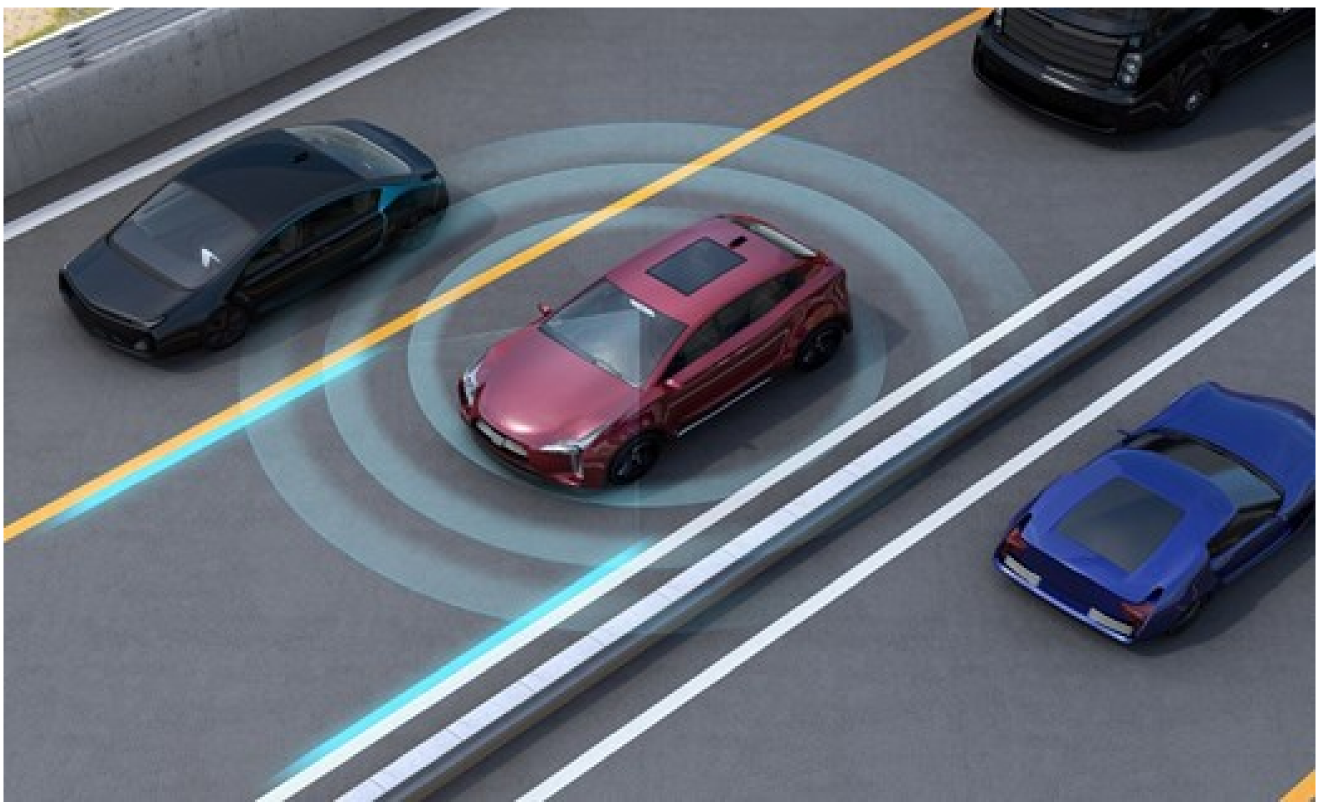
May
2018

Strategic Planning for Connected and Automated Vehicles in Massachusetts



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16. Abstract
Connected and Automated Vehicle (CAV) technologies are evolving at a fast pace, and new developments are occurring on a daily basis. These technologies have potential to significantly change transportation and travel, to make them safer, more accessible, and more efficient than they are today. There are many issues that will have to be investigated, such as the pace and extent to which CAV technologies become pervasive, the socioeconomic impacts of CAVs, their implication on privacy and security; to what extent will these technologies replace human drivers, and the legal and regulatory responsibilities for the safe operation of CAVs. State DOTs will need to plan to prepare for and accommodate CAV technologies. The purpose of this study is to provide baseline information pertaining to strategic planning for CAV technologies in Massachusetts. This information may be used to assist MassDOT to develop a strategic plan to accommodate the deployment of such technologies and for related infrastructure investment decisions.

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Strategic Planning for Connected and Automated Vehicles In Massachusetts

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Executive Summary

This study of Strategic Planning for Connected and Automated Vehicles In Massachusetts was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

Connected and automated vehicle (CAV) technologies are developing at a fast pace; new developments occur on a daily basis. These technologies have great potential to change transportation and travel: to make them safer, more accessible, and more efficient than they are today. There are many issues that will have to be resolved, such as the pace and extent to which CAV technologies become pervasive, the socioeconomic impacts of CAVs, their implication on privacy and security, the extent to which they will replace the human driver, and the legal and regulatory responsibilities for their safe operation.

The answers to these unknowns depend on a number of factors, including how CAVs will be used, infrastructure investment decisions, the overall costs and reliability of CAV technologies, and public policy and regulation.

Departments of Transportation (DOTs) may wish to consider developing a planning framework to prepare for and accommodate CAV technologies. The purpose of this study is to provide baseline information pertaining to strategic planning for CAV technologies in Massachusetts. This information will help state DOTs, including MassDOT, to develop a strategic plan for the successful deployment of such technologies and for related infrastructure investment decisions.

The objectives of this study are to provide MassDOT with:

- An understanding of the current state of practice and a vision of the future state of CAV technologies.
- An assessment of the potential future impacts of CAV on transportation across the Commonwealth.
- Identification of potential public/private partnerships that could help MassDOT leverage additional support for the development and employment of infrastructure-based CAV technologies.
- A planning roadmap to address forthcoming developments in the CAV industries, such as the introduction of new technologies, advances in private sector CAV products and services, and proposed new policies and regulations.

The key findings and conclusions of this research are summarized in four chapters:

1. CAVs—Current Activities and Future Challenges

Several federal efforts are underway in preparing for the deployment of CAV technologies:

- The U.S. Department of Transportation (USDOT) has published the *USDOT Intelligent Transportation Systems Strategic Plan 2015–2019* to provide a framework for research, development, and adoption of CAV technologies. The two strategic priorities of this plan are realizing CV implementation and advancing automation. It also contains five strategic themes: safety, mobility, environmental impacts, innovation, and data collection.
- The National Highway Traffic Safety Administration (NHTSA) is working on policies and regulations related to CVs, with a primary focus on vehicle-to-vehicle (V2V) communications, while the Federal Highway Administration (FHWA) has developed vehicle-to-infrastructure (V2I) technology guidance.
- The American Association of State Highway and Transportation Officials (AASHTO) adopted the Signal Phase and Timing (SPaT) resolution for deploying dedicated short-range communications (DSRC) infrastructure with SPaT broadcasts in each state by 2020.
- The Connected Vehicle Safety Pilot Program, launched by the USDOT in Ann Arbor, MI, in 2012, is for testing safety applications of V2V and V2I technologies. It has led to the development of the new Federal Motor Vehicle Safety Standards (FMVSS) by NHTSA.
- The USDOT started the CV Pilot Deployment Program in 2015 to deploy, test, and operationalize CAV technologies and applications. It also launched the Smart City Challenge, to encourage cities to develop integrated smart transportation systems.

The report identifies the following important challenges for state and local governments in addressing the emergence of CAVs:

- Traffic Management and Transportation Planning
- Infrastructure Investment Needs
- State and Local Revenue Streams and Budgeting
- Liability and Insurance Issues
- Police and Emergency Services
- Maintenance and Asset Management

2. Impacts of CAV Technologies on MassDOT

The potential impacts that CAVs will have on transportation in Massachusetts include:

- **Impacts on MassDOT mission**: CAVs will have significant impacts on traffic safety, traffic operations, mobility, congestion, system reliability, the environment, energy consumption, land use and land development, and more. All these aspects are closely related to MassDOT's mission and are analyzed in detail in this report.

- **Impacts on policy and planning**: These include institutional impacts with respect to the organizational structure of MassDOT and the distribution of funding, as priorities for projects may change with the advent of CAV technologies.
- **Economic impacts**: The introduction CAVs will require new infrastructure investments to fully benefit from these technologies, and many of these infrastructure investments will require extensive resources. Changes in transportation infrastructure are anticipated, including roadside communication units, travel lane markings, traffic signs and signals, etc.
- **Impacts on data availability**: CAVs will generate and utilize massive amounts of data. MassDOT will have to collect, process, disseminate, and store such information from and to CAVs. This will have significant implications with respect to data organization, processing, and utilization, as well as cybersecurity.

3. Potential Partnerships

Establishing partnerships with key public and private sector stakeholders could enable state DOTs to leverage the potential benefits of CAV in the maintenance and management of transportation systems and infrastructure. State DOTs may consider maintaining close collaborations with federal agencies to stay informed of the most recent developments and obtain funding for research, testing, and deploying CAV technologies. MassDOT may also consider maintaining collaborations with other state agencies to ensure that efforts are coordinated, and with neighboring New England states to ensure interoperability of the CAV systems when they are deployed. At the local level, MassDOT should consider working with municipalities to provide technical support, ensure system interoperability, understand local needs and constraints, leverage resources, and collaborate on CAV-related deployment and piloting projects.

State DOTs can foster collaborative relationships with research and higher education institutions—not only for research and development, but also for education, training, and workforce development.

State DOTs should also consider pursuing collaborative relationships with private sector representatives actively involved in advancing CAV technologies to identify public/private partnership opportunities for the deployment and evaluation of CAV technologies. Such public/private partnership opportunities may help state DOTs to better understand how CAV technologies perform, develop implementation and operational procedures and guidance for their use, and identify the need for new infrastructure investments to maximize the benefits of these technologies. Collaboration can also be established with both transportation network companies (TNCs), who are moving toward integrating CAVs, and companies that can provide important vehicle connectivity solutions needed for the operation of CAVs.

4. Strategic Recommendations for Connected and Automated Transportation Systems

State DOTs could play a key role in facilitating the deployment of CAVs, ensuring their safe use, and promoting their benefits. This report makes the following strategic recommendations for state DOTs, including MassDOT in that role:

- **Promote testing of CAV technologies** to gain valuable skills and expertise that will assist future CAV deployments. To facilitate testing, state DOTs could consider new legislation to establish standards for safely testing CVs/AVs on public roads and to establish testbeds to be used under different conditions.
- **Modify driver training and licensing requirements,** since CAV technologies will pose different requirements from the operator/owner of the vehicle than traditional vehicles.
- **Encourage the use of shared AVs (SAVs)** by providing operating guidelines to ensure a safe and efficient SAV system.
- **Invest in transportation infrastructure** to develop strategies to regularly inspect for future investments in CAV infrastructure (DSRC or cellular network), including a network of smart sensors that would benefit the CAV operators/riders and provide MassDOT with a wealth of important data that can be used and to maintain pavement markings and traffic signs on all freeways and major roadways.
- **Implement signal priority strategies** to improve mobility and safety and accelerate the market penetration of CAVs.
- **Provide dedicated lanes for CAVs** once market penetration is high enough, especially on freeways serving longer trips.
- **Invest in data analytics and cybersecurity** for the large stream of data that will be generated by CAVs.
- **Prepare the workforce** so new state DOT employees will be able to understand the opportunities and challenges brought by CAV technologies.

Specific recommendations for actions to be taken by state DOTs are also provided in this report. These recommendations for actions are categorized into three time frames: short, medium, and long term. In particular, a near-term pilot CAV study plan is outlined in this report, which considers the deployment of DSRC infrastructure with SPaT broadcasting capability along Route 9.

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List of Acronyms

Acronym	Expansion
ATMS	Advanced Traffic Management System
AASHTO	American Association of State Highway and Transportation Officials
AV	Automated Vehicle (or Autonomous Vehicle)
CAV	Connected and Automated Vehicle
CV	Connected Vehicle
DSRC	Dedicated Short-Range Communications
DUI	Driving Under the Influence
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FTA	Federal Transit Administration
FMVSS	Federal Motor Vehicle Safety Standard
HAV	Highly Autonomous Vehicle
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation System
ITSA	Intelligent Transportation Society of America
JPO	Joint Program Office
LIDAR	Light Detection and Ranging
MassDOT	Massachusetts Dept. of Transportation
MBTA	Mass. Bay Transportation Authority
NETC	New England Transportation Consortium
NHTSA	National Highway Traffic Safety Administration
OD	Origin-Destination
RMV	Registry of Motor Vehicles
RSU	Roadside Unit
SAV	Shared Automated Vehicle
SPaT	Signal Phase and Timing
TNC	Transportation Network Company
TOD	Transit-Oriented Development
TSP	Transit Signal Priority
UMTC	Univ. of Mass. Transportation Center
USDOT	U.S. Dept. of Transportation
V2D	Vehicle-to-Device
V2I	Vehicle-to-Infrastructure
V2I-DC	Vehicle-to-Infrastructure Deployment Coalition
V2V	Vehicle-to-Vehicle
VMT	Vehicle Miles Traveled

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Introduction

Connected and automated vehicle (CAV) technologies may bring significant changes to transportation and travel. Using advanced wireless communication, computing, sensing, and control technologies, these vehicles are able to identify safety threats and hazards, take proper actions, and share such information wirelessly with other vehicles/travelers and transportation management agencies.

A critical component of CAV technologies is the deployment of a wireless networked environment that supports real time information exchange between vehicles (V2V), and between vehicles and transportation infrastructure (V2I) or hand-held devices (V2D), to enable a wide range of real-time safety and mobility applications. Dedicated Short Range Communications (DSRC) – two-way radio communication operating on the 5.9GHz band – is typically used for the purpose of supporting V2V and V2I traffic applications.

CAV technology is advancing rapidly, and state DOTs should consider what steps their agencies can take to support and accommodate V2V and V2I transportation technologies. This study provides a roadmap for a strategic plan to incorporate CAV technologies on Massachusetts' transportation infrastructure. This roadmap supports the Commonwealth's Statewide Intelligent Transportation Systems Strategic Plan to improve safety, mobility, economic competitiveness, and sustainability through applications of advanced transportation technologies.

This report is divided into four main sections as explained below:

- **Chapter 1** reviews the state-of-the-art and future directions of CAV technologies, and their impact on the evolution of real time communication of vehicle movements, traffic performance and transportation systems capacity on roadways in Massachusetts. It also reviews the numerous field tests and demonstration projects that are being undertaken worldwide, their scope, results and implications for the future.
- **Chapter 2** examines the effects of the new technologies on transportation in Massachusetts, including potential effects on safety, mobility and the environment.
- **Chapter 3** identifies strategies that state DOTs, including MassDOT, can undertake to leverage the new technologies, including potential funding from federal sources, partnering with public and private enterprises and developers.
- **Chapter 4** provides a roadmap for strategic planning. Its purpose is to assist state DOTs to address forthcoming developments in CAV, including the introduction of new technologies advances in CAV products and services, and the development of policies and regulations.

