vehicle-to-infrastructure (V2I) applications], or pedestrians (Flockett 2017).

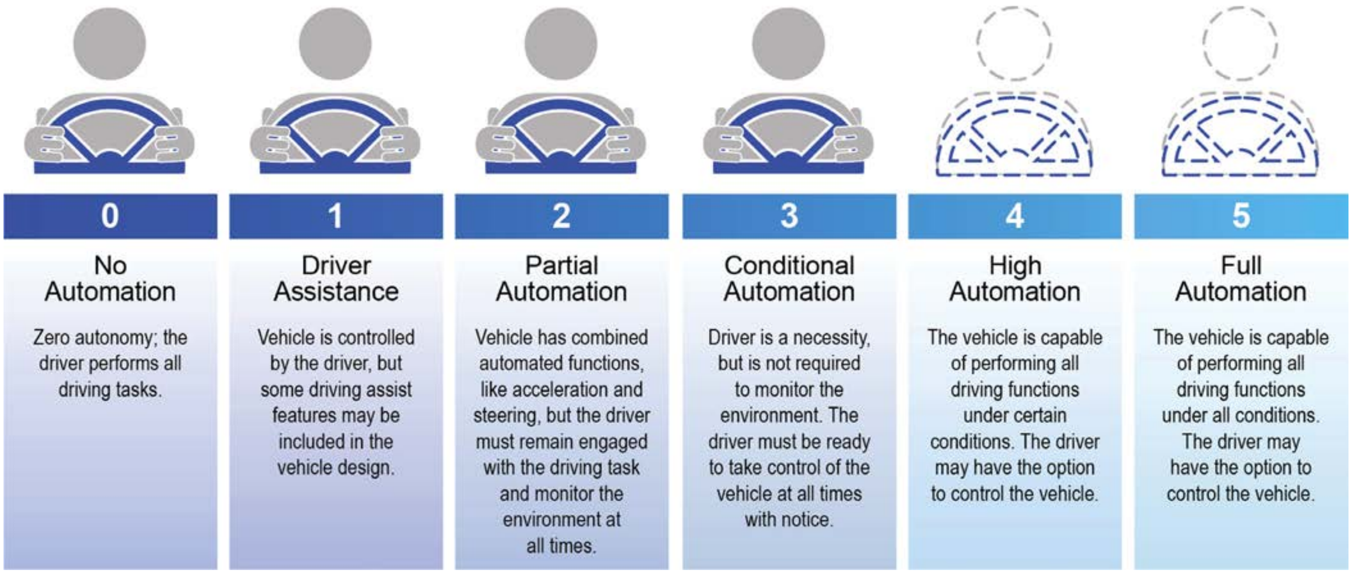
Currently, V2V applications primarily focus on crash avoidance while V2I applications focus on telecommunications, safety, mobility, or the environment. None of the current CV technology applications involve taking control of the vehicle; they simply provide alerts.

In general, autonomous vehicles (AVs) are able to conduct driving tasks either with or without human intervention (Arseneau 2018). They are also referred to as self-driving vehicles. AV technology provides a portion of, or all control needed from a human driver (Atkins 2017). For instance, adaptive cruise control AVs rely on sensors and equipment within the vehicle to gather and process information about the roadway environment, such as high-performance global positioning system (GPS) or camera data. AVs do not require CV technology, since, by definition, they can independently navigate the roadway (Murtha et al. 2015).

The levels of automation, as defined by SAE International (formerly named the Society of Automotive Engineers) and adopted by the National Highway Traffic Safety Administration (NHTSA) (CAAT 2018), are shown in Figure 1-1.

The level of automation may vary from minor driver assistance (Level 1) to full automation (Level 5), which does not require an intervention from a human driver. The most common current AV technologies are driver assistance technologies (e.g., adaptive cruise control or collision avoidance systems such as back up assist).

Although there are distinctions between connected and autonomous technologies, significant overlaps exist, thus making it difficult to differentiate infrastructure elements that are specific to one or the other. Additionally, the direction the two technologies will ultimately take is still largely unknown, making it difficult to project whether one will be dominant or the two will ultimately be intertwined into one system. As a result, the term CAV is used for the remainder of this report unless clarification is needed about a specific technology.



Source: NHTSA 2017.

Figure 1-1. SAE levels of automation.

1.4 Likely Scenarios and Expected Timeline for CAV Implementation

The expected timeline for CAVs is necessary since determination of maintenance needs for the short, medium, and long term depend on which CAV technologies and implementation scenarios are likely to be adopted and how quickly those technologies or scenarios are adopted.

Numerous reports have outlined an expected timeline for the adoption of different levels of CAV technology based on a number of factors, such as projections of available technologies, expectations of driver acceptance, fleet turnover, and readiness of the roadway infrastructure. In general, more is unknown than known about the likely implementation scenario and timeline for full automation, with estimates ranging from a few years to 40 years (Johnson 2017; Isaac 2016).

For instance, the Iowa Department of Transportation (DOT) conducted an analysis of different adoption scenarios and projected that 20% of the fleet operating on the Interstate system will be CAVs (Level 3 or above) by 2025, assuming an aggressive adoption scenario, or by 2040, assuming a conservative adoption scenario (Iowa DOT 2017).

Car manufacturers initially expected to have fully autonomous vehicles by 2020. For instance, Tesla, Inc. projected they would have hundreds of thousands of vehicles operate in "full self-driving mode" through an over-the-air update by 2020 (Siddiqui 2019). Some manufacturers predicted 2025 for full automation (Jiao 2019; Kolodny and Schoolov 2019).

However, more recent indications suggest manufacturers are backing away from earlier predictions about when fully autonomous vehicles will be on the road. The main hurdle is the complexity of driving environments, with additional testing being conducted by manufacturers on complex situations, such as unconventional roads, facilities with high pedestrian volumes, and construction. Policy and legal issues also complicate the move to full autonomy.

Self-driving software is based on machine learning algorithms and deep learning neural networks, which use training from millions of videos and images to recognize and classify objects. More training data allows the algorithms to improve at responding to different scenarios

(Dia 2021). Although artificial intelligence (AI) systems have trained with enormous amounts of data to recognize and respond to traffic situations, an unlimited number of scenarios exist that systems may not be able to detect or recognize. Additionally, a much higher level of safety is needed than with human drivers. As a result, developing technology to enable full autonomy in the near future is unlikely without major breakthroughs in AI (Mims 2021).

Several experts have suggested that deployment will be gradual, with more automated driver assistance technologies being incorporated. Most manufacturers offer Level 1 automation, such as adaptive cruise control, lane keep assist, or blind-spot monitoring, and Level 2 automation (such as Tesla Autopilot and GM Supercruise) (Thompson 2017).

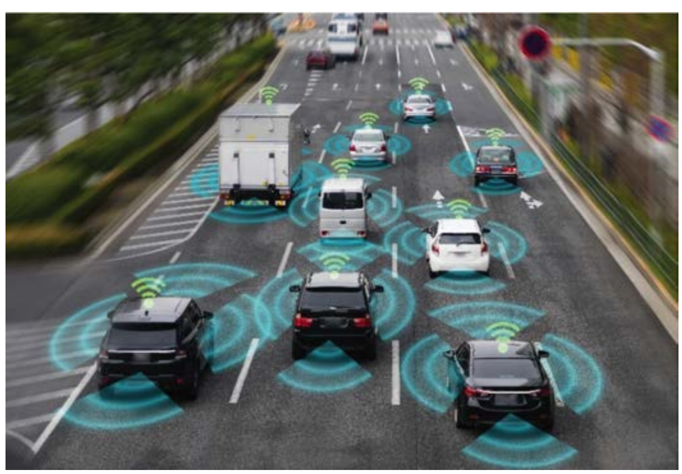
Consensus is growing among automated driving system (ADS) developers, which suggests that in the near- to mid-term, fully automated operations will be feasible only within a narrow set of conditions such as good weather, ideal lighting, well-defined traffic conditions, and locations that have been mapped with high precision. This includes dedicated lanes to minimize interaction between CAVs and human-driven vehicles in order to take advantage of connected technology.

The first wave of Level 4 vehicles is expected to be in corridors where supporting infrastructure technologies, such as high-definition and inventory mapping, have taken place (National Safety Council 2018) (see Figure 1-2).

Until full fleet penetration is achieved, the use of fully autonomous vehicles may require dedicated lanes or separation from other traffic, or only be allowed to operate on certain roads (Johnson 2017; Litman 2018).

Full automation is initially most likely for specialized uses such as local package delivery, long-haul trucking, and passenger ride hailing in limited locations.

Truck platooning is one CV application that several states have addressed laws to allow (see Figure 1-3). Minnesota Department of Transportation (MnDOT), for instance, allows platoons of up to three trucks (MnDOT n.d.). Under normal driving conditions, trucks ideally follow other vehicles at 500 feet or more to allow the driver time to perceive and react, and to account for brake lag and differences in braking power. The V2V System communicates with vehicles to align speed, acceleration, and braking so that vehicles can travel closer together (i.e., 30 to 50 feet), since the vehicles themselves are able to communicate, thus reducing perception/reaction



Source: metamorworks/Shutterstock.com.

Figure 1-2. Fully autonomous vehicle corridor.

Source: FHWA 2021a.

Figure 1-3. Truck platooning.

time and brake lag between vehicles. Fuel efficiency is the primary driver for trucking companies to adopt platooning (Carpenter 2018).

1.5 Summary of Findings

Through this research, a wide variety of assets implemented by states to accommodate CAVs have been identified and cataloged. Unfortunately, much less has been identified offering quantifiable results on the maintenance of CAV assets or assets with the increased burden of maintenance due to CAVs. The findings herein synthesize the deployments that have occurred, the lessons learned that piloting agencies have shared, and the concepts behind a greater impact on agency resources when running CAV-supportive transportation systems.

Stakeholders from the maintenance community will be able to leverage this report to plan for nationwide changes to uniform traffic control devices—primarily lane striping—that are in part driven by vehicle machine vision from CAVs. Agency operations and research departments can review this report to support planning of agency resources in pilot deployments of roadside units (RSUs) and on-board units (OBUs). Pilot technology deployment guidance specifically covers the importance of back-office operation staff, field staff with enhanced skills in electrical and computer troubleshooting, fleet operations staff, and in many cases, software and hardware engineers from third-party partners (e.g., universities, technology vendors, consultants, contractors).

1.6 Overview of Report

This report is organized in the following manner:

- Chapter 2 summarizes how information in subsequent sections of the report was gathered, which includes a literature review, survey of agencies, how assets were selected for further evaluation, and agency interviews.
- Chapter 3 includes responses from the survey of agencies to identify state-of-the-practice for the CAV assets that have been implemented.
- Chapters 4 through 13 describe the information gathered for individual assets, which includes a description of the asset, examples of applications, identified maintenance needs, standards or best practices in maintenance, and workforce needs specific to that asset.
- Chapter 14 discusses resource gaps that were identified during the course of the project, which are necessary to fully assess the maintenance impacts of CAV assets.
- Chapter 15 describes workforce implications for CAVs.
- Chapter 16 includes a summary and plans for implementation.

CHAPTER 2

Information Gathering

One of the project objectives was to identify which infrastructure assets had been implemented for connected and autonomous vehicles (CAVs), summarize maintenance needs for those assets, and identify likely workforce needs to maintain these assets. Several different methods were used to gather this information. A high-level summary is provided below in order to provide context for subsequent chapters. The specific information that was gathered was incorporated into the corresponding chapters.

2.1 Description of Literature Review

The first method to gather information was a comprehensive literature review. This included a Google search, Transportation Research International Documentation (TRID) search, engineering database search, gathering of relevant papers at conferences, and review of current and completed NCHRP projects. This yielded information about known infrastructure assets relevant to CAVs, including several that were smart city or smart infrastructure assets (e.g., smart parking). Information was also gathered about where specific assets had been applied, types of technology available, some examples of workforce needs, and limited information about maintenance.

A number of CAV-related assets were identified. Some of the assets identified are not specifically CAV assets. For instance, smart parking technology can interface with CAVs but is also utilized for traditional vehicles. As a result, assets included those that are needed only for CAVs as well as assets that are currently or likely to be used by CAVs and may require different standards of maintenance. For instance, pavement markings are a common asset but may need to be maintained to a higher standard to accommodate CAVs. Assets identified included the following:

- Vehicle-based on-board units (OBUs),
- Roadside units (RSUs),
- Dedicated short-range communication (DSRC),
- Other communications assets (e.g., fiber optics),
- Pavement markings,
- Cameras,
- Traffic signals,
- Machine-readable signs,
- Road weather information systems (RWISs),
- Data/digital infrastructure,
- Electric vehicle infrastructure,
- Smart intersections,

- Smart pavement,
- Smart parking,
- Pedestrian detection systems,
- Smart lighting,
- Bridge freeze warning systems,
- Wrong way driving detection,
- Red light running detection, and
- Curve warning systems.

2.2 Description of Survey

The next information gathering task was to survey state and local agencies. Survey questions were developed by the team and reviewed by the NCHRP Project 14-42 panel. The survey was coded so it could be accessed online. The survey was circulated to various national committees that were likely to have state, county, or local agency members in the areas of maintenance operations or design [e.g., the American Association of State Highway and Transportation Officials (AASHTO) Maintenance Committee]. The team also identified and sent the survey to contacts with cities that had implemented or were considering some type of smart city technology.

The survey asked which assets agencies were currently using or planned to use in the near future, whether additional maintenance was needed, and how maintenance was impacting their workforce. Since a wide range of CAV-relevant assets were identified in the literature review, the survey only focused on items one to 11 in the above list.

A total of 53 participants from 39 state DOTs completed the questionnaire. No counties or smart cities responded. A summary of survey results is provided in Chapter 3.

The survey was conducted in the fall of 2019 and survey responses reflect agency thinking at that time. The COVID-19 pandemic began in early 2020, which significantly impacted many immediate- and medium-term agency priorities.

2.3 Agency Interviews

Once survey responses were tabulated, the most common assets were selected based on the survey responses. Those which appeared to have been implemented by multiple agencies and were the most likely to yield results were identified. Agencies that participated in the survey and appeared to be the most mature in their application of one or more of the CAV assets listed below were selected for more targeted interviews. The list of potential agencies and most common infrastructure-related CAV assets were presented to and approved by the NCHRP 14-42 panel. The assets selected for further investigation included the following:

- OBUs,
- RSUs,
- DSRC,
- Pavement markings,
- Cameras,
- Signal control,
- Machine-readable signs,
- RWISs, and
- Data/digital infrastructure.

Thirteen states were identified, and interviews were requested. Each interview was planned for no more than 90 minutes to encourage participation and minimize the burden for agencies. As a result, only two to four assets from the list above were selected to be discussed per interview. Assets for discussion were specific to each agency based on which assets they indicated had been implemented in their state. An attempt was made to ensure representation across assets. The assets of interest were described in the communication so that each agency could invite the appropriate people to the discussion. Agencies were contacted through email, and several follow-up emails and calls were made when agencies did not respond. Ultimately, virtual interviews could only be scheduled with 10 of those contacted. Virtual interviews were held due to the COVID-19 pandemic.

Targeted interviews were conducted with the following agencies on the dates indicated:

- California Department of Transportation (Caltrans) (July 1, 2020).
- Colorado DOT (CDOT) (July 15, 2020).
- Florida DOT (FDOT) (July 10, 2020).
- Georgia DOT (GDOT) (July 8, 2020).
- Kentucky Transportation Cabinet (KYTC) (July 23, 2020).
- Michigan DOT (MDOT) (August 23, 2020).
- Minnesota DOT (MnDOT) (July 13, 2020).
- Nevada DOT (NDOT) (June 3, 2020).
- New Hampshire DOT (NHDOT) (August 24, 2020).
- Washington State DOT (WSDOT) (August 21, 2020).

All DOT interviews were conducted during the COVID-19 pandemic. As a result, some priorities had changed due to other, more pressing issues. This may have impacted short- and medium-term priorities for these agencies.

2.4 Selection of Assets for Further Evaluation

Following the agency interviews, information from the literature review, survey, and stakeholder interviews was organized by asset. Additional information needed was also summarized and gaps in the knowledge base about best practices for maintaining each asset were summarized. A summary report was prepared, and the team met with the NCHRP panel. One of the initial conclusions from Phase I was that none of the assets have been in place long enough for agencies to have developed performance measures or maintenance practices. As a result, the focus became gathering as much information as was available about operations and maintenance that would be useful to agencies.

In consultation with the NCHRP panel, it was determined that efforts for Phase II would focus on OBUs, RSUs/DSRC, and pavement markings. As a result, additional interviews with agencies and maintenance vendors were conducted, and all information about maintenance available for each of the three assets is detailed in Chapters 4 through 6.

It was also agreed that if any new information was available for maintenance of cameras, signing, traffic signal controllers, or RWISs specific to CAVs, the researchers would include it. These assets are described in Chapters 7 through 10, and typically include information from the literature review, survey, and targeted interviews. Information that was initially gathered during Phase I was summarized for an additional three assets (additional communications capacity, machine-readable signs, and digital infrastructure) in Chapters 11 through 13. No additional information was gathered for these three assets, so the provided information is limited to what was available in the initial literature reviews.

The next step in gathering information was to contact a few additional agencies identified as being more mature users of CAV assets. Virtual interviews were set up with the following, and each interview focused on the assets that had been identified as being utilized by that agency:

- Las Vegas, Nevada (October 27, 2021) and primary focus was RSUs.
- Tampa Hillsborough Expressway Authority (THEA), Florida (November 23, 2021) and primary focus was RSUs and OBUs.
- Columbus, Ohio (September 21, 2021) and primary focus was RSUs.

2.5 Vendor Interviews

The team also identified the primary vendors for several of the assets and sent email inquiries to ask about vendor recommended maintenance.

Five vendors were identified as having a camera system that included CAV applications (e.g., pedestrian/bike detection). Each vendor was contacted and asked about life cycle, regular maintenance, and whether any additional maintenance was suggested for applications specific to pedestrian or bicycle detection.

Four of these vendors responded and provided information about suggested maintenance and life cycles. One vendor that responded had a thermal camera system, which targeted a different intended application, so this information was not included. As a result, information was summarized for three vendors and is included in Chapter 7.

Seven vendors were identified who market OBUs and/or RSUs. Each was contacted and asked for general information about life cycle and regular maintenance. Two vendors responded. One provided information through an email exchange and a virtual interview was held with the second. The vendor contacts included the following:

- Cohda Wireless (October 12, 2021, email exchange) and primary focus was OBUs.
- Kapsch TrafficCom (November 16, 2021) and primary focus was RSUs.

Finally, the team identified private highway maintenance contractors, thinking they may have some experience maintaining CAV assets. Four contractors were identified as having large-scale operations in multiple states. One went out of business just as the interviews were being set up. Virtual interviews were set up with the remaining three:

- Ferrovial Services (January 17, 2022).
- Roy Jorgensen Associates, Inc. (January 18, 2022).
- Louis Berger International (January 18, 2022).

None of the three maintenance contractors were actively conducting maintenance for any CAV assets. They noted there has been minimal impact due to CAVs. In general, there are discussions with their clients about CAVs, but agencies have not yet formally incorporated maintenance into their programs. No formal specifications exist due to a number of uncertainties. Additionally, they noted most CAV assets in place were installed as pilots that had not planned for long-term maintenance. The contractors did have experience with other assets that had relevance for CAV assets, such as maintenance of intelligent transportation system (ITS) assets, so this information is captured in the corresponding chapter for that asset as appropriate.

All three of the vendors had valuable insight into future workforce needs for CAV assets based on their work with ITS infrastructure items. Their insights are incorporated into Chapter 15, which discusses workforce needs.

2.6 Summary of Information Gathering and General Insights

General insights about maintenance of CAV assets based on the targeted interviews with state DOTs, cities, and maintenance vendors included the following:

- Many agencies that have installed CAV assets are relying on vendors for maintenance and maintenance support.
- Maintaining roadway assets that support the safe deployment of CAVs is likely to increase current maintenance needs—and increase reliance on technology vendors.
- Information from the original equipment manufacturers (OEMs) about the direction CAVs are taking or how CAVs function has not been transparent or consistent, making it difficult to invest in assets or set performance metrics.
- Many technology standards (e.g., DSRC) are changing rapidly, making it difficult to focus investments. Still, pilots with well-qualified vendors can provide agency staff with development benefits and localized safety and mobility benefits. Scaling pilots to a full agency system at this point presents many technology obsolescence risks.
- Enabling transportation systems management and operations (TSMO) investments (e.g., advance transportation controllers for traffic signals) builds agency capacity for active monitoring and operations that the connected vehicle and connected infrastructure concepts rely upon.
- Agencies are interested in additional guidance for pavement markings and signing standards that support CAV deployment.
- Funding is often available for purchase of CAV assets (e.g., RSUs) or implementation of pilots; however, costs for installation and maintenance are not programmed in, which can make it difficult to maintain these assets longer term.
- A general consensus is that technology is changing so rapidly for some CAV assets (e.g., RSUs, DSRC) that agencies may be more likely to just replace assets rather than maintain them.
- Agencies discussed the need for a different set of work skills to address the maintenance issues resulting from the CAV assets.
- Not enough time has elapsed since installing CAV assets to allow the agencies to develop or monitor performance metrics.

Vendors were asked about the priorities or standards they would look for in maintainability of CAV assets. Interchangeability was listed as one recommendation. Purchase of initial assets are usually made from one source, because when different companies create assets that require components unique to that vendor, it becomes difficult for a maintenance contractor or agency to maintain later when there is only one source for a part. As a result, it was noted that having multiple vendors supplying a product/replacement part that can be interchanged is important. In addition to having multiple vendors, the supply chain needs to be set up so that contractors and agencies have ready access to the devices.

Maintenance contractors also noted that including those who maintain the systems in the conversation as new components are built would facilitate creation of assets that can be more easily maintained. They felt some expertise could be passed along to the OEMs. As a result, another recommendation in maintainability of CAV assets is the ability to transfer this expertise. For instance, it was noted that natural elements are brutal on all devices. Many pilots have failed because components were designed in a laboratory that didn't account for the elements. In general, devices need to be properly protected from the elements. Durability of the components is something else that has an impact on maintenance. As an example, many electrical components need to be able to survive a lightning strike. Durability is important so agencies don't have to keep fixing equipment.

Another recommendation was having a warranty as newer assets are added to the system. A warranty ensures the vendor is responsible for some period given that challenges are likely to arise in the early stages of deployment. A minimum warranty of a year was suggested to allow the asset to be exposed to a one-year cycle of the elements.

Operators also indicated a need to make sure the agency owns and houses the data. This allows maintenance operators or agency maintenance staff to directly access the data rather than having to go through a third party.

It was also noted that new technologies create an unknown scenario. Frequency and type of maintenance in these cases are not known, so to some extent, those responsible for maintenance adapt strategies to allocate and program resources.

CHAPTER 3

Survey of Agencies

State and local agencies were surveyed to determine which connected and autonomous vehicle (CAV)-related infrastructure assets had been implemented and their impact on maintenance practices. A survey was developed and circulated to various national committees as described in Chapter 2. A total of 53 participants from 39 state departments of transportation (DOTs), as shown in Figure 3-1, completed the questionnaire.

No counties or smart cities responded. The survey was conducted in the fall of 2019, and survey responses reflect agency thinking at that time. Subsequently, the COVID-19 pandemic began in early 2020, which significantly impacted many immediate agency priorities.

A summary of survey responses is provided in the sections that follow. Additionally, relevant information for many of the assets is discussed in the corresponding chapters (Chapters 4 through 13) that follow.

The questionnaire was structured in such a way as to differentiate between the changes that have already been made and changes that are planned for the near future (within the next 3 years). Questions were placed in four categories, each containing "principal questions," which were as follows:

- **Changes in Assets to Accommodate CAVs:**
  - What changes to physical infrastructure assets has your agency made to support CAVs?
  - What changes to physical infrastructure assets does your agency plan to make in the next 3 years?
  - How has asset data collection changed in creating digital infrastructure in your agency to accommodate CAVs?
- **Changes in Maintenance Practices to Accommodate CAVs:**
  - What changes in existing maintenance practices have been made in your agency to accommodate CAVs? For instance, more frequent winter maintenance to ensure lane lines are visible for CAVs?
  - Does your agency have any examples of successful maintenance practices to support CAVs?
  - Does your agency have any additional lessons learned about asset maintenance for CAVs?
- **Change in Maintenance Workforce Needs to Accommodate CAVs:**
  - How have CAV maintenance activities impacted your agency's workforce needs?
- **General Maintenance Needs to Accommodate CAVs:**
  - Has the adoption of CAVs impacted other maintenance needs?
  - Are you concerned about other aspects of maintenance related to CAV activities?
  - Any general concerns regarding CAV activities related to maintenance?

Whenever a participant's answers to the "principal questions" indicated that their agency had made any changes to assets and/or practices, the questionnaire was tailored to then present a set of "sub-questions" to ask for details about the changes.

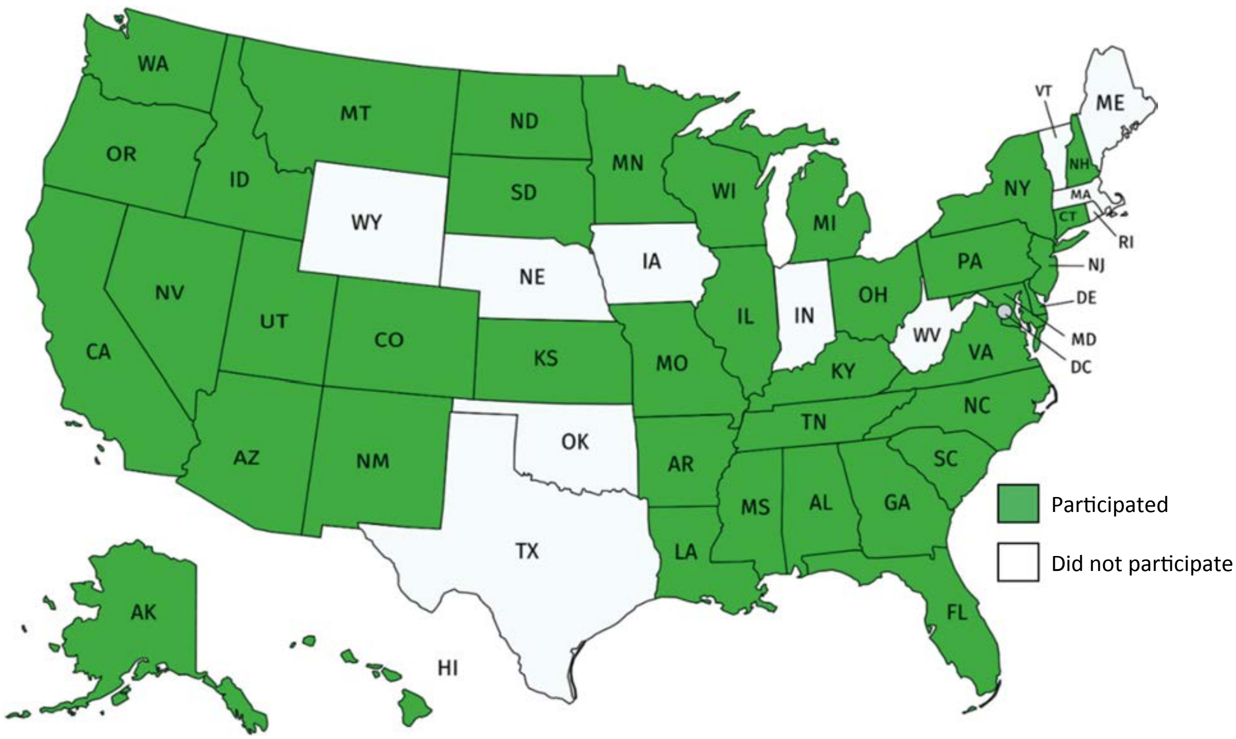


Figure 3-1. States participating in survey.

In several cases, more than one participant within an agency responded. Survey responses were combined for each state. For instance, if one participant indicated they had increased dedicated short-range communication (DSRC) and another indicated increased roadside units (RSUs), both assets would be included in their aggregated response.

3.1 Most Current Changes to Physical Assets

The first question asked for contact information. The second question asked about physical changes to assets.

Question 2: What changes to physical infrastructure assets has your agency made to support CAVs?

It was assumed that changes to physical assets included (1) adding, (2) increasing, (3) modifying, or (4) removing assets, and participants were asked to describe their agency's activities accordingly. Physical assets were categorized as the following:

- Communication and/or data:
  - DSRC RSUs,
  - Cellular RSUs,
  - Additional communication capacity,
  - Data service infrastructure, and
  - Others specified by participant.
- Intersection:
  - Traffic signal control,
  - Cameras,
  - Image processing units, and
  - Others specified by participant.

- Pavement marking and/or signing:
  - Durable pavement markings,
  - High-contrast pavement markings,
  - Pavement marking practices,
  - Nonreflective round raised pavement markers,
  - Signs, and
  - Others specified by participant.
- General Assets:
  - Road weather information system (RWIS),
  - Global positioning system (GPS) receiver/antenna reference points,
  - Electric vehicle (EV) infrastructure, and
  - Others specified by participant.

A total of 21 of the 39 participating state DOTs (46%) had changed physical assets to support CAVs, while 18 of the agencies had not changed any physical assets in response to CAVs. Figure 3-2 illustrates the changes that were made by the 21 agencies.

More than one response could be reported by an agency. For instance, an agency could have both added some assets and removed others. The most common change was adding new assets (49%), followed by increasing (44%), modifying (31%), and removing (5%) existing assets. Two states noted removing nonreflective round raised pavement markers (also called Botts' dots).

Figure 3-3 illustrates changes by asset category.

As shown, 38% of agencies added communication or data assets or both, 26% increased communication assets, 10% modified communication assets, and no agencies removed communication assets. As shown, 15% added intersection-related assets, 18% added pavement marking or signing assets or both, and 21% added other general assets.

Table 3-1 provides a summary of assets that agencies have changed by number of states.

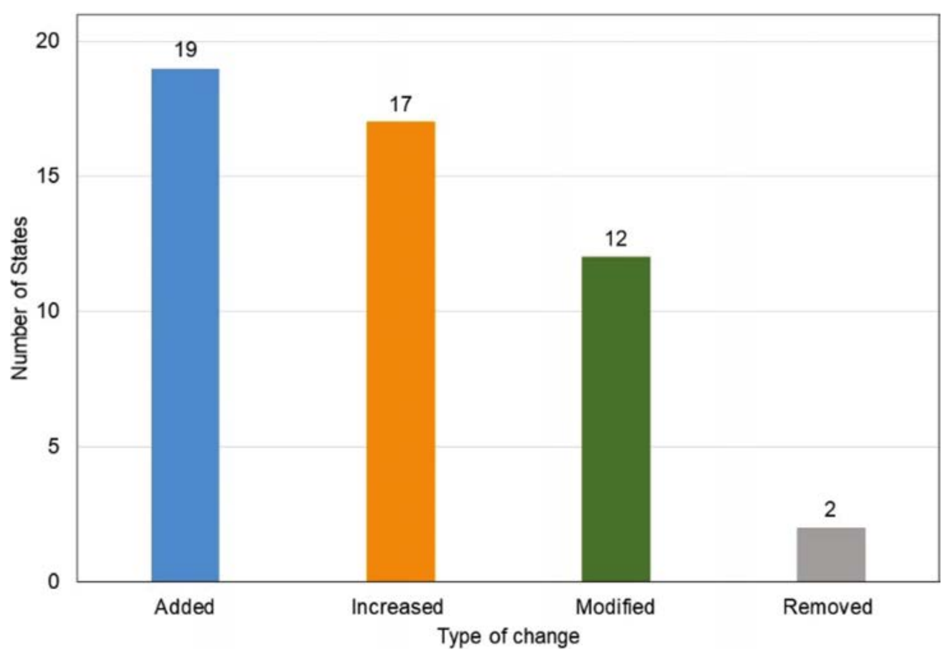


Figure 3-2. Current changes in physical assets by number of states.

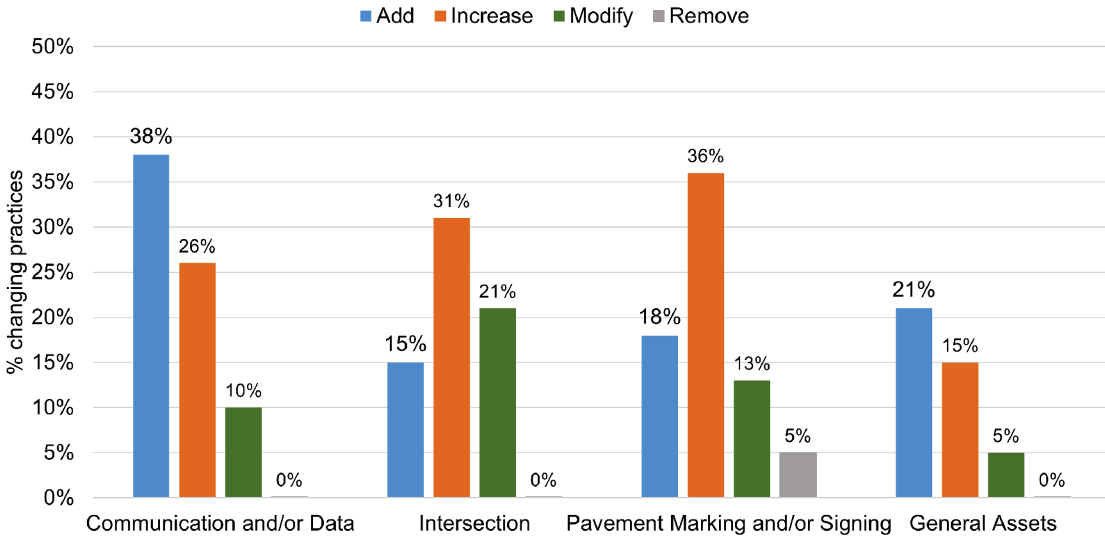


Figure 3-3. Current changes in categories of assets.

Table 3-1. Current changes made by number of states.

Change	Communication and/or Data	Intersections	Pavement Marking and/or Signing	General Assets
Added	15	6	7	8
Increased	10	12	14	6
Modified	4	8	5	2
Removed	0	0	2	0

As shown, adding communication- and/or data-related assets constituted the largest portion of changes made to physical assets by DOTs (in 15 states). DOTs increased assets related to pavement marking and/or signing, followed by intersections, and then communication or data or both.

Table 3-2 shows how different assets related to communication, data, or both have been changed by state DOTs to support CAVs.

As shown, the largest number of changes reported by states was the addition of DSRC RSUs (in 14 states), followed by increasing communication capacity (in seven states), and then by adding cellular RSUs and data service infrastructure (in six states). As expected, none of the responding DOTs reported removing any assets in this category. Responses in the "Other" category included adding onboard equipment (OBE) to state vehicles (in one state) and modifying signal controllers for advanced features (in one state).

Table 3-2. Changes made to communication- or data-related assets by number of states.

Change	DSRC RSU	Cellular RSU	Communication Capacity	Data Service Infrastructure	Other
Added	14	6	4	6	1
Increased	3	1	7	5	0
Modified	0	2	1	2	1
Removed	0	0	0	0	0

Table 3-3. Changes made to intersection-related assets by number of states.

Change	Traffic Signal Control	Cameras	Image Processing Units	Other
Added	5	0	1	1
Increased	6	9	2	0
Modified	6	2	0	0
Removed	0	0	0	0

Table 3-4. Changes made to pavement markings and signing by number of states.

Change	Durable Pavement Marking	High-Contrast Pavement Marking	Pavement Marking Practices	Nonreflective Round Raised Pavement Markers	Signs
Added	1	3	4	N/A	1
Increased	8	9	6	1	6
Modified	0	0	2	0	4
Removed	0	0	0	2	0

Table 3-5. Changes made to general assets by number of states.

Change	RWIS	GPS Receiver/ Antenna Reference Point	EV Infrastructure	Other
Added	3	1	5	0
Increased	4	0	4	0
Modified	2	1	0	0
Removed	0	0	0	0

Types of changes for intersection-related assets are shown in Table 3-3.

The most common change to this category of assets was increasing the number of cameras at intersections (in nine states). The second most common asset change at intersections was traffic signal controllers. Six states noted they had added and six had modified traffic signal control. In the "Other" category, one Linux board computer was added to the cabinet to process data and run applications and for added Power over Ethernet (PoE) capabilities. None of the participating DOTs removed any assets related to intersections.

Table 3-4 shows different types of changes for pavement markings and signing-related assets.

As noted, the most common change was increasing high-contrast pavement markings (in nine states), very closely followed by increasing durable pavement markings (in eight states).

The most common change for general assets, as shown in Table 3-5, was adding EV infrastructure in five states, followed by increasing RWIS and EV infrastructure, both in four states. None of the participants reported removing any general assets to support CAVs.

3.2 Changes to Physical Infrastructure in the Next 3 Years

The third question asked agencies about upcoming changes to physical assets.

Question 3: What changes to physical infrastructure assets does your agency plan to make in the next 3 years?

The majority of agencies (30 of 39 or 77%) indicated that they plan to make changes to their physical assets to support CAVs in the next 3 years. Only nine agencies responded that they do not have any plans to make changes.

Figure 3-4 shows the number of states that plan to add, increase, modify, or remove physical assets in the next 3 years.

Of the agencies that responded to the survey, 64% indicated that they were planning to add new assets, while 62% planned to increase existing assets, 41% planned to modify existing assets, and 8% planned to remove some type of asset. Figure 3-5 provides a summary of responses by asset category.

Three states planned to remove signs, one state planned to remove nonreflective round raised pavement markers (e.g., Botts' dots), and one state planned to remove RWIS units. Agencies may have provided more than one answer for this and subsequent questions in this category. For instance, an agency could plan to both add a new asset and plan to modify another asset.

Table 3-6 provides the distribution of the types of planned changes by category of physical asset.

Similar to changes already made by agencies, the most common planned change was adding communication- or data-related assets or both, with 18 agencies planning to add, 15 planning to increase, and six planning to modify. As shown, agencies planned to make changes to intersection assets with the majority planning to increase (14 DOTs) or modify (13 DOTs) existing assets. A total of 16 agencies planned to increase pavement marking or signing assets or both, while 11 planned to add them. Finally, 13 agencies planned to add general assets and 13 planned to increase existing general assets.

Table 3-7 shows the types of planned changes for different communication- or data-related assets in the next 3 years.

As noted, the most frequently planned change was increasing communication capacity (14 DOTs). The next two most frequent responses included increasing the data service infrastructure (10 DOTs) and adding DSRC RSUs (10 DOTs). None of the responding DOTs planned

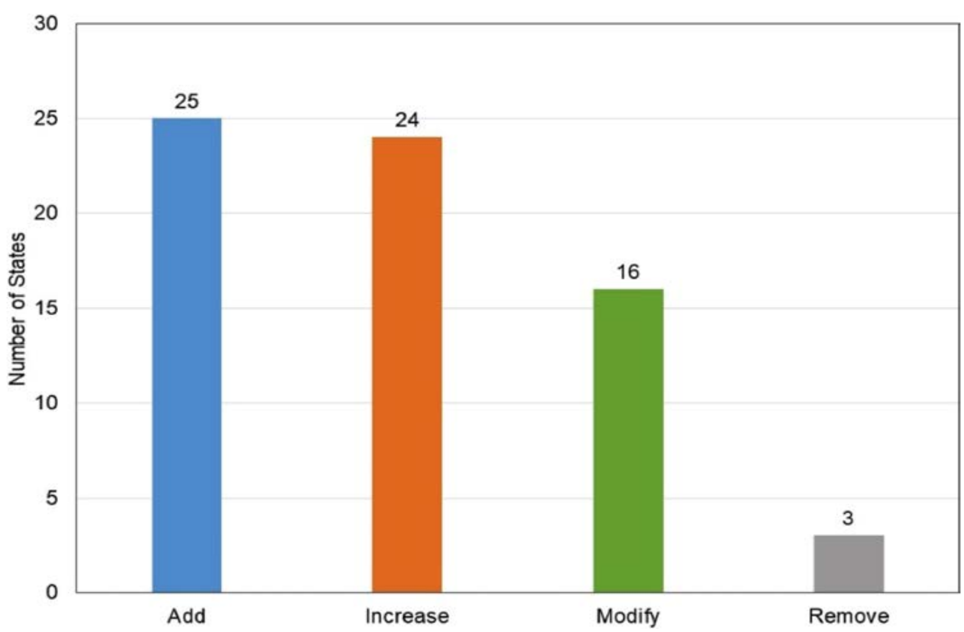


Figure 3-4. Planned changes in physical assets by number of states.

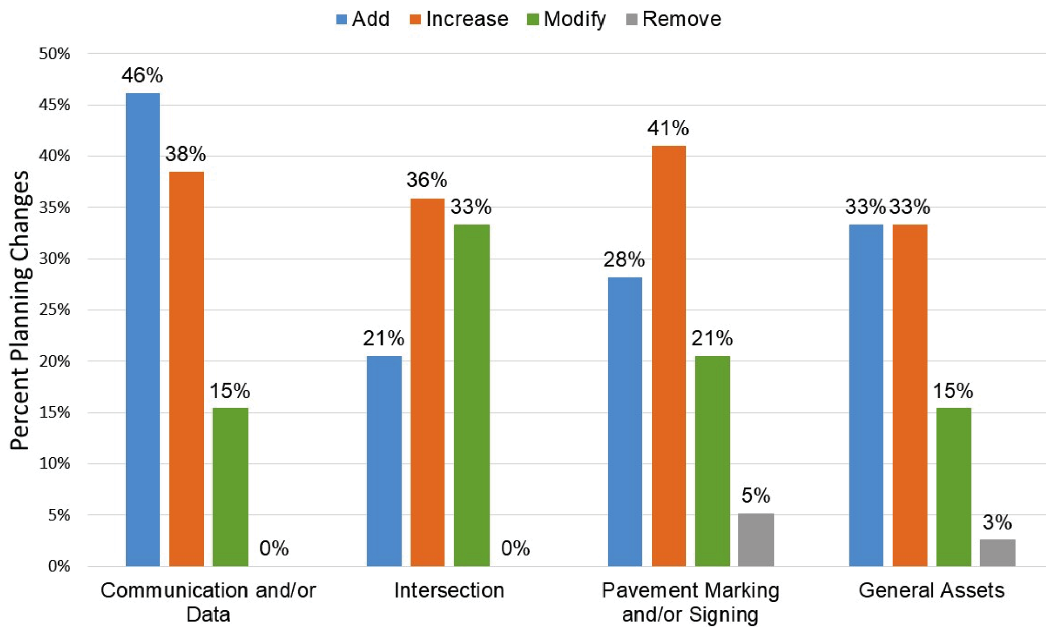


Figure 3-5. Planned changes by category of assets.

to remove any assets in this category over the next 3 years. Two agencies indicated adding other communication- or data-related assets, which included adding autonomous bus and related CAV equipment (one DOT), and adding preemption technology for transit with DSRC RSUs (one DOT).

A summary of the types of planned changes in the next 3 years for intersection-related assets is shown in Table 3-8.

The most common planned change was increasing the number of cameras at intersections (13 DOTs). The second and third most anticipated changes at intersections were related to traffic signal controllers, which were planned to be modified by 12 DOTs and increased by eight DOTs. Two DOTs mentioned planned changes in the category of "Other" assets: one DOT had plans to increase Linux board computers, Power over Ethernet (PoE) switches, and fiber switches in

Table 3-6. Number of agencies planning changes by type of asset.

Change	Communication and/or Data	Intersections	Pavement Marking and/or Signing	General Assets
Add	18	8	11	13
Increase	15	14	16	13
Modify	6	13	8	6
Remove	0	0	2	1

Table 3-7. Number of agencies planning changes for communication- or data-related assets.

Change	DSRC RSU	Cellular RSU	Communication Capacity	Data Service Infrastructure	Other
Add	10	9	7	9	2
Increase	8	3	14	10	0
Modify	3	3	3	1	0
Remove	0	0	0	0	0

Table 3-8. Number of agencies planning changes for intersection assets.

Change	Traffic Signal Control	Cameras	Image Processing Units	Other
Add	6	5	3	2
Increase	8	13	6	0
Modify	12	2	3	1
Remove	0	0	0	0

cabinets and to change their model to modify switches to include PoE switches; another DOT had plans to add end-of-queue warnings for signals near or at tight curves. None of the participating DOTs had plans to remove any intersection assets.

Table 3-9 shows the types of changes to pavement marking or signing assets planned by the agencies for the next 3 years.

Increasing the amount of durable pavement markings (15 DOTs), high-contrast pavement markings (14 DOTs), and increasing pavement marking practices (12 DOTs) were the most common planned changes. Also, many agencies (nine DOTs) had plans to add smart signs. No agencies had other pavement marking or signing changes planned.

Through other related work, the team was aware that some agencies had plans to remove nonreflective round raised pavement markers (e.g., Botts' dots). As a result, the researchers included the treatment as one of the questions to gauge how many agencies were planning to remove them. Due to the way the survey was formatted, it provided an option to respond add, increase, modify, or remove. One agency indicated they were planning to remove in the next 3 years. However, in response to the survey question, one agency indicated they were planning to increase, and two agencies indicated they were planning to add. This was unexpected, since it would be unusual for an agency to begin using Botts' dots if they were not already using the treatment. It is not clear if the agencies confused the treatment with "raised pavement markers," which would make more sense. As a result, it was assumed that one agency was planning to remove Botts' dots in the next 3 years, while it is unlikely others were planning to add the treatment.

Table 3-10 shows changes to general assets planned by the agencies in the next 3 years.

Table 3-9. Number of agencies planning changes for pavement markings and signing.

Change	Durable Pavement Marking	High-Contrast Pavement Marking	Pavement Marking Practices	Nonreflective Round Raised Pavement Markers	Signs	Smart Signs	Other
Add	4	4	6	2	2	9	0
Increase	15	14	12	1	8	1	0
Modify	4	4	5	0	6	1	0
Remove	0	0	0	1	1	0	0

Table 3-10. Number of agencies planning changes for general assets.

Change	RWIS	GPS Receiver/Antenna Reference Point	EV Infrastructure	Other
Add	3	5	11	0
Increase	8	7	7	0
Modify	5	1	0	1
Remove	1	0	0	0

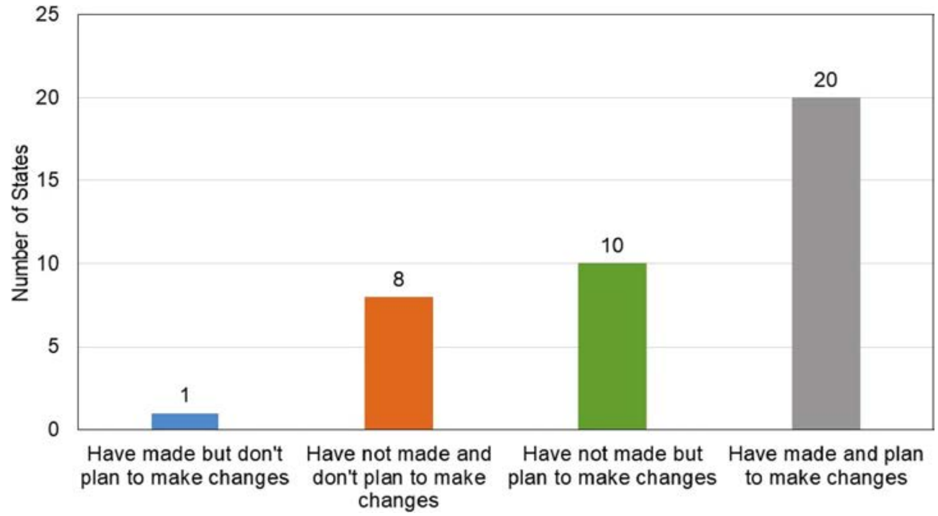


Figure 3-6. Summary of current and planned changes by number of states.

"General" was a catch-all category for assets that did not fit into one of the previous categories. The most common responses were adding EV infrastructure (11 DOTs) or increasing RWIS (eight DOTs). Seven agencies indicated they planned to increase GPS receiver/antenna reference points and EV infrastructure. One state DOT indicated they had other changes planned for general assets, and they noted plans to modify barrier shapes to support CAVs.

Figure 3-6 summarizes current practices (changes inquired about with Question 2) and future plans (in the next 3 years) (changes inquired about with Question 3) of state DOTs.

The four categories of combined past and future asset change regimes were defined as follows:

- Have made changes in the past but don't plan to make future changes.
- Have not made changes in the past and don't plan to make future changes.
- Have not made changes in the past but plan to make future changes.
- Have made and plan to make future changes.

As shown, 20 agencies that have made changes in the past are also planning to make changes in the future. Ten agencies have not made changes but plan to make changes. Eight have not made changes and do not plan to make changes, and only one had made no changes and had no plans to make changes in the next 3 years.

3.3 Changes in Asset Data Collection to Create Digital Infrastructure

The fourth question was about changes in an agency's digital infrastructure to accommodate CAVs.

Question 4: How has asset data collection changed in creating digital infrastructure in your agency to accommodate CAVs?

Twenty of the participating 39 agencies (51%) responded that they have either changed or plan to change (over the next 3 years) their asset data collection practices to address CAVs. It was assumed that most changes to asset data collection would occur in one of the following fashions:

- Not presently collecting a particular type of asset data and will start collecting.
- Increasing frequency of collecting a particular type of asset data.
- Modifying data collection practices related to collecting a particular type of asset.

Table 3-11 shows how agencies have applied or plan to apply changes in the collection of various types of asset data.

The most frequent response to the prompt was no change, as noted in the first column. The next most common response was modifying data collection practices. As noted, 11 DOTs indicated they were modifying data collection for sign retroreflectivity and the geolocation of assets, while 10 indicated modifying data collection practices for roadway characteristics. Many agencies also reported collecting some assets more frequently, with six indicating they would collect more weather data. Pavement marking retroreflectivity and pavement condition each received five responses from agencies, indicating they would collect them more frequently.

Four agencies mentioned changes in data collection for other assets. One of the key findings is that general probe data ingestion [like Waze or original equipment manufacturer (OEM) data] requires adjustments to the systems that read the data. Their responses included the following (any information that identified an agency was removed):

- One agency was looking into using Light Detection and Ranging (LiDAR) and other ways to collect data.
- One agency indicated they were modifying some aspect of data collection, but the changes were primarily due to their asset management program rather than CAV efforts.
- One agency provided the following note: "*Not sure where to put this comment: General probe data ingestion (like Waze or OEM data) that is then redistributed digitally to the public. Requires adjustments to the systems that read the data. General rules of the road mapping to report to autonomous vehicles, as a baseline everyone should use—planned, may not be completed in 3 years.*"
- One agency noted that a transportation asset management system (TAMS) and general performance-based maintenance has been added to collect geographic information system (GIS) and other asset data condition statements over the last 3 or more years. These systems will continue to grow and mature to complement other asset management tools, like their inventory systems for bridges and pavements.

Table 3-11. Current or planned changes in data collection.

Asset Data Type	None	Not Presently Collecting and Will Start Collecting	Collecting More Frequently	Modifying Data Collection Practice
Sign inventory	25	4	4	7
Sign retroreflectivity	25	2	2	11
Pavement marking inventory	23	5	4	7
Pavement marking retroreflectivity	24	4	5	8
Geolocating assets	24	1	4	11
Pavement condition	30	0	5	5
Roadway characteristics	24	2	3	10
Roadway features	27	1	4	7
Light Detection and Ranging (LiDAR) or other 3D mapping	27	3	3	6
Weather data	24	1	6	9

3.4 Changes in Existing Maintenance Practices to Accommodate CAVs

The fifth question was about changes in existing maintenance practices. The question asked whether agencies had or planned to change their practices.

Question 5: What changes in existing maintenance practices have been made in your agency to accommodate CAVs? For instance, more frequent winter maintenance to ensure lane lines are visible for CAVs?

The majority of participating agencies had not changed their maintenance practices. Only 10 agencies (31%) reported changes in maintenance practices to accommodate CAVs, as noted in Table 3-12.

The most common practices that had been applied or changed were work zone practices, followed by more frequent maintenance for some assets and added new equipment. A number of agencies had changes planned in the next 3 years, with the most frequent responses being new maintenance practices (eight DOTs), work zone practices (eight DOTs), adding new equipment (seven DOTs), and more frequent maintenance for certain assets (six DOTs). No agencies indicated that they were either conducting or planning less maintenance of non-CAV-related assets in the next 3 years.

Seven agency responses mentioned changes in maintenance practices other than those listed in Table 3-12. The descriptions provided for adopted changes of maintenance practices from six of these follows:

- One agency indicated that they were making changes from their operational plan for autonomous truck-mounted attenuators (ATMAs).
- One agency noted that they were uncertain of exact changes needed, but plan to accommodate CAV maintenance as deployment continues to mature.
- One agency noted that they were currently developing a concept of operations for 2020 for snowplows to have priority at DSRC-enabled signals. They were also piloting an ATMA in 2020, which would allow a fleet vehicle operating the TMA (or crash cushion) to be driven autonomously without a human driver. They had worked with a vendor on the ATMA project and concluded two major lessons learned before the pilot was launched: (1) They developed enhancements to the software to allow the vehicle to modify its following distance anywhere from 15 to 60 ft, and (2) they worked to ensure the automation software can be integrated

Table 3-12. Current or planned changes of maintenance practices by number of states.

Type of Change	None	Applied/ Changed	Plan to Change/Apply in the Next 3 Years
More frequent maintenance for certain assets	31	2	6
Additional inspection for existing assets	34	1	4
New maintenance practice	30	1	8
Less maintenance of non-CAV-related assets	39	0	0
Added new equipment	31	2	7
Winter maintenance	36	1	2
Changes in priorities	34	0	5
Changes in performance targets	35	0	4
Work zone practices	31	3	8
Implementation of maintenance management systems (MMS)	35	0	4

into the physical hardware of the vehicle without removing the AM/FM radio stations, which human operators rely on when not using the automation technology.

- One agency noted that, with the addition of more technology, the challenge to keep these (the assets) operating and maintained will be a challenge. They noted that they already have an underfunded maintenance program, and the amount of funding for maintenance needs to be addressed. Adding high-tech, short life-cycle equipment will add strain to an already limited budget. In a rapidly growing state of technology, CAV-supportive system expansion will still need to be focused on significantly.
- One agency noted that they are evaluating the issue and may move to 6 in. wide pavement markings.
- One noted they may collect data by other means, such as an unmanned aerial system (UAS).

3.5 Examples of Successful Maintenance Practices to Support CAVs

The sixth question asked about successful maintenance practices.

Question 6: Does your agency have any examples of successful maintenance practices to support CAVs?

Four agencies answered yes to the question and shared their examples of successful maintenance practices to support CAVs as follows. As noted, some are not actually maintenance practices, but the responses are reported as agencies responded to the question:

- One agency noted that they were using an ATMA program.
- One agency noted that they were using vehicle communications (for snowplows and pick-ups), data collection and deployment of a maintenance decision support system (MDSS), a website with vehicle (snowplow) movements and camera images, and a server/data management system to develop applications related to CAVs.
- One agency noted that they had some examples but had not yet completed pilots.
- One agency noted two activities:
  - Currently working on redefining performance measures that will impact ability to manage CAV systems.
  - Using DSRC vehicle-to-infrastructure (V2I) systems on a few corridors, which allows snowplows, when they are plowing, to request signal preemption at traffic signals. The system went operational in late winter 2019, will be fully operational on several corridors in 2019–2020, and will be expanded to more corridors in 2020. They have not completed a study of effectiveness, but driver response has been positive.

3.6 Additional Lessons Learned About Asset Maintenance for CAVs

The seventh question asked about lessons learned.

Question 7: Does your agency have any additional lessons learned about asset maintenance for CAVs?

Six agencies answered yes to the question. No common theme emerged, and, in most cases, the responses were more comments than lessons learned. One key finding was that exact maintenance needs are still unknown at this time. Since OEMs drive deployment, public agencies are left to react to infrastructure maintenance needs.

One agency noted that, since 2017, they have learned several operational and technical lessons when it comes to bringing an autonomous maintenance vehicle into the fleet. One agency noted that they have worked with a vendor on an ATMA. Although not stated, it is believed this ATMA project concluded with two major lessons learned before the pilot was launched. First, they learned that software could be enhanced to allow the vehicle to modify its following distance anywhere from 15 to 60 ft. Second, they had to ensure the automation software could be integrated into the physical hardware of the vehicle without removing the AM/FM radio stations, which human operators rely on when not using the automation technology. Other, more general comments are provided in Appendix A.

3.7 Impact of CAV Maintenance Activities on Workforce Needs

The eighth question asked about the impact of maintenance activities.

Question 8: How have CAV maintenance activities impacted your agency's workforce needs?

The impacts in question eight were defined as follows:

- Additional maintenance staff needed.
- Additional training needs to deal with new assets.
- Nontraditional maintenance staff needed (for instance, more specialized staff are needed to manage sensor replacement).
- More staff turnover due to CAVs.
- Software training to use maintenance management systems (MMSs).
- Organizational changes to address the increased or different maintenance activities (for instance, are new maintenance activities carried out under a different group within the agency?).
- Other (participants were asked to describe if they selected).

Table 3-13 shows the current impacts DOTs have on their agency's workforce needs (72% of the 39 participating agencies).

Eight of the agencies indicated they needed additional training, and seven agencies noted they required nontraditional maintenance staff. Six indicated additional maintenance staff were needed, and five agencies noted that software training was needed.

Two agencies answered "Other," with the following explanations:

- One agency noted: "The biggest impact it has had on the workforce to date is the ATMA American Federation of State, County, and Municipal Employees (AFSCME) labor negotiations, wherein we've developed talking points to address how this technology saves lives but won't impact the needs of DOTs to have workers in these vehicles performing other maintenance activities."
- Another agency answered: "Other noted impacts are not well understood at this point, but felt they would impact budgets and staffing."

Table 3-13. Impacts on agency workforce needs.

Impact	Agencies Responding
Additional maintenance staff needed	6
Additional training needs to deal with new assets	8
Nontraditional maintenance staff needed	7
More staff turnover	None
Software training to use maintenance management system	5
Organizational changes	3
Other	2

3.8 Impact of CAVs on Other Maintenance Needs

The ninth survey question asked about other impacts.

Question 9: Has the adoption of CAVs impacted other maintenance needs?

Twelve agencies indicated impacts. Major themes were cost, uncertainty in what maintenance needs will be, more frequent maintenance, and focus on CAV assets taking away from other activities. A key finding was that the ability to share data may be delayed due to internal processes that do not allow for it (no feeds, no data portals, etc.), thus impacting the ability to maintain data.

Specific responses are provided in the Appendix.

3.9 Concerns About Other Aspects of Maintenance Related to CAV Activities

The tenth question asked about other concerns.

Question 10: Are you concerned about other aspects of maintenance related to CAV activities?

A total of 21 agencies responded yes to this question. Answers were cataloged to identify themes in maintenance concerns with the following main concerns emerging:

- Additional costs to maintain,
- Additional staff or other resources to maintain,
- Additional time to maintain,
- Additional education and training needs,
- Need for additional information in general,
- Maintaining proper retroreflectivity and contrast of pavement markings,
- Concerns about ability to maintain at levels needed by CAVs,
- Winter maintenance,
- Direction industry will take,
- Financial or other unknowns, and
- Concerns about how CAVs will impact maintenance priorities.

One of the key findings was that agencies are concerned with maintaining proper retroreflectivity and contrast of pavement markings for CAV technology, particularly in winter conditions. Additionally, there are concerns about the ability of CAV technology to recognize and properly react to the different types of work zone traffic control devices used. Actual responses from the agencies are provided in Appendix A.

3.10 General Concerns Regarding CAV Activities Related to Maintenance

The final question asked if the participants had any remarks about CAV-oriented maintenance activities that were not covered by the rest of the survey.

Question 11: Any general concerns regarding CAV activities related to maintenance?

A total of 19 agencies responded yes to this question. Answers were cataloged to identify themes in maintenance concerns with the following main concerns/needs emerging:

- More standardization of assets is needed before adding, increasing, or modifying assets.
- Uncertainty and lack of information regarding the future timing and needs of vehicle technologies and their impact on highway maintenance.

- Lessons learned about CAV pilots and other research should be shared.
- Reluctance to adopt technology given all the unknowns.
- Short-term maintenance needs and impacts are unknown (e.g., How quickly will assets need to be repaired/replaced after vandalism or a crash? How quickly will assets need to be maintained in winter events?).
- Impact on maintenance cycles is unknown.
- Potential that CAV asset needs will require privatization of maintenance activities.
- Need for skilled, qualified, and trained staff to maintain the systems.
- Potential costs and resources.

One key concern was that pavement markings and signals need to be more uniform than they are at present. As a result, uniformity would necessitate more consistent maintenance. Another key concern was that CAV applications may preempt or accelerate privatization of maintenance activities, resulting in relinquishing ownership of facilities to technology companies or transportation services providers.

3.11 Summary of Survey

State and local agencies were surveyed to determine which CAV-related infrastructure assets had been implemented and their impact on maintenance practices. The survey was developed and circulated to various national committees as described in Chapter 2 and the responses summarized in Chapter 3. A total of 53 participants from 39 state DOTs completed the questionnaire. When more than one response was provided for a state, the information was collated to create a single response.

Around 46% of agencies had changed physical assets to support CAVs. Primary assets that were added, increased, or modified included pavement marking/signing, intersection assets (i.e., traffic signal, cameras), and RSUs or DSRC.

The majority of agencies (77%) indicated that they plan to make changes to their physical assets to support CAVs in the next three years. Only nine agencies responded that they do not have any plans to make changes. The most common planned change was adding communication or data-related assets.

Agencies were also questioned about existing maintenance practices to accommodate CAVs. The majority noted they had not changed their maintenance practices. The most common practices that had been applied or changed were work zone practices, followed by more frequent maintenance for some assets and adding new equipment. A number of agencies had changes planned in the next three years, with the most frequent responses being new maintenance practices, work zone practices, adding new equipment, and more frequent maintenance for certain assets.

Agencies were also asked about the impact of CAV maintenance on workforce needs. The most common responses were a need for additional training, additional maintenance staff, and nontraditional maintenance staff.

CHAPTER 4

RSUs for CV Applications

4.1 Description of RSUs

Roadside units (RSUs) primarily provide wireless communication between roadside infrastructure and on-board units (OBUs), and secondarily communicate traffic and asset information to the agency back office. They are placed along the roadside and send and receive data, such as speed, location, and time to and from OBUs. RSUs can be attached to an existing utility pole or to camera poles, dynamic message signs, toll gantries, or other existing infrastructure (NCTCOG 2017).

The main function of the RSU is to facilitate communication between vehicles and infrastructure by transferring data at sub-second latency over the Federal Communications Commission (FCC) radio spectrum in accordance with industry standards. Development of RSUs initially focused on the use of dedicated short-range communication (DSRC) over the 5.9 GHz band of the radio spectrum. Advances in cellular technology have enabled RSUs in some circumstances to work with a cellular connection. RSUs are primarily a connected vehicle (CV) application.

4.1.1 DSRC RSU Specifications

In 2014, the Federal Highway Administration (FHWA) Intelligent Transportation Systems (ITS) Joint Program Office (JPO) developed the *Dedicated Short-Range Communications (DSRC) Roadside Unit Specifications* publication that documents the requirements for RSU communications via the 5.9 GHz frequency, which was used until recent federal reallocation of bandwidth (latest document revision in 2017). DSRC-enabled technologies have been the federal standard for device capabilities and functionalities because of their low-latency and high-reliability performance for transmitting safety-critical information. DSRC adheres to IEEE 802.11, 1609.x standards, SAE J2735, and SAE J2945.

Conceptually, the DSRC RSU connects to in-vehicle or mobile equipment, traffic controller equipment, and a backhaul network to facilitate vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications.

An RSU that complies with DSRC requirements:

1. Supports single-channel continuous and dual-channel alternating DSRC channel modes simultaneously.
2. Contains internal computer processing and permanent storage capabilities.
3. Contains an integrated GPS receiver for positioning and timing.
4. Contains a Power over Ethernet (PoE) capable interface that supports both IPv4 and IPv6 connectivity, compliant with IEEE 802.3at.

Table 4-1. DSRC RSU operational states.

State	Definition
Initial State	Factory defaults
Standby	• Core operating system is operational. • DSRC radios are not operational/broadcasting. • Interface logging is disabled. • Configuration changes are enabled.
No Power Operate	Loss of power (e.g., knockdown as opposed to a power cycle)
No Power Standby	Operator already initiated standby then power is lost
Operate	• All DSRC radios are operational/broadcasting. • System log is enabled. • Configuration changes are disabled.

5. Is contained in a dedicated, NEMA 4X-rated enclosure.
6. Is corrosion-resistant (physical requirement).

DSRC standard RSUs operate in the states shown in Table 4-1.

Manufacturers of RSU technology adopted this standard as part of early implementation in the 2010s. The reallocation of the safety spectrum had increased the need for a new RSU standard. The Institute of Transportation Engineers (ITE) had an active project to modernize the DSRC RSU standard to focus on cellular vehicle to everything (C-V2X) at the time of drafting this report chapter (Narla 2021).

4.2 Gathering Maintenance Information for RSUs

Information was initially gathered through a survey of state department of transportation (DOT) maintenance practices (Chapter 3) and follow-up conversations with state DOTs (both during Phase I of this project). Next, RSU vendors identified in Chapter 2 were contacted to determine life cycles and suggested maintenance. Responses were received from one vendor. Finally, the team conducted interviews with agencies that were identified as utilizing RSUs.

4.3 Examples of Applications for RSUs

Of the 39 DOTs that responded to the agency survey (see Chapter 3), 20 indicated that they had added some type of RSU, and four had increased RSUs to accommodate CVs. Two noted they had modified RSUs. The majority had added or increased DSRC RSUs (14 added, three increased) while six had added cellular RSUs, one had increased, and two had modified cellular RSUs. These responses are summarized in Table 4-2.

Table 4-2 also summarizes DOTs that planned to add RSUs in the next 3 years, with 19 planning to add some type of RSU (10 DSRC and nine cellular), 11 planning to increase RSUs (eight DSRC and three cellular), and six planning to modify RSUs (three DSRC and three cellular).

Table 4-2. Survey responses for changes made to RSUs.

Change	Changes Made		Changes Planned in Next 3 Years	
	DSRC RSU	Cellular RSU	DSRC RSU	Cellular RSU
Add	14	6	10	9
Increase	3	1	8	3
Modify	N/A	2	3	3
Remove	N/A	N/A	N/A	N/A

As noted in Chapter 2, 10 DOTs and several cities were questioned about a subset of assets that they had implemented to address CVs. A description of how they implemented RSUs follows. It should be noted that information was provided in the early stages of the COVID-19 pandemic, which had an impact on many agency priorities in terms of estimates for future deployments.

4.3.1 California RSU Applications

California DOT (Caltrans) had multiple pilot deployments of RSUs. Caltrans and the University of California, Berkeley were early adopters of CV technology, developing the 2005 California Connected Vehicle Testbed. The testbed is along CA 82, also known as El Camino Real, a signalized arterial roadway between San Francisco and San Jose with average daily traffic (ADT) of more than 50,000 vehicles. The original testbed included 11 intersections with recent investment from Caltrans that would increase the scale of the deployment to 31 intersections.

While the original testbed focused on university equipment to interact with CV messaging, a recent expansion focused on the multimodal aspects of CVs—providing Valley Transit with priority for bus operations, which included five vehicles with OBUs.

Deployments for the latest technology upgrade included moving to 2,070 controllers at each location; adding transmitters to provide signal phase and timing (SPaT) and basic safety messages (BSM); and adding fiber in the existing conduit for data to the back office and localized computing with radio communication.

San Diego had also been active in the development of a CV proving ground. The San Diego Proving Ground comprised a varied area, including I-15 Express Lanes, the southern segment of the South Bay Expressway, and local streets and roads within the City of Chula Vista. The San Diego Proving Ground included public partners San Diego Association of Governments (SANDAG) and the City of Chula Vista, along with private partners.

4.3.2 Colorado RSU Applications

Colorado DOT (CDOT) had a three-year plan to deploy 600 RSUs. At the time, CDOT had RSUs in two corridors: I-70 Mountain and C-470. The I-70 corridor contained 100 dual band units [cellular vehicle-to-everything (C-V2X) and DSRC], and the C-470 corridor (southwest Denver from I-25 to I-70) contained 31 DSRC RSUs. CDOT planned to use a Better Utilizing Investments to Leverage Development (BUILD) grant to move into statewide development, including deployments on I-25 from Wyoming to Trinidad, a gap closure on C-470, I-70 east of Golden to Central (Denver International), and all metropolitan area interstates.

CDOT had 92 light duty vehicles with OBUs with 20 of those used in connected snowplows.

The cost was estimated to be $15 million for the initial CV deployment, $20 million for BUILD, and approximately $1 million for connected snowplows. The fiber backbone was expected to last for 20 years. They were to use $19.1 million in state-funded BUILD matches to contribute to new fiber segments.

4.3.3 Florida RSU Applications

Florida DOT (FDOT) had several RSU pilot deployments. The first deployments, in 2017, were in Tallahassee on US 90 (with 32 Waymobile RSUs and five OBUs). Another deployment was in Gainesville (with 35 Siemens RSUs and 70 Sirius XM OBUs). FDOT was also working on deployments for Pinellas County, along I-75 in Gainesville, and along I-4 in Orlando.

Across all deployments, the agency projected they would have implemented 650 operational RSUs by the end of 2021.

4.3.4 Georgia RSU Applications

Georgia DOT (GDOT) had deployed 400 RSUs in the greater Atlanta metro area, and planned to expand to 1,600 RSUs at traffic signals out of an estimated inventory of 9,000 signals in the state. This represented nearly 18% of all traffic signals and nearly half of GDOT owned or maintained traffic signals. The deployment was for building internal agency understanding and as a proof of investment in the concept for potential partners and original equipment manufacturers (OEMs).

GDOT also had a small rural pilot for C-V2X (six units) on I-85 in cooperation with Panasonic. This installation included an unspecified number of in-vehicle installations. This deployment was developed in partnership with RAY, a nonprofit in the area. The project would promote understanding of the technology and utilize a newer style of technology with dual-mode communication and a newer style of security compared to the Atlanta deployment. The rural deployment used 4G communication to the back office, which was not practical to broadening the scope of the deployment. The RSUs were a Kapsch product.