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1 Connected and Automated Vehicles (CAVs)—Current Activities and Future Challenges

This chapter provides a review of the state of the art and current efforts in the development of CAV technologies. This chapter and the associated Appendices A and B contain the following sections:

- Basics of CAVs
- Potential Impacts of CAV Technologies
- Challenges of CAVs
- Federal Government CAV Actions
- Review of State Government CAV Actions (Appendix A)
- CAV Pilot Test Sites and Implementation Issues (Appendix B)

It is important to emphasize that:

- CAV technologies are developing at a fast pace and new technological developments are occurring on a daily basis. This review, therefore, only represents up-to-date knowledge as of the time of its writing.
- Being a literature review, there is no claim of originality in the materials presented herein. All sections are given proper credit in each case.
- Web-based publications are noted with the latest date of access.

1.1 Basics of CAVs

CAV technologies are fast developing and will have wide-ranging impacts on transportation. CAVs are equipped with communication devices that enable them to exchange information with other road users or with the roadway infrastructure. This communication is referred to as vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I). Automated vehicles (AVs), or autonomous vehicles, rely on a variety of sensors, such as radar, LIDAR (light detection and ranging), and computer vision. These technologies enable AVs to identify their locations in the environment, determine an appropriate path, and avoid obstacles. Combining vehicle connectivity and automation (see **Figure 1.1** [*1*]) will maximize the benefits from AVs and CVs.

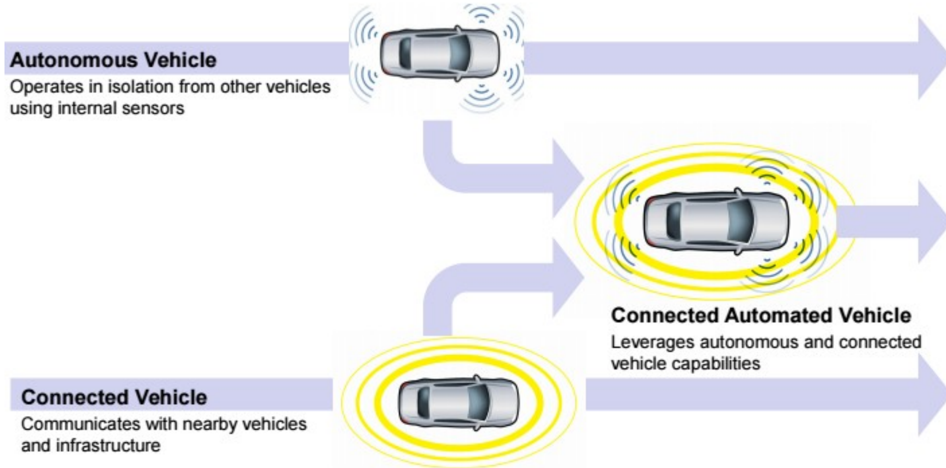

Figure 1.1: USDOT vision of a connected and automated vehicle

The National Highway Traffic Safety Administration (NHTSA) has defined five levels of vehicle automation technology (with Level 0 indicating full human driver control) [*2,3*]. Levels 1–3 automate certain vehicle controls but still require human driver interventions; and Level 4 is for fully automated control. SAE International has established a similar six-level taxonomy. **Table 1.1** [*4*] summarizes the SAE International definition, which is now the prevailing classification system to distinguish levels of driving automation.

Table 1.1: SAE International Levels of driving automation

Level	Name	Description
Human driver monitors the driving environment		
0	No automation	The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems.
1	Driver assistance	The driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver will perform all remaining aspects of the dynamic driving task.
2	Partial automation	The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver will perform all remaining aspects of the dynamic driving task.
Automated driving system monitors the driving environment		
3	Conditional automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene.
4	High automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene.
5	Full automation	The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.

1.2 Potential Impacts of CAV Technologies

CAV technologies could have a profound impact on transportation. There could be substantial benefits to society by reducing crashes, traffic congestion, air pollution, and other negative externalities associated with driving. On the other hand, there could also be drawbacks such as cybersecurity vulnerabilities.

One potential impact is on **travel demand,** as measured by Vehicle Miles Traveled (VMT). As the number of CAVs increases, when and how much people travel could change considerably. Several studies have estimated the potential impact of CAVs, particularly Level 3 and Level 4, on VMT. These studies are based on small-scale networks and on business models like automated taxis. While it is hard to estimate the exact impacts on travel demand and VMT, we can identify factors that may increase or decrease VMT.

Another potential impact is on transportation **infrastructure needs**. Existing road and highway infrastructure was designed for human-operated vehicles, which may not be optimal for self-driving vehicles. The transition from human-driven to computer-driven automated vehicles may require significant changes to the existing transportation infrastructure. Such changes may include lane width and road capacity, pavement markings, signage and signaling changes, and access management. New infrastructure investments may be necessary to maximize the benefits of CAVs, and to support automated driving systems and interoperability.

CAVs are also likely to produce complex impacts on **land use** patterns in the long term. Different deployment scenarios could lead to different land-use outcomes, and policymakers should consider how CAVs may affect planning and land-use decisions. In addition, the introduction of CAVs will have legal implications at all levels—federal, state, and local. While the federal government regulates vehicle technology requirements, states are left to regulate the operations of CAVs on public roadways.

A more detailed description of the potential impacts of CAVs is presented in Chapter 2 of this report.

1.3 Challenges of CAVs and Recommendations

This section presents some of the important challenges for state and local governments in addressing the emergence of CAVs and recommendations for possible actions. The material in this section has been adopted, with some modifications, from Reference [*38*]: "Driverless Seattle: How cities can plan for automated vehicles."

1.3.1 Challenge: Traffic Management and Transportation Planning

CAVs have the potential to significantly affect traffic flows. They could promote traffic efficiency—for example, by eliminating human inefficiency in the flow of traffic, encouraging ridesharing rather than driving alone, or promoting the use of public transportation. The use of

CAVs may also result in reducing the number of vehicle crashes caused by human errors.

CAVs also raise challenges to the transportation planning processes. Current transportation planning draws on economic forecasting (including benefit-cost analysis of proposed actions, as well as annual regional projections of total households, persons, jobs, and other economic and demographic variables), land-use forecasting, and travel demand forecasting (including activity-based travel models, trip-based travel models, and sketch planning). This forecasting relies on assumptions about the nature of travel—including models of vehicle ownership, route choice, and residence and work locations—that may need to be updated for a transportation environment with higher levels of CAVs.

CAVs will likely feature wireless communications, on-board computer processing, vehicle sensors, GPS, and connections to smart infrastructure, which may provide the opportunity to utilize the data generated from these sources for traffic management purposes. Current advanced traffic management systems (ATMS), for example, are limited in their ability to collect on-street traffic data. Data transmitted wirelessly from CAVs could measure traffic at the individual level, such as vehicle speeds, positions, arrival rates, rates of acceleration-deceleration, and queue lengths, and in turn, these data could allow for a better optimization of traffic patterns, either through manipulation of traffic signals or direct communication with vehicles via connected vehicle technology. Traffic management organizations should be prepared to take advantage of the new data made available by CAVs to facilitate greater traffic efficiency.

In addition, transportation planning organizations should be conscious of the extent to which current planning models are based on older automotive technologies, and should develop models better suited to capture the changes to vehicle ownership, route choice, VMT, and residence and work locations prompted by CAVs.

Recommendation: Utilize CAV data for traffic management, revise transportation planning processes, and explore efficient vehicle ownership and other models for transportation planning purposes.

1.3.2 Challenge: Infrastructure

CAV technologies are likely to require the development of new communications, data storage, energy, and transportation infrastructure. The potential benefits of CAV data for traffic management, for example, will likely depend on the development of vehicle-to-infrastructure communication systems capable of collecting CAV data in real time. Furthermore, the collection of CAV data will also necessitate new data storage facilities, which introduce cybersecurity concerns—including risk of data theft and cyberattack—as well as concerns about compliance with data protection and privacy regulations.

CAVs will also introduce challenges to traditional transportation infrastructure. For example, CAVs may increase the demand for energy infrastructure directly (e.g., electric vehicle charging stations) or indirectly (e.g., to support CAV communications and data storage infrastructure). Transportation agencies may need to redesign or create virtual counterparts for road signage and lanes. Additionally, different challenges are likely to arise with different models of CAV ownership and utilization. CAVs will have a significant impact on the location and size of parking infrastructure, and the redesign of curb access in some locations (e.g., transit stations) [*5*].

There is a need for robust decision making and multi-criteria analysis to compare costs of different technology alternatives across categories of infrastructure. There is also a need to cultivate relationships with the private industry in developing and implementing new CAV infrastructure technologies.

Recommendation: Plan for CAV infrastructure and collaborate with public and private industries in developing new infrastructures and standards.

1.3.3 Challenge: Revenue and Budgeting

CAVs are likely to have significant impacts on state and local revenue streams. Over the long term, CAVs could result in reduced transportation management costs. For example, CAVs may decrease the number of traffic accidents, which subsequently will reduce the need for police services and highway operational and maintenance costs (e.g., maintaining the retroreflectivity of traffic signs and line striping). However, these reductions may be offset by new costs presented by CAVs (e.g., new infrastructure) as well as possible economic adjustments (e.g., replacement of transportation jobs by CAVs).

A variety of tools are available to address the potential revenue losses introduced by the advent of CAVs, including the increase of vehicle registration fees (e.g., a specific CAV registration fee), the reallocation of other revenue streams, the introduction of new taxes on CAVs, and the introduction of broader taxes such as road usage charges.

Recommendation: Develop alternative revenue sources.

1.3.4 Challenge: Liability and Insurance

The advent of CAVs brings matters of both criminal and civil liability into sharp focus. Criminal infractions such as driving under the influence (DUI) and speed infractions rest on legal standards that become substantially less useful when automated vehicles handle a substantial portion of the driving task.

Recommendation: As with traditional vehicles, states retain the responsibility for regulating the insurance requirements for automated vehicles, though the NHTSA's Federal Automated Vehicle Policy requires manufacturers to insure for a minimum of $5 million.

1.3.5 Challenge: Police and Emergency Services

Given that CAVs can be used by both civilians and law enforcement, CAVs present challenges to many dimensions of police and emergency services. Transportation organizations should develop specific training procedures for police and emergency services interactions with CAVs. They should also investigate emerging standards for CAV technologies in relation to police and emergency services, such as technologically implemented CAV responses to police and emergency services.

Recommendation: Train police and emergency services for CAVs, and investigate police and emergency services–related CAV technologies.

Additional discussions on challenges and recommendations for actions can be found in [*5*]. Proposed actions specifically for Massachusetts are presented in Chapter 4.

1.4 Federal Role

1.4.1 Policies, Regulations, and Guidelines

At the federal level, the U.S. Department of Transportation (USDOT) is actively promoting the development of CAV technologies, which is well captured in the *USDOT Intelligent Transportation Systems Strategic Plan 2015–2019,* aiming to advance multimodal safety and reduce policy uncertainty [*6, 7*]. The different federal agencies are leading the development in different but parallel tracks, such as V2V by the NHTSA and V2I by the Federal Highway Administration (FHWA). Different types of policies are also proposed, with NHTSA to pursue rulemaking for V2V communications, and FHWA to provide guidance for voluntary V2I deployment.

Several significant efforts were put together to facilitate V2I deployment, including the creation of the Vehicle to Infrastructure Deployment Coalition (V2I-DC) to engage different stakeholders and identify major deployment issues. V2I-DC aims to develop solutions such as a series of programs to support CV pilot demonstrations initiatives (e.g., Wave 1 and Wave 2 CV pilot and Smart City Challenge) and a CAV research roadmap.

1.4.1.1 USDOT ITS Strategic Plan 2015–2019

USDOT has developed the “USDOT ITS Strategic Plan 2015-2019” [*7*]. It outlines the direction and goals of the ITS Program and provides a framework for ITS Joint Program Office (JPO) and other agencies to conduct research, development, and steps toward adoption to achieve the goals of the ITS Program. It has identified two primary strategic priorities, five strategic themes, and six program categories.

The purpose of the Strategic Plan “is to outline the direction and goals of the ITS Program and provide a framework around which the ITS JPO and other DOT agencies will conduct research, development, and adoption activities to achieve the outcomes and goals of the overarching ITS Program. The plan will be used to inform interested stakeholders about the activities and priorities of the ITS Program” [*6*]. The plan has defined two primary strategic priorities: Realizing Connected Vehicle Implementation and Advancing Automation. The former builds on the substantial progress in design, testing, and planning of CAVs, while the latter directs the ITS Program on research, development, and adoption of automation-related technologies.

The five strategic themes are: enable safer vehicles and roadways, enhance mobility, limit environmental impacts, promote innovation, and support transportation system information sharing. These are well aligned with USDOT’s goal areas and the Moving Ahead for Progress in the 21st Century Act (MAP-21).

The six program categories are: Connected Vehicles, Automation, Emerging Capabilities, Enterprise Data, Interoperability, and Accelerating Deployment. For each program category, potential benefits and research questions that guide the detailed programs are defined. "These questions will guide the individual program charters that will be included in the Operational Plan. In turn, those charters will specify activities that the ITS JPO will undertake in its mission to address the research questions"[*6*].

1.4.1.2 Federal Transportation Initiatives

The federal government has different tracks of regulation on the development of CAVs. The NHTSA focuses on V2V and has decided to pursue rulemaking, while the FHWA focuses on V2I and is pursuing the voluntary path by providing deployment guidance and products.

1.4.1.2.1 NHTSA's rulemaking on V2V

NHTSA is actively working on policies and regulations related to CVs, with the primary focus on V2V. It has issued a Notice of Proposed Rulemaking [*8*], which "proposes to establish a new Federal Motor Vehicle Safety Standard (FMVSS), No. 150, to mandate V2V communications for new light vehicles and to standardize the message and format of V2V transmissions. This will create an information environment in which vehicle and device manufacturers can create and implement applications to improve safety, mobility, and the environment." Implementation of the new standard will enable vehicle manufacturers to develop safety applications that employ V2V communications as an input.

In the supplementary information, NHTSA estimated that two safety applications of V2V, Left Turn Assist and Intersection Movement Assist, could prevent between 424,901 and 594,569 crashes, and save 955 to 1,321 lives each year if V2V is fully deployed throughout the light-duty vehicles.