GDOT's initial plans focused on two impetuses: the American Association of State Highway and Transportation Officials (AASHTO) signal phase and timing (SPaT) Challenge (20 by 2020), the state's host role for the AASHTO Committee on Transportation System Operations (CTSO), and the AASHTO Annual Meeting in 2018. The SPaT Challenge deployment was limited to 54 RSUs on two corridors. One corridor was close to downtown, and one was suburban. The two deployments used a turnkey contract (with procurement, installation, and integration included).

GDOT was able to, near seamlessly, build CV investment into a large existing program that focused on traffic operations for the Atlanta metro. The Regional Traffic Operations Program (RTOP) utilized two teams that were dedicated over a 10-year existing program. The program was funded at $20 million per team, so each team provided great efficiency to broadly apply past lessons learned. The teams had developed a plan to buy and install RSUs at signalized intersections (estimated $4,000 per intersection) within the corridors managed by the program. The department had not changed funding to RTOP for RSUs, but management felt the costs of the equipment per signalized location was not a big change.

4.3.5 Kentucky RSU Applications

The Kentucky Transportation Cabinet (KYTC) noted that one DSRC RSU was installed in 2018; however, no useful data were collected, and the cabinet of the RSU was destroyed in an accident. The latest deployment of DSRC RSUs was through the SPaT Challenge, and was underway as of 2020. DSRC RSUs were being installed in two large urban corridors. One location was in Bowling Green along a problematic roadway, and the other was in Richmond.

The KYTC was in the process of installing 48 DSRC radio controllers. The DSRC controllers were WAVEMOBILE Fiberwire 8011 RSU/OBU Radio. The installations were being done by a vendor (Blue Grass Electric). There had been challenges due to the COVID-19 pandemic, and they had issues using the DSRC due to FCC licensing requirements.

Considerations for future installations of DSRC RSU depended on several factors:

- KYTC had implemented RSUs as part of the SPaT Challenge; they were interested in seeing the utility of the RSU for that application before investing in more.

- Traffic signal controllers were becoming more sophisticated and met some of the data and other needs KYTC may have had for RSUs.
- Resources for existing needs took precedence over CV needs; even though KYTC can apply for federal funds to purchase RSUs, there are still costs for installation and maintenance.
- Buy-in from other agencies such as hospitals, schools, or police would dictate whether installation of additional RSUs were worth the resources. As a result, future investments would consider whether they provided an advantage to other agencies.

The DSRC RSUs were installed as part of the SPaT Challenge. Locations were selected based on which districts would be the most likely to take responsibility for maintenance as well as location. The Bowling Green corridor had a number of traffic issues, and the Richmond corridor had both a rural and urban component.

Part of the decision to install DSRC RSUs was that staff in systems operations wanted performance measures.

4.3.6 Michigan RSU Applications

Michigan DOT (MDOT) had increased communications capacity for DSRC RSUs. Mainly, they had added switches and cell modems to existing sites to power RSUs. They noted that fiber was not available in several areas, so if a location was not already connected, they were adding modems. Signal connectivity allowed them to obtain data, which could be analyzed remotely. Use of the connectivity also allowed MDOT to conduct traffic signal maintenance and fix other issues (e.g., drift) remotely. Ultimately, they planned to change signal timing "on the fly." They had recently contracted with a vendor to assist them with the process. The long-term plan was to have 3,200 signals with communications capability, with 500 going live in 2021.

RSUs had been deployed and were available for vehicles that were able to connect. However, use of the RSUs seemed to be limited by the available applications (e.g., weather specific). Additionally, their snowplows with connectivity options were not using RSUs.

4.3.7 Minnesota RSU Applications

Minnesota DOT (MnDOT)'s first deployment for CVs was the Trunk Highway (TH) 55 corridor for the AASHTO SPaT Challenge. The deployment included 22 intersections from downtown Minneapolis west to the I-494 corridor. The earliest discussions occurred in 2015 and considered manufacturer solutions that were viewed as a black box. The goal was to learn about DSRC technology. As of 2020, they had 18 months of experience transmitting SPaT and MAP messages. Message reporting was connected to data portals (Greenhill was the vendor).

The TH 55 deployment used an Intelight controller, although the project started with Econolite. Intelight MaxView was the MnDOT traffic management center (TMC) central software. MnDOT had been looking to improve their central software to provide application programming interface (API) access or feed a data portal with SPaT/MAP message data.

Another deployment was planned for Smart Snelling Avenue using newer technology—a deployment of 13 units with cellular communication that could be read/accessed using a smartphone. The Smart Snelling deployment would use Econolite.

The state was using two standard vendors for traffic signals for both corridors. From experience with these two vendors, MnDOT could see CV-ready controllers becoming standard.

Both corridors were looking at a priority solution for mobility. MnDOT was focusing their priority on snowplows with OBUs for signal request messaging. The snowplows would only test priority at a demo of four intersections. However, MnDOT had 22 snowplows equipped with DSRC radios from their research budget. The vehicles could perform V2V communications and had been focused on lane-keeping solutions. Research was being conducted with a MnDOT-owned or sponsored test track. The snowplows were also part of an agency weather information decision support system that pulled data back to the central office, fused and processed data and decision support, and then recommended winter maintenance treatment scenarios to the fleet.

The deployment was financed by state highway funding, specifically, a split between highway funding and research dollars institutionalized over time based on standard ITS. The TH 55 corridor improvements cost $1 million, and the Smart Snelling deployment was $0.5 million.

4.3.8 Nevada RSU Applications

4.3.8.1 Nevada DOT Applications

Nevada DOT (NDOT) had been conducting an Integrated Mobility Observation (IMO) program since 2011. Various communication methods for connected snowplows in the Lake Tahoe region had been tested to help manage the transportation system ahead of and during adverse weather events. The activity was a phased partnership between the U.S. DOT, NDOT, the University of Nevada, Reno, and the National Center for Atmospheric Research (NCAR).

The snowplows had the ability to communicate with each other and DSRC-based RSUs. A web interface incorporated real-time local, national, and mobile weather data and was making recommendations about roadway treatments and timing (e.g., sand, salt, brine applications).

Phase I used an Enhanced Digital Access Communication System (EDACS) radio for communication. EDACS uses a statewide 800 MHz radio system, which allows each vehicle to transmit approximately 500 bytes every five minutes. Vehicles are able to send basic telemetry information.

In Phase II, cellular capabilities were added and often replaced EDACS. Nine snowplows and one service patrol with DSRC and cellular communications technology (Lear) were added in Phase III. The sensors detected roadway temperature, wiper status, and snowplow status and had automatic vehicle location (AVL) capability.

Eighteen DSRC RSU sites were placed covering 32 mi along US 395 and I-580 between Reno and Carson City. Continuous coverage was available in some areas, and “drive-by hot spots” for data transfer were available in more sparsely covered areas. The DSRC RSUs allowed equipped vehicles to communicate with the National Data Exchange (N-DEx) to transmit weather and road data.

Another 54 mi of roadway had cellular connectivity along roads through mountain passes, which have more extreme winter weather, near Lake Tahoe over Mt. Rose (SR-431) and Spooner Summit (US 50). In areas where DSRC RSUs existed, equipped cars sent probe data or environmental log files to the Nevada DOT IMO server. Fiber was used for the network connection between the DSRC RSUs and the IMO server. The Transmission Control Protocol/Internet Protocol (TCP/IP) was used for the network protocol for cellular and fiber (Larkin-Thomason 2018; Guevara and Schilling 2018; NDOT n.d.; Schilling and Whalen 2016). The DSRC RSU units were BlueToad Spectra, and the OBUs were Lear (formerly Arada).

The system was initially developed to address adverse weather events as part of Every Day Counts Round 4 (EDC-4). The system was adapted to ensure a common platform. The decision to develop the application was a unified approach from the central offices and the districts.

NDOT was also identifying needs to develop a request for proposal (RFP) to create a platform that could utilize commercial off-the-shelf (COTS) equipment and ensure that standards are complied with to ensure the ability to customize disparate systems.

The funding was a combination of FHWA and state funds. The cost for the system was estimated at about $1 million for the infrastructure elements. However, other costs existed that were more difficult to quantify, such as cost for the use of maintenance personnel. After investing in the initial platform, the department was not investing much for any future implementations until the RFP went out.

4.3.8.2 Las Vegas, Nevada RSU Applications

Information about the City of Las Vegas is based on conversations with NDOT and City of Las Vegas representatives, along with information from web-based sources. The City of Las Vegas had a connected vehicle corridor program that included about 70 DSRC-enabled intersections that were broadcasting on the safety spectrum with additional planned installations (Larkin-Thomason 2018). Over the last four years, the city had installed more than 100 DSRC units. Clark County had 43 DSRC RSUs, with most along Las Vegas Boulevard from Sahara to Russell Road (the Las Vegas Strip).

The city was using devices from multiple vendors, but the majority were from Commsignia. The other vendors were Siemens, Caster, and Cohda radio. The DSRC units broadcast only MAP and SPaT messages (and traffic signal information).

The initial deployment was for a fully autonomous shuttle in the entertainment district (and six units were part of this initial deployment). Some of the initial installations were also proof of concept demonstrations for the Consumer Electronics Show, which is typically held annually in Las Vegas. Some installations had also been deployed in concert with vendors. The city was wrapping up a recent project with Cisco where 25 Commsignia units had been installed.

A Lyft/Motional partnership used AVs for a mobility on demand (MOD) service that traveled from the convention center to several resorts along the Strip and was the only current user. Lyft/Motional had announced that they would launch a fully driverless ride-hail service in Las Vegas in 2023 (Lyft 2021). As part of the partnership, installation was requested at specific intersections.

Although past installations had been motivated by vendors and pilot demonstrations, the City of Las Vegas representative also noted that they were considering how to decide future investments (i.e., should this be motivated by private users or should the city have a plan for expansion). Development of a plan was hampered by lack of information about how quickly CVs would expand and what the needs would be.

The city noted that the cost for each device was between $6,500 and $7,000. Installation required a crew of two maintenance workers with a truck and took about one hour to complete. Funding for the installations had come from Information Technology (IT), in-kind partnerships, and the Regional Transportation Commission. Although the current technology was DSRC, they were transitioning to C-V2X.

4.3.9 Washington RSU Applications

Washington State DOT (WSDOT) noted that they had 12 to 15 DSRC RSUs used in conjunction with traffic signals. The majority were part of the SPaT Challenge, but they had not fully utilized them or invested additional resources. WSDOT had considered requiring all intersections on state roadways be equipped with DSRC units, but there were some uncertainties about whether DSRC or 5G was a better option. Additionally, COVID-19 had delayed some decisions. The feeling, in general, was that most states had implemented DSRC as part of the SPaT Challenge to gain some experience, but may not be invested in the technology.

4.3.10 Tampa Bay, Florida RSU Applications

The Tampa Bay area had a CV pilot study that included RSUs and had been in place since 2017. They had a vendor maintenance contract, but no routine equipment review was in place due to a strong monitoring platform and its capabilities. The representative noted that a consideration when writing an RFP for a vendor was to state that RSUs are safety devices with similar reliability and repair times as signals instead of identifying them as communications assets.

One maintenance issue they had found was loss of communication due to lightning strikes; 17 of 44 devices went down in one storm. Another issue mentioned during the interview was installation on older mast arms. Each mast arm had to be grounded prior to installation.

The representative noted that staff needs to know how to load an intersection map into the RSU. This involved creating a map, loading it into the RSU, sending the map to OBUs, and testing. This effort took several hours per intersection, and routine maintenance can be required on these data. For example, if a right turn lane is constructed at an intersection, the reconfiguration of the intersection maps and messaging is a full day's effort.

4.3.11 Columbus, Ohio RSU Applications

An interview and literature review were conducted for the City of Columbus' CV pilot study. Interview discussions found that unexpected maintenance challenges included random RSU locations that failed unexpectedly. Regular monitoring of the central system software and confirming operations by driving the corridor at least once a week was a best practice noted to stay on top of unexpected errors and troubleshooting. The city had also been experiencing a server problem about once a month. The vendor was responsible for troubleshooting these kinds of problems.

An agency project manager spent about 75% of their time on system stand-up and was still spending 25% of their time on system operation and maintenance. This created a knowledge resource constraint for the short- to mid-term time periods while technology is deploying and then simultaneously maintained. To mitigate the training and staffing needs and aid in the transition from vendor to agency, the city had identified roles and responsibilities at different stages of deployment. The project of approximately 100 RSUs and 1,000 OBUs led to a 35% increase in agency staff responsibilities, a $150,000 per year cost to maintain RSUs, and $150,000 per year cost to have OBUs maintained by the vendor.

4.4 RSU Maintenance Needs

The researchers found that several agencies contract maintenance to private vendors or rely on the original maintenance contract. Caltrans had an RSU testbed that was on its third cycle of RSU technology (over 15 years). The maintenance was handled by skilled staff at a partner university. District 4 provided support by closing lanes to allow contractors to maintain RSUs, but they do not provide the actual maintenance.

The San Diego Proving Ground was part of a national call for collaboration between public and private partners sponsored by the U.S. DOT in 2017. Its maintenance needs had been met through the private sector.

MnDOT had utilized the University of Minnesota as well as provided some assistance, along with a consultant who provided support for planning and technical support of the installation.

Tampa Hillsborough Expressway Authority (THEA) also utilized a vendor to repair RSUs as needed.

CDOT had originally used vendors until 2020, and then took over maintenance of the system. They noted when looking for a vendor, the RFP language should dictate CV devices as safety devices to emphasize the importance of repair times. Pilot deployment literature that was reviewed also emphasized the importance of proper vendor contracts, because having a skilled vendor that prioritizes device maintenance was just as important as designing the system to avoid problems.

Other agencies had used a hybrid approach in which they took care of the maintenance that they were able to do, but also utilized a vendor as needed. GDOT noted that they used traffic signal system contractors to manage the installation and maintenance for RSUs. They also indicated a limited effort had been needed for maintenance to date. Their staff already had skills to maintain traffic signals, and they could install and configure the RSUs with those capabilities. Other maintenance was pushed exclusively to contractors.

The City of Las Vegas indicated that once they are notified about an issue, the city dispatched a crew to troubleshoot it. Their ability to fix the issue was limited because their staff did not have the technical expertise and because the user interface software did not have the appropriate capability to address the issue. The representative said that the majority of the time, the devices resynchronized and that resolved the issue. However, other issues were addressed by the vendor. They also said this support was covered under the initial installation contract rather than part of a maintenance contract.

The KYTC did minimal maintenance when they were able to devote resources to it. When other maintenance was needed, they had access to contractors that would be able to provide assistance.

Since RSUs were a relatively new technology, other agencies had either not yet decided how maintenance would be handled or were using the vendor from their purchase of the units. For instance, FDOT had no experience with maintenance needs yet, since the units were three years old. However, they were approaching the end of coverage by vendors. WSDOT noted that they had no experience in maintaining their DSRC RSUs.

4.4.1 Typical RSU Maintenance and Maintenance Frequency

Typical RSU maintenance included the following:

- Monitoring: Daily in management center to check status.
- Software-related maintenance: Regression testing and software archiving.
- Security-related maintenance (install and update certificates): 1 hour per device every 3 months.
- Inspection and evaluation (power to the device is verified in field, technician can access RSU from a secured connection, and drive-bys are performed to verify system operation): Every 6 months.
- Major feature updates: Annually (with periodic updates in-between if needed).
- Considerations:
  - Perform regular maintenance during off-peak hours and non-severe weather.
  - Reconfigure intersections due to changes: Update RSU with map of intersection to send to OBUs and test (several hours per intersection).

- Best practices:
  - Have a central monitoring system to maintain access to each device and its status.
  - Dedicate staff to monitor the system.
  - Carry a spare device and bring someone to train when traveling to a cabinet to perform an installation, if needed; then, diagnose the uninstalled RSU offline.

One vendor responded to the request for information and noted that typical regular maintenance included software updates for necessary bug fixes, release updates, and access to their support portal. They also noted that their RSUs do not need to have a regular program around a physical maintenance check. They are connected into a backend process, which identifies if they are not working. This would indicate software or hardware issues. Their maintenance program covers any software issues. Hardware is covered by a warranty program. One vendor responded to the request and recommended an annual maintenance program.

MnDOT indicated that maintenance needed to include replacement of cabinets and restoration of electrical service from knockdowns. They noted that an RSU antenna was normally mounted on a 4 ft mounting pole above the mast arm. MnDOT used health monitoring software to test whether locations had communication and power. The health check was performed once a day. It had resulted in some power resets and the need to push out updates (three updates in 18 months).

Las Vegas indicated that once they were notified about an issue, the city would dispatch a crew to troubleshoot, and the maintenance was limited to a power reboot. The majority of the time the devices resynchronized, and this had resolved the issue. Other issues were addressed by the vendor. Las Vegas had a few OBUs to check the system, but they did not have a regular inspection or monitoring program. Instead, they were relying on the primary user (Lyft/Motional autonomous taxi) to relay issues. Once notified about an issue, the city would dispatch a crew to troubleshoot it.

KYTC did maintenance as needed. They reported having some equipment (i.e., bucket truck) and had some experience with wiring, so they were able to do minimal maintenance. However, resources to maintain depended on competing priorities. Additionally, if resources were available, they had access to contractors that would be able to provide assistance.

NDOT noted that maintenance crews regularly checked to see if DSRC RSUs were reporting and, if needed, made a visit to ensure they were working. They had not noted a significant need for maintenance.

MDOT indicated that RSUs were typically placed for 3 to 5 years and then were just replaced given it was usually less expensive to replace than maintain. However, MDOT had not had the equipment in place long enough to decide on long-term maintenance.

THEA (THEA 2018; Beresheim et al. 2016) had developed a comprehensive installation plan for their CV pilot deployment program, which included routine maintenance and inspection requirements and schedules. They noted their RSUs (Siemens) had no calibration or optics that required periodic adjustment or cleaning. They planned one major feature update annually, and this was accomplished using traffic operations personnel. No additional information on lifetime or maintenance was provided. The vendor repaired RSUs as needed.

4.4.2 RSU Life Cycle

The summary of RSU life cycle findings was as follows:

- A reasonable RSU life cycle estimate range was from 5 to 7 years.
- The transition from DSRC to C-V2X to 5G made determining expected life cycle challenging. Because the technology was constantly evolving, a good practice was to replace devices on an update cycle like an IT product.

- A common finding during pilot team and CV technology vendor interviews was that maintenance measures (such as life cycle) are relatively comparable to other traffic technology.

RSUs had been installed within the last 3 to 5 years for most of the agencies surveyed. Although little information on life cycle was provided through the survey, one stakeholder noted that they have only had one or two RSUs fail out of 100. Another agency noted between 10% and 15% of the RSUs installed within the last 4 years were sent back for repairs. The City of Las Vegas noted that their oldest RSU had been in place for 4 years.

One agency noted that little information was available about life cycle or failure rate. A vendor that responded to the request for information did not yet have a life cycle estimate.

GDOT noted that technology ages poorly, and the long-term operations and maintenance for RSUs was probably replacement-like IT expenses.

Caltrans noted that their RSU testbed was a research partnership made to support future planning. To continue to provide useful information as the technology changes, they said the assets faced a continual cycle of upgrades to the latest technology every 5 years. As a result, it could be inferred that they were planning a 5-year lifespan for RSUs.

Another source (GAO 2015) estimated the lifespan of DSRC RSUs by comparing them to a similar existing technology (Cisco routers and switches that have an expected lifespan of 7 to 8 years and other Wi-Fi routers that have a lifespan of 1 to 10 years). Overall, the source estimated a lifespan of 10 years for hardware deployed for CV. They estimated a lifespan of 5 years for the operational software.

NDOT did not have performance metrics or a timeline for replacement of DSRC RSUs or other items. They were working on that through their transportation systems management and operations (TSMO) program for the performance and health index of their ITS assets.

4.4.3 Common Failure Issues for RSUs

The following common failure issues were identified for RSUs:

- Weather (lightning strikes, storms, water, etc.).
- Knockdowns.
- Installations on ungrounded mast arms.
- Security credentialing.
- Improper installation of antenna.

CDOT noted the main issues they have had so far are knockdowns by vehicles and power issues. They had only seen about one or two RSUs fail out of 100.

Vendors mentioned security credentialing was a challenge due to certificate updating requirements, as the standards are always changing. There were some weather-related failure issues seen with radio, antenna, and cable RSUs, but they were not reported as extremely common and were apparently dependent on the quality of the installation of the device.

4.4.4 Maintenance Challenges for RSUs

CDOT noted some maintenance challenges. For example, they had C-V2X antennas on specific vehicles come out of place on rougher roads. Additionally, they said over-the-air updates on the unit were time consuming.

NDOT noted that their communications structure was sparse in rural areas and more difficult to maintain. As a result, they urged some caution in committing to asset changes without considering the needed resources to maintain them.

GDOT noted that maintenance challenges included devices that were installed and assumed to be functioning properly, but GDOT could not easily collect data and ensure that they were functioning.

4.4.5 Costs for Maintenance of RSUs

Findings on RSU maintenance costs could be summarized as follows:

- Annual regular RSU maintenance costs could range from $1,800 to $3,500 or 2% to 5% of original hardware and labor costs per device. Costs included hardware, deployment, and configuration, which may vary depending on the vendor or other requirements.
- Site or intersection installation costs could range from $5,250 to $7,450.
- Recurring Security Credential Management System (SCMS) costs should be considered as regular maintenance costs and were estimated at $3.14 per vehicle.
- Maintenance cost considerations and best practices:
  - Pre-negotiate size of cost because of extra units (recommend 10% more in case of failure) and vendor support contracts.
  - As technology continues to evolve, some agencies may choose to replace devices rather than incur long-term maintenance costs.

The U.S. Government Accountability Office (GAO 2015) conducted a review of costs for DSRC. The report provided cost estimates for planning, acquiring, and installing infrastructure and equipment needed to support DSRC for V2I systems. Information was based on data gathered from AASHTO, NCHRP, and U.S. DOT research reports.

Costs for backhaul systems (communications links between RSUs and the local office) varied depending on the extent to which the system needed to be upgraded. The average cost to upgrade backhauls to a DSRC RSU was about $3,000, if sufficient backhaul was available, and up to $40,000, if a new backhaul system needed to be installed.

They estimated that the average cost for roadside equipment was $7,450 per site, with the cost of an individual RSU estimated at $3,000.

Routine maintenance for RSUs was estimated to be about 2% to 5% of the original hardware and labor costs. Recurring maintenance included realigning antennas and rebooting hardware. They also estimated that the equipment lifetime was 5 to 10 years. They indicated that the SCMS costs should be included as recurring costs. Average initial SCMS costs were estimated as $3.14 per vehicle. This was estimated to increase over time as the number of vehicles in the system increased.

No stakeholders had established performance metrics, which may include repair or replacement timelines, since many of the noted RSU deployments were relatively recent (within the last 3 years). As a result, long-term maintenance needs are not known. Some agencies may choose to replace rather than provide significant long-term maintenance for lower-cost assets such as RSUs, particularly if the technology changes frequently. One source estimates a cost of $1,200 to $3,300 per RSU (Leonard 2017).

FDOT did not yet have an idea of how maintenance would evolve. They had estimated $500 to $1,500 per RSU per year. Some initial reports estimated $1,800 to $3,500 per RSU per year.

One stakeholder felt the devices were cheap enough (and the technology changed often enough) that they would replace them within a 3- to 5-year time frame rather than do long-term maintenance. A different source estimated that the cost of a new RSU that provides both cellular and DSRC could be deployed for about $4,000 to $6,000 per intersection (U.S. DOT 2020). A third source indicated the cost per RSU was $1,300 per device with deployment costs of $850 and configuration costs of $2,000 per device (U.S. DOT 2018).

4.5 Standards, Guidelines, or Best Practices for Maintenance of RSUs

In addition to the information gathered through the survey and interviews, a literature review was conducted for the three U.S. DOT CV Pilot Deployment Program sites [THEA, Wyoming DOT (WYDOT), and New York City (NYCDOT)] and the Smart City Challenge winner (City of Columbus, Ohio) to find patterns in maintenance needs, system requirements, best practices, and lessons learned regarding RSU maintenance. The following is a summary of those findings, listed here as considerations and best practices for RSU maintenance:

- **Set realistic expectations for failure or degraded performance rates** over a specified life cycle to determine inventory needs.
- **Establish expected resolution time tiers** for non-safety-critical problems, for example:
  - Minor problems are diagnosed/resolved by agency staff within 4 hours.
  - Intermediate problems requiring over the phone or virtual troubleshooting by vendor and use of agency field staff resolved within 24 hours.
  - Serious problems requiring vendor to go into the field solved within 72 hours.
- **Use existing maintenance protocols** as standards for resolution times:
  - *THEA Pilot:* Respond within one business day when there are RSU communication failures; restore communication in accordance with City of Tampa response time for signal controllers.
- **Document roles and responsibilities** in terms of full-time employees (FTEs) for agency staff and vendors (including documenting operation and maintenance plans, lessons learned, research needed, etc.) to facilitate an easier transition when the demonstration period ended:
  - *Smart Columbus Pilot:* Defined periods within contracts and who is responsible for what aspects of the deployment during those periods (demonstration, extended support, post-support); helped identify training, staffing, and documentation/process needs.
  - *NYCDOT Pilot:* Developed a Lessons Learned Logbook (LLL) that incorporated a summary of any issues identified throughout the design/build/test phase, and will include documentation on the potential impacts, mitigation actions taken, and results identified (to date).
- **Develop internally or use vendor training modules:**
  - *Smart Columbus Pilot*: Vendor training modules were required for identified agency staff.

The list of training modules and their descriptions from the Smart Columbus Pilot are provided in Table 4-3.

Table 4-3. Vendor training modules from Smart Columbus Pilot project.

Module	Description	Duration
CV Introduction	The basics on what makes up CV systems and solutions including an overview of the CV products	45 mins
CV Messaging	An overview of the messages used for CVs	30 mins
Connected Mobility Control Center (CMCC) Introduction	An overview on using the CMCC	30 mins
CMCC Locations, Devices, and Messages	Setting up the network using the CMCC	60 mins
CMCC Administration	How to be a CMCC administrator	20 mins
CMCC Operations	Monitoring and troubleshooting the system using the CMCC	30 mins
CV Validator Operations	Setting up and using the CV validator	45 mins
RSU Introduction and Setup	Preparing the RSU for installation	45 mins
RSU Installation	Mounting the RSU at the roadside	30 mins
RSU Verification	How to verify the RSU installation	30 mins

4.6 Summary of Workforce Needs to Address RSU Maintenance

The literature reviews and interviews found the following on workforce needs to address RSU maintenance.

Potential "new hires" include software engineers (write and read code; Linux language was specifically mentioned) and electrical/signal technicians (or their skills).

Training, either vendor specific or developed internally, needs to be conducted on topics such as hardware maintenance, software maintenance (typically handled through a vendor contract), understanding of setup, configuration, enrollment, and mounting (beginning to end), and rebooting and troubleshooting (TMC operator specific).

Survey discussion indicated that DOT staff time is needed to routinely check RSU assets. Additionally, maintenance is difficult, because staff may not have the skills to fix minor issues, which may result in replacing devices rather than maintaining them. This should be accounted for when developing a team.

The City of Las Vegas noted that it had been challenging to dedicate staff to install and maintain RSUs, and these activities have directed resources away from other maintenance. City staff members had considered maintenance support through contract since they did not have the staff or technical abilities to fix devices beyond recycling the power or replacing the device.

A best practice is to offer certification to staff as an incentive to training. When selecting a vendor, look into transition period expectations on training for workforce development.

CHAPTER 5

OBUs for CV Applications

5.1 Description of OBUs

An on-board unit (OBU), in the context of connected vehicles (CVs), is vehicle-based equipment that can communicate with roadside units (RSUs) or other intelligent transportation system (ITS) infrastructure. OBUs receive warnings and other communication from the RSUs and can send position and other information to RSUs for vehicle-to-infrastructure (V2I) connectivity. OBUs have several components, which may include dedicated short-range communication (DSRC) or other cellular connectivity, message processors, GPS, and a method to interface with the driver (U.S. DOT 2021). For instance, the MobiWave OBU contains a processor, memory, various radios (DSRC, Wi-Fi, broadband, and cellular), and a GPS (Harman n.d.). OBUs are specific to connected rather than autonomous vehicles (AVs).

5.2 Gathering Maintenance Information for OBUs

A summary of the process to gather information on OBUs is provided in Chapter 2. Information was initially gathered through a survey of state department of transportation (DOT) maintenance practices and follow-up conversations with state DOTs (Phase I). Next, OBU vendors were contacted to determine life cycles and suggested maintenance. The team conducted interviews with several additional agencies identified as utilizing OBUs. The information gathered is summarized in this chapter.

5.3 Examples of Applications for OBUs

Several examples of OBU use for CV applications were found as described in the following sections.

5.3.1 OBU Applications for Snowplow Operations

One of the main CV applications for OBUs is improvement of snowplow operations. Liao et al. (2018) evaluated lane boundary guidance systems for snowplows in the Minneapolis-St. Paul area. The system consisted of a real-time kinematic (RTK) global navigation satellite system (GNSS) receiver, a radar sensing system, an in-vehicle display, an OBU, a cellular modem, and a processor.

The Utah DOT (UDOT) equipped snowplows in Utah County with OBUs that could send and receive messages from traffic signals using DSRC technology. The application was used to preempt traffic signals, allowing the plow operators to move through intersections and keep their snowplows moving at efficient speeds (UDOT 2022a).

Colorado had a similar project that equipped snowplows with OBUs to communicate with RSUs (see Figure 5-1).

The technology allocated early green or extended the existing green when a CDOT snowplow was detected. The system was expected to decrease plow time and increase traffic operations (CDOT 2021).

The Nevada DOT (NDOT) had a connected snowplow program in the Lake Tahoe region to help manage the transportation system ahead of and during adverse weather events. OBUs gave snowplows the ability to communicate with each other and with RSUs. A web interface incorporated real-time local, national, and mobile weather data and made recommendations about roadway treatments and timing (e.g., sand, salt, brine applications).

The Michigan DOT (MDOT) had also added communications capacity to their snowplow fleet. Instrumentation of the snowplows began in 2013 with 300 snowplows equipped, which represented most of their fleet. It should also be noted that MDOT had contracted out winter maintenance for about 70% of their lane miles. The snowplow communications were a mix of 3G and 4G. The most recent outfitting was 4G since the cellular provider (Verizon) no longer supported 3G.

The snowplows had a mobile data collector (MDC) unit that interfaced with a control unit with plow blade sensors (up or down), air and road temperature sensors, GPS, and spreader controllers. Data from the MDC was transmitted to the cloud-hosted MDOT central system where system administrators monitored, analyzed, and reported on the information. Delcan Technologies integrated a maintenance decision support system (MDSS) into an MDC touchscreen application. Specialized reports helped in monitoring efficient salt usage and identifying potential salting compliance issues (Delcan Technologies 2022).

The system transmitted data wirelessly via cellular to a website where reports could be generated, including vehicle location for the public. Information was also sent to maintenance garages and back to the snowplow drivers. This linkage allowed them to make forecasts and treatment recommendations. The next step was to utilize Bluetooth technology to do a self-contained wireless sensing unit on the snowplows to avoid wires and other connections back to the data logger for the snowplow units. However, a mix of the current technology and Bluetooth was expected since the latter was more expensive.

Source: https://grandavebridge.codot.gov/projects/snowplowsignalpriority.

Figure 5-1. Priority snowplow.

5.3.2 OBU Applications for Adverse Weather Monitoring

Wyoming DOT (WYDOT) developed a suite of applications using vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications technology to reduce the impacts of adverse weather on truck travel along the I-80 corridor. OBUs were utilized in a forward collision warning application to monitor Basic Safety Messages (BSMs) from other CVs. A distress notification application detected when the vehicle was in distress and sent a Distress Notification Traveler Information Message (TIM), which could then be picked up and rebroadcast by other systems. The work zone warning application received situational awareness and spot weather impact warnings to alert other drivers of warnings, and also to display truck parking information (Zumpf 2018).

5.3.3 OBU Applications for Bus Priority

California DOT (Caltrans) was using OBUs for bus operation priority in the California CV Testbed along CA 82 between San Francisco and San Jose.

5.3.4 Other Applications of OBUs

The San Diego Proving Ground included state vehicles with OBUs. Florida DOT (FDOT) deployed RSUs and OBUs on US 90 in Tallahassee (32 Waymobile RSUs and five OBUs).

The City of Las Vegas had teamed up with Qualcomm Technologies for implementation of cellular vehicle-to-everything (C-V2X) RSU vehicle communication technology. Vehicles equipped with aftermarket OBUs with C-V2X capabilities could access signal phases and timing and traffic messaging. The trial used Commsignia's C-V2X RSUs and OBUs, with ITS-RS4-C and ITS-OB4-C, respectively, both of which used the Qualcomm 9150 C-V2X chipset solution based on 3rd Generation Partnership Project (3GPP) Release 14 specifications (Commsignia 2020).

Smart Columbus was a region-wide smart city initiative between the City of Columbus, Ohio and the Columbus partnership (SMRT Columbus 2021). Smart Columbus was the winner of the U.S. DOT's first Smart City Challenge. One of the demonstration projects was the Connected Vehicle Environment (CVE), which was conducted from October 2020 through March 2021. The project created a connected infrastructure that allowed vehicles to provide safely alerts such as blind spot detection or forward collision warning. The system also allowed infrastructure such as traffic signals to receive alerts about emergency or freight vehicles. A communications network was developed using a high-speed fiber network and RSUs installed at 85 signalized intersections along four corridors. The project also installed OBUs in more than 1,000 vehicles, which allowed the vehicles to receive CV alerts. The OBUs were Siemens and were installed between March 2018 and June 2019. Overall, OBUs were installed in the following:

- 311 private vehicles,
- 195 public service city fleet vehicles,
- 30 Central Ohio Transit Authority (COTA) supervisor or security vehicles,
- Seven county engineer vehicles,
- 94 public safety vehicles,
- 17 private freight vehicles,
- 14 C-MAX transit buses, and
- 369 COTA transit buses.

5.4 Maintenance Needs for OBUs

Most agencies and maintenance vendors did not have significant experience with maintenance for OBUs. As a result, only minimal information was available, as summarized here. Two agencies conducted their own maintenance for OBUs, and two agencies noted that they used a vendor. The maintenance contract included over-the-air updates and tech support. The Smart Columbus demonstration project funded vendors to maintain OBUs for 15 months after the demonstration (SMRT Columbus 2021).

5.4.1 Typical Maintenance and Maintenance Frequency for OBUs

Three agencies noted that they were doing regular maintenance of OBUs. However, only one had a specific cycle (i.e., annual). The most common maintenance was software updates.

MDOT indicated that they conducted annual maintenance for OBUs. This included checking cables, firmware updates, calibration, and other preventive maintenance. MDOT noted that some equipment sensors can be calibrated, and others are older and cannot be calibrated.

Minnesota DOT (MnDOT) noted that the snowplow OBUs are regularly maintained. They had two staff members helping maintain the units (and they were not solely dedicated to this activity). They were also doing regular maintenance, such as checking and changing sensors. As needed, garage mechanics were assisting with maintenance.