On November 8, 2017, NHTSA issued the following statement [*9*]:"The Department of Transportation and NHTSA have not made any final decision on the proposed rulemaking concerning a V2V mandate. Any reports to the contrary are mistaken. In all events, DOT hopes to use the dedicated spectrum for transportation lifesaving technologies. Safety is the Department's number one priority."

"In response to the [proposed rulemaking], NHTSA is still reviewing and considering more than 460 comments submitted and other relevant new information to inform its next steps. An update on these actions will be provided when a decision is made at the appropriate time, taking into consideration the rich comments received in response to the proposed action published in December 2016. While DOT withdrew or revised 13 rules this year, V2V is not one of them, and it remains on DOT's significant rulemaking report."

1.4.1.2.2 FHWA's guidance and products on V2I

In 2015, FHWA developed a document providing V2I guidance. A revision was announced in January 2017 (full guidance not released yet), which complements USDOT's efforts to reduce crashes through the NTHSA V2V mandate [*10*].

At the 2016 ITS America Conference, the Connected Vehicle Program Manager at FHWA introduced the following new V2I vision and policy:

FHWA's V2I vision statement is "The Federal Highway Administration (FHWA) will provide national leadership and facilitate a smooth and effective deployment path for transportation owners/operators who are interested in implementing vehicle-to-infrastructure technology for a connected vehicle environment." [*11*]

FHWA's V2I policy statement is "Vehicle-to-infrastructure (V2I) technology will take advantage of and build upon emerging vehicle-based technologies being deployed to support vehicle-to-vehicle (V2V) technology. When leveraged with V2V, a V2I deployment will result in significant safety, mobility, and environmental benefits that will be of significant interest to state, regional, and local transportation agencies. <u>Deployments will be encouraged by FHWA but public agencies will not be required to implement V2I technology</u>. Nevertheless, state, regional, and local agencies will have guidance and products available to ensure efficiency and interoperability." [*12*]

FHWA's initiative No. 1 is the V2I deployment guidance. A few selected topics/subtopics are as follows:

- Significance of V2I and available connected vehicle standards
- Federal-aid eligibility for V2I deployments
- Hardware and software device certification, use of right-of-way, and use of public sector fleets

FHWA's initiative No. 2 is the V2I deployment products: [*11*]

- Model Approach to Advanced Technologies Procurement Using Agile System Engineering (Targeted release in 2017/2018)
- Connected Vehicles and the Planning Process
- Guide to Licensing DSRC
- Pre-Deployment Guidance for V2I Safety Applications (Targeted release in 2017/2018)
- Estimating Benefits and Economic Impacts of V2I Deployments
- V2I Message Lexicon
- Near Term Transition and Phasing for V2I Deployments
- Connected Vehicle Training Resources

Additionally, FHWA provides five basic steps for State DOTs and owners/operators if they are considering V2I deployments for Connected/Automated Vehicle Technology [*11*]:

- Initiate the Planning Process
- Update the Regional ITS Architecture
- Consider the Connected Vehicle Pooled Fund Study
- Join/Monitor the Affiliated Testbed
- Vehicle-to-Infrastructure Deployment Coalition

1.4.1.3 Other National Level Initiatives

1.4.1.3.1 Vehicle to Infrastructure Deployment Coalition

TheV2I-DC was created by AASHTO in collaboration with the Institute of Transportation Engineers (ITE) and the Intelligent Transportation Society of America (ITSA), aiming to achieve a comprehensive stakeholder input to accelerate V2I deployment activities [*13*].

At the highest level of V2I-DC is the executive committee and CAV Executive Leadership Team (CAV-ELT) [*14*]. At the lower level, it has five technical working groups: Deployment Initiatives; Deployment Research; Infrastructure Operator, Original Equipment Manufacturer (OEM) and Supplier Partnerships; Deployment Guidance; and Deployment Standards. The initial goal of V2I-DC is to help to accelerate the deployment of V2I applications related to intersections (signalized and non-signalized), end of queue warnings, work zone management, and curve warning systems. V2I-DC has identified 16 deployment issues, which are being addressed by the technical working groups. The focus for V2I-DC from 2016–2021 includes the following:

- Track and support resolution of initial 16 issues
- Initiate a process to address Issue 5: Security
- Identify and define additional issues
- Facilitate peer to peer/best practice exchanges
- Help "early adopters" plan for deployments
- Help identify funding sources to assist V2I deployments
- Provide feedback to pilot sites
- Provide feedback to CAMP and VIIC
- Provide alignment and support of training/education
- Support activities of CAV-ELT
- Seek ongoing funding sources for V2I-DC to continue operations

1.4.1.3.2 AASHTO SPaT Challenge

In November 2016, AASHTO adopted the SPaT (Signal Phase and Timing) Policy Resolution [*15, 16*]. The purpose of the resolution was "to approve an AASHTO nationwide challenge to deploy Dedicated Short Range Communications (DSRC) infrastructure with Signal Phase and Timing (SPaT) broadcast in at least one corridor (approximately 20 signalized intersections) in each of the 50 states by January 2020" [*17*]. A SPaT message defines the current intersection signal phases, which includes the current state of all lanes and any active pre-emption or priority. To broadcast the SPaT message, it needs to be extracted from a traffic signal controller and then converted to a standardized message that can be broadcast through DSRC roadside devices. The objectives of the SPaT Challenge are to "provide an entry into DSRC-based V2I deployment allowing them to gain valuable procurement, licensing, installation, and operation experience, which in turn will lay the ground work for more advanced V2I deployments and show a commitment to OEMs and applications developers" [*17*].

The resolution identified the short-term and long-term benefits of SPaT deployment and introduced the support available to agencies participating in the challenge. AASHTO established a website to facilitate information exchange on the SPaT Challenge [*18*]: https://www.transportationops.org/spatchallenge.

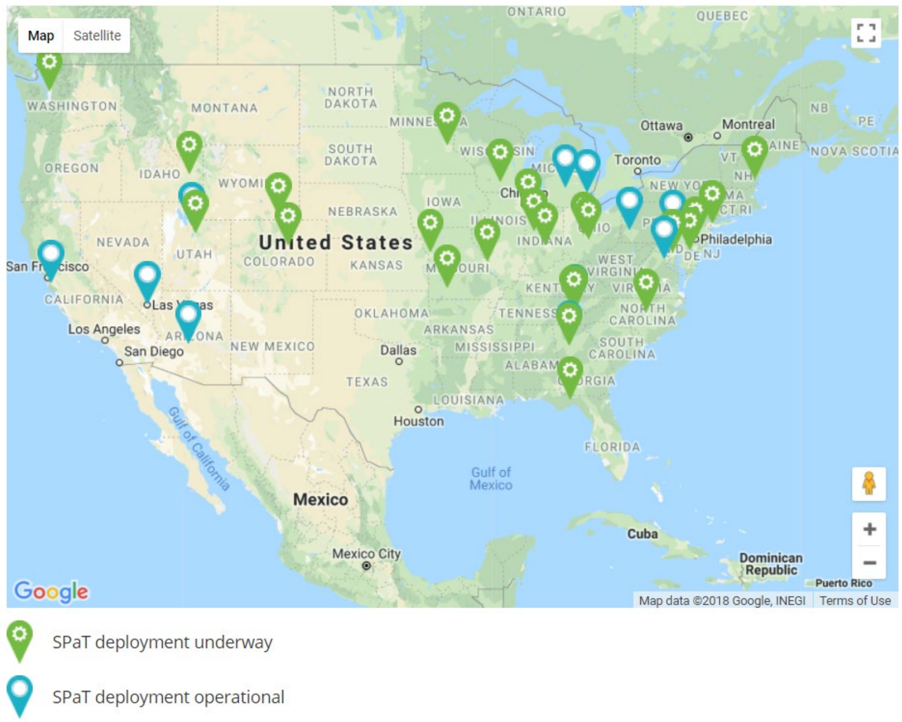

Figure 1.2: Participants of AASHTO SPaT Challenge [*19*]

Figure 1.2 shows the current participants in the SPaT Challenge. Nine sites are operational, while other sites have the deployment underway. The benefits of SPaT deployments include: (1) Immediate and short-term benefits "will largely be internal benefits to the agencies in the form of lessons learned and overall knowledge gained about deploying DSRC-based V2I infrastructure"; (2) Long-term anticipated benefits will originate from the applications enabled by SPaT broadcasts, including "Transit Signal Priority Applications; Red Light Violation Warning (RLVW) Applications; Intelligent Signal Systems (ISIG) Applications; In-vehicle displays of countdowns" [*18*]. The AASHTO SPaT Challenge offers the following key services and resources that are useful for the participants: (1) guidelines to assist agencies in selecting corridors for deployment; (2) procurement guidance; (3) DSRC licensing information; (4) implementation guidance; (5) estimated costs for installation, operations, and maintenance; and (6) identification of existing funding sources that agencies may consider.

1.4.2 Major Pilot Programs

1.4.2.1 Connected Vehicle Safety Pilot Program

The USDOT Connected Vehicle Safety Pilot Program was established to test the safety applications of V2V and V2I technologies enabled by DSRC. This research program was led by the ITS JPO and the NHTSA, with support from FHWA, Federal Motor Carrier Safety

Administration (FMCSA), and the Federal Transit Administration (FTA) [*20*].

The goals of this pilot program included the following:

- Support the 2013 NHTSA agency decision by obtaining empirical data on user acceptance, system effectiveness, and technical readiness.
- Demonstrate real-world connected vehicle safety applications in a data-rich environment.
- Establish a real-world operating environment for additional safety, mobility, and environmental application development.
- Archive data and make it openly available for additional research purposes by government and industry.

The Connected Vehicle Safety Pilot Program was launched in Ann Arbor, MI, in August 2012. It equipped about 3,000 vehicles and 29 infrastructure sites with wireless communication devices to test the safety applications of V2V and V2I through DSRC. The results of this program led to NHTSA's decision to propose a new FMVSS to mandate V2V for all light vehicles. It also identified the following safety applications:

- Blind spot warning
- Do not pass warning
- Emergency electronic brake lights warning
- Forward collision warning
- Intersection movement assist warning
- Lane change warning
- Red light warning
- Curve speed warning
- Pedestrian and turning transit vehicle crash warning
- Right turn in front of transit vehicle crash warning

Sponsored by ITS JPO, the Volpe National Transportation Systems Center conducted a study to derive lessons learned from the Ann Arbor Safety Pilot program [*21*] to benefit future CV activities. The study produced five key findings: (1) It is a significant challenge to select a single ideal deployment site, as the needs vary with the purpose of demonstration; (2) Management processes and maintained focus on critical activities resulted in project success.; (3) The program was able to accommodate the primary focus on the 2013 NHTSA agency decision on light vehicles and the other opportunities (e.g., V2I application and contextual data analysis); (4) The management processes were reasonable and successful, but future pilot projects should place greater emphasis on the technical-focused processes and tools; (5) Future pilot projects should budget greater time and resources in the planning and testing of various devices, equipment, and systems.

CV Pilot Deployment Program

The USDOT ITS JPO started a CV Pilot Deployment Program in September 2015. The goals of the program are threefold [*22*]:

1. To spur early CV tech deployment, not just through wirelessly connected vehicles, but also through other elements that are major players in this connected environment, such as

mobile devices, infrastructure, traffic management centers (TMCs), and other elements. Data can be integrated from these multiple sources to help make key decisions.

2. To target improving safety and mobility and environmental impacts and commit to measuring those benefits. Measurement of the impacts and benefits will be gathered from real-world deployments, rather than an isolated test bed or a computer-based simulation testbed. Differentiating and finding these benefits and identifying what can be attributed to these CV applications and technologies is an important component of the activity.
3. To resolve issues of various deployments.

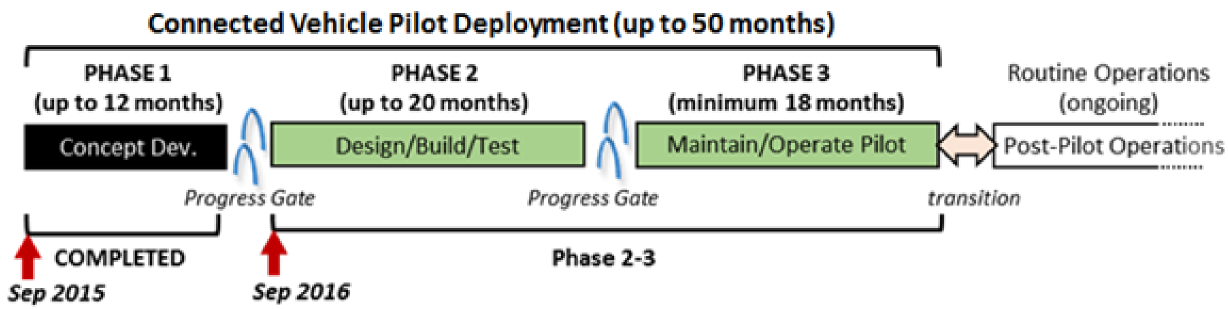

Figure 1.3: USDOT connected vehicle deployment plan

This CV Pilot Deployment Program consists of three phases (**Figure 1.3** and **Figure 1.4** *[21]*) over the period of up to 50 months. In September 2015, Wave 1 of the program selected three pilot sites—Wyoming, New York City, and Tampa—with approximately $40 million of funding. These pilot sites have completed Phase 1 activities and entered Phase 2 Design/Build/Test. In September 2016, the USDOT made three awards to initiate Phase 2, a Design/Build/Test phase of the CV Pilot Deployment Program, in the three selected sites. The three sites have different application focuses, but they will collectively explore the broad range of CV technologies. A description of the three pilot projects is given in Appendix B of this report.