Tampa Hillsborough Expressway Authority (THEA) noted that vendors were doing regular software updates over-the-air, although no specific cycle was indicated.

5.4.2 OBU Life Cycle

Most of the applications identified were reasonably recent, so none of the contacts had specific information about life cycle for OBUs. MDOT commented on the snowplow system in general, and noted some components were 3-to-5 years old and other components were 7 years old. However, they anticipated having to replace equipment due to changes in technology rather than equipment wear.

5.4.3 Maintenance Challenges for OBUs

One vendor noted that a concern with maintenance was the need to have the internet available to update certificates. One agency noted issues in doing over-the-air updates due to different software versions.

5.5 Standards, Guidelines, or Best Practices for Maintenance of OBUs

OBUs are a mature technology and were being used in a number of applications including fleet management, automated toll collection, and automatic vehicle location. CV applications for OBUs were not likely to require additional maintenance beyond what was typically conducted for applications at the time. As a result, no additional standards were likely to need to be developed.

5.6 Workforce Needs to Address Maintenance of OBUs

Given that OBUs are not specific to CVs, no unique workforce needs were noted. Skills such as computer and electronic as well as some understanding of vehicle maintenance were likely to be sufficient.

5.7 Summary of Maintenance Needs for OBUs

OBUs, in the context of CVs, are vehicle-based equipment that can communicate with RSUs or other ITS infrastructure. Although OBUs are a mature technology, most agencies and maintenance vendors did not have significant experience with their maintenance. The primary regular maintenance noted was software updates. None of the agencies had standards or best practices for OBU maintenance. The average life cycle for OBUs was estimated as 5 years.

CHAPTER 6

Pavement Markings for AV Applications

6.1 Overview of Pavement Markings for AV Applications

Pavement markings have been used in the United States for about 100 years to provide human drivers with longitudinal preview and lateral positioning information. The safety benefits of pavement markings for human drivers have been well documented (Carlson et al. 2009). The introduction of autonomous vehicles (AVs) has further enhanced the importance of pavement markings as they are one of the most relied upon physical infrastructure assets that AVs use.

Pavement markings are primarily relevant for AVs rather than CVs. Longitudinal pavement markings provide two functions for AVs. First, they indicate the forward road alignment. Second, they are used to locate the vehicle within the cross section of the road. As a result, pavement markings are particularly important for AVs (Moylan 2018; Knight 2016). Transverse markings (e.g., lane assignment arrows, curve ahead, stop, crosswalk) also provide important information that AVs use, such as presence of a stop sign.

When it comes to AVs on the road today, pavement markings are identified through image processing. A passive camera sends digital images to the image signal processor (ISP) and the information is decoded using pixel detection. Although each original equipment manufacturer (OEM) has their own proprietary algorithms, the basic premise of pixel detection remains the same. Each image is made up of pixels which are assigned a value based on intensity (light versus dark). Machine vision (MV) algorithms look for differences between pavement marking pixels and road pixels. The algorithms calculate and look for large differences between adjacent pixels; more complicated algorithms calculate the rate of change and create a linear slope with a steep slope, which is used to find edges; another algorithm uses similar calculations as the edge detection method but considers changes in two directions; a final method uses deep learning to train the system to detect and classify objects. All of the methods use "thresholding," which looks for values that meet a minimum threshold. As a result, sufficient contrast is the key criteria for identification of pavement markings (3M 2019). MV algorithms also discriminate between different types of longitudinal markings (such as color, continuous markings, single or double lines, and broken lines) to gather information.

Discontinuities in pavement markings make it difficult for sensors to predict where a vehicle is in a lane, causing the vehicle to rely on other features such as the edge of roadway, which is more difficult due to lower contrast and consistency (RSMA 2017). Discontinuities result from pavement marking wear or locations where traffic diverges (e.g., exit ramps). Another particular concern is overlapping markings that occur when markings are repainted, but some evidence of the former markings remain. Pavement sealing may also create contrast with existing pavement and may be misinterpreted as a pavement marking.

Source: Gorodenkoff/Shutterstock.com.

Figure 6-1. Use of cameras and image processing to identify lane lines.

A survey of the AV industry, including car and truck manufacturers, technology providers, and software developers, indicated lane markings are the most critical roadway infrastructure feature for both human drivers and AVs (Chan and Wang 2021). The authors noted that, in order to be effective, lane markings need to be visible in all light and weather conditions. Most survey respondents also agreed that most relevant infrastructure features would need to be monitored and maintained more stringently to improve the performance of an advanced driver assistance system (ADAS). However, no specific recommendations for maintenance were provided, although complete removal of old markings would be obvious given that old markings coexisting with newer markings may confuse AVs.

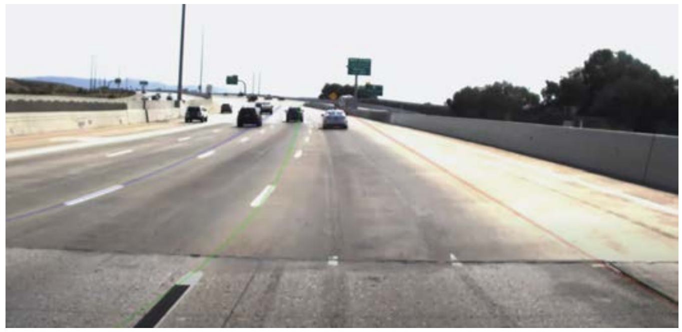
Wider pavement markings make markings more visible to vehicle sensors, particularly at longer distances and in inclement weather conditions. The increased width provides more opportunity for additional pixels to be picked up by the camera chip to include in the marking (see Figure 6-1).

6.2 Pavement Marking Standards for AVs

Within the past five to six years, a variety of activities have started to help in understanding what is needed and what is feasible from the perspective of improving the physical infrastructure to support AVs. A number of studies and tests have been conducted to determine how pavement marking enhancements can support safe AV deployment (Pike et al. 2018). In addition, meetings have brought the AV industry and infrastructure industry stakeholders together to discuss topics such as pavement marking enhancements. The Federal Highway Administration (FHWA) has also made an official request through the *Federal Register* to obtain an even broader perspective. A key takeaway from these activities has been the need to tighten national uniformity of pavement marking appearance and application. One recent example of how pavement markings can be enhanced to support AVs came from open road testing in Utah (see Figure 6-2—final report pending).

The *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) was going through the FHWA process of being upgraded. The proposed MUTCD has new pavement marking provisions designed to improve safety for the human driver as well as support AV deployment (NCUTCD 2020). The following proposed and pertinent provisions are designed to improve pavement marking uniformity across the United States:

- Change the default width of pavement markings. Previously, the default width for a normal line was 4 to 6 in. The proposed provisions now specify 6 in. wide markings for freeways,



Source: UDOT 2022b.

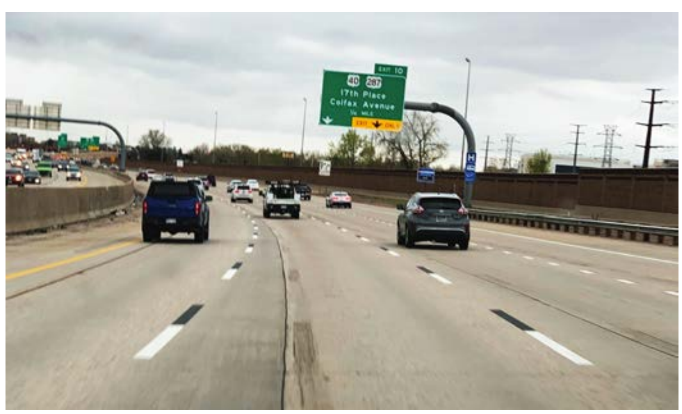
Figure 6-2. Assessing AV readiness in Utah for pavement markings.

expressways, and ramps, 6 in. wide markings for all other roadways with speed limits > 40 mph, and 4 to 6 in. wide for all other roadways. This change then led to a need to update the definition of a wide line, which is now proposed as a line at least 8 in. in width if 4 or 5 in. normal width lines are used and at least 10 in. in width if 6 in. normal width lines are used.

- Chevron markings should be used in the neutral area of exit ramps and entrance ramp gores.
- Regardless of the width of the normal line used on the roadway, edge lines on two-lane roadways should be at least 6 in. wide.
- A dotted extension of the right edge line through an exit ramp is now required, whereas it was previously optional.

Although the new MUTCD provisions did not address contrast markings, contrast markings can improve the daytime performance of vehicle sensors. AV stakeholders have been stating a preference for the lead-lag contrast pattern for skip lines where a black marking of the same dimensions is placed immediately behind the white skip line. This technique is particularly useful on concrete or worn asphalt pavements (as shown in Figure 6-3).

Some agencies have also updated their specifications to improve the durability of pavement markings by including grooves, using more durable pavement marking materials, or both.



Source: Paul Carlson, Texas A&M Transportation Institute (TTI).

Figure 6-3. High-contrast lane line markings in Colorado using the preferred lead-lag pattern.

6.3 Potential Impacts of Enhancements to Pavement Marking Standards

In an ongoing FHWA study, the national annual estimate to implement the MUTCD provisions listed above were estimated to be $115 million to $140 million. Because the MUTCD currently provides flexibility such as the use of 4 to 6 in. wide markings and the use of optional provisions that have been proposed to be tightened in the next MUTCD, some states will feel very little impact, while other states will have more catch up to do. For instance, the Ohio Department of Transportation (ODOT) has stated that the impact to them will be approximately $5 million annually (FHWA 2021b). However, Florida DOT (FDOT) has been using 6 in. wide markings for about 20 years, and, as a result, the impact for Florida will be practically negligible.

6.4 Examples of Agency Activities to Enhance Pavement Marking Practices

A number of agencies who responded to the agency survey had already started to utilize wider markings, more durable markings, and contrast markings. Many of the agencies surveyed indicated that the changes were most frequently to address the safety of human drivers but also to improve conditions for AVs.

Table 6-1 indicates changes made in pavement markings by the 39 DOTs that responded to the agency survey (Chapter 3). As noted, only a few had added pavement markings, with four indicating they had added new practices. The most common change was increasing either durable or high-contrast markings or making changes in practices. Only two noted that they were modifying practices, and none had plans to remove. Similarly, only a few had changes to add pavement markings in the next 3-5 years with the largest number noting that they had plans to increase. Five agencies indicated they were planning to modify pavement marking practices. None had plans to remove any type of markings. Specific changes are listed in Table 6-1.

More specific applications identified through targeted agency interviews or surveys of literature are described in the following sections. As noted, the main change for AVs and safety in general has been to move to 6 in. lane lines. Use of dotted extensions through ramps was also noted along with use of more durable markings.

6.4.1 Michigan Pavement Marking Practices

Michigan DOT (MDOT) was using wider lane markings and edge lines to facilitate cameras and sensors identifying the markings. MDOT was using 6 in. pavement markings to improve machine vision detection under adverse visibility conditions and on high-speed roads where

Table 6-1. Types of changes to pavement markings.

Change	Have Implemented			Plan to Implement in Next 3 Years		
	Durable pavement markings	High-contrast pavement markings	Pavement marking practices	Durable pavement markings	High-contrast pavement markings	Pavement marking practices
Add	1	3	4	4	4	6
Increase	8	9	6	15	14	12
Modify	0	0	2	4	4	5
Remove	0	0	0	0	0	0

conflicting images may confuse the system. MDOT only used 6 in. lane markings on freeways until 2020 but then moved to additional applications including using 6 in. edge lines on state trunklines and entrance/exit ramps. Wide dotted extension lines that were also placed on exit and entrance ramps to improve lane guidance were included as part of MDOT's annual restriping program. They planned to start with non-freeways for both white and yellow markings and estimated it would take three to four years to complete (MDOT 2022).

6.4.2 Georgia Pavement Marking Practices

Georgia DOT (GDOT) had changed its pavement marking practices to use wider pavement markings and changed the style to a following stripe. The striping width moved to 5 in., but they had started updating to a 6 in. standard in 2022. The changes in striping practice were influenced by AV needs, but they noted the wider markings have benefits to non-AV road users.

On the other hand, GDOT noted that they had not invested much effort at this stage, stating that the National Committee on Uniform Traffic Control Devices (NCUTCD) had not yet prioritized pavement markings, specifically for AV needs. They would like to see this committee promote guidance first, and then they feel like GDOT can catch up more easily.

The road striping change was seen as another opportunity to improve safe operations—both for AVs and for non-AVs. The AV industry was vocal about keeping up striping quality, and going to a wider striping leaves more paint to be processed.

GDOT had moved from a sales tax to fund transportation to an excise tax roughly 5 years ago. The change moved GDOT from a $2 billion program to a $3 billion program. The wider availability of funding supported pavement marking improvements; however, limited additional detail was available on where these costs were associated.

GDOT deployed lane striping technology (3M's Connected Roads All Weather Elements) along a stretch of I-85. The markings have tiny reflective beads embedded in the striping, making the markings more visible to both human drivers and vehicles equipped with advanced driver assistance (ADA) systems. The 13 mi project was a public-private partnership (PPP) between GDOT, 3M, and the Ray (Roads and Bridges 2020).

6.4.3 California Pavement Marking Practices

In August of 2017, California DOT (Caltrans) published new details within the division of construction, which increased 4 in. wide longitudinal traffic lines to 6 in. wide lines for permanent pavement delineation on state highways (Ayre 2017). Caltrans deployed striping projects in FY2017 and FY2018, covering 17,500 lane miles. Additionally, they eliminated the use of buttons (Botts' dots) as a substitute for lane lines in 2018. They also specified use of more durable pavement markings at higher elevations (> 3,000 ft) (Carlson 2021).

Caltrans noted that wider striping provides enhanced safety to all user groups, but particularly older drivers. The agency had noted maintenance challenges with Botts' dots, and the pilot I-80 project confirmed that the wider striping was preferable.

6.4.4 Colorado Pavement Marking Practices

Colorado DOT (CDOT) had a statewide safety goal to bring outside shoulder lines to 6 in. widths to improve visibility. CDOT was keeping an eye on AV research, but the focus of the 6 in. striping was for human drivers. Five new paint trucks were part of this effort, costing $0.5 million each.

6.4.5 Florida Pavement Marking Practices

Integrating wider pavement markings was a back burner issue for FDOT. They were waiting on guidelines from the MUTCD. FDOT intended to pilot first and then plan for full-scale work in 2023 or 2024.

6.4.6 Iowa Pavement Marking Practices

Iowa was adopting 6 in. markings for their primary highways and use of lane line groovings in addition to contrast markings (Carlson 2021).

6.4.7 Kentucky Pavement Marking Practices

The Kentucky Transportation Cabinet (KYTC) had recently modified their striping standards to 6 in. durable markings (thermoplastic on asphalt and durable tape on concrete) on the state primary road system. Previously, they had used 6 in. markings on freeways and 4 in. markings on other roadway classes. A draft policy was developed for installation of wider markings (6 in.) on non-interstate roadways. The document was currently under KYTC leadership review. This would include two-lane roadways with average daily traffic (ADT) greater than 1,000 and a width great enough for both centerlines and edge lines.

The changes were not made specifically for AVs, as wider lines and longer lasting striping should simplify the driving task for all drivers, whether human or autonomous.

6.4.8 Minnesota Pavement Marking Practices

Minnesota DOT (MnDOT) was working on improving pavement striping generally for safety purposes. While the agency's basic research function had investigated the topic, they did not have plans to deploy anything across the state. MnDOT was experimenting with merge, entry, and exit markings on I-94 between Saint Cloud and the Twin Cities.

6.4.9 Nevada Pavement Marking Practices

Nevada DOT (NDOT) had widened lane lines from 4 to 6 in. on all US routes and increased them to 8 in. on interstates two years earlier. Changes were made as part of the normal restriping cycle. The changes were reflected in the *Nevada DOT Road Design Guide* (2019), which noted:

> Marking width: Interstates and freeways require 8 in. wide edge line and lane line stripes. Gore lines, auxiliary lane lines, and dotted lines leading up to the gore shall be 12 in. wide. For all other roadway types, edge line and lane lines are typically 6 in. wide.

NDOT was using Botts' dots and had no plans to remove them.

The decision to increase lane line widths was due to comments from OEMs. Addressing safety for regular drivers, and particularly older drivers, was also a factor in their decision to increase lane line width.

The only additional costs indicated were for additional paint. They noted that the cost for paint was approximately $10 per gallon. Presumably, the change from 4 to 6 in. would increase paint costs 50% and from 6 to 8 in. would increase costs by one-third.

Costs for the increase in lane line widths were included in each district's operating budget and had not been specifically called out as a line item. They felt the improvement in safety was worth the additional cost.

6.4.10 New Hampshire Pavement Marking Practices

New Hampshire DOT (NHDOT) implemented wider edge lines, but not specifically for AVs; 6 in. markings were used on interstates and limited-access facilities, primarily for safety. One application in particular was the use of extension lines on highway exit ramps. The original intent was for guidance for human drivers. NHDOT had discussed whether they should also apply extension lines along entrance ramps, but had not decided to implement those. Safety was the main reason for implementing 6 in. markings on exit ramps.

Specific costs were not available for the 6 in. lines. No additional equipment was needed, so the cost was primarily for the extra paint. They had been applying these for 10 to 15 years. They did note that the markings were milled in and that durable markings were used.

Although their exit marking program had been in place for some time, the work was initially done using a contractor that was already laying paint and just added the extension. As a result, no specific costs for that were available.

The NHDOT representative did not think that the wider edge lines resulted in any less maintenance given that the main metric is retroreflectivity rather than the amount of marking remaining. They noted that they do have retroreflectivity standards for pavement markings, but none specific for AVs.

6.4.11 Washington State Pavement Marking Practices

Washington State DOT (WSDOT) was following California's lead in removing Botts' dots and Type 1 raised pavement markings (RPMs). The plan was to leave them in place until they wear off. However, regions were able to determine whether to remove them or not. As a result, WSDOT was not unilaterally removing these treatments.

Their standard pavement marking was 4 in. They were conducting trials with wider edge lines. The objective was to have higher contrast between the markings and roadway. They did note that their resources could be spent on fully funding 4 in. edge lines at locations where not currently required rather than on widening pavement markings.

WSDOT also implemented off-ramp edge extensions in areas with fog. This included about 20% of exit ramps. Originally, it was for human drivers. At the time, they were extending during normal repainting to meet AV needs. The change was being implemented in their standard plans.

Also, they had done additional pavement markings in other areas, such as adding lane lines in roundabouts (brighter entry or yield lines). Forty roundabouts had received the markings and WSDOT planned to implement these at all 250 roundabouts within three years.

They had also implemented high-performance markings in one corridor.

WSDOT had adopted the use of 6 in. markings in the eastern half of the state and 4 in. high-build waterborne paint in the western half (Carlson 2021).

6.5 Increased Maintenance Needs for Pavement Markings to Accommodate AVs as Reported by State DOTs

Given that national AV pavement marking standards are not yet available, the maintenance impact is not known, but is likely to increase maintenance and possibly the frequency of restriping. On the other hand, wider markings and the use of more grooving and more durable marking materials could result in less maintenance. Additional studies will determine how this will play out, and a shift in terms of maintenance funding allocations could occur. As more AVs enter the US vehicle fleet, a significant crash reduction rate (such as that for lane departure crashes) could emerge, provided the vehicle technology performs as promised. Hypothetically, shoulder rumble strips and pavement edge treatments may become less useful than a well-maintained edge line.

Several of the state representatives interviewed provided feedback on maintenance needs as documented in the sections that follow. In general, none of the agencies felt that maintenance needs had increased due to the use of wider edge lines, dotted extensions through ramps, or more durable markings. Conversely, none indicated less maintenance was needed with more paint being present in 6 in. markings. However, none of the agencies had yet established standards or best maintenance practices for AVs.

The maintenance contractors noted that they had not yet seen any requests for changes in pavement marking maintenance.

6.5.1 California AV Pavement Marking Maintenance Needs

Caltrans had not planned for increased maintenance for wider lane lines, nor had they collected data on maintenance costs for striping since the 2017 change in standard.

6.5.2 Colorado AV Pavement Marking Maintenance Needs

CDOT had challenges with maintenance of markings on interstates and freeways. Additionally, five new paint trucks were purchased; however, it was not specified whether this was necessary to accommodate the additional installation and maintenance requirements for the wider edge lines or was a needed purchase for all pavement marking maintenance.

6.5.3 Georgia AV Pavement Marking Maintenance Needs

GDOT noted that maintenance levels are important for pavement marking initiatives. The provision of striping was noted as a labor job, not a materials job. The GDOT view was that the cost difference for wider stripes and different configurations was not meaningful but were instead based on essentially no change to the frequency of maintenance. It should be noted that the GDOT highway system overwhelmingly consisted of asphalt material.

6.5.4 Kentucky AV Pavement Marking Maintenance Needs

The KYTC reported that most districts stripe every year. No additional metrics were added for 6 in. markings. Painting was typically contracted out.

6.5.5 Minnesota AV Pavement Marking Maintenance Needs

No relevant maintenance information was obtained from MnDOT.

6.5.6 Nevada AV Pavement Marking Maintenance Needs

NDOT was maintaining pavement markings on the same schedule as they had previously. They had not seen any notable change in maintenance for pavement markings, except the additional cost for increased width.

In terms of retroreflectivity, NDOT indicated they do not have the resources or workforce to keep pavement markings at the desired level. Additionally, they were using Botts' dots, which they said also made maintenance difficult.

6.5.7 New Hampshire AV Pavement Marking Maintenance Needs

Specific costs were not available for the 6 in. lines. No additional equipment was needed, so the cost was primarily for the extra paint. They had been applying these for 10 to 15 years. They did note that the markings were milled in and that durable markings were used.

Although their exit marking program had been in place for some time, the work was initially done using a contractor that was already laying paint and just added the extension. As a result, no specific costs for that were available.

The NHDOT representative did not think that the wider edge lines resulted in any less maintenance since the main metric is retroreflectivity rather than the amount of marking remaining. They noted that they do have retroreflectivity standards for pavement markings, but none specific for AVs.

6.5.8 Washington State AV Pavement Marking Maintenance Needs

WSDOT had maintenance standards for pavement markings. Additionally, they had purchased two mobile retroreflectivity machines to do readings.

Washington State (2019) estimated the cost for WSDOT to implement 6 in. markings. The estimate was based on standard bead 15 mil paint for eastern Washington, which has a drier hot/cold climate, and an all-weather bead 22.5 mil high-build paint for western Washington, which has a wet, temperate climate. The estimated additional cost was $3.5 million annually. No information was provided about additional maintenance to maintain retroreflectivity standards or different equipment to place 6 in. versus 4 in. lines.

6.6 Standards, Guidelines, or Best Practices for Maintenance of Pavement Markings for AV Applications

National or otherwise proposed requirements for pavement markings based on AV needs were not currently available. Research was starting to show that the retroreflectivity needed for nighttime conditions was less than that for humans. However, the same research was also starting to show that daytime conditions can be more challenging for AV systems than nighttime conditions. As a result, some research studies were recommending that a minimum contrast ratio be established to help ensure that camera systems can robustly detect the markings.

To implement such a metric, American Society for Testing and Materials (ASTM) international test methods and specifications that do not yet exist would need to be established. Of course, before that, more study of the existing equipment that might be able to measure contrast is needed. Therefore, a fair amount of work is still needed to establish AV standards for pavement markings. A similar need was identified by Congress when they mandated that the FHWA include minimum retroreflectivity levels for pavement markings in the MUTCD in 1993. That work is still underway, although the FHWA recently reported it to be completed about the same time as the new MUTCD is released (on or before March 2023).

6.7 Workforce Needs for Maintenance of Pavement Markings for AVs

Although national standards are not yet available and the maintenance impact is unknown, it is not anticipated that pavement marking maintenance will require additional workforce skills. One of the most critical aspects of a long-life pavement marking is proper preparation and installation.

Today, very few qualified DOT inspectors know what to look for when inspecting a pavement marking job, at least partly because retroreflectivity by itself does not provide an indication of whether the marking was installed correctly. It is not difficult to provide a newly installed pavement marking that will meet initial retroreflectivity requirements. However, the retroreflectivity may be short-lived, the line might be thinner than specified, and the adhesion might be less than desired. In some states, the only criterion that a newly installed pavement marking must pass is initial retroreflectivity.

DOT inspectors will likely need to become better informed. Organizations such as the American Traffic Safety Services Association (ATSSA) have discussed how to improve their pavement marking education offerings to accommodate this anticipated need, but no official movement on training has started. This will be an area that will need to be developed, as pavement markings appear to be growing in their importance to provide a safe and AV-ready roadway.

6.8 Summary of Maintenance Information for Pavement Markings for AVs

Pavement markings are growing in terms of their importance to provide a safe roadway for human drivers as well as an AV-ready roadway. AV developers have stated that pavement markings are one of the most useful physical infrastructure assets used to provide certain vehicle automation features. Based on the results of research, industry engagement, and surveys, the FHWA has started the process of updating the MUTCD with new provisions to tighten national uniformity on pavement markings—with the intent to improve safety for human drivers as well as for AVs.

Many agencies are already starting to upgrade their pavement marking practices knowing that their maintenance needs may also increase. Research is starting to show a path that is needed to establish AV pavement marking standards, although that work seems years out. As it progresses and a deeper understanding of how pavement markings can support AV deployment is realized, some workforce development will also likely be needed in terms of training DOT inspectors to be more informed when inspecting newly installed pavement markings.

CHAPTER 7

Infrastructure-Based Cameras for CAV Applications

7.1 Description of Infrastructure-Based Cameras

Digital camera and image processing units are commonly used for traffic (and security) surveillance. Image processing units analyze videos and images from cameras and convert them into traffic data. Visual systems are advantageous due to large coverage areas and can replace multiple inductive loop detectors and other detection sensors. The main challenges with camera systems are their limitations in unfavorable environmental conditions, cost, and processing power requirements. Cameras in the context of connected and autonomous vehicle (CAV) technology are typically used as sensors in conjunction with other systems.

7.2 Gathering Maintenance Information for Camera Uses Specific to CAVs

Information was initially gathered through the survey of state department of transportation (DOT) maintenance practices, interviews with state DOTs and cities, contact with vendors, and interviews with maintenance contractors (as described in Chapter 2). General information about use of cameras for CAVs was gathered during the initial phase of this work and is summarized in Section 7.3 that follows.

Information gained during Phase I was presented to the NCHRP panel at the end of Phase I. Cameras were not a high priority item, but panel members were interested in gathering additional information about increased maintenance of digital cameras for pedestrian and bicycle detection systems in particular. As a result, the team identified vendors that had a camera system for this application, and each vendor was contacted and asked about life cycle, regular maintenance, and whether any additional maintenance was suggested for applications specific to pedestrian or bicycle detection. Information specific to use of digital cameras for pedestrian and bike detection is summarized in Section 7.4.

7.3 General Camera Applications for CAVs

Initial survey results indicated that none of the 39 DOTs that responded to the agency survey had added cameras to accommodate CAVs. Nine had increased and two had modified cameras. Five DOTs noted that they had plans to add cameras in the next 3 years, 13 planned to increase cameras, and two planned to modify cameras. None specified what their applications were.

One DOT had added image processing units, and two had increased image processing units. Three DOTs planned to add image processing units in the next 3 years, six planned to increase them, and three planned to modify them.

Several infrastructure owner operators (IOOs) were asked about a subset of assets that they had implemented to address CAV technology. Responses specific to cameras are provided in the subsections that follow.

7.3.1 Michigan Camera Applications for CAVs

Michigan DOT (MDOT) noted that they were utilizing image processing for snowplows. However, the application was not specifically for CAVs.

7.3.2 Nevada Camera Applications for CAVs

The City of Las Vegas had a partnership between the Southern Nevada Traffic Management Center (SNTMC) and Waycare, a startup technology firm. An experimental pilot was developed using the Waycare platform, which shared and analyzed data between the coordinating agencies in 2017. Waycare used a cloud-based system that collected information from cameras, in-vehicle data, mobile apps (like WAZE), and weather and traffic sensors. Artificial intelligence (AI) aggregated real-time and historical traffic incident data to identify locations where potential traffic incidents were possible.

Nevada Highway Patrol (NHP) vehicles had automatic vehicle locating (AVL), so all vehicles could be tracked. Cameras could be repositioned to view incidents and record a video of the incident, and the coordination allowed for the sharing of information, such as the location of 911 calls and traffic information (e.g., congestion, queues). NHP troopers were able to view active and potential incidents and to prioritize resources and respond more quickly. Responder vehicles were also outfitted with AVL and tablets, so responders could login and view the system as well as enter real-time data. Las Vegas dispatchers were also able to log disabled and abandoned vehicle calls, which allowed integration of data into the system (NOCoE 2019).

When actual incidents or a location that appeared to be high risk for a crash was identified, partners were contacted so they could respond. Predictive data helped NHP get ahead of potential crashes. In addition, dynamic message boards delivered an initial warning, which let drivers know to reduce speed and pay attention.

In this context, the camera and image processing were similar to typical traffic operation or intelligent transportation system (ITS) applications.

7.3.3 New Hampshire Camera Applications for CAVs

New Hampshire DOT (NHDOT) had piloted the use of cameras to assess congestion on the interstate. The system could only track in real time since no recording was allowed due to privacy issues. Additionally, NHDOT made changes to cameras at intersections. This was an enterprise solution that could interface with any type of camera. They had also reviewed cameras with different processing speeds and resolution. The changes to cameras at intersections were not specifically for CAV.

7.4 Description of Camera-Based Pedestrian and Bicyclist Detection Systems

Infrastructure-based digital cameras and image processing are well-established assets primarily used for traffic monitoring and surveillance. As noted above, most of the IOOs asked about use of cameras for CAV applications responded about their general use of cameras.

Infrastructure-based cameras in the context of CAV technology are typically used as sensors in conjunction with other systems. The main CAV applications are detection of pedestrians or bicyclists for smart intersection or pedestrian crossing applications (either at a signalized intersection or at a mid-block crossing).

At signalized intersections with actuated pedestrian phases, pedestrian detection can be used for one or more of the following: truncate the pedestrian phase if no pedestrians are detected, extend the phase if additional pedestrians are present, notify vehicles of pedestrian presence (Larson et al. 2020). At mid-block crossings, a system detects the presence of pedestrians that may not have activated the pushbutton and then triggers the pedestrian signal or other warning device to alert drivers. A system can also provide notifications to surrounding vehicles through vehicle-to-infrastructure (V2I).

In addition to cameras, some pedestrian or bicyclist detection systems use thermal sensors, infrared, radar, ultrasonic, laser scanner, or piezoelectric technology (Steindel n.d.). However, only digital video cameras are included in the scope of this report.

7.5 Examples of Application of Pedestrian and Bicyclist Detection Systems

Agencies that have implemented pedestrian or bicyclist detection applications were identified. Given that none were identified in the survey or interviews with state and local agencies, the agencies were primarily found through a web search. Six agencies were identified as having pedestrian or bicycle detection systems as described in the following sections.

7.5.1 Gainesville, Florida Pedestrian Detection System

Florida DOT (FDOT) implemented a passive pedestrian detection technology at 13 signalized intersections and eight mid-block crosswalks at the University of Florida campus to improve pedestrian safety, as shown in Figure 7-1.

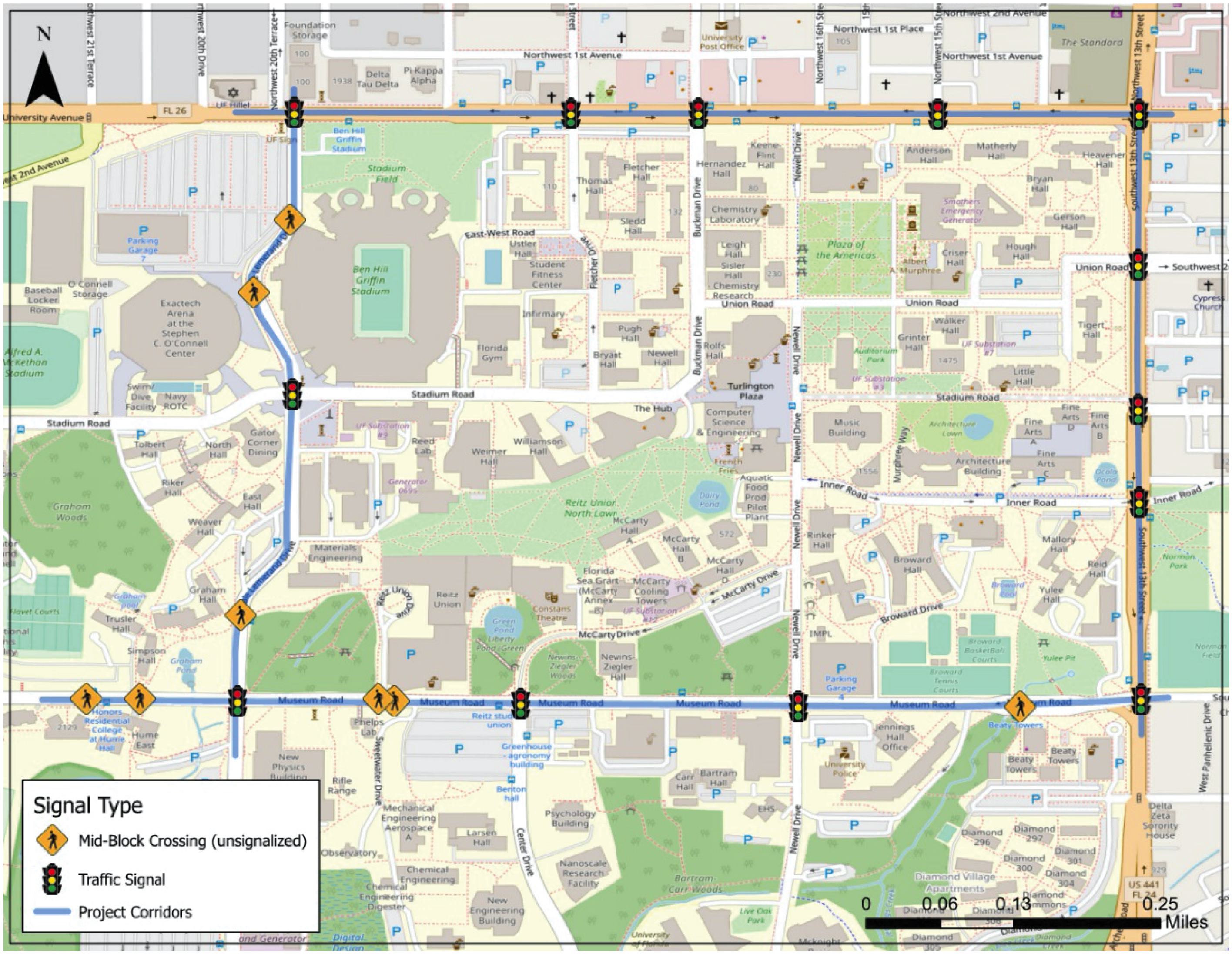
The system included roadside units (RSUs), passive pedestrian detection systems, on-board units (OBUs), and rectangular rapid flashing beacons (RRFBs). The detection systems included infrared, microwave, thermal sensors, pressure mats, and cameras. Additionally, the researchers were working on a smart app for pedestrian detection (Tillander and El-urfali 2019).

7.5.2 Dunedin, Florida Pedestrian and Bicyclist Detection System

A passive detection system for bicyclists and pedestrians was installed along the Fred Marquis Pinellas Trail and Skinner Boulevard in Pinellas County, Florida (City of Dunedin). It was noted that thermal sensors and cameras were linked to an installed RRFB (Kissel 2020).

7.5.3 Miami-Dade, Florida Pedestrian Detection System

Miami-Dade used video-detection technology to identify pedestrians to put in a call to a mid-block traffic signal on Alton Road. They used an Autoscope camera and processor, and two zones were created on the sidewalk approaching the curb. The system identified the presence of a pedestrian and the direction of vehicle travel to determine if a call to the signal needed to be placed. Miami-Dade noted maintenance needs were as of yet unknown, but expected maintenance would be similar to that for other camera systems (University of Florida Department of Civil and Coastal Engineering and Miami-Dade County Department of Public Works 2008).



Source: https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/bikesafety.shtm.

Figure 7-1. Pedestrian detection applications in Gainesville, Florida.

7.5.4 Tucson, Arizona Pedestrian Detection System

Tucson, Arizona installed a modified pedestrian signal that was equipped with active and passive pedestrian detectors [Pedestrian User-Friendly Intelligent Intersection (PUFFIN)] at 8200 East Broadway Boulevard. The system was installed in 2003 (McGrane 2013).

7.5.5 Washington County, Oregon Pedestrian and Bicyclist Detection System

Larson et al. (2020) evaluated optical and thermal sensors for a dynamic passive pedestrian detection (DPPD) system, which was installed at one signal (Scholls Ferry Road and Nimbus Avenue) and one mid-block crossing (Evergreen Parkway and Rock Creek Trail) in Washington County, Oregon. The optical system was a 4K resolution, fisheye lens camera with a 182-degree horizontal view and 176-degree vertical view. The camera system was able to differentiate between pedestrians, bicyclists, and types of vehicles.

The researchers found a common problem with the camera system was occlusion of the pedestrian by a heavy vehicle or movement of the camera by gusts of wind. They also found that shadows had the potential to cause false detection. Typical weather (dry, rain) did not appear to affect the camera's ability to detect. Conditions such as snow or fog were not evaluated.

7.5.6 San Francisco, California Pedestrian Detection System

San Francisco installed a pedestrian detector at Howard and 9th Street. The system used an Econolite camera (San Francisco Municipal Transportation Agency and University of California Traffic Safety Center 2008). They noted that the detector's camera required physical adjustment to ensure it was positioned to the crosswalk. No other maintenance needs were noted.

7.6 Maintenance Needs for Cameras for Pedestrian and Bicyclist Detection Applications

None of the agencies interviewed had experience in maintaining cameras specific to pedestrian and bicyclist detection systems.

7.6.1 Video-Detection Camera Life Cycles

Two of the vendors noted that most video-detection cameras are warrantied for 3 years with options of extending for up to 5 years. One vendor noted an average life span of 10 years and the other noted the mean time to failure was 12.8 years. One indicated some of the newer cameras were less robust due to changing technologies and may fail sooner than 10 years. The third vendor indicated an expected life cycle of 10 years but said that many agencies use 7 years to program funding. They also noted some vendors had cameras in place for at least 22 years. As a result, the average life cycle for cameras was estimated at about 10 years.

7.6.2 General Maintenance Needs for Video-Detection Cameras

All vendors recommended regular cleaning of the camera lenses to remove dirt or grime build up (regardless of the application). Two recommended annual maintenance, which included cleaning and tightening bracket screws. One indicated cleaning was most important in situations in which the camera is placed in a location where trucks could cause splashing of dirt and other residue (e.g., camera being placed low on a mast arm). They indicated some customers only do regular maintenance in these situations, and a cleaning cycle of 6 months was recommended. Two vendors also noted that, in more severe environmental conditions, more frequent cleaning is required. It was also suggested that, in these situations, agencies periodically track visibility to understand how these factors impact the visibility of the cameras.

Vendors also recommended that camera position be monitored to ensure it does not deviate from its original position. Although this is not expected to be a common problem, it may occur with excessive wind or poor installation.

It was noted that another factor to consider is deterioration of cables due to ultraviolet (UV) rays (even when they are jacketed with UV protection). As a result, it may be necessary to replace the cables or connectors periodically.

One of the maintenance contractors conducts maintenance on cameras. While not specific to pedestrian or bicyclist detection systems, they noted that they have conducted monthly maintenance of ITS equipment including cameras. This included ensuring the cameras were working properly, as well as cleaning the camera if needed. They also noted one of their clients randomly checks assets such as cameras 4 times a year.

7.6.3 Maintenance and Resource Needs Specific to Pedestrian and Bicyclist Detection Systems

Several agencies were identified as having camera-based pedestrian or bicyclist detection systems (section 7.5) and noted maintenance issues. In particular, they noted proper positioning of the camera was necessary to ensure they are operating properly and angled correctly to the sidewalk, crosswalk, or other desired location (San Francisco Municipal Transportation Agency and University of California Traffic Safety Center 2008; Larson et al. 2020). Given that pedestrians and bicyclists are smaller objects than vehicles, lens visibility may also be a concern that requires more frequent cleaning.

Vendors did not recommend specific additional cleaning for pedestrian or bicyclist detection. One vendor felt that due to AI and camera detection capabilities, some identification of maintenance issues could be detected by the camera system. One did note that, while no additional maintenance needs to be programmed, agencies should be aware that, due to the size discrepancies between pedestrians or bicyclists and vehicles, a greater impact on detection would be noted if the camera had dirt or grime buildup or was misaligned.

Given that agencies already have experience maintaining cameras for other applications, no additional resources were anticipated.

7.6.4 Common Failure Issues for Video-Detection Cameras

A common failure issue noted was cameras becoming misaligned primarily due to wind. No additional failure issues specific to pedestrian or bicyclist detection were noted.

7.7 Standards, Guidelines, or Best Practices for Maintenance of Cameras Used in Pedestrian and Bicyclist Systems

Traffic-based cameras are a mature application. No standards or guidelines specific to pedestrian or bicyclist detection systems were noted. However, as outlined in section 7.6.3, most vendors have a recommended maintenance schedule (best practices).

7.8 Workforce Needs to Address Camera Maintenance Specific to CAV Applications

The expected maintenance for cameras, which includes cleaning, checking cables, and ensuring line of sight, was already managed by agencies for other camera applications. As a result, no additional workforce skills were anticipated.

7.9 Summary of Maintenance Needs for Video-Detection Cameras

Infrastructure-based cameras in the context of CAV technology are typically used as sensors in conjunction with other systems. The main CAV applications are detection of pedestrians or bicyclists for smart intersection or pedestrian crossing applications.

Cameras are a mature technology. Vendors noted an average life cycle for cameras was about 10 years regardless of the application. No standards specific to pedestrian or bicyclist detection were noted, but agencies have recommended maintenance schedules for cameras in general. Maintenance needs specific to pedestrian and bicyclist detection include ensuring proper positioning of the camera and regular cleaning, neither of which is expected to increase maintenance costs or to impact workforce needs.

CHAPTER 8

Sign Maintenance for AV Applications

8.1 Description of Signing

The need to interpret traffic signs is primarily an autonomous vehicle (AV) application. The first generation of AVs use optical cameras for traffic sign recognition (TSR). As a result, the vehicle's machine vision (MV) system has to first notice and then interpret the lettering, symbol, or other sign messages (McMahon 2018). Although a number of approaches exist for TSR, the process primarily consists of three stages. The first is region segmentation, where color is recognized. Next, shape analysis classifies the sign into primary shapes (e.g., circle, rectangle), and the third stage identifies class and meaning (Wahyono et al. 2014).

MV systems are used to classify the sign using feature extraction and then match the information to a library of images to identify the sign message (Snyder et al. 2018). Neural networks evaluate differences such as differences in angles, sign condition, light levels, and weather conditions. The more traffic control devices a vehicle's camera "sees," the more it is able to store and interpret differences. However, the more standard a sign is, the more likely an AV application is to correctly identify the sign.

Current AVs use optical cameras and machine visioning, which capture and then classify objects, such as street signs, using feature extraction and matching (Snyder et al. 2018). Similar to pavement markings, current AV systems are confused by damaged, faded, or noncompliant signs (Sage 2016). Current AV systems also rely to a greater degree on signing to provide needed information. As a result, AVs require signing to be consistently placed and may require a higher level of maintenance than the current practice provides (Johnson 2017). In addition, smart signs may become the norm, which may require different asset management practices. (Smart signs are covered in Chapter 12.)

A survey of AV industry players, including car and truck manufacturers, technology providers, and software developers, identified the most significant infrastructure issues for AVs (Chan and Wang 2021). Issues identified relative to traffic signs included challenges with sign recognition when signs are visually obstructed (e.g., tree branches or vegetation). They also noted signs were problematic when they were either too bright under high beam illumination or too dark to be recognized due to low contrast. Another issue noted was ambiguity in what the sign applied to due to sign location or angle.

8.2 Gathering Maintenance Information for Signing for AV Applications

Information was initially gathered through the survey of state department of transportation (DOT) maintenance practices, interviews with state DOTs and cities, contact with vendors, and interviews with maintenance contractors (as described in detail in Chapter 2). Information gained during Phase I was presented to the NCHRP panel at the end of Phase I. After discussions at the conclusion of Phase I, panel members showed interest in gathering any new information that was available about maintenance of sign systems, but this was not the focus of subsequent interviews. As a result, an additional literature review was conducted, and all the available information is summarized in the sections that follow.

8.3 Examples of Signing Applications for AVs

Of the 39 DOTs that responded to the agency survey (Chapter 3), seven indicated that they had added pavement markings or signing, 14 had increased, five had modified, and two had removed them to accommodate AVs. Additionally, 11 had plans to add pavement markings, signing, or both in the next 3 years. Sixteen had plans to increase, eight had plans to modify, and two had plans to remove in the next 3 years.

None of the 10 DOT representatives interviewed provided additional information about changes to signing.

8.4 Maintenance Needs for Signs Specific to AVs

8.4.1 Typical Sign Maintenance and Frequency

Currently, no standards exist for maintenance of signs specific to AVs. However, typical sign maintenance includes regular clearing of vegetation to ensure line of sight or replacement to maintain visibility.

8.4.2 AV Impacts on Sign Maintenance

Maintenance impacts were expected to be minimal in the short- to medium-term given that no standards or guidelines were available. One maintenance vendor that was interviewed did note that they were seeing an increased emphasis on retroreflectivity. In general, they were seeing a trend toward a demand for signing and markings to be more visible. However, they indicated that they had not yet seen any recommendations for performance specifications.

8.5 Standards, Guidelines, or Best Practices for Use and Maintenance of Signs Specific to AVs

No standards or guidelines for sign maintenance were found specific to AV needs. A number of recommendations were made, which were relevant to both maintenance and placement.

8.5.1 Consistent Application of Signs

One of the most common recommendations relevant to signing was consistency. This applies to standardization in sign message, placement, and application. Roper et al. (2018) evaluated TSR under real world conditions in Australia. One key finding was that electronic signs could not be consistently read by TSR, which may be due to differences in illumination, refresh rate, sign size, height, and approach angle. Results of a stakeholder workshop, which included original equipment manufacturers (OEMs), road agencies, and suppliers and manufacturers, indicated that application, uniformity, and design of traffic signs can be problematic (Gopalakrishna et al. 2021).

The most cited concern with signing was consistent application (FHWA 2017). Consistent application entails placing signing at regular locations, heights, and angles. For instance, curve warning signs or chevrons are not always placed the same from location to location. As a result, a curve with a certain radius may be signed in one location and not in another. It has also been suggested that signs be installed on both sides of the roadway and in standard locations (Carlson 2021; Gopalakrishna et al. 2021). Recommendations from a National Committee on Uniform Traffic Control Devices (NCUTCD) Connected and Automated Vehicle (CAV) Task Force indicated that speed limit signs should be placed to ensure they are clearly associated with the corresponding lane or roadway (Carlson 2021).

Other recommendations for consistency include standardization for particular signs. Recommendations from the NCUTCD CAV Task Force included specific recommendations for school zone signing as follows:

- Use of yellow SCHOOL sign directly above speed limit sign.
- Standardized text for condition school signing (e.g., WHEN CHILDREN ARE PRESENT).
- Consistent sign height and width.
- Use of END SCHOOL ZONE with no additional text for end school zone signs.

Another recommendation from stakeholder workshops (Gopalakrishna et al. 2021) was use of pictograms versus text when possible (an example is provided in Figure 8-1).

The NCUTCD CAV Task Force and stakeholder surveys also suggested consistent use of a stop line or yield line for YIELD HERE TO PEDESTRIANS signs (Carlson 2021).

8.5.2 Consistent Maintenance of Signs

Consistency also entails ensuring signs are in similar conditions (Gopalakrishna et al. 2021). Current AV software uses neural networks, which "learn" to identify objects through studying a library of images (Bliss 2017). As a result, nonstandard, blocked, damaged, or faded signing (Figure 8-2) can result in misclassification.

Sources: Jeffrey Wright/Shutterstock.com (left); Mike Kuhlman/Shutterstock.com (right).

Figure 8-1. Use of text (left) versus symbols (right) for signing.

Sources: FHWA (left); Structured Vision/Shutterstock.com (middle); BHamms/Shutterstock.com (right).

Figure 8-2. Examples of problematic signage with sign blocked **(left)** ***and damaged signs*** **(middle and right)*.***

Sign maintenance is important because faded or damaged signs are difficult for both humans and AVs to read. Roper et al. (2018) evaluated TSR under real world conditions in Australia and noted that TSR systems could not handle significant variations in sign maintenance (e.g., different levels of retroreflectivity or color). High levels of retroreflection are also often cited as a need by the AV industry (Carlson 2021). As a result, consistent maintenance standards are needed.

Consistent maintenance may also include ensuring sensor line of sight is not blocked, specifically at intersections, and clearing space along road edges to allow for higher speed operations, which requires additional vegetation control.

8.5.3 Electronic Sign Recommendations

Another challenge for AVs is reading light-emitting diode (LED) signs, such as variable message signs, which may be due to the refresh rate and legibility issues attributable to LED luminance that can appear to have bleeding between alphanumeric characters and can make the sign difficult to read (Huggins et al. 2017).

Results of the NCUTCD CAV Task Force and stakeholder surveys indicated consistent refresh and flicker rates are also needed, so the signs can be more easily detected and identified by AVs (Gopalakrishna et al. 2021). One recommendation was a refresh rate for LEDs greater than 200 Hz. If the refresh rate is standardized for all electronic signs, AV systems can detect them more easily (Carlson 2021).

8.6 Workforce Needs for Maintenance of Signs Specific to AVs

Sign maintenance includes replacement of worn signs and vegetation management, which are currently performed by agencies. As a result, no additional workforce needs were noted.

8.7 Summary of Maintenance Needs for Signs Specific to AVs

AVs use optical cameras and machine visioning to interpret signs. Current AV systems find damaged, faded, or noncompliant signs more challenging to interpret than human drivers. No guidelines existed for sign maintenance specific to AVs. However, some recommendations had emerged from OEM stakeholders, suggesting consistency in use, placement, and maintenance are desired. The recommendations were similar to requirements at the time of the study, and as a result, do not require any additional workforce skills.

CHAPTER 9

Traffic Signal Controllers for CAV Applications

9.1 Description of Traffic Signal Controllers

It is expected that connected vehicles (CVs) will ultimately integrate with traffic signals and rely on traffic signal controllers that generate signal phase and timing (SPaT) messages, including green, yellow, red, and the amount of time until the next phase. Early applications for intersection components had only included roadside units (RSUs) and dedicated short-range communication (DSRC). As a result, these applications were the same as those described in Chapter 4. Autonomous vehicles (AVs) also need to be able to interpret traffic signal phases, usually through image recognition.

Smart intersections were one application that had been piloted for connected and autonomous vehicles (CAVs) and will require additional components. Smart intersections use an array of infrastructure-mounted sensors for object detection. The systems allow intersections to adapt and better manage demand. They can function independent of CAVs, but are also capable of broadcasting messaging. In addition to regular equipment, the signal cabinet at a smart intersection includes a plurality of equipment depending on the intended applications. The equipment in the smart signal cabinet includes the following:

- **Automatic traffic controller (ATC):** e.g., Siemens 2070 traffic signal controller or Cobalt rack mount controller.
- **ATC processor [or central processing unit (CPU)]:** For example, 1C CPU was used for ATC in a Salem, Oregon signal phase and timing (SPaT) Challenge Project. This type of CPU is commonly used with a 2070 traffic signal controller.
- **Memory:** This is used to store security certificates, application data, etc.
- **Multi-modal intelligent traffic signal system (MMITSS) and MMITSS roadside processor (MRP):** e.g., the Savari StreetWave processor was used in Arizona (Multi-Modal Intelligent Traffic Signal System: System Design—California Portion 2016).
- **Managed field Ethernet switch (MFES) or Ethernet switch.**
- **GPS receiver and antenna reference point (ARP).**
- **RSU:** DSRC or cellular.
- **Power supply:** A centralized power supply assembly able to provide power to all units or appropriate power supplies for the ATC, ATC processor, and wireless communication device's processing units. All controllers already have a source of power.
- **Input/output (I/O) assembly.**
- **Power over Ethernet (PoE) switch and required accessories such as cables and splitters.**
- **Message processor for roadside equipment (RSE).**
- **Backhaul modem.**
- **Wireless transmitter-receiver unit other than RSU:** This unit is required for communication between the ATC and sensors, lights, audio devices, etc. These are short-range radio access channels with 20 to 300 m of range and work in frequencies at about 430 to 900 MHz.

- **Sensor controller or processing units:** These vary depending on the type, configuration, and number of sensors.
- **Cameras or other sensors:** Applications such as pedestrian detection require video, thermal, or other types of cameras.

9.2 Gathering Maintenance Information for Traffic Signals for CAVs

Information was initially gathered through the survey of state department of transportation (DOT) maintenance practices, interviews with state DOTs and cities, contact with vendors, and interviews with maintenance contractors (as described in detail in Chapter 2). Information gained during Phase I was presented to the NCHRP panel at the end of Phase I. After discussions at the conclusion of Phase I, panel members showed interest in gathering any new information that was available about maintenance of traffic signals, but traffic signals were not the focus of subsequent interviews. As a result, an additional literature review was conducted, and all the available information is summarized in the sections that follow.

9.3 Examples of Applications of Traffic Signals for CAVs

Of the 39 DOTs that responded to the agency survey, five indicated they had added, six had increased, and six had modified traffic signal controllers to accommodate CAVs. In the next 3 years, six planned to add, eight planned to increase, and 12 planned to modify traffic signal controllers to accommodate CAVs.

In total, 10 DOTs were questioned about a subset of assets that they had implemented to address CAVs, and three were asked about implementation of traffic signal controllers (Florida, Kentucky, and Minnesota). Responses are summarized in the subsections that follow.

9.3.1 Florida Traffic Signals for CAVs

Florida DOT (FDOT) was spending roughly $50 million per year on maintenance of 8,600 traffic signals and was adding CAV equipment as the signal equipment was maintained. The state had an arrangement where the DOT provided the maintenance funding, but individual municipalities operated the traffic signals.

9.3.2 Kentucky Traffic Signals for CAVs

The Kentucky Transportation Cabinet (KYTC) had switched to automatic traffic controllers (ATCs) (Intelight 2070 ATCs running MaxTime). The controllers were being managed through a central software suite called MaxView. The decision had been made to replace aging 170 Wapiti controller architecture with an upgraded model. The controllers were being implemented statewide.

The decision to replace the aging 170 Wapiti controller architecture was not to accommodate CAVs, but to help facilitate integration of CAV technology. The decision for placing controllers was made primarily by their central office working with the districts to select the corridors. The KYTC had been implementing 2,070 controllers over 5 years.

The new controllers were Intelight 2070 ATCs running MaxTime. The DSRC radios were WAVEMOBILE Fiberwire 8011 RSU/OBU Radio.

9.3.3 Minnesota Traffic Signals for CAVs

Minnesota DOT (MnDOT)'s first deployment of CAVs was on the TH 55 corridor for the American Association of State Highway and Transportation Officials (AASHTO) SPaT Challenge. The deployment included 22 intersections from downtown Minneapolis to the west to the I-494 corridor. The earliest discussions had occurred in 2015 and considered manufacturer solutions that were viewed as a black box. The goal was to learn about DSRC. At this stage, they had 18 months of experience transmitting SPaT and MAP messages. They were connecting this message reporting to data portals (Greenhill was the vendor). The TH 55 corridor deployment used an Intelight controller, although the project started with Econolite. Intelight MaxView was the MnDOT traffic or transportation management center (TMC) central software. The agency had been looking to improve the central software to provide application programming interface (API) access or feed a data portal with SPaT/MAP message data.

Another deployment was planned with newer technology for Smart Snelling Avenue—a deployment of 13 units with cellular communication that could be read or accessed using a smartphone. The Smart Snelling deployment would use Econolite.

Across both corridors, the state was using two standard vendors for traffic signals statewide. From experience with these two vendors, MnDOT was seeing CAV-ready controllers becoming standard.

Both corridors were looking at a priority solution for mobility. MnDOT was focusing their priority on snowplows with on-board units (OBUs) for signal request messaging. The snowplows only had test priority at a demo of four intersections. However, MnDOT had 22 snowplows equipped with DSRC from their research budget. The vehicles could perform vehicle-to-vehicle (V2V) communications and had been focused on lane-keeping solutions, with research currently happening on a MnDOT-owned or sponsored test track. The snowplows were also part of an agency weather information decision support system that was pulling data back to the central office, fusing and processing data and decision support, and then recommending treatments to the fleet.

Financial backing came from state highway funding, and more specifically, a split between highway funding and research dollars institutionalized over time based on standard intelligent transportation system (ITS). The TH 55 corridor improvements cost $1 million and the Smart Snelling deployment cost $0.5 million.

9.4 Maintenance Needs for Traffic Signals for CAVs

Short- and mid-term maintenance needs will be subject to the adoption of CAV components by agency operators. Electronics have shorter wear cycles compared to rugged transportation infrastructure. A higher level of maintenance attention may be required to address equipment failures and upgrades to ensure they are adequate for CAV needs. Maintenance standards were unknown at the time. The surveyed states that responded about the use of traffic signal controllers were questioned about maintenance needs or practices. Their responses are summarized in the following subsections.

9.4.1 Kentucky Traffic Signal Maintenance Needs for CAVs

KYTC controllers were being replaced as needed at a material cost of about $2,500 per controller. The labor involved was probably about 1 to 2 person-hours per controller replacement.

No performance measures were noted, and no changes had been made to data collection practices.

9.4.2 Michigan Traffic Signal Maintenance Needs for CAVs

Michigan DOT (MDOT) had increased communications capacity for RSUs. Mainly, they had added switches and cell modems to existing sites to power RSUs. They noted that fiber was not available in several areas, so if a location was not already connected, they were adding modems. Signal connectivity allowed them to obtain data, which could be analyzed remotely. Use of the connectivity also allowed MDOT to conduct traffic signal maintenance and fix other issues (e.g., drift) remotely. Ultimately, they planned to change signal timing "on the fly." They had recently contracted with a vendor to assist them with the process. The long-term plan was to have 3,200 signals with communications capability, with 500 going live in 2021.

RSUs had been deployed and were available for vehicles that were able to connect. However, use of the RSUs seemed to be limited by the available applications (e.g., weather specific). Additionally, their snowplows with connectivity options were not using the RSUs. They were doing creative TIM messaging and relaying that information to the associated dynamic message sign (DMS).

9.4.3 Minnesota Traffic Signal Maintenance Needs for CAVs

Signals on the TH 55 corridor had limited maintenance needs to date. MnDOT worked with support from the University of Minnesota. A consultant also provided support for planning and technical support of the installation. The agency direction had been to keep as much work in-house as possible. Both the metro signal and maintenance staff had worked on this equipment.

Maintenance could include the replacement of cabinets and restoration of electrical service from knockdowns. RSU antennas were normally installed on 4 ft mounting poles above the mast arms. MnDOT had documented a location mounted lower to achieve line of sight if it was hit by a vehicle.

MnDOT also had health monitoring software which determined whether locations had communication and power. The health check was being performed once a day. It had resulted in some power resets and the need to push out updates (with three updates needed in 18 months). Contractors had provided support to agency forces that would have long-term, hands-on responsibility.

9.5 Standards, Guidelines, or Best Practices for Application and Maintenance of Traffic Signals for CAVs

No standards or guidelines for traffic signal maintenance were found specific to CAV needs. A number of recommendations, which were relevant to both maintenance and placement, had been made.

Hietpas and White (2019) assessed CAV infrastructure needs and indicated the following needs for traffic signal infrastructure:

- Install traffic signal controllers with SPaT capabilities,
- Assess whether larger traffic cabinets are needed for the future,
- Address electrical code issues for conduit for electrical conductors and Ethernet cabling separately, and
- Develop standards to assess small cell installation or other technology.

One of the most common recommendations relevant to traffic signals was consistency. Recognition of traffic signal presence and state was more complicated than for pavement markings and signing, but less information is available. The National Committee on Uniform Traffic Control Devices (NCUTCD) conducted a survey of the automotive industry to support CAV deployment

Source: Mike Kuhlman/Shutterstock.com (left); viphotos/Shutterstock.com (right).

Figure 9-1. Example of inconsistent signal placement.

and made the following recommendations for traffic signals (NCUTCD 2019; Chan and Wang 2021; Carlson 2021):

- Signals should be uniformly placed; horizontal traffic signals are particularly problematic as shown in Figure 9-1.
- Signals should be standardized, including position, location, color, shape, and refresh rate.
- Back plates may be beneficial for east or west placement, particularly in low sun conditions.
- Signals should have a clear, unambiguous association with a specific lane.
- High and low brightness should be standardized.
- A 12 in. diameter signal head is preferred over an 8 in. signal head.
- Signals that target different classes of vehicles (e.g., cyclist or bus signals) should be placed and located at sufficient distance from each other so that their individual applications can be differentiated.
- Use green lights rather than flashing beacons where possible (e.g., pedestrian crossing control is better as standard green-yellow-red lights rather than flashing red), and STOP and GO directives should be explicit.

9.6 Workforce Needs for Maintenance of Traffic Signals for CAVs

Traffic signal workforce skills already exist in some agencies, but higher adoption of smart intersections could drive up the demands on maintenance staff with these skills. Additional workforce and appropriate training may be a required strategy for agencies leading the adoption of CAV technology and smart intersections.

Additionally, many agencies may contract out maintenance for some electronics-based assets.

9.7 Summary of Maintenance Needs for Traffic Signals for CAVs

It is expected that CVs will ultimately integrate with traffic signals and rely on traffic signal controllers that generate SPaT messages. Early applications for intersection components have only included RSU and communications needs. As a result, maintenance needs are primarily specific to those assets. However, some recommendations had been made specific to AVs, which need to interpret traffic signal state. Recommendations to accommodate AVs were similar to those for signing and included consistency in placement and maintenance.

CHAPTER 10

RWISs for CV Applications

10.1 Description of RWISs for CV Applications

A Road Weather Information System (RWIS) is a set of sensors that collect, transmit, process, and send road weather and pavement condition information. This information may include one or more of the following: traffic flow, meteorological conditions, pavement conditions, stream flow or depth, snow depth, visibility, environmental pollutants, solar and terrestrial radiation, soil temperature, and soil moisture. An RWIS includes hardware and software to process observations that can be used to develop current forecasts. This information can be used to improve traffic and road maintenance operations (Lee et al. 2020). The following are the key RWIS components (Lee et al. 2020):

- Roadside unit (RSU),
- Central processing unit (CPU),
- Telecommunications equipment to transmit data (modem),
- Tower support structure,
- Cabinet enclosure,
- Internet protocol (IP) surveillance system [closed-circuit television (CCTV)],
- Software for end user computer,
- Pavement condition sensor,
- Surface temperature sensor,
- Subsurface sensor,
- Air temperature and relative humidity sensors,
- Wind direction and speed sensor,
- Precipitation sensor,
- Barometric pressure sensor,
- Visibility sensor,
- Presence of precipitation sensor,
- Water-level sensor,
- Solar radiation kit, and
- Traffic sensor [e.g., microwave vehicle detection system (MVDS)].

An RWIS or environmental sensor station (ESS) can provide messages, including road surface and weather condition. As a result, they are primarily a connected vehicle (CV) application.

CVs have some sensors that can provide information on general weather conditions. Machine visioning has been used to detect presence of precipitation (e.g., snow, rain) as well as general road condition (e.g., wet, partially snow-covered) from cameras. Light Detection and Ranging (LiDAR) can detect type of precipitation and light conditions (Vaidya et al. 2021). As a result, longer-term weather information from CVs can be transmitted back to an RWIS. This is particularly useful to fill in gaps in weather information between RWISs if roadside units (RSUs) are available at appropriate intervals.

10.2 Gathering Maintenance Information for RWISs

Information was initially gathered through a literature review, the survey of state departments of transportation (DOTs), and interviews with state DOTs and cities (as described in detail in Chapter 2). Information gained during Phase I was presented to the NCHRP panel at the end of Phase I. After discussions, panel members showed interest in gathering any new information that was available about maintenance of RWISs, but these were not the focus of subsequent interviews. As a result, an additional literature review was conducted, and all the available information is summarized in the sections that follow.

10.3 Examples of CV Applications for RWISs

All states had some type of RWIS, with about 2,500 deployed in the United States. About 2,400 ESSs, which measure atmospheric, pavement, or water levels, were also owned by state transportation agencies that deployed an ESS in conjunction with an RWIS (about 84% of them) (FHWA 2020a).

As noted, although RWISs are not specific to CVs, they were included as a question in the survey (Chapter 3) given that CV applications require weather information. Of the 39 DOTs that responded to the agency survey, three indicated that they had added RWISs to accommodate CVs. Additionally, four noted they had increased and two noted they had modified RWISs to accommodate CVs. In the next 3 years, three agencies were planning to add, eight were planning to increase, five were planning to modify, and one was planning to remove RWISs to accommodate CVs.

Ten DOTs were questioned about a subset of assets that they had implemented to address CVs. One DOT [New Hampshire DOT (NHDOT)] provided a response about RWISs.

10.3.1 New Hampshire RWIS Applications

NHDOT would ultimately have 40 RWISs. Specifications had been changed from the original RWIS, and they were in the process of piloting another RWIS. The pilot was a virtual RWIS where, ultimately, the RWIS data would feed into advanced transportation management.

The RWISs were being changed so they could be integrated into traffic management. The brand being used was Vaisala/Campbell Scientific.

NHDOT noted that their RWISs were initially placed based on highway maintenance staff input. Maintenance crews did not usually see their value initially, but once they had been used, staff usually bought in.

The RWISs were initially financed through the turnpike using federal funds. Some RWISs were placed during a large project using those funds. NHDOT was allowing 1.5% of construction project funds for intelligent transportation system (ITS).

10.3.2 RWIS Applications for Ice Warning Systems

More specific to CVs, several warning systems were being utilized that provide spot weather warnings for vehicle drivers. One example was ice warning systems that use RWIS components

Source: Johann56/Wikimedia Commons/CC BY-SA 4.0.

Figure 10-1. Ice warning system sensor array.

such as precipitation, ambient and road surface temperature, wind, rainfall intensity, humidity, and ice sensors (see Figure 10-1).

The sensors measure the presence of ice. In most cases, the system activates a beacon or other type of warning signal for all drivers. The system can also be equipped with cellular or other communications, which can notify a traffic or transportation management center (TMC) or others through vehicle-to-infrastructure (V2I). The system can also send alerts to snowplows or other maintenance vehicles.

California, for instance, has an icy curve warning system along CA 36. The system has an RWIS, which includes pavement sensors in conjunction with extinguishable message signs (EMSs) with flashing beacons. The RWIS is placed near the center of the curve and monitors road surface conditions to identify ice or packed snow. The EMSs are placed at the curve approach to provide adequate stopping sight distance (FHWA 2020b).

10.4 Maintenance Needs for RWISs

10.4.1 Typical RWIS Maintenance

NHDOT was interviewed about maintenance practices. The representative noted that they conducted regular preventive maintenance inspections every year, which extended the life of the RWIS. Most of their RWISs were 10 years old (since 2012), although some components had been replaced.

NHDOT was in the process of developing a life cycle plan for all assets. The issue was that ITS assets were exponentially growing in number but still had to be maintained without the funds or staff to meet maintenance needs.

Table 10-1. Estimated lifespan for RWIS components.

Component	Average Life (years)	Standard Deviation (years)
Entire RWIS station	15	3.3
Internet protocol (IP) surveillance system (CCTV) (optional)	7	1.1
Pavement condition sensor	8	2.5
Water-level sensor	4	N/A
Air temperature/relative humidity sensor	9	1.6
Wind direction and speed sensor	9	1.6
Precipitation sensor	10	1.6
Barometric pressure sensor	10	N/A
Visibility sensor	8	2.3
Ultrasonic snow depth sensor	9	1.5
Subsurface sensor	8	3.1
Solar radiation kit	10	N/A
Surface temperature sensor	8	2.9

Source: Lee et al. 2020.

A report from Washington State DOT (WSDOT) recommended regular maintenance of environmental sensors and communications systems. They also recommended regular testing and validation of the environmental sensors to confirm that conditions were detected reliably and accurately. However, specific recommendations or maintenance frequency were not provided (WSDOT 2022).

10.4.2 RWIS Life Cycle

NHDOT does regular maintenance of RWISs and felt they have a 10- to 12-year life cycle. A report by Lee et al. (2020) developed a life cycle cost analysis for RWISs. The researchers conducted a literature review as well as a survey of 10 state DOTs to obtain information about each state's RWISs. The survey included cost, design service life, applicable warranties, recommendations about preventive maintenance, software, and procurement methods. The researchers also surveyed manufacturers and vendors. They evaluated the lifespan for the components shown in Table 10-1.

10.4.3 Maintenance Challenges for RWISs Specific to CVs

Given that RWISs had been in use for some time for other applications, no specific maintenance challenges were noted specific to CVs.

Integrating RWISs with CV applications will primarily require V2I communications (e.g., RSUs). As a result, the only additional maintenance expected was for the additional communication devices. Longer term, some weather items may be crowdsourced, with CVs contributing some information. This could potentially reduce the need for some RWISs. At least one state agency reported that they planned to use CV crowdsourced data to supplement their existing RWIS information in the hope of providing richer data while eliminating the need to spend precious resources to expand their own RWIS equipment.

10.5 Standards, Guidelines, or Best Practices for Maintenance of RWISs for CVs

Given that CV applications were expected to be integrated into current RWISs, no additional standards or guidelines for maintenance were noted.

10.6 Workforce Needs for Maintenance of RWISs for CVs

Given that CV applications were expected to be integrated into current RWISs, no additional workforce needs were anticipated.

10.7 Summary of Maintenance Needs for RWISs

RWIS and environmental sensor station (ESS) technologies are mature technologies used by agencies for a variety of purposes. They can be configured to send or receive messages from CVs, which primarily require RSUs and possibly additional communications capabilities. As a result, these do not have maintenance needs specific to CVs beyond regular maintenance. Most agencies have an annual maintenance program for RWISs. Life cycles depend on the individual component, with estimates ranging from 4 to 15 years.