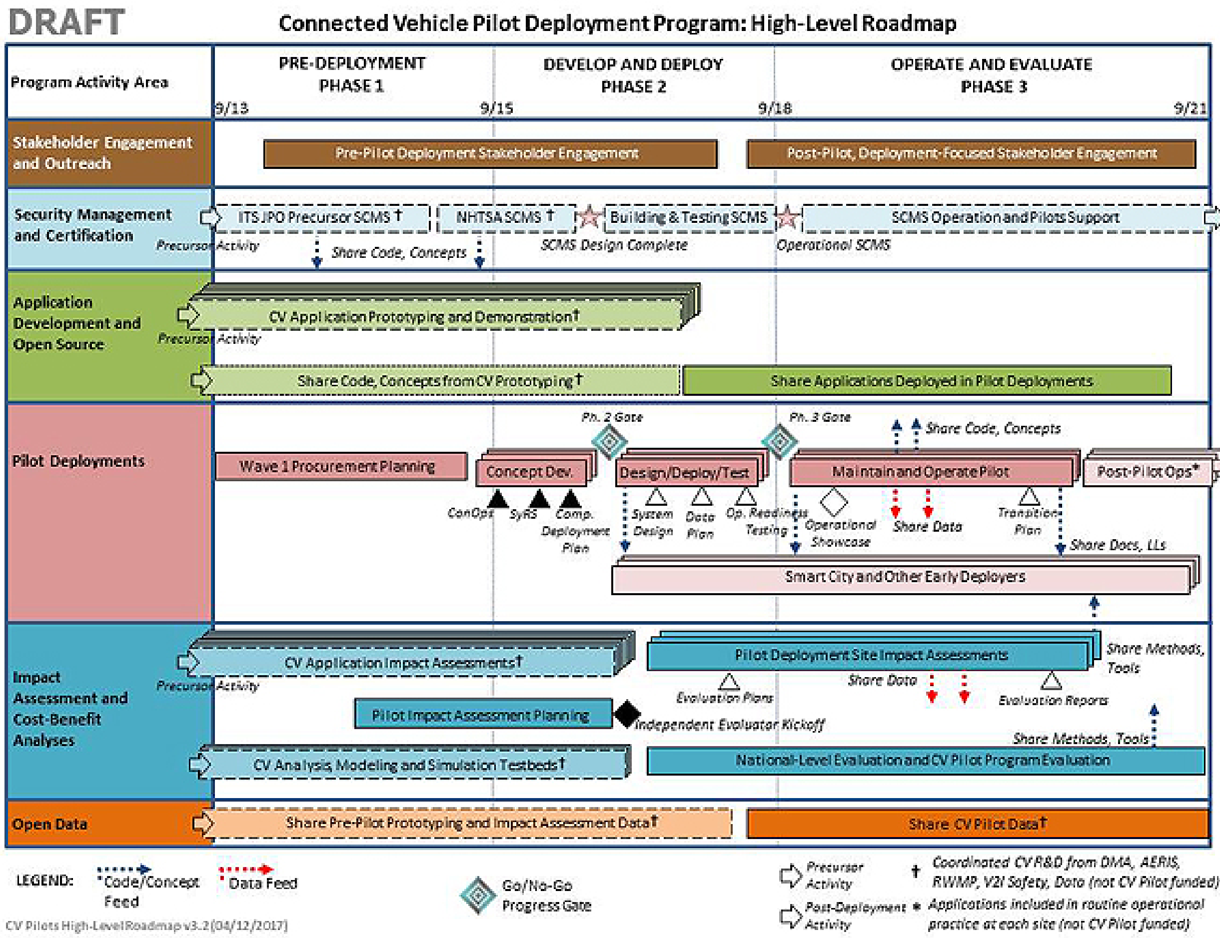

Figure 1.4: Roadmap of USDOT CV Pilot Deployment Program [*21*]

1.4.2.2 Smart City Challenge

In December 2015, USDOT launched the Smart City Challenge to encourage mid-size cities to develop an integrated smart transportation system that "would use data, applications, and technology to help people and goods move more quickly, cheaply, and efficiently." In total, 78 cities responded to the challenges. Seven finalists were selected, and the final winner was Columbus, OH. The winning city received $40 million from USDOT and $10 million from Vulcan Inc. to reshape its transportation system and develop a "smart city." It was believed that Columbus was successful because of its impressive and holistic vision showing how technologies "can help all of the city's residents to move more easily and to access opportunity" [*23*].

In this challenge, USDOT engaged broad public-private partnerships. The partners from the private sector included "Paul G. Allen's Vulcan Inc., cloud partner Amazon Web Services, NXP® Semiconductors, Mobileye, Autodesk, Alphabet's Sidewalk Labs, AT&T, DC Solar and Continental Automotive" [*22*]. This challenge had stimulated broader and deeper interest from the applicants, and the seven finalists were able to raise $500 million more in funding.

Following the Smart City Challenge, USDOT published a report to share the lessons learned:

Smart City Challenges: Lessons for Building Cities of the Future [*24*]. The report stated that many of the cities faced similar urban challenges, including the “first-mile and last-mile” issue, the movement of goods into and within cities, and parking efficiency problems. Proposals from applicants offered solutions on how travelers move (e.g., add advanced traffic signals and vehicles with DSRC technology), how to move goods (e.g., use truck platooning to reduce carbon-dioxide), how to adapt to climate changes (e.g., convert public fleets and buses to electric vehicles or incentivize shared-use mobility options), how to move better (e.g., use new technologies to collect, analyze, and share transportation system data), how we grow opportunity for all (e.g., create smart corridors and smart payment projects to improve access to jobs, provide training, reach underserved areas, and ensure connectivity for all), and how we align decisions and dollars (e.g., to use new data source to inform policymakers and promote better allocation of taxpayers’ dollars).

1.5 State Role

State governments play an important role in facilitating CAVs, ensuring they are safely deployed and promoting their benefits. In September 2016, USDOT and NHTSA issued guidance for the development of a State Policy for Automated Vehicles in which states retain their traditional responsibilities for vehicle licensing and registration, traffic laws and enforcement, and motor vehicle insurance and liability regimes [*95*]. The guidance also includes a Model State Policy, which is summarized as follows.

The Model State Policy identifies a clear division of regulatory responsibility for motor vehicle operation between federal and state authorities. NHTSA responsibilities include:

- Setting FMVSS for new motor vehicles and motor vehicle equipment (to which manufacturers must certify compliance before they sell their vehicles).
- Enforcing compliance with the FMVSS.
- Investigating and managing the recall and remedy of non-compliances and safety-related motor vehicle defects and recalls on a nationwide basis.
- Communicating with and educating the public about motor vehicle safety issues.
- Issuing guidance for vehicle and equipment manufacturers to follow, such as the Vehicle Performance Guidance for CAVs presented in this policy.

The states’ responsibilities include other aspects of motor vehicle regulations:

- Licensing (human) drivers and registering motor vehicles in their jurisdictions.
- Enacting and enforcing traffic laws and regulations.
- Conducting safety inspections, where states choose to do so.
- Regulating motor vehicle insurance and liability.

The DOT and the federal government are responsible for regulating motor vehicles and motor vehicle equipment, and states are responsible for regulating human drivers and most other aspects of motor vehicle operation. As motor vehicle equipment increasingly performs “driving” tasks, the DOT’s exercise of its authority and responsibility to regulate the safety of such equipment will increasingly encompass tasks similar to “licensing” of the non-human “driver” (e.g., hardware and software performing part of or the entire driving task). NHTSA believes that eventually there should be a consistent set of laws and regulations governing the testing and operation of CAVs within a state. The following administrative actions are recommended [*95*]:

- Each state should identify a lead agency responsible for consideration of any testing of CAVs.
- Each state should create a jurisdictional automated safety technology committee that is launched by the designated lead agency and which includes representatives from the governor's office, motor vehicle administration, state department of transportation, state law enforcement agency, state highway safety office, office of information technology, state insurance regulator, state office(s) representing the aging and disabled communities, toll authorities, and transit authorities.
- Other stakeholders should be consulted as appropriate, such as transportation research centers located in the state; the vehicle manufacturing industry; and groups representing pedestrians, bicyclists, consumers, and other interested parties.
- The designated lead agency should keep its state automated safety technology committee informed of the requests from manufacturers to test in their jurisdiction and the status of the designated agency's response to the manufacturers.
- The designated lead agency should take necessary steps to use or establish statutory authority to implement a framework and regulations. Each state should examine its laws and regulations in the areas of: (1) licensing and registration; (2) driver education and training; (3) insurance and liability; (4) enforcement of traffic laws and regulations; and (5) administration of motor vehicle inspections, in order to address unnecessary barriers to safe testing, deployment, and operation of Highly Autonomous Vehicles (HAVs).
- Each state should develop an internal process that includes an application for manufacturers to test in the jurisdiction as described in sections 2 and 3 below.
- The motor vehicle agency should establish an internal process for issuing test vehicle permits as described in sections 2 and 3 below.
- The designated lead agency should review state statutes to identify any legal issues that need to be addressed prior to the deployment and operation of automated vehicles.

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2 Impacts of CAV Technologies in Massachusetts

This chapter describes the potential impacts that CAVs are likely to have on transportation in Massachusetts. Included are:

1. **Impacts on the mission of MassDOT**: CAVs will have significant impacts on safety, mobility, congestion, environment, and energy consumption, and ultimately land use patterns could change, making other impacts more variable.

2. **Impacts on policy and planning**: Included are institutional impacts on the organization of MassDOT and the distribution of funding, as priorities for projects may change with the advent of CAVs.

3. **Economic impacts**: The introduction of CAVs will require new infrastructure investments to maximize the benefits of these technologies, and many of these projects will require extensive resources and funding. However, the introduction of these technologies may also result in savings.

4. **Impacts on data availability**: CAVs will generate and utilize massive amounts of data. State DOTs will have to collect, process, and disseminate information from and to CAVs. This will have a number of implications with respect to data organization, processing, and security.

2.1 Impacts to MassDOT's Mission

The core mission of any state DOT is to provide a safe transportation system that ensures the mobility of goods and people and enhances quality of life. CAV technologies have the potential to substantially affect safety, congestion, energy consumption, and local land use decisions. CAV operations are inherently different from those of human-driven vehicles: they can be programmed to comply with traffic laws; they do not drink and drive; their reaction times are quicker; they can be optimized to smooth traffic flows, improve fuel economy, and reduce emissions; and they can deliver freight and transport disabled and unlicensed travelers to their destinations [*25, 26*].

2.1.1 Safety

While the frequency of crashes is generally in decline in the United States, such incidents remain a major public health concern. The total number of roadway crashes on a per-VMT basis fell at an annual rate of 2.3% from 1990 to 2011, while roadway injuries fell at an annual rate of 3.1% [*24*]. The number of fatalities shows a similar trend: a 25% decrease from 2005 to 2014. However, a marked increase of 7.2% from 2014 to 2015 (from 32,744 to 35,092) represents the largest increase in the last 50 years [*27*]. This is partly because Americans drove more and partly because they drove more poorly (e.g., distracted driving due to smartphone usage) [*28*].

The main factor contributing to the reduced rate and severity of crashes is that vehicles were getting safer for their occupants, by the gradual adoption of on-vehicle safety technologies such as airbags, antilock brakes, electronic stability control, head-protecting airbags, and forward collision warning. On the other hand, for more than 90% of crashes, the critical cause is human errors. CAV technologies have the potential to significantly reduce severity. Safety warnings provided by V2V and V2I technologies enable drivers to take actions that could reduce the severity of collisions or avoid them completely. CAVs, depending on the level of automation, can avoid many of the common perception, decision, and execution mistakes that human drivers make, and CAVs do not suffer from fatigue or cognitive impairment.

Level 3 automation is expected to substantially reduce crashes due to driver errors. In 2011, about 50% of fatalities were attributed to single-vehicle crashes. Crashes involving multiple vehicles are also likely to be reduced, since automated vehicles may be able to recognize drivers who are distracted, impaired, or reckless and take proactive safety measures [*29*].

However, some categories of crashes may increase if drivers become over-reliant upon safety systems enabled by CAVs. Flawed software or hardware could cause severe crashes, which humans would not make. It is expected that level 4 and 5 highly autonomous vehicles will further reduce crash statistics, as vehicles at these levels will be responsible for all, or nearly all, driving tasks.

2.1.2 Mobility

CAV technologies will also improve mobility for those who are currently unable (blind, disabled, too young) or unwilling to drive, since level 4 and 5 AV technologies will not require a human driver. At the present time, these groups can be serviced by public transportation, but mass transit typically operates on fixed routes and paratransit could be costly. SAVs could overcome these difficulties and operate in a similar manner as paratransit but would be less expensive and thus improve social welfare [*3*].

2.1.3 Traffic Operations

The introduction of CAVs will affect the way an agency develops, maintains, operates, and manages transportation facilities and services. Existing ITS investments could become outdated, reduce demand for transit and parking services, or shift infrastructure maintenance focuses—e.g., from roadside VMSs to pavement markings. At this point, it is uncertain whether these technologies will improve or worsen traffic congestion levels.

2.1.3.1 Potential Traffic Operational Strategies

A number of traffic operational strategies can be improved or developed with the introduction of CAVs and their V2V and V2I capabilities [*30*].

Such strategies would include:

- Intersection Signal Control (transit priority or vehicle-based control)
- Freeway Metering (cooperation between vehicles for optimal merging)
- Managed Lanes

- Traveler Information (signal and traffic information, mitigate congestion)
- Road Weather Management
- Road Usage Charges
- Work Zone Management
- CV-enabled Traffic Management
- Shared Vehicle Mobility
- Auto-valet Parking

In addition, it is anticipated that over the next few decades, more fundamental infrastructure changes are likely to be necessary as the market penetration of CAV technologies increases [*31*].

- **Update traffic signs and markings.** MassDOT will need to monitor as well as provide feedback on any updates to the FHWA's Manual on Uniform Traffic Control Devices.

- **Reduce lane width**. Assuming lanes are marked appropriately and where dedicated travel lanes can be provided, AVs will not require the traditional 10- to 12-foot lanes, which could result in increased capacity or provide space for bike lanes or pedestrians. However, reducing the lane width may require changes in the geometric design of certain roadway segments.

- **Alter speed limits**. Due to the increased safety of CAVs, it may be safe to increase speed limits in certain areas. CAVs will be traveling at or below the speed limit, depending on roadway and traffic conditions, so it is likely that the procedures for setting speed limits will change over time.

- **Adjust traffic signal locations and timing**. As V2V and V2I applications become more sophisticated, traffic signals will be highly adaptive to traffic patterns or they may become unnecessary. On the other hand, pedestrian and biker safety may be of concern at certain locations, so new signals may be needed, prioritizing pedestrians and bikers.

2.1.3.2 Role and Relevance of Traffic Analysis Tools

Traffic analysis tools are required to evaluate a wide range of operational strategies or roadway modifications at individual locations or across an entire network (see **Figure 2.1**). The disaggregate approach used by simulation models allows them to precisely and quantitatively capture the effects of advanced operational strategies at an individual vehicle level. Stochastic driver effects also are captured through the assignment of different combinations of driver parameters to each vehicle in the simulation.

Typically, planning and analysis of traffic conditions need to be conducted in advance of the implementation of infrastructure projects. Simulation tools are better equipped to address such questions related to CAV technologies than other tools, as other tools require empirical data for the development of the models themselves. Simulation tools can estimate many CAV outcomes through modification of their existing models. Microscopic simulation models, in particular, incorporate a high degree of detail associated with the traffic and roadway characteristics, allowing for the simulation of hypothetical CAV strategies and operational characteristics even before empirical data become available. Furthermore, many CAV strategies have impacts and outcomes that are expected to scale with penetration rates. These effects can be modeled through direct adjustment of the penetration rates in the models themselves, even when supporting empirical data are not yet available for validation. Additionally, mesoscopic and macroscopic simulation models can be used to evaluate operational strategies across large-scale networks in an approximate manner.