CHAPTER 11

Additional Communication Capacity for CV Applications

11.1 Description of Additional Communication Capacity for CVs

Connected vehicles (CVs) require communication and processing equipment to enhance vehicle awareness beyond onboard sensors. Early adopter agencies had begun early deployments of dedicated short-range communication (DSRC) roadside units (RSUs) and roadside equipment (RSE) to enable vehicle-to-infrastructure (V2I) communications, which add new radio equipment, processors, fiber, and an uninterruptible power supply to agency assets to be maintained by tech-savvy personnel. Additional communication capacity was primarily relevant for CVs.

During an average day, each self-driving car may produce more than 4 terabytes (TBs) of data (Beevor 2019). The New York City (NYC) Smart City coalition indicated that the 1.2 million vehicles in the city would broadcast 83 TBs of data per day, and the 13,000 signal phase and timing (SPaT)- and MAP-enabled intersections broadcast 3 TBs of data per day (Rausch 2018). As a result, Smart City IT infrastructure must be able to capture, store, protect, and analyze data from these vehicles (Beevor 2019).

CV systems require electricity and communications to allow connectivity between the vehicle and infrastructure. This requires wireless connectivity networks (Murtha et al. 2015). Additionally, backhaul communications are needed to transmit CV data to a transportation operations center (Krechmer et al. 2016).

Implementation of many CV applications require additional communication capacity. Some agencies have made significant investments in fiber optic. Cellular is also being used. Some have used a hybrid of multiple different communications mediums.

11.2 Gathering Maintenance Information for Additional Communication Capacity Specific to CVs

Additional communication capacity was not selected for further review after Phase I. As a result, information was gathered through a literature review, the survey of state department of transportation (DOT) maintenance practices, and targeted interviews with state DOTs and cities.

11.3 Examples of Applications of Additional Communication Capacity for CVs

Of the 39 DOTs that responded to the agency survey (see Chapter 2), 15 indicated they had added additional communication or data capacity, 10 had increased it, and four had modified communications. Eighteen DOTs noted they had plans to add communication or data capacity in the next 3 years, 15 planned to increase it, and six planned to modify it.

Several specific examples of how agencies have increased communication capacity to meet CV and other needs are summarized in the following subsections.

11.3.1 Florida's Additional Communication Capacity for CVs

Florida had a statewide fiber optic network to connect management centers and infrastructure (e.g., intersections). Whenever possible, they were replacing copper communication cables with fiber optic since fiber has high-bandwidth security, is resistant to electromagnetic interference and surge, is small and lightweight, and is lower cost (Murtha et al. 2015).

11.3.2 Virginia's Additional Communication Capacity for CVs

Virginia was also using fiber optic. The Virginia Telecommunications Act of 1996 required telecommunications providers to allow competing vendors to have access to facilities to enable deployment of broadband. It also mandated removal of state and local barriers to telecommunications competition (Gustafson 2018).

11.3.3 Ohio's Additional Communication Capacity for CVs

Ohio had placed fiber optic cable along a 35 mi stretch (Columbus West to East Liberty) to provide Wi-Fi for sensors along the highway to communicate with CVs. Ohio selected a 6 in. conduit that can support seven different fiber cables. Additionally, they were placing communication towers using DSRC. Short-range radio transmitters would also be installed every 2,000 ft (600 m) along the route (Sabin 2017).

11.3.4 Pennsylvania's Additional Communication Capacity for CVs

The Pennsylvania Turnpike was installing fiber optic cable along 550 mi of the turnpike to handle tolling data and current intelligent transportation system (ITS) applications. They were including future data needs for CVs. The installation was using a public-private partnership (PPP or P3), which took advantage of private sector expertise in installing, operating, marketing, and maintaining the fiber optic (DuPuis 2016).

11.3.5 Texas's Additional Communication Capacity for CVs

The North Central Texas Region was developing a plan to expand their communication network to allow better communication within and between agencies, as well as to facilitate infrastructure operations, advanced traveler information, and traffic management. The plan would also allow fire and police to leverage the network to improve incident response and management. The region had implemented more than 423 mi of fiber optic cable and 226 mi of wireless communication infrastructure and planned to add an additional 124 mi of fiber optic cable (NCTCOG 2017).

11.3.6 Minnesota's Additional Communication Capacity for CVs

Duluth, Minnesota, was building a local traffic management center (TMC) that included fiber optic, which would be supplemented with cellular modems at suburban and rural signals (McLellan 2020).

11.4 Maintenance Needs for Additional Communication Capacity Specific to CVs

Additional communication capacity was not identified as a high priority topic for further investigation, and no specific information was readily available through the initial information gathering. However, cellular and fiber optic are mature technologies, and neither is typically maintained by DOTs.

11.5 Standards, Guidelines, or Best Practices for Maintenance of Communication Capacity for CVs

Cellular and fiber optic are mature technologies, and neither is typically maintained by DOTs. As a result, it was not likely that guidelines would impact DOT operations.

11.6 Workforce Needs for Maintenance of Communication Capacity for CVs

Given that cellular and fiber optic are not typically maintained by DOTs, no additional workforce needs were anticipated.

11.7 Summary of Maintenance Needs for Communication Capacity for CVs

CVs require communication and processing equipment to enhance vehicle awareness beyond onboard sensors. Additional communications capacity was not identified as a high priority topic for further investigation for this project, and no specific information was readily available through the initial information gathering. However, cellular and fiber optic are mature technologies, and neither is typically maintained by DOTs.

CHAPTER 12

Machine-Readable Signs for AVs

12.1 Description of Machine-Readable Signs

Machine-readable signs contain quick-response (QR) codes that are readable by sensors but not by human drivers. Typically, these codes are embedded in traditional signs, and their application is focused on autonomous vehicles (AVs) rather than connected vehicles (CVs).

12.2 Gathering Information for Maintenance of Machine-Readable Signs for AVs

Machine-readable signs were not selected for further review after Phase I. As a result, information was gathered and summarized in the following section. The information was gathered only through a literature review, the survey of state department of transportation (DOT) maintenance practices, and targeted interviews with state DOTs and cities.

12.3 Examples of Machine-Readable Signs for AV Applications

Nine of the 39 DOTs that responded to the agency survey indicated they were planning to add machine-readable signs in the next 3 years. One DOT planned to increase, and one planned to modify to machine-readable signs in the next 3 years.

Machine-readable signs had only been utilized in pilot projects. It also did not appear that the signs were widely available commercially.

12.3.1 California Machine-Readable Signs for AV Applications

California DOT (Caltrans) was part of a limited pilot with the 3M Company that focused on machine-readable signs. The signs used similar technology to a QR code to be nearly invisible to humans. The deployment included eight signs as well as the development of an AV reader that could be installed in AVs. The project had been terminated in a short timeframe with no plans to carry it forward.

12.3.2 Michigan Machine-Readable Signs for AV Applications

Machine-readable signs had been part of a demonstration project with the 3M Company and Michigan DOT (MDOT). The signs had been placed in construction zones on I-75 in the southeast region of Michigan. MDOT had ultimately decided not to continue because the signs required them to maintain a library of information. Additionally, the signs could only be read by vehicles with a 3M sensor. Ultimately, MDOT had decided not to invest in the technology.

However, MDOT noted that they were discussing utilizing smart technology in work zones. For instance, smart arrow boards could be connected to vehicles to verify information.

12.3.3 Minnesota Machine-Readable Signs for AV Applications

Minnesota DOT (MnDOT) had been working actively with the 3M Company on machine-readable signs on a MnDOT-sponsored low-volume test track. The research included a truck driving around a loop with cameras. At that time, the agency had 2 years of monitoring data of the vehicle interacting with a sign embedded with a QR code. The experiment was testing the parameters of reflectivity and material related to aging.

12.4 Maintenance and Workforce Needs for Maintenance of Machine-Readable Signs for AVs

None of the agencies interviewed had sufficient experience with machine-readable signs to provide any information about sign maintenance. No standards existed for regular sign maintenance specific to AVs. It was also not known whether the QR code technology would require the signs to be maintained at a higher level.

Workforce needs were similar to those for regular static signing. As a result, no additional workforce skills were anticipated.

12.5 Summary of Maintenance Needs for Machine-Readable Signs for AVs

Machine-readable signs contain QR codes that are readable by sensors but not by human drivers. Typically, QR codes are embedded in traditional signs and can be read by AVs. Machine-readable signs were in the pilot stages when this project was in development. As a result, the direction and likely adoption of the technology was unknown.

CHAPTER 13

Data and Digital Infrastructure for CAV Applications

13.1 Description of Digital Infrastructure for CAV-Related Assets

Digital infrastructure was defined as the digital assets needed to accommodate connected and autonomous vehicles (CAVs). The assets may include inventories of the locations and condition of assets (e.g., signs, markings), high-resolution maps, as well as computing, processes, storage, and security resources to share data and run applications.

To accommodate electronic inventories of roadway features, data collection practices were reviewed to determine whether any changes had been made due to CAVs. Gopalakrishna et al. (2021) noted that autonomous vehicle (AV) developers had called for a digital database that inventories sign type and location. The Virginia Department of Transportation (VDOT) recommended a national standard for a digital traffic controller device (TCD) protocol to support CAVs (Atta-Boateng et al. 2019).

13.2 Gathering Information for Digital Infrastructure for CAV-Related Assets

Digital infrastructure was not selected for further review after Phase I. As a result, the information summarized in the following section was gathered only through a literature review, the survey of state DOT maintenance practices, and targeted interviews with state DOTs and cities.

13.3 Examples of Applications of Digital Infrastructure for CAV-Related Assets

Of the 39 DOTs that responded to the agency survey, six indicated they had added data service infrastructure to address CAVs. Five noted they had increased and two indicated they had modified data service infrastructure. In the next 3 years, nine agencies had plans to add, 10 had plans to increase, and one had plans to modify data service infrastructure to accommodate CAVs.

Twenty of the participating 39 agencies (51%) responded that they either had changed or planned to change (over the next 3 years) their asset data collection practices to address CAVs. Most changes to asset data collection occur in one of the three following fashions:

- Not presently collecting a particular type of asset data and will start collecting.
- Increasing frequency of collecting a particular type of asset data.
- Modifying data collection practices related to collecting a particular type of asset.

Table 13-1 shows how agencies had applied or had plans to apply changes in the collection of various types of asset data. Agencies were able to respond to more than one question. For instance, an agency could collect sign inventory more frequently as well as modify data collection practices.

The most frequent response to the prompt was no change, as noted in the first column. The next most common response was modifying data collection practices, as shown in the rightmost column. As noted, 11 DOTs indicated they were modifying data collection for sign retroreflectivity and geolocation of assets, while 10 indicated modifying data collection practices for roadway characteristics. Many agencies also reported collecting some assets more frequently, with six indicating they would collect weather data more frequently. Pavement marking retroreflectivity and pavement condition each received five responses from agencies, indicating they had plans to collect them more frequently.

13.3.1 Colorado Digital Infrastructure for CAV-Related Assets

Colorado DOT (CDOT) reported having successfully digitized assets and modernized to cloud-based services. They expected that CAV data would have a value-added effect to other data sources and assets.

CDOT was contracting and bundling a collection of pavement conditions and video analysis for signage. Their current sign inventory contained 177,000 assets. Their private sector data collection may be used in the future because it comes with higher accuracy and lower costs, but there were long-term privacy or cybersecurity challenges. They noted that opportunities to monetize DOT data may exist.

The agency had found it very important to communicate internally and with data governance officers about CAV data architecture to ensure that efforts were not repeated.

13.3.2 Minnesota Digital Infrastructure for CAV-Related Assets

Minnesota DOT (MnDOT) had developed a centralized sign inventory. They had also added additional portable dynamic message sign (DMS) trailers to share information to areas without permanent communications (as conditions required). MnDOT had continued to expand data capabilities with smart signs focused on truck parking availability.

Table 13-1. Current or planned changes in data collection.

Asset Data Type	None	Not presently collecting and will start collecting	Collecting more frequently	Modifying data collection practice
Sign inventory	25	4	4	7
Sign retroreflectivity	25	2	2	11
Pavement marking inventory	23	5	4	7
Pavement marking retroreflectivity	24	4	5	8
Geolocating assets	24	1	4	11
Pavement condition	30	0	5	5
Roadway characteristics	24	2	3	10
Roadway features	27	1	4	7
Light Detection and Ranging (LiDAR) or other 3D mapping	27	3	3	6
Weather data	24	1	6	9

Overall, the level of CAV adoption in the near future was stated to not warrant large-scale investment toward short-life assets (e.g., signing and striping). However, initiatives like work zone data were of interest. MnDOT was working to use their existing 511 and lane closure datasets to work with the U.S. DOT initiative on standardizing data exchange. The process was early on, but assets like arrow boards with communication capability could improve both CAV awareness and MnDOT management.

MnDOT was developing more centralized data inventories in response to current trends (with CAV being one). The agency had begun geolocating assets more broadly. The agency noted challenges with data silos and fully leveraging data. To get the full value of the data, it must be ingested, analyzed, and synthesized, but the agency was still a generation behind this type of smart data environment, even with advanced management centers and capabilities.

13.4 Summary of Maintenance and Workforce Needs for Digital Infrastructure for CAVs

Digital infrastructure is broad and can include databases as well as the hardware to collect the location and condition of assets, and the hardware and software to maintain these systems. Given that storage of digital infrastructure does not require specialized resources, it was not likely to require different maintenance.

Skills to collect digital data already existed for the most part at state DOTs. As a result, additional skills were not anticipated.

CHAPTER 14

Resource Gaps

14.1 Background/Setting the Stage

The objective of this chapter is to discuss resource gaps that were identified during the course of the project which are necessary to fully assess the maintenance impacts of connected and autonomous vehicle (CAV) assets.

14.1.1 What Are Resources?

Resources were defined as any dollar, staff time, agency knowledge (e.g., guidebook, institutional knowledge), or equipment that may be leveraged by the operating agency.

14.1.2 What Are Resource Gaps?

Resource gaps were defined as the shortfall of all agency-possessed resources in comparison to the agency need to deliver transportation service to their intended level. Here, “intended” was used because an agency may desire to provide even greater service but recognize they cannot within a practical number of resources. Intended meant how well the system would operate if all agency assets were managed to a state of good repair and staff were engaged.

14.1.3 Which Resource Gaps Exist Outside of the Impact of CAVs?

In 1993, the federal gas tax rate was set at 18.3 cents per gallon, and it has not increased in the nearly three decades since, even though inflation on costs of construction time and materials have risen. By 2018, the purchasing power of the federal gas tax rate had decreased by 64% to complete roadway projects compared to the purchasing power in 1993 (ITEP 2018). In the current era, agency financial resources expand or contract based on federal transportation bills that draw from federal general funds. The Infrastructure Investment and Jobs Act (IIJA) added significantly to agency financial resources, but much of the added funding will need to be applied to rebuild infrastructure after many years of inadequate maintenance funding rather than being targeted to maintenance.

Agencies also struggle to maintain staffing levels to adequately fill all agency-required skills and abilities. Individual agencies may be at different levels of staff need, but the general situation is that agencies have key staff retire or leave the agency and cannot replace all positions due to the lack of qualified professionals, strength of the private market, and weak resource activities by governmental agencies.

Agencies may also have gaps in agency knowledge, particularly in emerging areas. The transportation industry promotes knowledge sharing through a variety of strategies to help develop knowledge in emerging and niche fields. In many cases, the knowledge can be added to the agency most accessible by contracting the services of established private sector specialists or consultants. In adding specialty and consulting services, an agency must thoughtfully find avenues to retain the knowledge it leverages so it is not rented short term but can be accessed long term. Knowledge retention can take the form of training, guidebook development, longer-term mentoring type arrangements, etc.

Equipment shortages can also be present in agencies under other than normal conditions. Agencies must supply their staff with standard vehicles (e.g., light duty trucks), specialty work vehicles (e.g., snowplows, paving machines), and standard office equipment (e.g., computers). Equipment assets that are in-house for state transportation agencies range from purchased equipment that could age out to rented or leased equipment that must be managed to return equipment in appropriate conditions to the leaser. Equipment can be expensive, depreciate quickly, and be tied to specific staff skills and abilities, which can lead to inadequate equipment accessibility for staff of some agency operations.

14.1.4 Perceptions of CAV Impacts on Resource Gaps

A variety of views exist on how CAVs will impact resources and resource gaps. Optimistic views of the technology perceive CAVs to adaptively reuse the existing hard infrastructure system much more effectively—dramatically reducing the need for expansion of road and bridge spending and design. Pessimistic views perceive CAVs as dramatically expanding the use of individual vehicles and sprawling urban spaces that increase emissions and decrease the value of community places while still driving heavy infrastructure spending on system expansion.

CAVs may change the business objectives and process of transportation agencies. From project interviews, most state transportation agencies polled view CAVs as increasing agency assets. The same state agencies replied that they do not perceive CAVs as increasing transportation resources. In this way, CAVs may further cost state transportation agencies at the expense of existing agency priorities.

The increase in CAV dependence on lane markings is one area where this perception resonates and existing industry report cards on the quality of infrastructure show lane marking maintenance as inadequate. Further, CAVs may shed light on existing areas of degraded conditions at transportation agencies.

One area where the industry often cites under-management is the upkeep of traffic signal systems. Procured as capital investments at the corridor level, traffic signal systems need ongoing operations to fine-tune the delays they induce to be appropriate for current traffic levels.

Additionally, signals include technology that fails over time more quickly than pavement and bridge deterioration. The Institute of Transportation Engineers (ITE) Traffic Control System Operations guidebook recommends maintenance of traffic signals at a level of 42 hours per intersection per year (BMTS 2012). Anecdotally, that level of maintenance is a gap for some agencies even before adding that CAVs will communicate and transfer data with intersection controllers more frequently, generating data the agency needs to manage for broadcast consistency and accuracy to travelers. Moving to greater vehicle system reliance on signal-generated messaging enhances the criticality of signal uptime and state of good repair.

14.1.5 Which Resources Will CAV Deployments Require?

Field Devices. The consensus for CAV deployment is that agencies will need to place more technology in the field to create a more conducive environment for CAV safety. The CAV devices are likely to work together to achieve a combination of monitoring conditions, standardizing messages of the current system operation, communicating or transmitting messages to vehicles, advanced control devices (other field technology), and back-office operators. Corridor and sub-area pilots are common for gaining early agency adoption and are frequently subsidized with funding outside of typical transportation construction projects. More expansive systems of field devices are just conceptual at this time, and this concept will grow in importance if future CAV market penetration grows to mainstream use levels.

Expanded Communication Networks and Back-Office Technology. Communication networks such as fiber optic and radio communication networks are foundational to CAV-supportive technologies. Early CAV deployments have either leveraged existing communication networks or built them with new field devices. Back-office technology includes assets such as advanced traffic management systems software, video walls, and servers. Communication networks and back-office technology have become agency fundamental assets in the current norm for agency-wide transportation systems management and operations (TSMO) (Cambridge Systematics, Inc. 2016).

New capital funding sources have been committed at the federal level to expand communication networks and back-office technologies. Further, industry developments are frequent in the relationship between the public and private sector on access to broadband and 5G cellular networks. This report does not focus on how communication and back-office technology is expanded, but expansion is a prerequisite for understanding the resources to adapt to CAV adoption.

Vehicles and Other Equipment. Transportation agencies will need feedback from CAV vehicles to verify their work in implementing a CAV ecosystem. High-functioning CAVs at this stage are not commercially available, but transportation agencies likely already possess vehicles with low-level AV safety features. The vehicles in a DOT's fleet are an early opportunity to expand agency knowledge of AVs through staff use and agency exposure to vendors in the AV marketplace.

In the case of CV technology, one strategy to be more proactive is to purchase on-board unit (OBU) equipment and then retrofit the equipment onto agency fleet vehicles. Agencies will need CVs to functionally confirm that roadside unit (RSU) systems can pass system acceptance testing, but they must conduct risk analysis in determining which CV type(s) and the quantity of vehicles to avoid sunken costs as technology evolves. Further in the future, even more classifications of CVs, AVs, and CAVs will need to be considered, but right now the technology is still in the early stages of market availability.

Staff. Staff knowledge, skills, and abilities are an important agency resource. In the discussion of resource gaps, the ability or inability of staff to conduct needed tasks will drive how an agency may proceed from the information in this report. Staff development is an important enough topic that this report dedicates a separate chapter to growing agency capabilities in that area and will frequently refer the reader to workforce issues and opportunities. In this chapter on resource gaps, note that CAVs may require more staff skilled in the areas of data analysis, computer and data engineering, and information and operations technologies (IT and OT), or CAV deployments will fall into disrepair, obsolescence, or be generally underutilized in their benefit to collecting key performance information for the agency.

Agency Knowledge. Staff are a resource that can grow with and be flexible to an emerging transportation service area like CAVs. However, not all staff will be knowledgeable on CAVs and not everything there is to know about CAVs will start at transportation agencies. Research agencies and universities may have been more invested in CAV technologies and may have more topical knowledge. Agencies can tap into that knowledge in a number of ways—and they will need to. Engaging the private sector to dedicate additional time to demonstrate the technology and train staff is one avenue. Nurturing creative university and transportation agency relationships is also a possibility to tap into a diversity of necessary CAV skillsets. In thinking through agency knowledge, at the outset, it's advised to request that any partners deliver a thorough set of trainings, guidebooks, and tools so the agency can begin to grow additional capability maturity through each experience, project, and deployment.

14.2 CAV Resource Planning Process

In this research, the actions of agencies have clearly taken two paths of implementation, with substantial variation in each path. The first path is programmatic or system-wide improvement, and the second path is pilot-to-permanent adoption with a gradual increase in capability maturity as individual deployments start to build on one another to create a bigger system. The remainder of this section focuses on these two paths across the CAV asset classes studied in prior chapters.

The remaining subsections address these concepts, starting with programmatic or system-wide improvement, pilot-to-permanent-deployment, process, and procurement.

14.2.1 Programmatic or System-Wide Improvement

The first path is programmatic or system-wide improvement. With this improvement type, agencies have focused on pavement markings based on widely distributed information as to their importance in machine vision (MV) lane-keeping. Agencies have gone this route not solely for CAVs but have incorporated other research on topics, including increased visibility and safety for human drivers to decide that a 6 in. wide stripe width, and in some cases, use of contrast will be the state's new standard. With the programmatic or system-wide improvement path, an agency must start from a limited portion of their system in compliance with their new standard and make widespread modifications.

Widespread modifications require substantial resources. Thus, as agencies with narrower lane striping pursue wider striping or other programmatic modifications, the agency needs to carefully plan equipment and field staff as well as striping material to reach the new standard. Chapter 6 discussed lane striping for CAVs more completely, but at least one agency noted an expected cost increase.

It is within this category that proposed changes to the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD), and any future adopted standards, need to be planned. Future research needs to support any expansion of planning for resource gaps in this part of the process as standards for pavement marking upkeep and other MUTCD changes for CAVs are in an early stage of adoption, and empirical data to support such planning for changes in standards is sparse.

14.2.2 Pilot-to-Permanent Deployment

Through this project, a high-level process was developed for the adoption of resources that transportation agencies can use in planning for CAV deployments through a pilot-to-permanent approach to consider whether adequate resources will be available to support the deployment. Key caveats include the following:

- **CAV Systems Scaling.** All transportation agencies have recently been at a nascent stage of maturity in their CAV systems. The technology has not reached a level of mainstream use where all areas of technical, institutional, and policy aspects of operation are at a low rate of change. Every transportation agency, even those with many CAV devices, is still growing from a pilot environment while the technology matures. Long term, it's anticipated that support for CAV needs will have to become a core service of state transportation agencies, but such program maturity will take an evolution of the agency to achieve it. The pilot mindset of early programs focuses on growth from innovation, but may have a bias to a short horizon for completing the pilot.

- **CAV Deployments Range Dramatically.** In collecting industry feedback, a practical average for CAV deployment does not exist. The variety in operational concepts, coverage area, roles and responsibilities, and intended outcomes complicate the development of a simple model for scaling a small set of industry deployments into a more robust estimate of state agency resource needs.
- **CAV Deployments are ITS Deployments.** The converse to the first consideration is that CAV deployments do share a reducible commonality in that they all center on ITS deployments, which have been deployed by state transportation agencies for some time. The adoption of the system engineering process within a portion of the transportation industry decades ago helps make ITS and technology deployments much more structured and likely to succeed in maintaining system operation and in generating outputs that serve goals and objectives generated in planning. Greater detail will be provided on how to conduct system engineering planning as a baseline for any further resource gap assessment. As agencies build their system architecture and concepts of operations, the number of vague elements in the planned CAV system decreases, which will make it easier for agencies to project future resource needs for CAVs.
- **Partnerships are Critical to the Plans.** Agency owners often communicate to partners like contractors through plans, specifications, and bid documents. In CAV deployment environments, there are similar controlling documents to develop, but the partnership models may differ. CAV pilots to date have utilized closer to a design-build-operate-maintain approach for deployment. Transportation agencies in this arrangement tend to introduce bid documents using purchasing departments and best-value principles. The value can include cost for up-front solutions design and deployment, but can also likely include support through operations and commitments to partially support maintenance.

With those caveats in mind, the process can be understood as comprised of six facets: (1) Planning, Design, and Procurement, (2) Field Device Installation and Operations, (3) Back-Office Operations, (4) Fleet Operations, (5) Maintenance Activities, and (6) End of Life Cycle/Replacements (as detailed in Figure 14-1).

14.2.3 CAV Resource Planning Process Summary

The CAV resource planning process is a synthesis of effective practices shared by multiple agencies that is generalized to be scalable to the wide breadth of potential CAV deployments and the variety in size or scale of the pilot deployment extent. The core actions are shared here concisely and then expanded in the following sections:

- In CAV deployment conception, agencies should outline a rough acceptable return on investment.
  - Tools exist to estimate at a high level the benefits of CAV strategies in theory. Early-stage U.S. DOT-funded projects continue to be conducted to translate that theory into practice. Presentations and publications from these pilots will increase the knowledge available on the value attributable in both quantified benefits and intangibles and the agency costs.

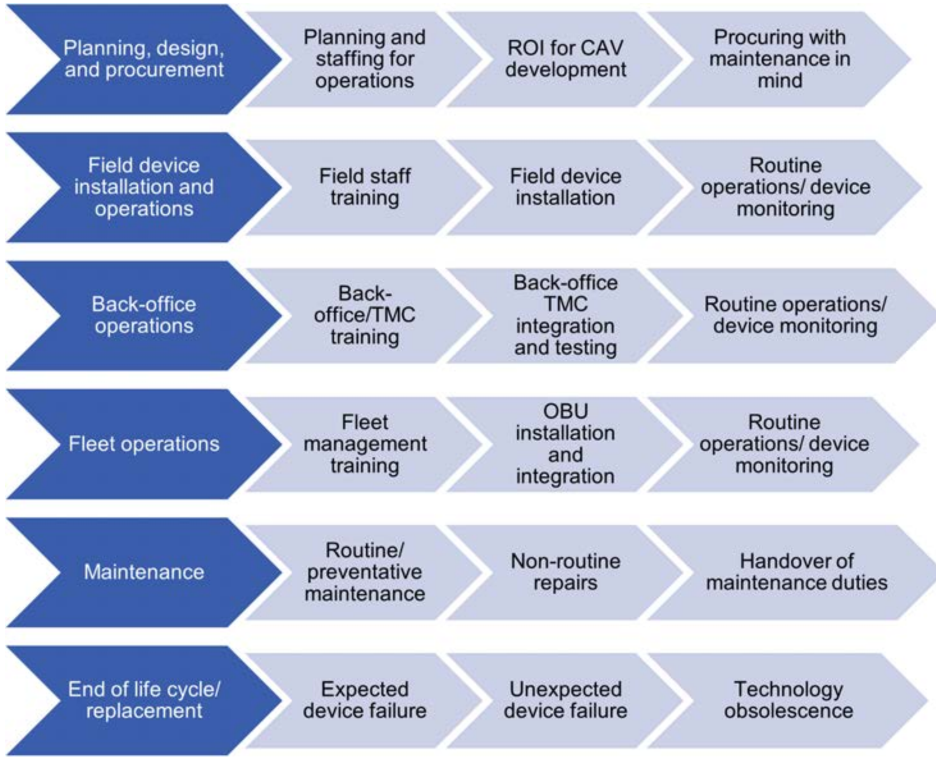


Figure 14-1. CAV resource planning process.

- In planning and design, develop CAV deployment business plan resources in four categories: (1) funding (capital, operating, and maintenance), (2) staff, (3) agency knowledge, and (4) equipment.
  – The systems engineering process should be employed as with mainstream intelligent transportation system (ITS) and technology agency projects. The development of a sound concept of operations and system requirements likely establishes the staff and agency plan for operations and maintenance responsibilities.
  – Utilize procurement methods that allow for support in addition to merely furnishing and installing technology/equipment.
- Develop estimates of resources needed for each of the following: field device installation and operations, back-office operations, and fleet operations.
  – Within each category, estimate for the impact to staff knowledge, skills, and abilities of the upcoming deployment and contractually secure any training needed from a contractor, vendor, or other paid provider.
  – Within each category, estimate for the short-term-but-resource-intensive deployment, integration, and verification, resulting in communication devices and a monitored system of information shared.
  – Within each category, estimate the period following deployment for a pattern of monitoring device uptime and monitoring the messages communicated by CAV systems.
- Develop estimates of resources needed for CAV maintenance, including routine and preventive maintenance, nonroutine repair, and handover of maintenance duties.
- Interrelated with the prior steps, use scenario planning principles to consider risk to device end of life.
  – Resource commitments should be for the horizon of the project. The horizon of the project should be knowledgeably chosen based on an industry expected lifetime of the CAV technology and not based on a more mature technology like mainstream ITS technology.

  - As with other agency-owned technology, rules to account for unexpected failures should be observed. Generally, a 10% overage should be planned for spare devices as part of procurement.
  - A nontrivial scenario (or multiple scenarios) should be the scenario anticipating technology obsolescence. Equipment may need replacing even if the concept is still sound, so risk acceptance decisions must be evaluated.
- Finally, the procurement, although preceding operations and maintenance, should be developed to set the agency up with support during the initial agency adoption period. The procurement should specify devices, the amount of support service coverage, any terms of responsibility for equipment maintenance or failure, and concrete deliverables for training, guidebooks, planning, or job aids the agency perceives in planning and design to be necessary for long-term, in-house deployment ownership.

14.2.4 Planning, Design, and Procurement

Transportation agencies should approach planning, design, and procurement consistent with agency ITS deployments. The systems engineering process represents a best practice and is recommended to be considered for use to plan the linkages between system concepts and requirements from the user vantage point as well as system acceptance, validation, and verification criteria from the owner and operator vantage point. Deployments, like any agency decision, are recommended to focus on a productive return on agency investment over the project life cycle, and that business case is recommended to be communicated through agency leadership to secure necessary support at the outset. The planning, design, and procurement phases are also recommended to purposefully address unique operations and maintenance needs of emerging CAV technology.

14.3 Systems Engineering

Many guidance documents exist based on the use of the systems engineering process. In this report, the focus is on helping identify where the agency is, capability-wise, for ITS and CAV maturity. CAV technology deployment requires coordination with agency systems engineering support to properly document plans for operations and maintenance, and understanding these steps can help certify that all staff will engage the right people at the right time. The U.S. DOT pilot deployment program provides assistance documents for each step in the 13-step process, identifying key challenges and considerations. To discuss the U.S. DOT pilot deployment and systems engineering process as it relates to the proposed CAV resources planning process, three use cases are described in the remainder of this section.

14.3.1 Use Case 1

U.S. DOT supports pilot programs deploying vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) equipment. Concept Development, Design/Build/Test, and Maintain/Operate phases are implemented with federal performance oversight. The key to this use case is a need for firm responsibility sharing amongst multiple agencies in the context of novel or innovative technology or use of technology. The value of such deployments can be equally heavily influenced by lessons to be learned about the technology and measurable change in user travel performance. Additional documents are recommended to be developed to clearly articulate the roles of federal transportation agencies, state and local transportation agencies, private, third-party project team members, users of pilot technology, and the public at large. Entering into this use case can initiate a process that allows for future deployments to grow organically in the systems and responsibilities settled through the pilot. Use Case 1 requires the most up-front investment in developing and documenting process, but with potential advantages to clarity of the project plan and setup and maintenance of processes that may benefit the agency beyond the scope of the pilot.

The CAV resource planning process interfaces with this use case as the agency considers how this new system will eventually proceed from a joint party project to primary state or local agency ownership. The up-front, capital resources in this use case may come heavily from the federal agency, but the state and local agency need to determine the sources of funds for operations, maintenance, potential expansion, and ultimate retirement or replacement. The CAV resources planning process also helps early on in tracking how knowledge that may be generated through partners outside the state and local agency will be retained. The CAV resources planning process can help as decisions are made regarding the pilot for key project staff to report back to their state and local agency management as to how future agency work in CAV deployments may affect the agency regarding needed funding, requirements for staffing, and potential investments in equipment and supportive infrastructure.

14.3.2 Use Case 2

Small research project with primary purpose of advancing institutional knowledge of V2I equipment. For states with the appropriate local university support, their initial foray into CAVs may be a controlled experiment with primarily RSUs or OBUs without human subjects to test their functionality. Many states would have worked on this use case as part of the American Association of State Highway and Transportation Officials (AASHTO) signal phase and timing (SPaT) Challenge leading up to the year 2020. In some instances, this use case could be on a test track, but with a concept of operations like SPaT, the research could occur passively on traffic signals and other control devices and without impact to human users. In this use case, some of the acquired knowledge is not documented and may no longer be directly accessible by the agency when the project relationship ends with the vendor, consultant, or university partner.

At minimum, the agency should develop a program management plan to capture project details, a tailored concept of operations (Con Ops) and system requirements specification, a security management operational concept, a safety management plan, and a performance measurement and evaluation support plan. In this use case, the Con Ops and requirements may leverage existing documents like the federal specification for RSUs, adding only details about how their operation may differ here because of local conditions. The project-level Con Ops is also a tool for capturing roles and responsibilities as the process enumerates system users. The security management operation concept is listed as recommended, assuming the agency has not participated in any other RSU or OBU pilots, so professionals in cybersecurity representing the project for the agency must develop a plan for adding these assets to an agency's existing IT network. The performance measurement plan established up front the format and methods for collecting data to allow an evaluation of the pilot throughout and eventually as a backward-looking assessment of the benefit of the CAV pilot investment.

The CAV resource planning process interfaces with this use case as the agency considers how this new system fits with their existing operation. In some instances, the project is maintained in a primarily separate atmosphere and the biggest interfaces are agency cost of participation and a staff participation plan for on-the-job learning. In other instances, the small deployment is intended to be pilot-to-permanent, and then, the idea of resource planning becomes even more important as decisions tracked early can help determine plans for future maintenance, expansion, and even retirement and replacement.

Table 14-1. CAV deployment checklist.

Step/Document	Case 1	Case 2	Case 3
Program Management	X	X	X
Concept of Operations	X	X	X
Security Management Operational Concept	X	X	
Safety Management Plan	X		
Performance Measurement and Evaluation Support	X	X	X
System Requirements Specification	X	X	X
Application Deployment Plan	X		X
Human Use Approval	X		
Participant Training and Stakeholder Education	X		
Partnership Coordination and Finalization	X		
Deployment Outreach Plan	X		X
Comprehensive Pilot Deployment Plan	X		
Deployment Readiness Summary	X		X

14.3.3 Use Case 3

The agency has mainstreamed CAVs along one corridor or area and are now extending their current V2I or V2V functionality, or both, to a new corridor (e.g., geographic growth of deployments). An agency building off an existing CAV deployment can substantially leverage from the processes developed in the pilot deployment and agency knowledge gained through system operation and maintenance. In this more advanced use case, many of the areas of the CAV resource planning process are already in place. Back-office staff have experience monitoring and checking performance of an asset, and field staff and fleet staff have qualifications to monitor CAV assets for their physical condition and reporting relationships to involve other project team members if troubleshooting, maintenance, or replacement is needed. In this use case, the agency may trust staff experience to extend the system with only cursory documentation for systems engineering. However, the CAV resource planning process draws from the information at each local deployment to determine if the current resource levels (and particularly staff time) are adequate for this extension of CAV assets. It is recommended to use each deployment as an opportunity to at least revisit how system expansion affects the concept of operations, system requirements, and performance measurement systems and practices.

Table 14-1 provides a CAV deployment checklist of steps and documents for each of the three use cases outlined above this.

While a continuum of deployment use cases exists, the examples demonstrate how early pilots captured well in documentation and communicated to stakeholders within the agency allow for deployments to become permanently adopted and for expansion projects to add to an already robust system. In the future, one could postulate a fourth use case, or a deployment of V2I equipment, where the agency has experience, staff, and knowledge surrounding CAV equipment deployments, and it is a mainstreamed practice. In that circumstance, the agency's incremental investment in resources could still be added via the CAV resource planning process but with even greater staff efficiency and more streamlined resource commitments.

14.4 Return on Investment

Transportation agencies are exploring CAV technology because of societal benefits to safety and mobility while actors like vehicle original equipment manufacturers (OEMs) and technology contractors and fabricators advance CAV technology for buyers with similar considerations but also seek to maximize profits. This synergy can be summarized as follows:

- Return on investment decisions:
  - Resulting value exceeds the life cycle cost of implementation and operation. In certain cases, value is quantifiable and a number of economic methods apply. In cases with some

level of unquantifiable benefits, two unlike measures are being compared and a method of cost effectiveness may be adopted.

- At the planning stage of development, public agencies should plan the value they hope to see from the deployment:
  - Value may mean outcomes—reductions in delay or crashes to transportation system users based on the proposed technology strategy.
  - Value may mean institutional capability increases—staff are now more skilled or have increased knowledge or abilities attributable to the experience gained working on the pilot.
- Pilots may be targeted to both types of value but should be pragmatic about the outcomes that rely on vehicle penetration unless the deployment will be designed to increase CAV-equipped vehicles in the study area.
- Return on investment can change dramatically depending on the primary decision maker on the agency side and manner of project initiation. One supporting element typical of determining return on investment is the benefit-cost analysis. One example of benefit-cost analysis on CV technology is the final technical report for NCHRP Project 03-101, *Costs and Benefits of Public-Sector Deployment of Vehicle-to-Infrastructure Technologies* (NCHRP 2014), which focused on theory of agency benefits excluding vehicle automation capabilities. Further, the study provided depth on three case studies of deployments that predate the CAV deployments that were the focus of interviews and data gathering for this research project.
- Site selection is a critical factor for CAV investment. Implementing technology such as RSUs will be significantly less expensive in locations already along a communication network and configurable to be operated from an existing traffic or transportation management center (TMC).

14.5 Procuring with Maintenance in Mind

- State DOTs predominantly procure up to the build or construction phase for their full programs of pavement, bridge, and other infrastructure projects.
  - ITS projects, however, represent a unique element and often require either an operations and maintenance agreement with deployment or separate contracting with an ITS maintenance contractor.
- CAV technology such as RSUs have short cycles of operation compared to traditional transportation infrastructure.
- CAV technology also includes recently emergent components or systems to interface with systems that may have a period of unreliability without close oversight.
- CAV technology as reviewed often relies on a mentality of limiting field downtime. One method to reduce field downtime is an intervention strategy that prioritizes replacing with spare components and moving failed technology back to the workshop for repair. Leveraging this swap-first strategy, field technicians may require moderate electrical and computer programming skills. The staff at the off-site workshop may require advanced skills in electrical and computer programming to bring devices back to a functional state.

14.6 Field Device Installation and Operations

CAV systems include a variety of installations for fixed equipment in the field. Equipment may be installed in traffic cabinets or affixed to other infrastructure such as traffic signal mast arms. In planning for an RSU installation, placement needs to consider the layout of the traffic controller and appropriate mounting locations to enable transmissions of messages with low latency to vehicles. The most common RSU for sites was the traffic-signal-based installation focused on providing SPaT to vehicles. The SPaT message set is coordinated with a message set-entitled MAP that allows for spatial detail about the location of each signal head at the enabled location.

14.6.1 Field Staff Training

Execution of CAV deployment requires placement of devices in the field. An effective agency practice concluded by this research is the delivery of structured training on installation to agency field staff by expert staff—usually from the hired CAV deployment support team of vendor, contractor, and consultant. The agency should select field staff with electrical and computer engineering skills to take part in the field training. The staff training should include initial installation, periodic preventive maintenance checks, minor equipment maintenance scenarios, major equipment maintenance scenarios, as well as end of life removal or replacement. In cases like the RSU, the device is of a size and cost that most field activity will focus on swapping a spare unit in (at least temporarily), while the unit with issues is inspected back at the workbench.

14.6.2 Field Device Installation

In most deployments studied, a support team of vendor, contractor, and consultant took responsibility for supervising installation, configuration, and field verification. In this setup period, more staff time may be required than an agency can dedicate, leading to contracted services. The primary impact to agency resources is the time it takes per location to place and configure equipment and the time per system to verify technology operation.

Initial setup of an RSU-equipped intersection was estimated at up to 4 hours, including configuration of messages with detailed position locations for intersection geometric features.

14.6.3 Routine Operations and Device Monitoring

Field staff are critical to transportation system operations through the monitoring they perform for the state of working condition given their transportation assets. The CAV device class of assets can lessen the burden to an extent on field staff because these assets frequently communicate the status of their operation (e.g., are they sending data, are they receiving data). Even still, routine checks on the conditions of the CAV device from the field can help prevent more major maintenance and early failure. The field staff inspecting can more astutely capture potential issues in visual assessment if they are trained in the operation of typical electrical systems and basic computer systems.

Monitoring for field devices here may, as an example, cover the following [with this list adapted from the CV Pilot Program in Wyoming (Garcia et al. 2018)]:

- Inspection of mounting brackets and bolt tension.
- Visual inspection for device power and status.
- Check for network connection by logging into the RSU through a secured connection.
- Inspection of backup batteries.
- Broadcast check for messages from equipped maintenance vehicles.

14.7 Back-Office Operations

14.7.1 Back-Office and TMC Training

CAV devices require training to staff that perform office support work for transportation operations. The most critical aspects are staff that focus on real-time transportation operations, like those working stations at the TMC. Real-time operations staff need to be able to react quickly to maintain a safe operating environment for travelers in the face of traffic incidents, adverse weather, and other events. The incorporation of CAVs adds additional information on the flow of vehicles, the status of infrastructure such as traffic signal phasing, and other conditions. The real-time operations staff need to have that CAV information structured through systems that make the information easily identifiable and actionable. The most common strategy is use of an advanced traffic management system (ATMS), and CAV devices may, at the agency's discretion, feed into an existing agency-licensed ATMS or use a new ATMS. The ATMS is typically vendor-developed and then agency-customized. Training should focus on the functionality of the ATMS and utilize methods of information delivery that both show the agency trainee key system information and verify the trainee's proper use of the system outside of an active traffic situation. The back-office staff will likely require up-front training that covers the common system cases, but an effective practice is the use of a longer-duration support period that allows for the vendor to engage and reinforce training after the initial training period has subsided.

14.7.2 Back-Office TMC Integration and Testing

In the case where CAV deployments add to an existing agency system of ITS devices, the back office may already use an ATMS to monitor and modify system operations in real time. The ATMS investment can lead an agency to decide that new CAV device monitoring must functionally operate within their base practices for the TMC. In that case, augmentation will be needed to integrate the existing ATMS with new CAV ATMS capabilities. In integration, it is paramount that software engineering and IT capabilities attend to user requirements, mesh data and communication, and mitigate security vulnerabilities of two potentially standalone systems. The effective practice identified in this research was strong planning through systems engineering and contracting services that allow for vendor support through and including integration and testing.

14.7.3 Routine Operations and Device Monitoring

After the initial CAV deployment, the role of the back office is to continue to monitor device status and the information transmitted. The monitoring from the back office adds some workload to TMC operators. The workload added to TMC operators is in line with their typical function, but the quantity of work needs careful assessment for proper operator levels. As an example, a new CAV deployment for 100 RSUs has been activated and the TMC is monitoring. In the normal course of monitoring, an RSU that communicates the status of a reversible lane to traffic is malfunctioning. The TMC alerts maintenance staff due to the safety-critical nature of the event to potential head-on collisions, and the RSU is serviced before the event is cleared. The example illustrates some potential positives and negatives to the introduction of CAV devices in the back office:

- **Positive:**
  - **Reduced time to notification.** CAV deployments are concepted to increase situational awareness for TMCs and other users. The added devices each gather information, and in an area with a robust amount of communicating vehicles, exponentially expand the real-time operations data. With greater data coverage, incident or event identification times may decrease. Even short time reductions in event response can improve outcomes of safety and event clearance.
- **Negative:**
  - **Back-office overload.** CAV deployments will stream in large quantities of data on system condition and performance. The large quantities can lead to potentially negative impacts to agencies in cost of storage, cost of data processing, cost in staff to utilize the information,

and potential impacts to efficiency of current TMC operations when adding to their workloads.

An effective practice would be to communicate in planning documents the requirements of users in the back office and include that ongoing cost in the CAV deployment budget or business plan. If costs are agreed upon within the agency up front, the execution of the plan can account for adding staff and adding supporting software, hardware, and contract services to mitigate potentially negative consequences.

14.8 Fleet Operations

14.8.1 Fleet Management Training

Agencies regularly have vehicle assets that require fleet management and maintenance. As CAV technology adoption grows, the potential for vehicles with automation functions at various levels increases, so fleet management staff may have near term lessons to learn about specific automation functions. Engaging in a CAV deployment furthers the commitment to have vehicle fleet manager staff understand CAV elements.

The piece of technology that stands out for a big change in fleet management is the OBU. Fleet managers need to acquire knowledge of OBU physical mounting, OBU initial configuration, OBU normal operation, OBU issues and maintenance, and OBU retirement. Training is often provided by equipment vendors or manufacturers and delivered as part of a CAV deployment agreement, but opportunities may exist to develop training for fleet managers to support skill adoption more organically.

14.8.2 On-Board Unit Installation and Integration

Introduction of OBUs through a CAV deployment often floods new knowledge, skills, and ability requirements on an existing fleet management staff. In some agencies, the ongoing computerization of vehicles has helped fleet management staff become savvy to technology components similar to OBUs. However, the OBU may introduce elements such as communication over the air (non-radio, different part of the spectrum) and security credential management that are new to fleet managers.

OBU installation in CAV deployments has frequently been conducted as contracted services due to the significant time to physically mount the OBUs across a large number of vehicles (often in the range of 500 to 5,000 vehicles) and the work to configure and integrate the OBUs into the CAV deployment so they receive messages from other outfitted vehicles and the equipped infrastructure. Interviews also identified that contracting the responsibility of OBU installation and maintenance to a third party protects state agencies' fleet managers from the risks of working on privately owned vehicles.

14.8.3 Routine Operations and Device Monitoring

Fleet management of CAV devices like OBUs require regular monitoring of operations after initial installation and configuration. The status of OBUs will require confirmation of sent and received data, likely through a back-office ATMS. Fleet management staff would be one group that could receive some access to the ATMS, focusing on the OBUs in their fleet vehicles. Vehicles with CAV device issues can be addressed so that those in normal operation will continue their operation without fleet staff response. OBUs with normal operation status are likely a small part of any per use safety pre-check before a fleet vehicle goes into operation.

Fleet monitoring is also extended here to discuss activities for an update to software or firmware for OBUs.

14.9 Maintenance

In planning, design and procurement, agency decisions are made to set aside the proper staff and financial resources for an initial procurement and ongoing performance. Once a CAV deployment is procured, three systems will see a change: (1) agency-owned devices in the field, (2) agency-owned equipment and services as part of the back office, and (3) agency-owned fleet vehicles. Staff resources in each of these areas have an increase in workload to accommodate the CAV pilot, and in the case of initial implementation and configuration, the amount of staff time significantly increases. In many cases, this increase is satisfied through contract services to confirm appropriate knowledge, skills, and abilities for new equipment and for short-term dedicated availability to the deployment. In the post-deployment operational period, the total workload induced from the CAV project begins to reduce to non-startup operations levels and more periodic maintenance. Agency staff can then, with training and potentially a period of contract support, adopt into practice the operation and maintenance of CAV devices.

The maintenance function requires a greater understanding of CAV elements than normal operation. The maintenance staff at the agency may assume all of this understanding, but, in most cases, the research showed that agencies had not fully assumed maintenance responsibility as most were in an initial period of vendor support after procurement.

14.9.1 Routine and Preventive Maintenance

Field staff will have responsibilities to conduct routine inspection of CAV assets. In many cases, this routine inspection will be a small portion of their existing job functions. The routine and preventive maintenance will assist in safety of equipment to public and agency users and will help extend the functional life of the assets.

Maintenance for field devices is also extended here to discuss activities for an update to software or firmware for RSUs. The following steps were generalized from the U.S. DOT CV Pilot Program in Wyoming (Garcia et al. 2018):

1. State agency receives new firmware version from vendor.
2. State agency bench-tests the new firmware, and, if it passes, the firmware is then tested on test RSUs.
3. Once tested and approved, the state agency uploads the new firmware version to an update server (centrally managed) and updates a subset of RSUs and performs testing.
4. After testing is completed and approved, new firmware is established as the latest version for broadcast and sent for dispersal to RSUs.

14.9.2 Nonroutine Repairs

CAV equipment will experience situations where technology is noncommunicative, returns suspect data or an error, or the physical mounting and operation of the equipment may fail. The lesson learned in nonroutine repairs is that maintenance staff must have a process to address CAV deployment interruption based on the criticality of the operational services.

For example, if the CAV deployment controls traffic signal indications so that vehicles may end up in an all-red condition, maintenance staff needs to be dispatched immediately, regardless of current assignments and workload. This type of worst-first mentality to address issues is common in fields like IT, so existing transportation asset and maintenance management software may need to adopt that type of workflow for their specific ITS and CAV assets. Some agencies have this approach already and would just need to scale it and differentiate certain business rules to accommodate CAVs.

A discussion of common CAV issues and their resolution follows. The scenarios are generic and may become more intricate depending on other factors about the CAV deployment and the agency's typical operation:

- **Device not communicating.** In this case, a combination of back-office staff monitoring their ATMS or agency field staff performing a preventive check may uncover the communication failure. The recognition of a noncommunicative device likely generates a request for services to both back-office and field staff so that troubleshooting can be performed both remotely and on-site. Field staff, in this case, would drive to the site and access the unit or device, with the visual inspection also including assessment of possible physical damage to the device (see the last item in this list). Assuming no signs of physical damage, the device can be accessed locally (i.e., without data transfer to a network) and should read back one of a few standard status types. If in a failure or standby status, the device should be reset. If upon resetting, the communication is still not received, the failure is likely impacting a larger group of assets and possibly a subset of the communications network. With this procedure, field staff operate much like an IT or telecommunication customer support professional working on a lost household internet signal. Staff with skills and abilities in electrical and computer troubleshooting would be most appropriate to deploy to the site.
- **Device messaging suspect or erroneous.** In certain cases, a CAV device is in operation, but the output data is suspect or not sensible. For example, consider a device reporting only half the usual amount of activity registered by that device, or a specific traffic signal phase is no longer being called. To register suspect activity, agency staff at some level (field staff, back-office staff, or other) would need to be alerted to the irregularity of the device information. However, once the irregularity is identified, this field task will take attending staff with a strong understanding of the programming to resolve potential errors saved in a log by the device's built-in software controls for error states. In many cases, the troubleshooting or diagnostics is too complex for work in the field. The field technician may try to reset the device, and a reboot potentially resolves the issue and saves the use of a spare device. In other cases, the field staff judgment may be that the suspect or erroneous message is best handled by turning off the current field device and installing a spare device. Upon placing a device back into operation or placing the spare, verification of the correct unit functionality is needed. The back office may need to support in this situation.
- **Vehicle-based device not active.** One maintenance issue for fleet management staff may be that a vehicle-based device is not active. As an example, a snowplow vehicle may not be able to initiate their CAV-enabled weather-reporting capabilities. The operator may need to contact the correct fleet repair staff to restore that operation before leaving the garage. The repair staff need the correct tools and skills for checking the OBU status. The device's inactivity may require a sequence of typical troubleshooting activities that can be handled by a number of technicians (for redundancy). If reactivation proves to be a significant hurdle, steps may be taken to focus on replacement.
- **Physical damage to device.** In some cases, the CAV failure will not be software-based or failure based on the components of the unit but will come from external damage. The RSU and OBU are operating outdoors in the elements (e.g., rain, extreme cold, extreme heat) and are subject to damage from vehicle impacts, storm damage, and malicious actors. The physical damage use scenario routinely requires a replacement with spare units. The units may be salvageable but should be taken to the workbench and given the hardware and

software attention needed, which takes time. Research conducted for this study identified that physical damage from vehicles and weather were the most common issues with pilot CAV deployments.

14.9.3 Handover of Maintenance Duties

Maintenance duties have been described throughout this section as agency-owned since longer term it is expected that much of the actual maintenance will be done within an agency. However, as noted in discussions with agencies for this project, a number of agencies are currently maintaining CAV assets through maintenance contracts. The agency can use the maintenance support period to assimilate their staff to CAV maintenance and operation responsibilities without overloading them at once. The effective practice identified by the research team in this case is purposeful staff planning to allow on-the-job training of CAV maintenance responsibilities to occur prior to the maintenance support ending.

In some agencies, the market for hiring to cover all maintenance and operations support functions for CAV will be too onerous for all functions to move in-house. The combination of needing electrical skills, computer technician skills, back-office skills in programming and data management, and security management skills may be difficult for agencies to acquire based on a number of factors, potentially including the following: outdated labor classifications, salary disparities within the private sector, limits in the supply of the skills needed, and challenges in training in-house staff to grow these skills. In this situation, agency interviews showed a propensity to continue to rehire the support needed. The industry as a whole was more qualified to adapt to the needs of new knowledge, skills, and abilities than an isolated agency. Agencies that seek to hire for these skills long term need to effectively plan to maintain resources in-house in enough capacity to serve as effective managers of shorter-term contract support.

14.10 End of Life Cycle and Replacement

14.10.1 Expected Device Failure

Agency interviews discussed CAV device deployment and more mainstream deployments in ITS. A prevailing sentiment was that a 7-to-10-year life cycle range for technology is a norm for mainstream ITS, and that, once CAVs reach this level of reliability in service life, agencies could effectively plan for their natural replacement or retirement. A 10-year service life technology allows cycling of equipment every few years, which puts newer models in the agency's stockpile but spreads out agency financial spending to tackle the perception that money may be wasted on technology.

At end of life or replacement, the agency needs to plan equipment and staff for field operation to their sites. A small and relatively quick work zone operation for replacement of less than 1 day is likely. The agency may supply a traffic control tech and an electrical or computer tech, or the second role may be contract-supported.

14.10.2 Unexpected Device Failure

The CAV devices described in the last section occasionally advance past a condition where repair or refurbishing is possible. In those cases, the agency must decide if a location can go without the failed CAV device or if a spare takes the device's place. In most cases that were collected via interviews, the deployments have been able to cover unexpected failures with a roughly 10% quantity of spares. In cases where unexpected device failure is hardware- or software-driven, the maintenance action is typically to return the device to the workbench, and, if it is under warranty or a service contract, they likely return the device to the contractor for them to repair or refurbish it. Repairs and replacement outside the device warranty may be handled by a vendor service contract or managed as at risk by the agency. When an agency is used to contracts that do not include a period of support or warranty, an effective practice may be to review literature on performance-based contracting or best-value contracting of services.

14.10.3 Technology Obsolescence

CAV devices are primarily seeing the potential for early replacement due to the threats to the operation of the technology itself. While dedicated short-range communication (DSRC) RSUs and OBUs continue to work appropriately, they have been discontinued by the change in ownership of the previously entitled safety spectrum for DSRC communications. The nascence of CAV standards affects the risk level of those technology standards changing, and, in some cases, those changes make an entire generation of technology obsolete.

However, the planning work to conceptualize how the system can benefit the public may still be of value, even though agencies that adopted DSRC units have now reached a point with technology obsolescence where the units are (after a relatively short period of time) no longer usable. Early adopter agencies have found they must then justify to agency management further requests for funds to swap DSRC units with cellular vehicle-to-everything (C-V2X) units.

Over time, CAVs are likely to mirror other technologies where the private sector continues to promote change to drive new vehicle purchases. The agency considering a CAV deployment should be well educated about the ecosystem's maturity and consider such risks at the project outset. In the proposed practice of scenario-based planning, the agency may find that the planning for a CAV deployment is critical to agency objectives, but the CAV component itself is a risk to evaluate. The agency can then use an objective strategy for either replacing CAV assets with a more mature technology, going with the originally planned CAV deployment with risk mitigation in mind, or pausing efforts as a whole until CAV ecosystem maturity grows to a certain level.

14.11 Summary of the Impact of CAVs on Resource Gaps

The research team gathered information from state and local transportation agencies, university partners, transportation consultants, vendors, and maintenance contractors. Publications were also reviewed that capture additional information from federal transportation agencies and automotive OEMs. The totality of the information gathered highlighted two trends: (1) data on realized costs of operations and maintenance were available in limited quantities, and (2) the diverse nature of deployment contexts, intended operations, and confounding factors made any reduction to a quantitative estimate of future operating and maintenance costs for a hypothetical deployment unproductive.

The research team instead leveraged concepts on agency business processes to help structure the institutional knowledge shared on CAV deployment so that agencies new to CAVs or growing their program can find effective practices. The first step to structure the information was to clarify resources and resource gaps. In this step, the research team established that external factors for state agencies preceding CAVs have led to resource gaps and that CAVs may add to those resource gaps over time, although the conditions felt by individual agencies will vary widely.

The second step covered the introduction of two potential paths that agencies take in focusing resources on CAV assets. The first path was termed programmatic or system-wide implementation. The programmatic path primarily aligns with changes like those made to conform with a common standard, such as updates to the MUTCD. In the earliest case, changes to pavement markings to improve MV will likely be implemented programmatically across the full agency system. The research team did not enumerate steps for this path, hypothesizing that agencies have already mainstreamed the practice of applying pavement markings, although future research is needed to establish the cost of incremental pavement marking and other asset maintenance due to the needs of CAVs.

The second path was termed pilot-to-permanent deployment, as previously discussed. The final and primary section on resource gaps focused on a proposed CAV resource planning process, which is helpful as agencies approach CAVs from a pilot-to-permanent deployment mindset. The CAV resource planning process draws from six focus areas: (1) Planning, Design, and Procurement, (2) Field Device Installation and Operation, (3) Back-Office Operations, (4) Fleet Operations, (5) Maintenance, and (6) End of Life Cycle or Replacement.

The process proposed for resource planning is intended to help agencies: (1) conceptualize and communicate agency benefits of pilots throughout their organization, (2) program funding for initial capital costs, operations time for agency staff and third-party support, and costs of maintenance and eventual replacement, (3) form partnerships that fill key skill gaps of electrical technician, computer and software engineers, system engineers, management center staff, and fleet operations staff, and establish on-the-job training opportunities for agency staff, and (4) enable successful execution and mainstreaming of pilot-acquired knowledge through proper allocation of staff, budgets, systems, and equipment.

CHAPTER 15

CAV Workforce Implications

The introduction of the assets described in the previous chapters of this report require a shift in workforce skills. While state departments of transportation (DOTs) are just beginning to understand the maintenance implications of connected and autonomous vehicle (CAV)-supportive infrastructure, recent publications have identified potential ways that CAVs and related technologies, such as intelligent transportation system (ITS) technology, will shift the workforce needs of DOTs. Due to the lack of widespread data on CAV asset maintenance needs, transportation systems management and operations (TSMO) skillsets have also been considered as required workforce skills, particularly as they relate to back-office management. Trends identified in the available literature included the following:

- Difficulty in keeping up with the workforce skill needs for emerging technologies as they shift over time.
- Need for professionals other than civil engineers (that typically staff state DOTs).
- High level of dependence on outside consultants to operate and maintain CAV-supportive technologies.
- Lack of suitable position classifications to hire staff with the required skillsets at a salary competitive with the private sector.

Many of these themes were reinforced in one-on-one interviews with state DOT representatives:

- The current mix of skills within the DOT workforce is not oriented toward technology.
- Position classifications and pay ranges are not sufficient for recruiting and retaining needed new talent.
- Internal training programs to develop skills within the current DOT workforce are needed or have not yielded the expected benefits.
- Many states are currently using contractor labor to maintain CAV equipment.
- Some agencies noted that uncertainty about the adoption timelines of technology and the absence of guidance from automakers makes planning future investments difficult.

Between the literature reviewed and one-on-one interviews, the following high-level recommendations are proposed to resolve key gaps:

- Modify and develop new position descriptions oriented around CAV technology.
- Assess salary trends to determine suitable pay bands for staff with CAV skills.
- Partner with educational institutions and develop apprenticeship programs to close CAV skill gaps.
- Develop nationally consistent CAV credentials and training programs.
- Monitor long-term maintenance needs of CAV infrastructure and vehicle-based equipment that has remained operational beyond vendor contract or warranty periods.
- Monitor new and emerging standards and guidance related to CAV infrastructure and vehicle standards.

15.1 Review of CAV Workforce Literature

The range of literature considering DOT workforce needs varies from observations of overall technology trends to identifying specific challenges associated with maintaining CAV assets. One challenge is the relatively few CAV deployments at present; many of these deployments are recent enough that they are still maintained under vendor warranty periods or service contracts. Where connections existed, this evaluation considered the workforce needs of a broader set of technologies, including ITS and TSMO deployments.

As Park and Harrison (2019) summarized for NCHRP Project 20-24 (95), *Ensuring Essential Capability for the Future Transportation Agency*, the following high-level trends were impacting transportation agencies:

- Continued development of CAV, shared mobility services, and electric vehicles.
- Adoption of new information technologies that will impact transportation agency management (including maintenance and operations).
- Changing political landscapes characterized by funding instability, shorter legislative tenures because of term limits, and high expectations for accountability and transparency.
- Increased emphasis on TSMO to better utilize available capacity.
- Growing need for resilience to manage risk and recover from transportation system disruptions caused by extreme weather and other emergency situations.
- Challenges in recruiting and retaining employees caused by competition with the private sector, changing expectations of flexibility and upward mobility, legislative limitations of public agency staff, erosion of public-sector benefits, and changes in the public perception of civil service careers.

15.1.1 Highway Maintenance Workforce Pipelines

Recruitment and retention of employees extends beyond the issues introduced by new CAV assets. As Cronin and Goldstein (2019) noted, transportation agencies across the country have observed the following workforce challenges:

- Transportation agencies often maintain narrow pipelines that connect to a single source, such as a local technical or vocational program. The same talent source is often tapped by private sector employers that are able to offer better wages.
- Budget-constrained agencies are often forced to cut internal development programs, leading to higher turnover rates as workers are unable to meet increasingly complex job requirements. At the same time, agencies that rely on developing an internal pipeline often experience leakage of staff to industry.

Adams et al. (2019) evaluated potential routes for advancement within the maintenance workforce and found that one key challenge in the talent pipeline is that agencies struggle to fill entry-level maintenance positions. The University of Wisconsin-Madison's Midwest Transportation Workforce Center (MTWC) evaluated maintenance apprenticeship programs to map career pathways for skilled maintenance occupations and found that the absence of entry-level talent creates a gap that cascades into middle-level skilled positions, such as the mechanics and equipment maintainers that will likely encounter CAV technologies in the future. As part of their study, the authors documented how skills are acquired through a combination of classroom training and hands-on experience. Many activities related to maintaining CAV assets will be highly dependent upon classroom learning, such as the following:

- Apply MUTCD standards;
- Use computers and mobile devices to perform job functions;

- Deploy, monitor, and adjust TCDs; and
- Verify the locations of utilities.

Others will be highly experiential, as follows:

- Perform maintenance on equipment;
- Inspect, repair, fabricate, and install signage;
- Inspect, repair, and install pavement markings; and
- Record and inventory equipment locations.

As Zimmerman (2019) noted from a relatively recent maintenance peer exchange, gaps existed between the skills needed in the past and those needed today by maintenance workers. For example, maintenance programs were heavily reliant upon data to effectively make maintenance decisions. High turnover was putting agencies at risk by resulting in the need for continued training of new staff on equipment and devices. Agencies participating in the peer exchange identified several potential solutions to these challenges as follows:

- The Maintenance Leadership Academy, which is provided by the Federal Highway Administration (FHWA)'s National Highway Institute (NHI), was offered annually by several state DOTs to develop the leadership skills required for their maintenance supervisors to support their agency's performance-based management philosophies.
- Colorado DOT (CDOT), Washington State DOT (WSDOT), and Utah DOT (UDOT) each had formal maintenance training programs in place to develop the leadership skills of their maintenance workforces.
- WSDOT had initiated a two-way training program that paired experienced and inexperienced maintenance personnel to develop the field skills of the newer workers and get experienced workers more comfortable with using technology.
- Maintenance departments were adding data analysts and programmers to their teams to improve the way data were used to make decisions.
- Map-based interfaces and touchscreen applications on tablets were revolutionizing the way maintenance inventories were updated. Work activities could now be entered in real time and shared throughout the agency.
- Several DOTs were using Light Detection and Ranging (LiDAR)-equipped vans to collect and update asset inventory data; the use of drones was also being explored.

15.1.2 Back-Office and System Management Workforce Pipelines

The volume and types of data created by new CAV assets will create similar challenges for back-office roles such as program managers, traffic engineers, and traffic or transportation management center (TMC) staff. These issues had been evaluated as part of several ongoing and recently completed projects relating to the emerging workforce needs for TSMO functions. As CAVs will create a new data point for managing operations, these trends will likely act as an extension of current TSMO workforce challenges.

Szymkowski and Ivey (2019) conducted a series of interviews with the staff of more than 30 DOTs related to TSMO workforce development for NCHRP Project 20-07 (408), *Transportation System Management and Operations (TSMO) Workforce: Skills, Positions, Recruitment, Retention, and Career Development*. As part of their study, the authors listed the following 19 new and emerging positions that the interviewed DOTs identified as future positions in TSMO:

- **Traffic Data Scientist/Statistician:** An emphasis on data science is needed as very large amounts of data become more important.
- **TSMO Manager/Chief/Bureau Director:** As TSMO is elevated in government agencies, the roles and responsibilities of higher-level executive management are necessary.

- **TSMO Program Manager:** Several early adopters of TSMO have created program manager positions to coordinate across the wide array of functional areas and to implement activities that call for a broad range of internal and external stakeholders.
- **Computer Engineer:** Specialized computer engineering is required as processing becomes more distributed and as more and more operational decisions are made through edge computing in the field as opposed to a centralized model.
- **AI Scientist:** Government agencies currently have very little experience with AI, but this will rapidly change as cooperative autonomous transportation becomes more broadly deployed.
- **Telecommunications Engineer:** As private and public communication networks become ubiquitous and more bandwidth is required for emerging technologies, staff who can design the best ways to communicate with fixed and mobile assets will become more critical.
- **Data Management Specialist:** As a complement to computer engineers and data scientists, data management specialists are responsible for curating data in a way that ensures a high level of reliability and accuracy.
- **Visualization Specialist:** Along with analysis performed by data scientists, visualization of large amounts of data in an easy-to-understand format becomes important. The information is used to make better operational decisions and to demonstrate the benefits of TSMO.
- **CAV Program Manager:** Many government agencies have hired program managers to work on issues related to developing the capacity to support CAV technologies through research, testing, and partnerships with industry.
- **Traffic Incident Management Program Manager:** Working with partners to improve responses to traffic incidents is crucial to driving down clearance times and secondary crashes. The best programs around the country have varying levels of participation from local and statewide agencies.
- **Cybersecurity Engineer:** Cybersecurity is a growing concern as the internet of things, smart communities, and CAV technologies spread along transportation networks.
- **Transportation Data Ethicist:** The most forward-looking of all the positions, this job is dedicated to making sure data are being used for the right reasons and that all data are properly anonymized.
- **Surface Weather Specialist:** As climate change continues to affect the transportation network, engaging weather specialists within a TMC environment will aid in understanding the impacts and in improving responses.
- **Systems Engineer:** As software, hardware, and communications networks become more complicated, it will become even more vital to have expertise on how all the pieces interact with one another.
- **TSMO Modeling Specialist:** As integrated corridor management strategies become more prevalent, agencies will need staff with advanced modeling and simulation skillsets to help plan for operations and assess impacts.
- **Emerging Technologies Industry Liaison:** Several organizations have identified a need for an industry liaison to facilitate collaboration among local private sector technology companies and government agencies, recognizing the direct benefits of new approaches to solve problems and a less-direct economic development impact.
- **Transportation Systems Performance Manager:** Telling the story of how the transportation system is functioning, both in real time and over a longer period, has been critical to demonstrating the benefits of TSMO. A performance manager sees the big picture and can demonstrate the collective benefits of the various functions of TSMO.
- **Integrated Corridor Management (ICM) Manager:** As management of freeways and arterial networks converge, it is important to have dedicated staff overseeing the strategies across the facilities that promote safety while improving corridor-wide mobility.
- **TMC Manager:** Although many government agencies have TMC managers that oversee staff in daily operations, reacting to incidents and other events, the growth of CAV and other

technologies within a control-room environment will require an added level of sophistication and understanding of how different actions affect network operations.