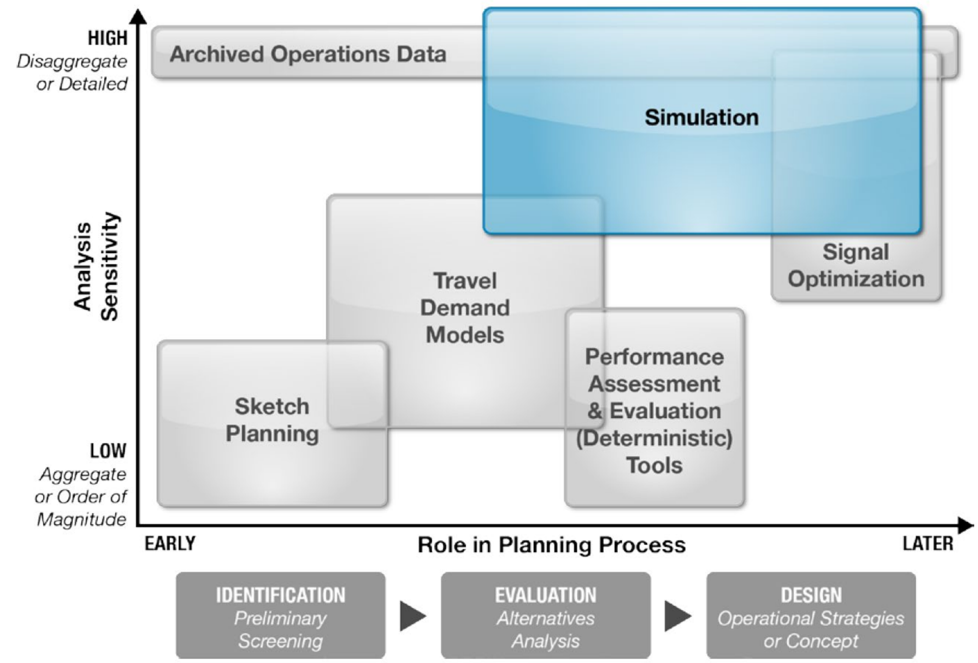

Figure 2.1: Role of traffic analysis tools in the transportation planning process [*32*].

Traffic analysis tools generally fall into one of three categories, according to their levels of modeling precision. The analysis of CV strategies generally requires detailed, high-resolution data and tools, such as simulation models for the analysis of ITS, Integrated Corridor Management (ICM), and Active Transportation and Demand Management (ATDM) strategies. The following list describes the three current classes of simulation tools used by planners and their potential relevance to CAV analyses. The list also includes a fourth class, CAV-specific simulation models, which is an emerging specialized type of model specifically developed for certain CAV analyses.

- **Macroscopic Models** rely on traffic flow theory relationships to model traffic at an aggregate level. This type of analysis is suitable for larger geographic scales, such as a freeway network, arterial grid, or rural highway system.

- **Microscopic Models** incorporate lane-changing and car-following models to simulate driver behaviors and vehicle trajectories in time steps measured on the order of seconds or fractions of seconds. Such models can provide valuable operational insight and detailed performance measures for a variety of strategies that affect the interactions between individual vehicles.

- **Mesoscopic Models** blend the characteristics of both microscopic and macroscopic models to achieve a balance between larger network size and realism/precision in the simulation model. For example, a mesoscopic model may assign a full set of driver parameters to each vehicle in the simulation and apply basic lane-changing and car-following models to capture interactions, but may also apply macroscopic models from traffic theory to represent behaviors at nodes in an effort to reduce processing time.
- **CV-Specific Simulation Models**. This emerging class of tools can simulate individual sensors, vehicles, and CV equipment at a microscopic level. However, recognizing that institutions that use and rely on more popular traffic simulation software will not have the time, resources, or motivation to migrate or adapt their systems, processes, training, and staffing to incorporate or accommodate these relatively purpose-specific CAV models, it is expected that there will be substantial market pressure to integrate the capabilities of these CAV-specific models into existing general-purpose microscopic and mesoscopic simulation software for added flexibility, extensibility, and workflow integration (which this research roadmap accomplishes).

2.1.4 Effect on Traffic Congestion and Its Costs

Vehicles operated by humans impose costs not only to the driver (e.g., fuel, depreciation, insurance), but also substantial external costs on other people (congestion, chance of being involved in a crash). These externalities have been estimated to cost approximately 13 cents per mile [*24*, *33*]. CAV technologies have the potential to substantially reduce both categories of costs.

Congestion may occur because of random or scheduled events, such as traffic crashes, disabled vehicles, weather, construction (non-recurrent), or on a regular basis due to prevailing traffic patterns when the number of vehicles trying to use a road exceeds the road's capacity (recurrent).

For non-recurrent congestion events, CAV safety applications could mitigate the delays through informing CAVs of the events, thus enabling them to choose a different route. CAV mobility applications could positively impact recurrent congestion by increasing system efficiency through CAV-facilitated platooning. These impacts would be maximized if there were widespread adoption of V2V capabilities and V2I infrastructure.

AVs of Level 3 or higher will reduce the number of crashes, thus reducing crash-related delays. AVs are expected to operate in a manner that is much safer for travelers than human drivers. With enough market penetration of these technologies, exclusive AV lanes could result in increased roadway capacity, since AVs could operate with shorter headways and on narrower lanes.

Levels 3 and 4 AVs are likely to substantially reduce the costs of congestion, since occupants of CAVs could undertake other activities even when stuck in traffic, making the waiting less stressful and increasing the productivity of their in-vehicle time. This will help to reduce the perceived costs of congestion. On the other hand, a decreased perceived cost of driving may lead to an increase in overall VMT. Thus, the overall effect of CAV technologies on congestion is uncertain.

2.1.5 Effect on Land Use

An effect of the reduced perceived cost of travel could be the commuter willing to travel longer distances. This might cause people to locate further from an urban core or job center, leading to more dispersed and low-density land use patterns.

However, if CAV technologies are incorporated into transit vehicles and shared vehicles, the effect could be the opposite. Shared CAVs could lead to lower car ownership and use, which in turn could result in higher-density land use patterns. The decreased need for proximate parking, which occupies considerable space, could also lead to increased development opportunities. Additionally, SAV strategies may decrease reliance on private automobiles, resulting in reduced parking needs.

Level 4 CAVs could drop passengers off and drive away to remote parking areas. This will also reduce the need of parking lots and increase the need for drop-off and pick-up points. Space currently used for parking could be converted into drop-off and pick-up points or redeveloped for other more valuable uses. For example, on-street parking space can be turned into bike lanes, wider sidewalks, or green spaces. The increase in drop-off and pick-up points has the potential to increase vehicle conflicts with pedestrians and bikes [*3*].

To ensure efficiency, MassDOT, in coordination with local authorities, may need to recommend design standards for CAV drop-off and pick-up areas, such as dimensions, number of spaces based on the type of land use and level of activity, and setback standards for new developments.

2.1.6 Effect on the Environment

Automobiles that use fossil fuels generate air pollution (e.g., particulate matter, hydrocarbons, nitrogen oxides, and carbon monoxide) and greenhouse gases, posing an enormous public health cost. The overall effect of CAV technologies on energy use and pollution is uncertain.

CAV technologies can improve fuel efficiency by using smoother acceleration and deceleration than a human driver. CAVs will be able to travel in platoons reducing air resistance and as the number of crashes is, reduced vehicles could be made much lighter. The National Research Council (NRC) estimates the potential fuel economy improvements to conventional vehicles between now and 2050 to be 130 to 250 percent (up to 87 and 110 mpg) for cars and 140 to 220 percent (up to 61 to 77 mpg) for light trucks [*34, 35*].

Fuel economy improvements enabled by Levels 1, 2, and 3 CAV technologies would first be realized through the automated and optimized driving (such as smooth acceleration and deceleration), often referred to as "eco-driving." Eco-driving can improve fuel economy by 4 to 10 percent [*34*].

The NRC studies [*33,34*] also speculate that "networked AVs with safer, smaller vehicles could enable fuel consumption reductions more than twice their estimates for conventional and hybrid vehicles—and that pod car AVs (much smaller and lighter vehicles carrying one or two passengers) might reduce fuel consumption by an order of magnitude as compared to today's vehicles." Folsom [*36*] estimates that a networked pod car AV system could enable fuel economies as much as 500 to 1,000 mpg. . **Figure 2.2** [*24,34,35*]shows the range of possible fuel economy improvements based on these estimates.

On the other hand, passengers may prefer larger AVs to allow them to take better advantage of the opportunity to do things other than driving.

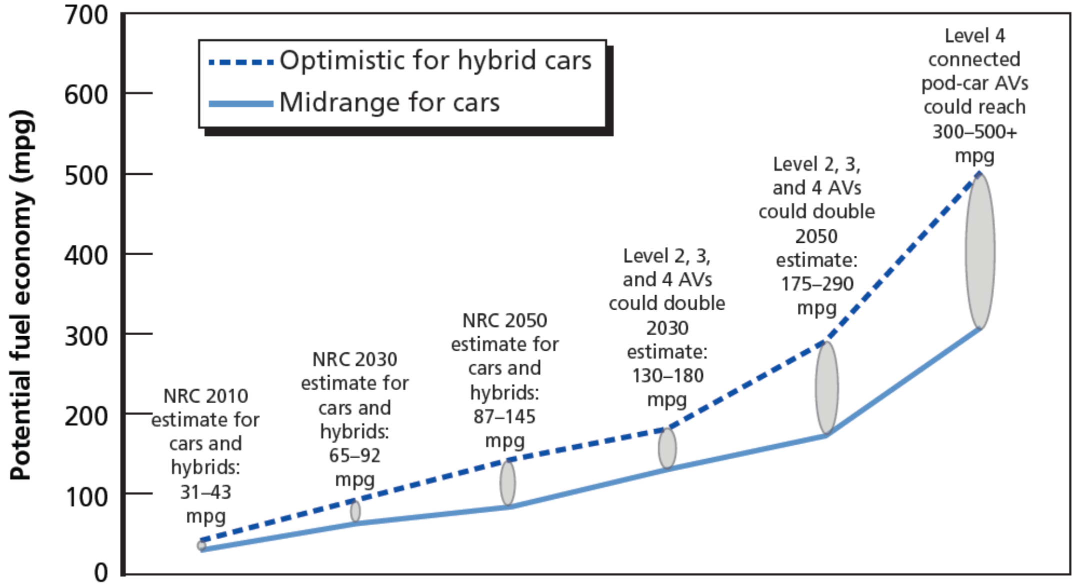

Figure 2.2: Range of potential fuel economy improvements for conventional, hybrid, and autonomous vehicles [*24*].

The National Renewable Energy Laboratory (NREL) considered VMT and fuel efficiency under four different scenarios of CAV automation [*37*]:

- "Conventional," the base case of current (without automation or connectivity) privately owned vehicles
- "Partial," partially automated and connected, privately owned vehicles
- "Full-No Rideshare," fully automated and connected vehicles with no ridesharing
- "Full-With Rideshare," fully automated and connected vehicles with ridesharing.

They grouped the impacts of CAVs on VMT in six categories:

- Less hunting for parking
- More travel due to it becoming easier (from faster travel and decreased cost of travel)
- Increased travel by populations whose transportation needs are currently underserved
- Mode shift from walking, transit and regional air
- Empty vehicle miles traveled
- Increase in ridesharing

For each category and for each scenario, the estimated upper and lower bounds (UB/LB) of possible VMTs is shown in **Figure 2.3**. "The largest potential increase is associated with easier travel (due to faster travel and reduced travel-time cost).

As is evident from the wide differences between upper and lower bounds on VMT, there is enormous uncertainty in the effect of CAVs on travel demand for the full automation scenarios" [*36*].

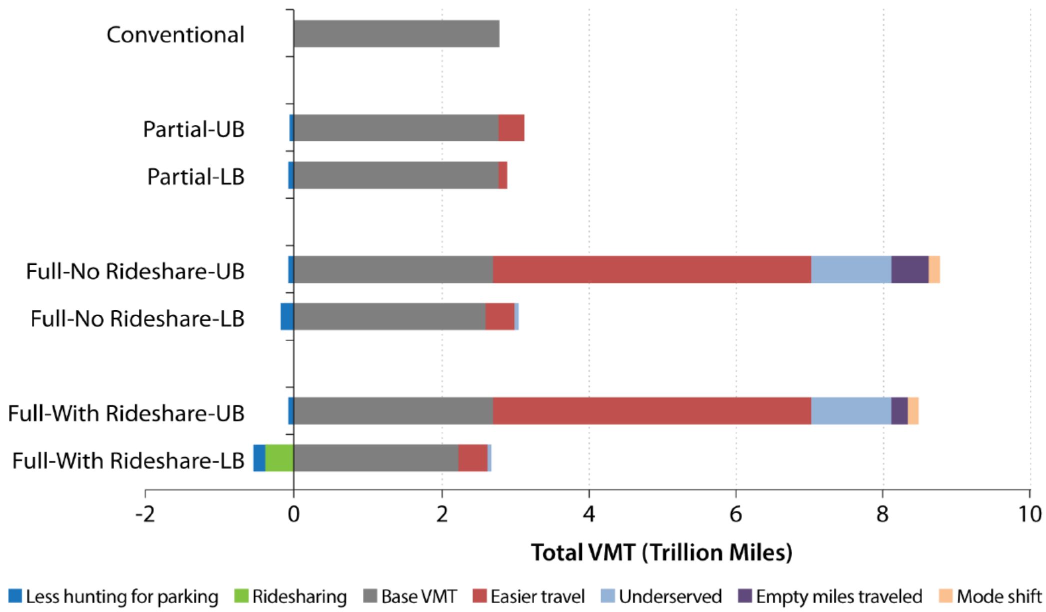

Figure 2.3: Potential light duty vehicle VMT under Conventional and CAV Vehicle scenarios [*36*]

With respect to fuel efficiency the main CAV technologies that will influence it are:

- Drive profile and traffic flow smoothing
- Faster travel
- Intersection vehicle-to-infrastructure (V2I)/infrastructure-to-vehicle (I2V) communication
- Collision avoidance
- Platooning
- Vehicle/powertrain resizing

Figure 2.4 shows the estimated UB/LB impacts on the average vehicle fuel consumption rate in each scenario. "The 'negative fuel consumption' bars illustrate the magnitude of different CAV features' reduction of the baseline fuel consumption rate from the conventional scenario.

Note that vehicle/powertrain resizing offers large potential reductions, but that the bounds are wide, indicating large uncertainty in this factor. Similarly, potential reductions due to drive profile and traffic flow smoothing are large but also uncertain. [*36*]"

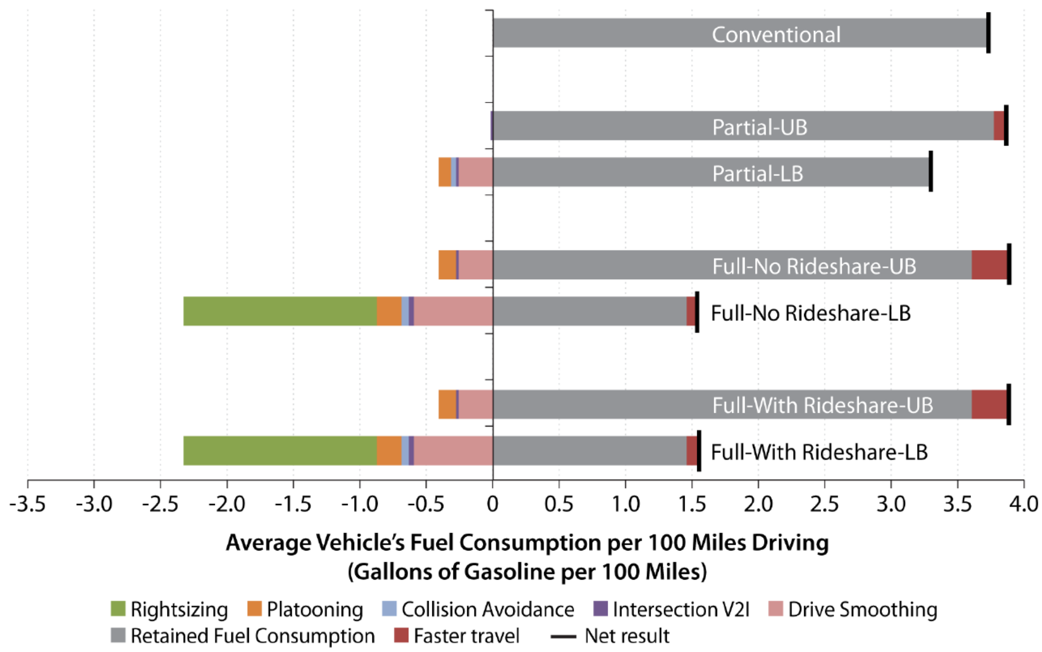

Figure 2.4: Vehicle fuel consumption rate for each of the scenarios [36]

2.1.7 Travel Behavior Impacts

The proliferation of CAVs most likely will have a significant impact on traveler behavior. The impacts of CAVs on traffic safety, mobility, congestion, parking at the end of the trip, and conceived cost of travel may result in increased travel demand and more VMT. Increased VMT may result in increased pollution and greater fuel/energy consumption. Ridesharing programs could expand using SAVs and offset some of these impacts.

Zmud et al. [*38*] argued, "it is very uncertain if self-driving vehicles would increase or reduce VMT. Some speculate that people would live farther away from work or school because they could do other activities while on their commutes, which would increase VMT per capita. Others believe that self-driving vehicles will be making lots of zero-occupant trips because owners would not want the vehicles to sit idle, which would add to overall VMT. The assumption also exists that the mobility challenged (e.g., elderly or disabled) would travel more often, and that this too would increase VMT. On the opposite end of the spectrum, some believe that self-driving car-sharing programs will decrease VMT per capita, as has been found with conventional car-sharing programs."

2.2 Policy and Planning Impacts

The fast-paced development and future deployment of CAV technologies will have a significant impact on policy and planning practices of transportation agencies. The exact impact of these technologies on safety, mobility, congestion, and environment is still uncertain. As these developments unfold, agencies will need to prepare for changes in their own activities and in how they serve the public interest through the provision of transportation infrastructure. The following summarizes the potential impacts on transportation agencies in three categories: institutional and operational, funding/financing, and transportation planning.

2.2.1 Institutional and Operational Impacts

Institutional impacts affect a transportation agency's focus, areas of authority, and organizational structure. This includes how an agency prioritizes its responsibilities and chooses to allocate its funding. Proliferation of CAVs may enable transportation agencies to increase their focus on broader goals; increase responsibility for data integrity, security, privacy, and analytics; and increase reliance on internal and external expertise for implementing analytical solutions and making use of big data systems. **Table 2.1** and **Table 2.2** [*27*] summarize the potential intuitional and operational impacts of CAVs on transportation agencies.

Table 2.1: Institutional impacts [*27*]

Potential CAV Outcome	Transportation Agency Impacts
Institutional Impacts	
CAV systems could reduce crashes and increase overall safety.	Increase focus on broader transportation goals.
Commercial and transit AV fleets could reduce reliance on professional drivers, which increases safety by reducing vehicle incidents.	
CAV systems could raise road users' expectations for ITS-related services for which transportation agencies lack institutional expertise.	Increase reliance on contracting, new relationships with the private sector or find ways to develop this expertise in-house.
CAV systems could require physical infrastructure assets, data management, and ITS services for which agencies lack funding.	Examine long-term purchasing decisions through capital planning.
AVs could require changes in basic road design and geometry in the long run to accommodate safe and efficient operations.	Change roadway construction practices based on changed standards.
CAV systems could increase reliance on data-intensive services and applications.	Increase responsibility for data integrity, security, privacy, and analytics.
CAV systems could provide benefit to existing operations and maintenance, particularly safety benefits in transit operations.	Change maintenance/operations practices to account for this efficiency.
CV applications could provide asset health information.	Improve operational awareness and update asset management systems.

Table 2.2: Operational impacts [*27*]

Potential CAV Outcome	Transportation Agency Impacts
Operational Impacts	
Existing technology assets could become obsolete with rapidly changing technology.	Reflect technological advancements in ITS investment decisions.
SAVs could increase average vehicle occupancy and usage, improving system management and reducing congestion without the need for traditional ITS.	
Various communications technologies used in CAV applications could provide ITS-type traveler information to drivers within the vehicle itself.	
AVs or SAVs could reduce demand for transit and traditional paratransit.	Allow efficiencies to occur, and invest and modernize transit system infrastructure that remain viable.
SAVs or usage of Level 5 AVs could reduce need for urban parking.	Encourage alternative uses of municipal or state-owned parking facilities in such locations.
AV systems could increase need for visible lane striping, more visible signs, and removal of roadway obstructions.	Increase certain maintenance activities.
Commercial AV fleets could increase volumes (by lowering shipping costs), thereby increasing wear and tear on the system.	
AV systems could increase the development of low-density suburban development by lowering the cost of commuting, thereby increasing the infrastructure network to be maintained.	
CAV systems could facilitate the more efficient movement of vehicles through congested intersections.	Mitigate capacity issues associated with recurring and non-recurring congestion.
CAV systems could provide enhanced transportation system asset awareness by transportation agencies.	
CAV systems could allow transportation agencies to better use existing capacity through various ITS management and operations practices	
CV systems could provide travelers with dynamic, real-time information on construction projects that impact mobility.	
CAV systems could provide drivers with information on impending bad weather and weather-related road conditions.	
AV systems could lower the cost of driving, thus increasing VMT.	Respond to these trends by providing other mobility options, and use "carrot" and "stick" approaches to address negative externalities.
AV applications could require additional headway relative to human drivers, thus reducing available capacity[1]	

[1] This is taken from reference [***Error! Bookmark not defined.***]. However, the authors think this conclusion is doubtful, since many other studies indicate AVs will operate with more precision than human drivers, requiring shorter headways and narrower lanes, thereby increasing capacity.

2.2.2 Funding and Financing Impacts

Proliferation of CAVs could change the funding and financing sources available for constructing, maintaining, and managing transportation infrastructure and related services. Existing sources of funding such as driver licensing and moving violations could be disrupted. On the other hand, CAV technology could be used to provide an alternative funding source by establishing road usage charges.

Table 2.3 [*27*] summarizes the potential funding and financing impacts of CAVs on transportation agencies. While these impacts are presented independently, they are related. Funding and financing impacts may shift how a transportation agency prioritizes its activities at the *institutional* level, which in turn impacts how assets are deployed and managed at the *operational* level. It is critical that MassDOT and affiliated agencies are aware of these potential impacts, so they will be able to adjust their institutional, operational, and financial frameworks if needed [*27*].

Table 2.3: Funding and financing impacts [*27*]

<table>
<tr><th>Potential CAV Outcome</th><th>Transportation Agency Impacts</th></tr>
<tr><th>Funding Impacts</th><th></th></tr>
<tr><td>CAV applications could increase passenger and commercial VMT, increasing the costs associated with maintaining and operating roadways.</td><td rowspan="2">Examine and modify investment decisions accordingly, to address changing transportation demands.</td></tr>
<tr><td>CAV systems could increase need for visible lane striping, more visible signs, removal of roadway obstructions, physical infrastructure to support CAV applications, and detailed infrastructure-related data to support CAV applications.</td></tr>
<tr><td>SAVs could reduce the amount of revenue derived from vehicle registration fees.</td><td rowspan="3">Potential decreases in vehicle registration and licensing revenue may necessitate alternative funding sources.</td></tr>
<tr><td>SAVs could bring about a decline in vehicle ownership and then a decline in vehicle production (and associated decline in vehicle sales).</td></tr>
<tr><td>SAVs could result in fewer professional drivers and traditional taxi services, thus bringing about a decline in revenues from sources such as commercial driver's licenses and taxi medallions.</td></tr>
<tr><td>AVs could be deployed with electric-motor-based technologies.</td><td>Decreases in fuel tax revenue through traditional motor fuels tax may require looking into other mechanisms.</td></tr>
<tr><td>CAV systems could increase VMT and include technology for usage-based revenue measurement.</td><td>Increases in user revenue if funding or financing mechanisms are tied to road usage.</td></tr>
<tr><td>CAV systems could reduce driver error.</td><td>Potential decreases in revenue from moving violations.</td></tr>
<tr><td>AVs or SAVs could reduce mass transit utilization.</td><td>Potential decreases in transit fare revenue and impacts on agency funding if federal apportionments are tied to ridership levels, which could require additional and/or alternative funding sources for transit.</td></tr>
</table>

2.2.3 Impacts on Transportation Planning

One of the major goals of transportation planning is to forecast future transportation demand with future transportation capacity in optimal ways, based on defined criteria and subject to available or planned resources. This goal faces serious challenges with the emergence of CAVs [*39*]. Forecasting future transportation demand and capacity relies on assumptions about vehicle ownership, route choice, and residence and work locations. Not all these assumptions may be valid for CAVs: commuters choosing SAVs may tolerate longer commutes or choose different travel routes if they are able to perform other tasks in the car (e.g., work, sleep) instead of driving.

There is not yet a general consensus regarding the overall impact of CAVs on traffic and traffic management. At best, CAVs improve transportation efficiency—reduce the number of crashes, eliminate human inefficiencies in the flow of traffic, and promote ridesharing and the use of public transportation by alleviating the “first/last mile” problem. At the same time, there is a risk that CAVs could lead to more vehicles on the road due to their increased attractiveness and the longer trips people will be willing to make.

The acceptance and use of CAV technologies are highly uncertain. The following basic questions exist:

- How likely are people to use self-driving vehicles?
- What are the factors that influence acceptance and intent to use?
- What is the appeal of self-driving vehicles for people?
- In what ways would people change their current travel behavior because of access to self-driving vehicles?
- How might self-driving vehicles on roadways impact traffic and congestion?

Thus far, answers to these questions are speculative future visions with little or no empirical evidence. A study conducted by the Texas A&M Transportation Institute [*40*] attempted to establish an evidence base for transportation policy and decision making. The information derived from an online survey and qualitative interviews with Austin, TX, metropolitan area residents. However, the findings are representative of this sample only and are largely inconclusive. People are in a wait-and-see position in terms of acceptance and use of self-driving vehicles. Clearly, continued studies and observations are needed and should produce rational, reliable, and long-range transportation planning decisions.

2.3 Economic Impacts

This section considers the impacts on investments that will be required and savings that may be achieved with CAV technologies, in addition to the performance advantages outlined previously.

2.3.1 Investments

The following are potential investments that MassDOT may want to consider:

- **Sensors**: While CAVs can serve as mobile sensors for data collection, MassDOT should deploy additional sensors to complement the mobile sensors and create a comprehensive and dynamic sensor network for monitoring the entire transportation system. Smart sensors can be used to monitor the conditions of infrastructure (e.g., pavement, bridges, retaining walls, tunnels, rail tracks) and operations of highway and transit networks (e.g., origin-destination (OD) data, density, delay, incidents), and vehicle operating environment (e.g., heavy rain, snow, ice, fog, strong wind). The infrastructure data can be used to develop lifecycle models and optimal infrastructure maintenance/utilization plans. For example, based on the data and models, some highway segments may need to be closed to heavy vehicles during certain time periods to increase their lifespans. The collection of operational data such as vehicular OD and transit passenger OD can be used to predict travel demand under normal conditions, emergency conditions, optimize transit network design and scheduling, optimize traffic control, evaluate transportation policies, etc. Today's accidents are mostly caused by human errors. In the future, most accidents could instead be completely caused by poor vehicle maintenance, malfunctioning sensors, software bugs, cyber-attacks, and inclement weather conditions. In Massachusetts, wintery weather can significantly change the operating characteristics of pavement and bridge decks, affecting the safe speed limits. In-vehicle sensors may not accurately detect some of these changes. To improve highway safety and minimize MassDOT's liability, it is important to invest in weather sensors and notify CAVs of hazardous weather and roadway conditions.

- **Smart Infrastructure and Roadside Units**: The private sector has been investing heavily in CAV-related technologies. To facilitate the deployment of CAVs, MassDOT should invest in smart infrastructure to accommodate the needs of CAVs, particularly communication infrastructure and roadside units.

- **Smart Control Algorithms**: MassDOT may want to invest in smart control algorithms for intersections, work zones, ramps, transit signal priority, etc. Such algorithms are critical to take advantage of the rich information generated by CAVs and enabling them to respond quickly and cooperate with each other.

- **Data Analytics**: It is important for MassDOT to look into the rich data sets generated by CAVs and compare them with bike sharing, parking, transit ridership, weather, special events, transportation policies, incidents, etc. Such data can be used to study travelers' mode choice, trip start time, and route choice behaviors, and thus can be used to predict future travel demand with detailed time resolution.

- **Cybersecurity**: With large-scale deployments of CAVs, safety may become more of a security issue. MassDOT should invest in cybersecurity to ensure that the highway infrastructure (particularly the communication network, traffic controllers, and roadside units) in Massachusetts is properly protected.

- **Workforce**: MassDOT should train employees to fully understand the opportunities and challenges brought by CAVs. This will also require changes to the curricula of existing transportation engineering problems. MassDOT may want to reach out to universities and invest resources in workforce development.