In addition to these new and expanded TSMO roles, Szymkowski and Ivey (2019) identified potential future roles and responsibilities for existing roles within agencies as follows:

- **Traffic Engineer:**
  - Use spatial data, such as geographic information system (GIS) and relevant spatial analyses and statistics, for data-driven decision-making.
  - Advocate for the appropriate TSMO countermeasures during the planning, design, and construction of highway projects, as appropriate.
  - Consider CAV impacts on traffic operations.
- **Traffic Signal Engineer:**
  - Incorporate ICM techniques into the operations of traffic signals.
  - Consider CAV impacts on traffic signal operations.
  - Effectively use GIS and other analytical tools such as Statistical Package for the Social Sciences (SPSS) or STATA and traffic simulation and signal timing software (e.g., VISSIM, CORSIM, and Synchro) to create information that enhances operational decision-making.
- **Freeway Operations Engineer:**
  - Incorporate ICM and other demand-management techniques into the operations of freeway facilities.
  - Consider CAV impacts on freeway operations and consider and manage new techniques such as autonomous vehicle-only lanes.
  - Take a multimodal approach to freeway operations.
  - Use real-time data to make real-time operational decisions.
  - Implement and use prediction software to make operational decisions.
- **Arterial Operations Engineer:**
  - Incorporate ICM techniques into the operations of arterial facilities.
  - Consider CAV impacts on arterial operations.
  - Take a multimodal approach to arterial operations.
  - Use real-time data to make real-time operational decisions.
  - Implement and use prediction software to make operational decisions.
  - Identify, analyze, and interpret trends or patterns in complex data sets.
- **ITS Design Engineer:**
  - Integrate connected vehicles into ITS design (for example, add DSRC or 5G connectivity as needed).
  - Use modern technology in ITS design (including civil information modeling).
- **ITS Planner:**
  - Use big data to analyze benefits of TSMO strategies and implement if feasible.
  - Mainstream TSMO into the project planning process.
  - Implement modeling for analysis, visualization, planning, and training related to TSMO programs.
  - Perform scenario planning for CAVs.
- **Transportation Planner:**
  - Mainstream TSMO into the project planning process.
  - Integrate management and operations strategies into the metropolitan transportation planning process to maximize the performance of the existing and planned transportation system.
  - Implement modeling for analysis, visualization, planning, and training related to TSMO programs.
  - Take a multimodal approach to transportation planning.

For each of these new and modified DOT positions, Szymkowski and Ivey (2019) included a detailed position description with required knowledge, skills, and abilities. Each position also included a diagram that identified the potential improvement that an agency will experience for varying business processes by hiring a specific type of position. For example, hiring a computer engineer will most benefit an agency's systems and technology dimension, as shown in Figure 15-1.

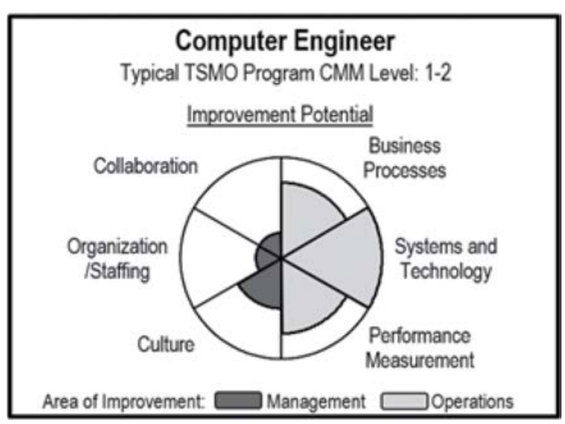
15.1.3 CAV Workforce Issues Identified in State DOT CAV Strategic Plans

The Minnesota DOT (MnDOT) CAV Strategic Plan (Hietpas and White 2019) identified two key initiatives related to workforce readiness for CAVs. First, MnDOT intended to evaluate its organizational capabilities to support CAVs. This recommendation included the following steps:

1. Develop an employee engagement plan to identify and mitigate the risks and impacts of CAVs within the next year.
2. Evaluate CAV staffing abilities using a capability maturity model framework within the next 3 to 5 years.
3. Develop a plan to address skill gaps and assess whether CAV staffing and skills should be directly hired, consulted to third parties, or privately managed.

MnDOT identified the following position types that would potentially be needed:

- Cybersecurity experts;
- Data scientists;
- Electrical engineers;
- Electricians;
- Equipment operators;
- Mechanics;
- Mobility managers;
- Network architecture, directory, server, and database administrators;
- Permits and right-of-way staff; and
- Radio frequency engineers.



Source: Symkowski and Ivey 2019.

Figure 15-1. Example of modified DOT position.

MnDOT's Strategic Plan (Hietpas and White 2019) recognized the challenges associated with competing against private industry to recruit and retain anticipated future positions. To address this, the following recommendations were included:

- Review and update civil service requirements to create additional classifications and work with technical schools, colleges, universities, and training programs to evaluate skills and compensation structures over the next 3 to 5 years.
- Develop a CAV talent pipeline and partner with schools to develop curriculum to train students in necessary skills. MnDOT anticipated the following vocations would be targeted:
  – Data science,
  – Cybersecurity,
  – Project management,
  – Radio technologies,
  – STEM and systems engineering,
  – Planning, and
  – Policy.

The Florida DOT (FDOT) CAV Business Plan (FDOT 2019) also included the following steps related to education and outreach:

1. Identify education and outreach aimed at organizational change management.
2. Develop new skillsets related to technology, deployment, integration, and software development.
3. Develop a program aimed at educating transportation planners, managers, engineers, local agencies, and users about the agency's CAV initiatives.

15.2 One-on-One Agency Interview Findings

Interviews with state DOTs for this project confirmed or enforced many of the themes from the literature, particularly related to the challenges associated with recruiting and retaining a workforce with the skills that CAV assets require. The following specifics were conveyed to the researchers conducting the interviews:

- California DOT (Caltrans) noted that position descriptions focus on construction skills; specialized skills related to software development, computer engineering, and electrical engineering will be a significant need in the future.
- CDOT noted challenges associated with high staff turnover, particularly for people capable of operating the agency's autonomous attenuators.
- Kentucky Transportation Cabinet (KYTC) had experienced high staff turnover. As staff were trained on new controller and roadside technologies and learned new computer literacy skills, staff were able to find work outside the agency at higher salaries.
- MnDOT noted that higher salaries outside of the DOT made it difficult to attract and retain technical staff. For example, the salary for an electrician outside of the DOT might be double. Flexibility and consistent work may be one point of attraction to work at a DOT, although technical skills may not translate elsewhere.
- Nevada DOT (NDOT) observed that certain positions, such as commercial vehicle drivers, were difficult to retain with state pay being low compared to that in the private sector.
- New Hampshire DOT (NHDOT) noted that a major challenge was not only having the funds to hire, but also the ability to hire the correct skill set based on the pay compared to market value. In particular, the after-hours needs of maintenance staff also made work-life balance difficult.

In addressing the lack of workforce skills related to these needs, a few agencies highlighted challenges related to existing agency position classifications and pay scales, as follows:

- KYTC noted that, while they were attempting to improve pay for maintenance positions, existing classification grades made it difficult to alter salaries.
- NDOT observed that the shift to new technology assets would require analysts who understand data requirements and how to leverage incoming data; hiring people with these skills was difficult under the current position classification system.
- NHDOT noted that most positions were engineering centric, making it difficult to hire data management staff.

Retaining existing staff was one way that agencies attempted to fill the gap created by new CAV assets. Several of the agencies interviewed were at varying stages of developing new training resources, as follows:

- Caltrans districts had attempted to use certification courses to keep up with new technology but found that these had limited effectiveness.
- KYTC had considered a maintenance training academy but had not addressed the cost and how to administer it. One particular issue was that they do not have a journeyman program for electricians, meaning they have no licensed electricians on staff.
- Michigan DOT (MDOT) noted that needs were shifting from civil engineering to technology, but educating the existing workforce and recruiting a workforce with new skills was a challenge.
- MnDOT had developed a CAV 101 program that they broadly and frequently offered to staff. In the long term, the agency expected the need for a workforce with more technical skills.
- NDOT was assessing its workforce development needs as part of its TSMO program.
- NHDOT observed that maintenance and IT staff already saw high demand for learning new skills, with ITS communication equipment maintenance needs already consuming all available resources.

One-on-one interviews also included the discussion of current practices and challenges associated with different types of technology assets. With respect to roadside units (RSUs), the following observations were conveyed to the research team:

- RSUs at FDOT were currently maintained by vendors, but some of these contracts would end soon with maintenance duties shifting back to the agency.
- Georgia DOT (GDOT) noted that long-term maintenance of RSUs may take the form of replacement due to how quickly technology was aging. Staff time would be required to routinely check assets; if staff were not trained to fix minor issues, replacement was the likely route.
- KYTC observed that finding staff with the skills needed to maintain RSUs was the biggest challenge due to a lack of resources to train or allocate staff to these duties.
- MnDOT noted that their signal and ITS group had mature technology capabilities with respect to signal-based RSUs, with an agency philosophy of including maintenance staff in pilot projects.

Maintenance of enhanced pavement markings was discussed in one-on-one interviews; however, most agencies indicated that pavement marking application and maintenance will be fundamentally the same with no anticipated workforce challenges. CDOT did note a learning curve related to equipment settings when moving to high-contrast pavement markings.

For agencies that operate vehicles with CAV technologies within their fleets, interviews included discussion of the unique needs associated with maintenance of onboard equipment:

- CDOT highlighted the importance of achieving buy-in from light- and heavy-duty fleet staff, and noted that, while DOTs have experience programming technology, ITS equipment has additional training needs. In particular, skills were lacking to develop graphic-user interfaces for in-vehicle equipment.

- MDOT observed that fleet maintenance staff were not overly familiar with IT equipment and newer technologies. Many maintenance staff were largely self-trained on new equipment, although the agency did have a contract with a maintenance vendor to provide 24/7 support to staff.

Finally, with respect to the workforce needs for back-office data collection, a couple of agencies noted potential challenges and opportunities, as follows:

- CDOT noted that workforce needs were currently being met by contractors who were using this time period to train agency staff with hands-on experience.
- MnDOT observed that the TMC workforce had data skills aligned with CAV data types; however, data were typically siloed, and the agency was still a generation behind the capabilities to ingest and synthesize broad data sets at TMCs.

15.3 Insights from Maintenance Contractor Interviews

Several of the maintenance contractors interviewed also provided feedback about likely workforce skills that would be required for CAVs. In general, they agreed that skills needed for maintenance of CAV assets would be similar to those for ITS assets. In particular, this included electronics and computer backgrounds. One vendor supplied the following list of skills required for ITS-related activities:

- Low- and high-voltage electrical license,
- Professional civil and electrical engineering license,
- Information technology certification,
- Computing technology certification, and
- Fiber optic cable training and certification.

One vendor noted the main skills needed for ITS devices were related to power, hardware, and software. The skills needed by workers addressing power issues (electricians) and those installing or changing hardware were evolving since an understanding of logic and network programming is needed for both types of activities. They indicated that just replacing hardware was a thing of the past given that many types of hardware, once installed, needed to be able to communicate with other devices.

The dynamics of the maintenance workforce was also evolving. Field work was requiring more sophisticated skills. While this may require additional training, it may be more attractive to workers of younger generations who have more skill with computers and automation. Additionally, it creates more of a challenge to workers than just conducting routine maintenance, which could also be attractive to high-quality workers.

One vendor also noted that they would invest in additional training for their staff when they perceived a sufficient need to do that. The main criteria was having enough of the work requiring a specialized skill to warrant the resources needed for additional training.

15.4 Key Themes and Suggestions

Table 15-1 summarizes key CAV workforce implications that emerged from this work.

Table 15-1. Summary of key themes and suggestions for CAV workforce implications.

Key Theme	Suggestions
Current position descriptions are not oriented around CAV technology	• Evaluate trends in agency job classifications to identify opportunities for insertion of new technology skill requirements into *existing position descriptions*. • Where new CAV-oriented skill sets cannot be incorporated effectively, build on existing research to develop consolidated set for *new position descriptions*.
Lack of suitable pay bands for staff with CAV skills	• Conduct salary analysis for industries currently utilizing labor types similar to those anticipated to be needed for CAV assets. • Quantify total compensation package information for government positions to present the overall value of public-sector benefits to new employees.
Agencies do not have reliable talent pipelines for CAV skill sets	• Develop curriculum guidance for four-year degree programs, community colleges, and vocational programs related to CAV assets. • Analyze agency apprenticeship programs to identify opportunities for enhancement and replication at other agencies.
Lack of nationally consistent CAV credentials and training programs	• Leverage the work of one or more national organizations (e.g., Transportation Curriculum Coordination Council, American Public Works Association, NHI) to develop credentials for roadside equipment (RSE) maintenance, onboard equipment maintenance, and back-office operations and management. • Develop model CAV training programs that can be customized for individual agencies based on the above topics.
Lack of data on long-term maintenance needs for RSUs and OBUs	• Engage vendor community to better understand the anticipated long-term maintenance needs for RSUs. • Monitor agencies with ongoing CAV deployments to assess the maintenance trends of assets operational beyond vendor contract and warranty periods.
Uncertainty about infrastructure and vehicle standards	• Monitor maintenance needs arising from the shift to cellular and dual-mode RSUs. • Monitor the progress of proposed *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) standards and guidance on machine-readable infrastructure. • Continue engagement of automotive manufacturers to understand required and desired infrastructure enhancements to support CAVs.

CHAPTER 16

Summary and Implementation

16.1 Summary

The objectives of this project were to identify common infrastructure elements that agencies have implemented for connected and autonomous vehicles (CAVs), document maintenance needs for those assets, identify any available guidance or standards for maintenance practices, and assess workforce implications.

The following summarizes project activities and findings:

- The research on CAV maintenance did not find agencies with mature practices or data concerning the maintenance of CAV assets.
- The research team gathered emerging CAV information from 39 states via survey and conducted 18 follow-up interviews with states, municipalities, vendors, and maintenance contractors. The totality of this information demonstrated that within 3 to 5 years, some level of CAV maintenance history would be available from most of the responding states.
- Research identified that CAVs were likely to impact a broad array of agency assets, contributing to a system that is more actively managed, interconnected, and in need of enhanced levels of maintenance to serve CAVs.
- Research particularly focused on three major asset types that will significantly impact transportation agencies in the next decade.
  - Pavement marking national standards were changing through proposed updates to the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) that benefit both human driver safety and image processing at the heart of CAVs. The increased standards for lane marking widths to 6 in. will affect states at different levels based on their current practices but, overall, were expected to increase maintenance costs.
  - Opportunities like the U.S. Department of Transportation (DOT) sponsored Smart City Challenge and CV Pilot Program, along with federal grants like the Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD), had enabled agencies to invest reduced capital funding into more emerging asset types such as roadside units (RSUs) and vehicle-based on-board units (OBUs). Out of these deployments, agencies were gaining value in the needs for staff advancement into electrical maintenance, computer programming, and information technology skills. The pilot deployments cataloged were mostly short in duration and filled temporary skill gaps with support from third parties, like universities, vendors, consultants, and maintenance contractors.
- The research team conceptualized from all information gathered that the growth in CAV technology assets represents a natural extension of current intelligent transportation system (ITS) and transportation systems management and operations (TSMO) programs in the

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relationship between field staff needs and activities and the staff operating the system in the back office or in a traffic or transportation management center (TMC).
  - CAV assets, like ITS and TSMO assets:
    - Best achieve user and agency benefits when applied through the systems engineering process. The research team describes the Federal Highway Administration (FHWA) guidance documents that support systems engineering for CAVs and ancillary plans for early CAV pilot testing. The outcome of systems engineering is typically a traceable plan for validation and verification that the implemented system serves all users in a measurable way.
    - May require a strong business case to agency management to elicit up-front and continued investment support. Several tools exist to begin to demonstrate agency return on investment of CAV pilots, but the research team noted that some of the agency interviews highlighted intangible returns like greater agency awareness that may not easily translate into an economic analysis.
    - May struggle from a lack of operations and maintenance funding even though these assets may be safety-critical to travelers. A proven remedy for limited operations and maintenance funding are procurement requirements that enable vendor-led maintenance and training of agency maintenance staff through the early deployment period.
    - Represent a high risk of sudden failure to agencies that frequently invest in pavement and bridges. Failures may be temporary or may be mitigated, but they require a different response mindset than traditional schedule- or proactive-based maintenance.
- Ultimately, the research team captured that instability in national technology and communication standards throughout the project led to functional obsolescence of some of the CAV assets studied, which is cautionary for state agencies as they consider their future investments in CAV assets. While even short-life deployments can help agencies start to adopt early changes for CAV readiness, the potential growth to agency workforce knowledge, skills, and abilities must be balanced with the risk of technology deployment costs with limited public benefit.

16.2 Suggestions for Implementation

Agencies were in earlier stages of implementation than expected. As a result, none of the agencies or maintenance contractors had much experience with maintenance of CAV assets. Only limited information about maintenance practices was available, and standards and best practices could not be developed. Further activities could include the following:

- Identify several states or agencies that have had one or more of the assets that were a focus of this project (e.g., pavement markings, RSUs). This would include agencies that have conducted widespread implementation of the asset(s), several years of experience with the asset(s), and willingness to participate. Databases could be developed with a structure that will allow gathering additional data to track performance (historical information if available and an additional two years of data). Using this information, initial performance estimates could be developed, along with cost estimates.
- Conduct focus groups with asset vendors to develop initial performance estimates. Many agencies indicated that they were using initial vendor contractors for maintenance due to the newness and uncertainty of the technologies. The research team obtained some limited information from vendors. However, contacting vendors was not within the scope of the original work since it was initially felt that agencies would be more mature in implementations of the assets.

Among the most significant findings of the research were direct agency interviews and survey responses validating that states are acting in anticipation of CAVs, but with significant limitations in workforce knowledge, skills, and abilities. The agencies addressed that gap temporarily by contracting work to third parties in the form of universities, vendors, consultants, and contractors. Public-private partnership (PPP) relationships also represented an effective method to pilot emerging technology, but long-term adverse outcomes could result if agency planning for the technology project does not retain the deployment knowledge.

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Abbreviations, Acronyms, and Initialisms

3D	three-dimensional
3GPP	3rd Generation Partnership Project
AASHTO	American Association of State Highway and Transportation Officials
ADA	advanced driver assistance
ADAS	advanced driver assistance system
ADS	automated driving system
ADT	average daily traffic
AFSCME	American Federation of State, County, and Municipal Employees
AI	artificial intelligence
API	application programming interface
ARP	antenna reference point
ASTM	American Society for Testing and Materials
ATC	automatic traffic controller
ATCMTD	Advanced Transportation and Congestion Management Technologies Deployment
ATMA	autonomous truck-mounted attenuator
ATMS	advanced traffic management system
ATSSA	American Traffic Safety Services Association
AV	autonomous vehicle
AVL	automatic vehicle locating, location, or locator
BUILD	Better Utilizing Investments to Leverage Development
BSM	Basic Safety Message
Caltrans	California Department of Transportation
CAV	connected and autonomous vehicle
CCTV	closed-circuit television
CDOT	Colorado Department of Transportation
Con Ops	concept of operations
COTA	Central Ohio Transit Authority
CPU	central processing unit
C-V2X	cellular vehicle-to-everything
CV	connected vehicle
CVE	Connected Vehicle Environment
CMCC	Connected Mobility Control Center
COTS	commercial off-the-shelf
CTSO	Committee on Transportation System Operations
DMS	dynamic message sign
DOT	department of transportation
DPPD	dynamic passive pedestrian detection

DSRC	dedicated short-range communication
EDACS	Enhanced Digital Access Communication System
EDC-4	Every Day Counts Round 4
EMS	extinguishable message sign
ESS	environmental sensor station
EV	electric vehicle
FCC	Federal Communications Commission
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FTE	full-time employee
GDOT	Georgia Department of Transportation
GIS	geographic information system
GNSS	global navigation satellite system
GPS	global positioning system
ICM	integrated corridor management or manager
IIJA	Infrastructure Investment and Jobs Act
IMO	Integrated Mobility Observation
I/O	input/output
IOO	infrastructure owner operator
IP	internet protocol
ISP	image signal processor
IT	information technology
ITS	intelligent transportation system
JPO	Joint Program Office
KYTC	Kentucky Transportation Cabinet
LED	light-emitting diode
LiDAR	Light Detection and Ranging
LLL	Lessons Learned Logbook
LTE	long-term evolution
MaaS	Mobility as a Service
MDC	mobile data collector
MDOT	Michigan Department of Transportation
MDSS	maintenance decision support system
MFES	managed field Ethernet switch
MMITSS	multi-modal intelligent traffic signal system
MMS	maintenance management systems
MnDOT	Minnesota Department of Transportation
MOD	mobility on demand
MRP	MMITSS roadside processor
MTWC	Midwest Transportation Workforce Center
MUTCD	*Manual on Uniform Traffic Control Devices for Streets and Highways*
MV	machine vision
MVDS	microwave vehicle detection system
NCAR	National Center for Atmospheric Research
NCHRP	National Cooperative Highway Research Program
NCUTCD	National Committee on Uniform Traffic Control Devices
N-DEx	National Data Exchange
NDOT	Nevada Department of Transportation
NHDOT	New Hampshire Department of Transportation
NHI	National Highway Institute
NHP	Nevada Highway Patrol

NYC	New York City
O&M	operational and maintenance
OBE	onboard equipment
OBU	on-board unit
ODOT	Ohio Department of Transportation
OEM	original equipment manufacturer
PoE	Power over Ethernet
PPP	public-private partnership
PUFFIN	Pedestrian User-Friendly Intelligent Intersection
QA	quality assurance
QR codes	quick-response codes
RFP	request for proposal
RPM	raised pavement marking
RRFB	rectangular rapid flashing beacon
RSE	roadside equipment
RSU	roadside unit
RTK	real-time kinematic
RTOP	Regional Traffic Operations Program
RWIS	road weather information system
SANDAG	San Diego Association of Governments
SNTMC	Southern Nevada Traffic Management Center
SOP	standard operating procedure
SPaT	signal phase and timing
SPSS	Statistical Package for the Social Sciences
TAMS	transportation asset management system
TCD	traffic controller device
TCP/IP	Transmission Control Protocol/Internet Protocol
TH	Trunk Highway
THEA	Tampa Hillsborough Expressway Authority
TIM	Traveler Information Message
TMA	truck-mounted attenuator
TMC	traffic or transportation management center
TRB	Transportation Research Board
TRID	Transportation Research International Documentation
TSMO	transportation systems management and operations
TSR	traffic sign recognition
TTS	Traffic Technology Services
UAS	unmanned aerial system
UDOT	Utah Department of Transportation
U.S. DOT	United States Department of Transportation
UV	ultraviolet
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VDOT	Virginia Department of Transportation
WisDOT	Wisconsin Department of Transportation
WSDOT	Washington State Department of Transportation
WYDOT	Wyoming Department of Transportation

APPENDIX

Additional Comments from Survey

A number of additional comments were available from the survey and are provided below.

Additional comments from **Question 7** ***(Does your agency have any additional lessons learned about asset maintenance for connected and automated vehicles (CAVs)?)*** include the following:

- One agency noted that they are just in the early stages but expect there will be lessons learned, with changes in their program not yet anticipated.
- One agency noted: *Still unknown exact maintenance needs at this time. Original equipment manufacturers (OEMs) will drive deployment, and public agencies will react to what's needed on the infrastructure. So, still a lot of questions and guesswork on what we really need to do to be ready for CAVs.*
- One agency noted that most are still relatively new; however, the cost to install initially is often a barrier. The real barrier is the ongoing cost to operate and maintain.
- One agency noted: *Many agencies are budget constrained to the point where additional maintenance will need to come with funding and, likely, mandates. For example, increased retro numbers for delineation or dotted lines across ramp openings or higher contrast ratio goals. Not many improvements for automated vehicles/connected vehicles (AVs/CVs) are revenue neutral, so the key is guidance/mandates and associated funding to meet them. Also, during AV Level 2 or 3 fleet turnover (50% fleet rollover within ± 15 years), increased delineation efforts may facilitate higher rates of AV system use penetrating farther into the urban/congested areas and with the resulting increased headways seen with these systems' automated cruise control/car following, we could see temporal and spatial congestion increases due to reduced lane capacity since the systems will not allow sub-second headways as some areas experience today without these AV systems.*

Specific comments for **Question 9** ***(Has the adoption of CAV impacted other maintenance needs?)*** are summarized below. Since most of the comments were specific, they were not paraphrased:

- *The benefit and use of the technology is dependent on a functional maintenance truck. The age of the vehicle (and its own maintenance needs) forced us to not acquire as many autonomous miles as we had hoped for and impacted our ability to achieve the paint striping miles.*
- The resources needed to implement have taken away from other activities.
- *More technical effort needed.*
- *There is a need for regular maintenance of our roadside units (RSUs) to ensure that they are "up" and functioning as intended.*
- *More frequent/detailed maintenance of intelligent transportation system (ITS) equipment. Upgrades of advanced traffic management system (ATMS) and automatic terminal information service (ATIS) systems.*

- *Internal processes. I realize this is not physical infrastructure, but the ability to share signal phase and timing (SPaT), for example, may be delayed due to internal processes that do not allow for the data to be shared (no feeds, no data portals, etc.) So, our ability to improve our maintenance of the data has changed.*
- *Operational and maintenance (O&M) expenses continue to increase as ITS/CAV asset deployment increases. Becoming more and more difficult to expand ITS/CAV architecture with increased O&M costs. Workforce (e.g., electricians) need additional training to understand dedicated short-range communication (DSRC) RSU communication, fibers, sensors, etc. installation/inspection [quality assurance (QA) on contractors], etc. as architecture continues to expand.*
- *At this time, no, but we have planned pilots.*
- *Based on my understanding, lane markings will need to be inspected often and replaced at a much higher frequency than done previously.*
- *Adding features adds to maintenance requirements. Data needs may drive needs for better, more accurate, lane impact data from work zones. We are waiting to see what infrastructure standards may be necessary and how that will impact maintenance needs. Increased connectivity has benefits for remote management of roadside equipment.*
- *Traditionally, deployments at signalized intersections are maintained by the local municipality. Equipment to support the deployment of CAV technology will be maintained by the department of transportation (DOT).*
- *Normal routine activities such as road sweeping have been increased to ensure the visibility of our pavement markings.*

Specific comments for **Question 10** ***(Are you concerned about other aspects of maintenance related to CAV activities?)*** are provided below:

- *As additional devices are installed, they require an increase in resources and staff to operate and maintain. And that is all tied back to funding availability.*
- *Education and training to improve human trust and use of the system.*
- *There are concerns with staffing capabilities, time for maintenance for CAV technology, priority of maintenance for CAV technology, and cost of maintenance.*
- *As we are just beginning to implement, we are not sure yet what this may bring.*
- *We are just starting out, so we are concerned about what we do not know yet.*
- *We are concerned with maintaining proper retroreflectivity and contrast of pavement markings for CAV technology. We are also concerned with maintaining visibility of pavement markings in winter conditions. There is also concern with the ability of CAV technology to recognize and properly react to the different types of work zone traffic control devices used.*
- *How to get information out about maintenance functions.*
- *Worried if agencies, within limits of current funding structure, will be able to maintain systems at the levels needed by CAV technologies.*
- *Unsure if roads/highways/bridges can be kept in a good state of repair on a statewide basis sufficient to support CAV applications.*
- *Increase in ITS devices and the lack of funds to maintain them in adequate shape for full CAV functionality. Breakdown of autonomous maintenance vehicles (e.g., Autonomous snowplows that break down while in operation). Increase in need to resurface due to increase in vehicular trips (i.e., funding) in work zones, therefore safety issues.*
- *Yes, because CAVs cannot "see" in snow, rain, sleet, blowing ice, or fog. We are conducting research at a research facility to understand how cameras and LiDAR can be programmed to see through these inclement weather conditions.*
- *Lack of understanding of how CAVs will impact maintenance practices. For instance, how will CAVs respond to temporary markings that are largely nonexistent by the time that final striping is applied?*
- *Yes, we are concerned with the unknown impacts at this time.*

- *Winter operations are a great concern, as conditions often change at a rate faster than we can adjust to.*
- *Depends on the approach the industry takes.*
- *Cost implications of increased maintenance requirements for infrastructure are a concern.*
- *The deployment of CAV technologies has yet to have a significant impact on our current maintenance practices outside of experimental and pilot projects. We are taking small steps like ensuring line width consistency (6 in). We need more direct guidance on actionable steps to update our maintenance practices.*
- *What concerns me is the unknown future impacts and demands to the system and what it means to our resource allocation.*
- *Financial unknowns are vast.*
- *Need for digital infrastructure, common data dictionaries, updating and reconciling DOT traveler information sources and third-party sources, incident management.*

Specific comments for **Question 11** ***(Any general concerns regarding CAV activities related to maintenance?)*** are provided below. The specific responses were as follows after some editing for clarity:

- *We are chartering a CAV planning task force with members from throughout the DOT as well as from other state agencies. At this time, the DOT is waiting for more standardization before adding/increasing/modifying system assets. Maintenance impacts certainly will influence decisions on rolling out asset direction tied to CAVs.*
- *How does CAV function around nonstandard maintenance activities on and around the dynamic envelope of CAVs?*
- One state agency had multiple comments:
  - *At this point, there is still a lot of uncertainty and lack of information regarding the future timing and needs of CAV technologies and their impact on highway maintenance.*
  - *CAV standards are needed for transportation agencies to be able to make substantial preparations for CAV technologies. This is an immense challenge given that standards take time to develop, and CAV technologies are still evolving.*
  - *In the meantime, lessons learned from CAV pilots and other research and development activities should be more widely shared to allow the transportation community to gain better knowledge, build consensus, and be prepared for a CAV future.*
  - *We have not adopted CAV technology. There is uncertainty, and not enough information has been provided. With the adoption of such technology, the systems engineering process should be followed to ensure that maintenance and operations staff are capable with this advancement. If current staff cannot support such technology, it will fail. If more maintenance is required so that CAV activities are accommodated, this is a major concern.*
  - *CAV standards are needed and the sharing of information for CAV pilots will be crucial for adoption of these practices. We are actively participating in webinars, doing research, and learning from others about CAV pilots. CAV communications will also need to be determined.*
- *High technology aspect.*
- *Though not directly maintenance, pavement markings and signals need to be more uniform than they are at present; the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) provides considerable latitude for different pavement marking implementations and signal displays; autonomous technology stands to benefit from consistent application of traffic control devices.*
- *As we are new at this, we are unsure how our maintenance cycles in regard to striping and paving will be affected. We also know that we will need additional staff to deal with the new traffic controllers and any sensors we may decide to add in the future.*
- *Short-term maintenance, winter weather information, how quickly infrastructure would need to be repaired or replaced due to crashes, vandalism, etc.*

- *Will CAV applications preempt or accelerate privatization of maintenance activities? Being the owners of infrastructure, will CAV require relinquishing ownership of facilities to technology companies or transportation services providers?*
- *Developing the mechanisms to support CAVs internal to the agency, not just the infrastructure but the standard operating procedures (SOPs) needed to make the maintenance of the infrastructure work effortlessly.*
  - *Impact on workforce/communities. Example: Some maintenance activities actually support workforce development programs; if maintenance is replaced with an autonomous mower, what happens to that workforce development program?*
- *Too many unknowns. Demand driven by private sector OEMs not public agencies. Future costs and how to generate revenue. P3 needs to accommodate added technology-based mobility, including Mobility as a Service (MaaS), mobility on demand (MOD), and CAV (just a few examples of what we know today). More maintenance demand on infrastructure and too many unknowns as to how public agencies need to support it. What will the workforce look like, training needs, systems integration, change funding needs, legislative/law needs, policies/procedures/guidance documents (one example is the MUTCD), etc.*
- *Other maintenance items that have been brainstormed at a high level include automated mowing and trash collection, automated flagging and automated striping; however, we are not pursuing that research at this time.*
- *We are not planning modifications for CAV technology; however, we believe many of the things we are doing (maybe not specifically for CAV) do align with this direction to some degree or another, so, below are some of the initiatives we believe would be relevant to your study:*
  - *While we do not have a concrete/defined plan for implementation of any major infrastructure improvements in the next three years for CAVs, our current focus is generally on pavement and bridge (surface) preservation. However, as CAV technology evolves and we get a clearer picture of what is needed, I fully expect we will evaluate the need to add this aspect to our program, prioritizing with our planning partners and available funding.*
  - *However, our direction with surface is an effort for uniformity in the condition of the surface, keeping our major routes in good condition with reasonable overlay cycles and one of our predominate treatments for our minor roads is chip seals. We do not have a typical practice of sealing individual cracks, for example, which I have seen causes issues with mechanical vision.*
  - *With respect to winter snow removal operations, we are predominantly a plow-to-clear pavement state. For higher volume routes, including interstates and major and minor highways greater than 2,500 average daily traffic (ADT), our crews fight winter events from the onset of the storm until pavement is virtually dry. We are also migrating to a rubber edged snowplow blade to help reduce damage to the pavement and pavement markings. However, any snow removal operation is hard on pavement markings, so the effort to clear snow has a negative impact on the condition of our markings in the spring.*
  - *With respect to pavement markings, we adopted 6 in. lines on all of our major routes (5,500 mi of divided and two-lane arterial) as well as utilizing an American Society for Testing and Materials (ASTM) Type III glass bead on these lines for wet night performance. We also initiated a quality over production philosophy with respect to pavement markings, conducting annual trainings for our striping crews and conducting a couple of different types of quality assurance reviews to help them keep on target for applying a quality line. Our goal is to have a high-quality pavement marking that provides levels of guidance as well as a quality line that will have the greatest chance of making it through winter and providing that guidance until we restripe the road in the spring (we are a waterborne paint state). We also implemented a new pavement marking database two years ago to help us better manage this resource.*
  - *With respect to signing, we have a stateside sign inventory system, and we conduct night sign inspections on 50% of our signs each year. Our urban areas have significant efforts underway to upgrade aging signing along their major roadways.*

- *With respect to temporary traffic control, we have a pretty aggressive program to provide the best temporary traffic control possible. We conduct annual work zone inspections as QA to look for ways to improve our program. Probably one of our areas of greatest improvement is our use of temporary tabs following a surface treatment, which I understand mechanical vision doesn't recognize.*
- *With respect to data collection, as I mentioned in the pavement marking response, we are conducting QA reviews to maintain and improve pavement marking quality. This involves both mobile retroreflectivity data collection as well as handheld retroreflectivity studies, which include photographic evaluation of paint and bead applications. We also have automated road analyzers (ARAN vans), which are used to collect pavement and road asset data.*
- *We have seen an increase in truck-mounted attenuator (TMA) hits the last few years and the goal of the automated truck-mounted attenuator (ATMA) is to eliminate operator injuries when the rear protective vehicle is impacted by removing the operator from the vehicle. We are currently testing the equipment.*
- *Traffic Technology Services (TTS) is an information service provider for connected vehicle applications. We have executed agreements with TTS (and are working on executing an agreement for another portion of the state), at no cost, to allow them access to our signal timing data from our advanced traffic management system (ATMS). TTS delivers the data to OEMs, etc. to integrate to in-dash systems (currently in Audi's) to show signal timing.*
- *HAAS Alert/Makeway Pilots. We are currently piloting these technologies. The technology alerts the driving public of the presence of our field crews through crowdsourcing applications to increase awareness, slow down or move over, etc. Equipment is installed in our emergency response fleet and through the use of GPS and cloud-based solutions, the driving public is notified through the Waze app when our emergency response fleet lights are on.*
- *We collaborated among members of various American Association of State Highway and Transportation Officials (AASHTO) committees within our department on our one response to the survey and this email. If you have any questions, please feel free to contact us.*

- *Looking to the foreseeable future, CAV and human drivers will need to coexist. We are focusing our efforts where new technology and changes to systems and other actions can benefit both.*
- *Having skilled, qualified, and trained resources to maintain the systems.*
- *Uncertainty related to needs/applications related to CAV make planning for the future difficult.*
- *Work zones, CAV technology, inclement weather, etc.*
- *Concerns regarding the additional costs and level of efforts that will be needed to provide a safe and efficient transportation system.*

Abbreviations and acronyms used without definitions in TRB publications:

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

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