2.3.2 Savings and Benefits to State DOTs and Society

The following are the potential savings and benefits that MassDOT may want to consider:

- Congestion due to excessive traffic demand and incidents results in losses of hundreds of millions of dollars each year. CAVs and the enabled safety and shared mobility technologies can substantially reduce congestion, travel time, fuel consumption, and traffic emissions, as well as improve safety. This will result in reduced or complete elimination of costs associated to traffic crashes.

- Improved traffic safety will help to reduce the costs of auto repair, health and auto insurance, and legal services (e.g., injury attorneys).

- Driverless trucks and truck platooning will help to address the shortage of truck drivers and will significantly drive down the cost of logistics.

- SAVs have great potential to solve the "first-mile/last-mile" problem. This may significantly increase the ridership of public transit, particularly for medium- to long-distance public transit lines.

- With CAVs, expensive safety features such as guardrails, traffic barriers and cones, and pavement markers may no longer be needed. Additionally, existing lanes can be made narrower, and lane configuration may be changed dynamically. This means an "HOV zipper machine" to move barriers and the travel direction of a lane may no longer be necessary, as roadway widths can be changed electronically and dynamically.

- With CAVs, highway law enforcement may no longer be needed.

- Without the need to worry about distracted driving, MassDOT can set up more advertising signs/devices along highways and inside transit vehicles.

2.3.3 Costs

While CAV technologies offer the potential of substantial benefits, there are also potential additional costs. For example, CAV technology may increase total VMT, which in turn may lead to more congestion, energy consumption, and pollution.

By making proximate parking unnecessary, Level 4 CAV technology may reduce parking revenues that are an important and reliable source of funding for many cities. Providing a new level of mobility for some users may result in reducing ridership (and support) from public transit systems. This is similar to the effects that carpooling has on transit ridership (it reduces the latter), thus eroding its comparative advantage.

Further, many jobs could be lost once drivers become unnecessary. Professional drivers (taxi, truck, and bus) may require retraining to enter into different professions that would grow because of the positive economic impacts to other employment sectors. If crashes decline in frequency, an entire "crash economy" of insurance companies, body shops, chiropractors, and others will be disrupted [*27*].

2.4 Availability of Data

The USDOT has identified a list of potential applications of CAVs (**Table 2.4**). Based on each specific application, the data needed differs. AASHTO has analyzed the infrastructure needs of data acquisition and management for each application, which is detailed in Appendix A of the report of *National Connected Vehicle Field Infrastructure Footprint Analysis* [*41*]. This section describes the types of data potentially derived from CAV technologies and their utility for the maintenance and management of transportation systems of interest to state DOTs, including MassDOT. The section introduces the data requirements that could lead to useful applications in traffic operations, planning, and the environment, and then presents some important issues related to data usage.

Table 2.4: Applications of CVs [*40*]

V2I Safety

- Red Light Violation Warning
- Curve Speed Warning
- Stop Sign Gap Assist
- Spot Weather Impact Warning
- Reduced Speed/Work Zone Warning
- Pedestrian in Signalized Crosswalk Warning (Transit)

V2V Safety

- Emergency Electronic Brake Lights (EEBL)
- Forward Collision Warning (FCW)
- Intersection Movement Assist (IMA)
- Left Turn Assist (LTA)
- Blind Spot/Lane Change Warning (BSW/LCW)
- Do Not Pass Warning (DNPW)
- Vehicle Turning Right in Front of Bus Warning (Transit)

Agency Data

- Probe-based Pavement Maintenance
- Probe-enabled Traffic Monitoring
- Vehicle Classification-based Traffic Studies
- CV-enabled Turning Movement & Intersection Analysis
- CV-enabled Origin-Destination Studies
- Work Zone Traveler Information

Environment

- Eco-Approach and Departure at Signalized Intersections
- Eco-Traffic Signal Timing
- Eco-Traffic Signal Priority
- Connected Eco-Driving
- Wireless Inductive/Resonance Charging
- Eco-Lanes Management
- Eco-Speed Harmonization
- Eco-Cooperative Adaptive Cruise Control
- Eco-Traveler Information
- Eco-Ramp Metering
- Low Emissions Zone Management
- AFV Charging / Fueling Information
- Eco-Smart Parking
- Dynamic Eco-Routing (light vehicle, transit, freight)
- Eco-ICM Decision Support System

Road Weather

- Motorist Advisories and Warnings (MAW)
- Enhanced MDSS
- Vehicle Data Translator (VDT)
- Weather Response Traffic Information (WxTINFO)

Mobility

- Advanced Traveler Information System
- Intelligent Traffic Signal System (I-SIG)
- Signal Priority (transit, freight)
- Mobile Accessible Pedestrian Signal System (PED-SIG)
- Emergency Vehicle Preemption (PREEMPT)
- Dynamic Speed Harmonization (SPD-HARM)
- Queue Warning (Q-WARN)
- Cooperative Adaptive Cruise Control (CACC)
- Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)
- Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)
- Emergency Communications and Evacuation (EVAC)
- Connection Protection (T-CONNECT)
- Dynamic Transit Operations (T-DISP)
- Dynamic Ridesharing (D-RIDE)
- Freight-Specific Dynamic Travel Planning and Performance
- Drayage Optimization

Smart Roadside

- Wireless Inspection
- Smart Truck Parking

2.4.1 Data for Traffic Operations

- **Roadway maintenance**: CAVs may automatically detect and report potholes, pavement anomalies, device failure, etc. Based on this information, roadway maintenance crews can plan work accordingly.

- **Traffic monitoring and information sharing**: Cameras mounted on CAVs can be used to obtain and report traffic information such as speed, which can be used to estimate queue length and traffic delay (e.g., at work zones). In addition, such information can be shared with other road users for queue warnings and detours.

- **Incident assessment**: CAVs can detect roadway incidents and traffic slowdown in response to the incidents. The detected incident information can then be used to assess frequency of incidents to identify hotspots and assess the impacts of incidents on queue length and delay.

- **General traffic condition monitoring:** Utilizing the CAV-generated speed and flow (estimated based on vehicle trajectories) information, queue length and delay at highway bottlenecks and intersections can be quantified, and improvement plans (e.g., traffic signal retiming) can then be developed.

- **Routing data:** The routing data contributed by CAVs can be used for understanding traveler route choice behaviors. Note that passengers in a CAV can direct the vehicle to a specific route. The routing data can also be used to derive the demand for specific road segments and can be used for mileage-based tolling.

2.4.2 Data for Planning

- **Traveler OD information**: Many studies have been conducted to estimate traffic OD information, due to its significance to transportation planning and traffic management. The OD information shared by CAVs from multiple days can be integrated with land-use transportation models and employment data, and can provide valuable information for transportation planning.
- **Traffic demand for parking and SAVs**: This information can be extracted by analyzing the historical data.
- **Travel behavior**: Such as travelers' response to pricing and tolling.
- **Traveler person and vehicle:** Throughput data at the corridor level.
- **VMT changes**.

2.4.3 Data for Environment

- **Emission estimation**: This can be estimated more accurately, as vehicles may constantly monitor their fuel consumption and emission level.
- **Assessment of emission reduction from different methods**: Emission reduction can be from eco-driving, SAV, VMT change, or other methods, which can be more accurately estimated with CAVs.

2.4.4 Potential Issues with Data Collection, Sharing, and Usage

2.4.4.1 Infrastructure Needs, Data Ownership, and Cost

For the data supporting the applications discussed previously, ownership, infrastructure needs, and cost vary significantly, depending on the sensing and communication methods used.

- CVs: For CVs, in most cases, the human drivers/passengers do the "sensing" and then the information can be communicated using DSRC, cellular, or other forms of wireless communications.
    - If DSRC is used, it usually requires an on-board-unit (OBU) and roadside unit (RSU) to provide V2V and V2I communications. Infrastructure for data storage and management may be needed as well. For this approach, state DOTs are more likely to be involved in the infrastructure construction and operation and thus own the data. The overall cost to DOTs of this DSRC scenario will be much higher compared to the following cellular network option.

- If cellular networks are used (e.g., 4G, 5G, or 6G), CAVs are more likely to use commercial cellular channels with very little (or no) involvement from state DOTs. In this case, the cellular network operators and/or drivers will own the data, and traffic operators (e.g., state DOTs) may have to acquire the data by purchasing or via a data exchange.

- AVs: Most AVs use their own sensors (Radar or LIDAR) to collect data and transmit data. They have very different infrastructure needs than CVs, such as enhanced lane marking and machine-readable devices. Most likely, the data collected by AVs will be owned by the private sector (e.g., OEM, manufacturers, and software owners). However, since state DOTs will provide some infrastructure to support the AV operation (e.g., lane marking), it is possible that DOTs can request certain data from the private sector or use some data owned by DOTs for exchange. For example, DOTs provides data such as road construction and incidents, and in return, the private sector provides the data for the purpose of operation improvement.

2.4.4.2 Data Usage Issues

The use of CAV data faces many challenges [*42*]:

- Privacy issues related to the level of anonymity provided to drivers.
- Governance issues, such as roles of participants and who may access the data.
- Spectrum issues, such as compromised safety by other applications adjacent to the selected spectrum.
- Ownership issues related to data sharing.
- Interoperability issues between roadside units and on-board units.
- Timeline issues, such as when DSRC will be available.
- Security issues between outside sources, including roadside units and on-board units.
- Liability issues, such as liability for faulty data.
- Social equity issues, such as how well the connectivity protects non-motorized users.

Most of these issues are being addressed at the national level, but state DOTs are highly recommended to explore different approaches to expedite CAV deployment, such as identifying and prioritizing applications that are feasible and are less costly to deploy in the near- and mid-term. Since the data will contain much information about individual users, it is likely that the data owners will be concerned about data security and will be reluctant to share them with the traffic operator. A potential way to overcome this issue is to anonymize the data and use the aggregate information. Among the many data issues listed above, cyber-security is of particular concern. As one vulnerability is found and closed, others are detected. "A comprehensive threat management strategy is key to staying ahead of problems and to being able to respond to issues in close to real-time. There won't be a comprehensive 'hands off' system for automakers and fleet providers to rely on, there has to be some manner of manual intervention at some point in most attacks" [*43*]. The National Institute of Standards and Technology (NIST) has established a framework_that recommends an acceptable level of protection of critical infrastructure that can be used as a guide [*44*]. State DOTs may wish to consider adopting stricter rules on cyber-security for the manufacturers and developing a response plan to address potential incidents caused by cyber-attacks that may spread on a large scale and cause catastrophic failure.

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3 Potential Partnerships

In order to ensure a smooth and successful introduction of CAVs, state DOTs may wish to consider developing public and private partnerships as described in the following sections.

3.1 Public Sector Partnerships

3.1.1 National Level

State DOTs should maintain close collaborations with national level agencies such as USDOT ITS JPO, US Department of Energy, AASHTO, NHTSA, FMCSA, FTA, Institute of Transportation Engineers (ITE), ITS America, and the Transportation Research Board to be informed of the most recent developments of CAVs in terms of new technologies, regulations, policies, deployments, lessons learned, and innovative applications. In addition, MassDOT should seek funding from programs such as the following, to test CAV technologies in Massachusetts.

- Every Day Counts (EDC) program
- Accelerated Innovation Deployment (AID) Demonstration program
- State Transportation Innovation Council (STIC) Incentive program
- Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD)
- Connected Vehicle Pilot Deployment Program
- ARPA-E

3.1.2 State and Regional Levels

State DOTs should give consideration to collaborating with other state agencies, such as their state Department of Public Safety, to ensure their efforts to facilitate the testing and implementation of CAV technologies are coordinated. MassDOT may wish to consider collaborating with other states, especially those in the New England region, to learn from their experiences and to ensure the interoperability of future connected and automated transportation systems. These states share similar weather, driver, and roadway conditions, and many travelers work in Massachusetts while living in neighboring states (or vice versa). Additionally, MassDOT may also consider collaborating with regional organizations such as the I-95 Corridor Coalition to address the impacts of CAVs on cross-border freight transportation that require multistate cooperation.

3.1.3 Local Level

State DOTs should work with cities, towns, planning agencies, and local transit agencies' Central Transportation Planning Staff (CTPS) to:

- Provide technical support for them to prepare for CAVs.
- Ensure future transportation system interoperability.
- Understand their specific needs.

- Leverage their available resources.
- Collaborate with them on CAV-related projects.

MassDOT and cities could work together to look at the impacts of reduced parking needs and increased demand for CAV charging facilities.

3.1.4 Other

State DOTs may consider collaborating with traffic law enforcement agencies and first responders to address their specific needs (e.g., signal preemption for emergency service CAVs) related to CAVs. MassDOT may wish to consider reaching out to organizations representing aging and disabled populations, highway safety advocates, trucking associations, bike and pedestrian groups, and taxi providers to take their concerns into consideration when preparing for CAVs.

3.2 Private Sector Partnerships

State DOTs are responsible for constructing, operating, and maintaining infrastructure, while technologies (e.g., LIDAR, radar, DSRC, 5G, collision avoidance system) enabling CAVs have mainly been developed by the private sector. Smart vehicles will demand smart infrastructure as well as smart traffic operations and infrastructure maintenance practices. At this stage, it might be premature to invest in smart infrastructure on a large scale to accommodate the potential needs of CAVs, since CAV technologies are evolving almost every day and their infrastructure needs and impacts are uncertain. However, it would be helpful for state DOTs to partner with automobile manufacturers and/or tech companies to conduct pilot tests of CAVs. Preferably, these pilot tests will be funded and led by those manufacturers or tech companies to minimize the financial burden on DOTs. This will allow DOTs to gain first-hand experience of not only the impacts of CAVs, but also the potential infrastructure needs of CAVs.

In addition to CAV manufacturers, it is important for DOTs to collaborate with Transportation Network Companies (TNCs). Many people believe that mobility in the future will be provided as a service. In the future, TNCs may operate like today's mobile carriers, such as AT&T and T-Mobile. Travelers can sign up for a limited or unlimited monthly plan to use their mobility services. Given that a major TNC operates (i.e., plans routes for) hundreds of thousands of CAVs at a specific time, their impacts on traffic operations and congestion should not be underestimated. A major task for future DOTs in terms of traffic operations might be coordinating the route planning practices of different TNCs.

Finally, state DOTs should consider collaborating with communication companies. These companies also have strong interest in CAV development and deployment utilizing the 5G technology [*45*]. 5G technology provides another promising solution for enabling vehicle connectivity. MassDOT could work with these communication companies and test their vehicle connectivity solutions in conjunction with CAV pilot studies.

3.3 Academic Partnerships

State DOTs could further strengthen their collaborative relationship with academic research organizations. In Massachusetts, these include state universities, the University of Massachusetts Transportation Center (UMTC), and the New England Transportation Consortium (NETC). Such collaborations should not be limited to research and development, and should include the important missions of education, training, and workforce development.

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4 Strategic Recommendations for Connected and Automated Transportation Systems

This chapter provides strategic recommendations in a number of key areas and highlights the critical issues to address. It also provides action plans for three different time frames, identifying specific and actionable items.

4.1 Strategic Recommendation

4.1.1 Promote CAV Testing

Testing will help state DOTs to better understand how to operate CAV systems in the safest and most efficient way. It will also help the MassDOT Highway Administration and its partner agencies, such as the Massachusetts Bay Transportation Authority (MBTA), gain valuable knowledge, skills, and expertise that will help with future CAV deployments.

Testing new systems can provide state DOTs, including MassDOT, with information on how these technologies function and perform. This process will facilitate the development and improvement of implementation and operational procedures. Additionally, state DOTs will be able to assess more accurately the cost, effectiveness, and efficiency of investments needed to deploy CAV systems and gain other valuable institutional knowledge and expertise.

Most CAV applications will require roadside and infrastructure CAV technologies that will collect, aggregate, process, and distribute information from and to equipped vehicles. Most likely, state DOTs will be responsible for the deployment, operation, and maintenance of such infrastructure CAV technologies. Testing a CAV system can provide valuable knowledge, skills, and expertise, and help with setting priorities for infrastructure investments. Without testing such CAV technologies, Massachusetts will not be able to fully capitalize on the potential environmental, mobility, and safety benefits of CAVs.

At the current stage, MassDOT can establish partnerships with private companies to facilitate testing of CAV technologies on public roads with limited risk. Once such systems become more mature, MassDOT can decide the scale and mechanisms of investment. Currently, the City of Boston has a partnership with nuTonomy and Optimus Ride for testing AVs in the Seaport District (see section B.4.6). Recently the City of Boston announced that nuTonomy has been authorized to expand testing city-wide [*46*].

To achieve these goals, state DOTs should consider:

- Recommending the enactment of legislation for setting standards for safely testing CAVs on public roads.
- Establishing testbeds to be used under different conditions with respect to weather (e.g., dry, wet, snowy), lighting, different levels of CAV market penetration, and pedestrian

traffic in urban and rural environments. This will also attract partnerships with private and public sector stakeholders.

4.1.2 Modify Driver Training and Licensing Requirements

To maximize the potential safety and mobility benefits of both CAV technologies, vehicle operators and owners should be fully aware of the capabilities and the limitations of these technologies. CAV technologies may pose different requirements from the operator/owner of the vehicle; therefore, new training and licensing procedures such as those outlined in the *Jurisdictional Guidelines for the Safe Testing and Deployment of Highly Automated Vehicles* [*47*] will be needed to be considered.

For CAV technologies, driver training and licensing requirements will depend largely on the level of automation. For level 3 CAVs, the operator must be able to recognize when she or he can engage automated driving functions and, if automated driving is on, when to take over vehicle control. Without appropriate training, the reduced human control of the vehicle can result in degradation of reaction times, poor decision making and awareness, and overreliance on the autonomous driving function. Therefore, testing and licensing requirements will need to include the driver's ability to take over driving when it is necessary. Training will have to be expanded to reflect the operator's dual role, monitoring the roadway/vehicle conditions and driving the vehicle when needed. Level 3 CAV operators will have to be attentive to V2V and V2I warning messages in the vehicle. In the future, driver training and testing materials may need to be expanded to include these aspects.

For levels 4 and 5 CAV automation, driver licensing in the traditional form may be unnecessary. However, if the rider of a CAV is expected to intervene in an emergency, he or she still needs to be trained to do so. In addition, the owners of the vehicles will have to be educated about purchasing safe vehicles, the basics of their operation, and their maintenance requirements.

The transition to CAVs from traditional vehicles could take place over a long period of time. Vehicles may have different levels of technology, and operators/owners of vehicles may have access to vehicles with different capabilities. Therefore, changes in licensing will have to accommodate drivers of traditional vehicles as well as CAVs of differing levels of automation. Licensing requirements can be either comprehensive to ensure that drivers can operate safely all types of vehicles with multiple levels of automation, or specific to the types of vehicles a driver will be allowed to operate.

4.1.3 Encourage the Use of Shared AVs (SAVs)

As CAV technologies advance, SAVs could emerge as an alternative to individually owned vehicles. While SAVs could have significant positive impacts, it will be important for Massachusetts to consider developing operating guidelines for SAVs to ensure a safe and efficient SAV system.

CAVs have the potential to increase congestion and pollution problems due to reduced perceived cost of in-vehicle time, increased mobility to those who are unable to drive, unoccupied CAV travel, and long trips from additional urban sprawl. SAVs, on the other hand, could mitigate these issues. SAVs can provide transportation to more than one party, thus increasing average vehicle occupancy. They can focus on providing first-mile/last-mile service, thereby complementing existing transit systems. While vehicles need to relocate to serve new travelers, unoccupied travel is likely to be significantly shorter than for private CAVs. In order to control the amount of zero-occupant travel that SAVs will be making while repositioning themselves, special regulations should be developed and enforced. Such regulations can also be applied to level 4/5 CAVs. SAVs will operate most effectively in densely populated areas, reducing the potential for expanded urban sprawl.

SAVs will operate in a similar fashion as TNC services like Uber and Lyft, and will most likely start gaining popularity in metropolitan areas. It is important for the state to coordinate with local authorities on expected SAV regulations. This will facilitate creating uniform standards that each local SAV system can use. Although SAVs will require level 4/5 automation, which will be used extensively only in the long term, the state should plan to make the transition easier.

The provider of SAV services most likely will be transit agencies like the MBTA or regional transit authorities. Transit agencies should consider focusing on SAV applications such as:

- Providing first-mile/last-mille connections.
- Providing paratransit services to the disabled and elderly.
- Providing service for rural/low density areas where regular transit services could be considered not efficient or are not present.

For providing such services, SAV systems most likely will be subsidized. Local transportation agencies should explore innovative partnerships with TNCs and shared mobility providers to leverage federal funds.

In order to encourage individuals to use SAVs, transit benefits should be allocated to SAV users as well. Transit Oriented Development (TOD) policies can be used to promote SAV usage. The FTA defines TOD as “compact mixed-use communities near transit where people enjoy access to jobs and services” [*48*]. Reduced parking requirements can also be used to promote SAV usage. Finally, the state should consider applying road pricing, since appropriate road user charges (RUCs) can also promote the use of SAVs.

4.1.4 Invest in Infrastructure

Several existing CAV technologies, such as lane keeping assist, lane departure warning, traffic-jam assist, and truck platooning depend on clear pavement markings. Low-level CAVs use optical means to identify the limits of the traveling lane. Due to roadway use, pavement markings become less visible over time and thus less detectable by vehicle sensors. State DOTs may wish to consider developing a strategy to regularly inspect and maintain pavement markings on all freeways and major roadways. In the short term, emphasis can be given to urban and suburban areas where most CAVs will be operating.

Similarly, low-level CAVs will be using optical means to detect traffic signs and take appropriate action. Therefore, traffic signs must have high retro-reflectance so vehicle sensors can easily detect them. State DOTs and municipalities may have to establish standards and monitor the retro-reflectance of traffic signs along roadways periodically.

Investment in infrastructure will also be necessary for enabling the function of connected transportation systems. The DSRC-enabled CAV will mostly rely on state DOTs for investment. CAV infrastructure refers primarily to DSRC instrumentation, but it also includes supporting infrastructure such as backhaul communications system, CAV data center, CAV-equipped traffic signal controllers, etc.

Investments in CAV infrastructure will benefit CAVs that will have V2I and V2V instrumentation, but state DOTs will also gain the benefit of the wealth of data collected by the CAV-enabled system. Such data could be used to offset the investment required.

While the entire network will have to be instrumented, priority should be given to locations that will provide the highest benefits. Such locations include certain signalized intersections and arterials, locations with challenging geometry (sharp curves, narrow lanes, construction zones, etc.), and locations with high frequency of traffic incidents. This is also likely to promote the use of SAVs and result in reduction of total VMT.

Notably, there are discussions concerning which CAV technologies, DSRCs, or cellular networks should go first and what role they should play. Some believe that the private sector might be able to roll out cellular networks (like 5G) first to create a large user population, and then extensive DSRC can follow to enable meaningful applications [*45*]. Nevertheless, the CAV technology development will affect the timing and scale of DSRC infrastructure deployment.

As discussed in Section 2.3.1, state DOTs should also consider investing in the deployment of a network of smart sensors for monitoring roadway and traffic conditions. Such sensors will supplement the information collected from CAVs, and the data collected can be used for the development of maintenance plans, improve the lifespan of highway pavements and bridges, improve highway safety, and minimize state DOT liability.

4.1.5 Implement Signal Priority Strategies for CAVs and SAVs

Traffic signal priority for CAVs with emphasis on transit, SAVs, and commercial vehicles can be used to improve mobility by reducing delays of high occupancy vehicles, improve safety by reducing the number of stops of large vehicles, and accelerate the market penetration of CAVs. Traffic controllers in the future will need to be able to dynamically adjust timing plans in response to changing traffic, receive notice from CAVs approaching an intersection, use advanced control algorithms that can estimate the time of arrival of a platoon of CAVs, and evaluate whether to grant priority, and transmit signal timing information back to CAVs for adjusting their speeds to arrive at intersections during a green interval. Most traffic signal controllers installed in the past 20 years need to be upgraded to fully accommodate these needs.

The overall signal priority impact will depend on the level of CAV market penetration. At low market penetration levels, signal priority may be reserved only for transit vehicles. In addition, priority treatment should be used only during low and medium levels of saturation. During congested operations, priority treatment may cause disruptions to traffic flow and may provide negligible benefits to CAVs.

4.1.6 Provide Dedicated Lanes for CAVs

As the CAV market penetration increases and the anticipated benefits of AV use becomes more apparent, MassDOT may wish to consider providing AV-only lanes, accounting for their different operating characteristics. Such a strategy could serve to make travel more efficient for all users.

Dedicated CAV lanes can be provided on different types of roadways, from freeways to local streets, but the best candidates will be on freeways serving longer trips. On freeways, CAVs on dedicated lanes will be able to operate at higher speeds, in tighter platoons, and possibly on narrower lanes. Separating CAVs from regular vehicles may also improve human drivers' overall experiences, as CAVs follow each other more closely and may cause human driver discomfort and anxiety. In urban areas, exclusive CAV lanes will depend on the availability of space, but when possible priority should be given to SAVs to support the reduction of total VMT.

4.1.7 Invest in Data Analytics and Cybersecurity

CAVs will be generating large streams of data providing information about drivers, vehicles, and real-time traffic and roadway conditions. This data will need to be stored and analyzed so it can be used for the applications discussed in Sections 2.4.1 to 2.4.3.

The additional connectivity offered to support CAV "infotainment" systems opens potential cyber threats. While CAVs should be equipped with the most up-to-date software to minimize threats, state DOTs may wish to consider investing in cybersecurity to ensure that the highway infrastructure (particularly the communication network, traffic controllers, and roadside units) is properly protected.

4.1.8 Prepare the Workforce

State DOTs will need employees to fully understand the opportunities and challenges presented by CAVs. This will require changes to the curricula of existing transportation engineering programs. State DOTs may wish to consider reaching out to universities and invest resources in workforce development.

4.2 Action Plans

This section identifies practices that state DOTs, including MassDOT, might consider initiating in three different time frames: short, mid, and long term. One important note is that, as CAV technologies are developing rapidly, there is substantial uncertainty even in the short term. Therefore, these recommendations may change across different time frames. Moreover, the duration of each time frame will depend on the pace of technology evolution. Currently, it is still unclear whether CAVs will first enter the market in a large scale and whether these technologies will take a revolutionary or evolutionary path. However, with the aggressive moves of CAV developers and manufacturers, it is likely that the direction will become clearer in two to five years. For instance, Waymo has planned to deploy a fleet of 20,000 vehicles by 2020, which will complete 1 million trips per day [*49*]. If Waymo's goal is successfully achieved, it will be a strong signal that the CAV technologies will mature first and gain prevalence on the road. In that case, most states in the country will likely switch from the current research-testing stage to the build-and-deploy stage. This will also have positive impacts on the development and deployment of CAV technologies.

In the short term, the authors think that CAV technology development is still too uncertain, and it is unwise and risky for MassDOT to adopt any aggressive action plans. Most of the short-term recommendations therefore focus on facilitating CAV testing and staying aware of technology development. In the mid-term, presumably the development trends around CAVs will become clearer. MassDOT may wish to consider taking actions that are more intensive. This period will involve more extensive planning and field deployments of CAVs. In the long term, CAV technologies are expected to be more mature, and the focus of state DOTs would then be on system optimization.

4.2.1 Short Term (0–5 Years)

In this time period, it is recommended that state DOTs consider:

1. Establishing a CAV working group within a state DOT. This can be built by expanding the current CAV working group in Massachusetts. The mission of this working group is to:
    - Coordinate all CAV-related issues with federal agencies (e.g., AASHTO, TRB committees, and other states), state agencies and offices in Massachusetts (e.g., Governor's office, RMV, Department of Public Safety), local cities and towns, private sectors, and universities and research institutes.
    - Stay aware of CAV development trends and provide an annual update of the CAV development status.
    - Provide support and recommendations for the state-level CAV development (e.g., CAV legislation, regulation and licensing).

2. Initiate CAV pilot studies and facilitate further testing.
    - For CAVs, establish a pilot test site to gain first-hand experience of CAV technology (e.g., hardware and software maintenance, device compatibility, data collection and storage, and cybersecurity) and prepare for future large-scale deployments (see more detail in Section 4.3 regarding the Massachusetts SPaT corridor).
    - For CAVs, encourage, facilitate field-testing of AVs in Massachusetts, and monitor the testing results to gain a thorough understanding of potential opportunities and issues (e.g., data sharing).

3. Conduct research to identify and potentially address CAV issues that are unique to Massachusetts or the New England region (e.g., severe snowstorms, cross-border traffic, etc.). MassDOT can designate state research funds and/or leverage the New England Transportation Consortium funds to conduct such research.

4. Monitor research and developments of CAVs in the following priority areas:
    - CAV testing and deployment.

- o Impacts of AV-only lanes and vehicle platooning.
- o Data collection, management, and analytics, including sharing, mining, privacy, and security.
- o Impacts of CAVs on driving safety and traffic operation efficiency.
- o The impacts of SAVs and TNCs (e.g., Uber, Lyft) on future transportation (they will play a critical role in traffic operations).
- o Infrastructure needs of CAVs.
- o Multimodal transportation in a CAV environment (e.g., how do subway, commuter rail, and SAVs work together).

5. Prepare the workforce for future CAV deployments. It is well agreed that for the deployment of CAV technologies, it is not an issue of "Yes or No," but "When and How." Large-scale deployment of CAVs will significantly affect key offices and divisions within MassDOT, including Highway Operations, ITS, Traffic Data Collection, Traffic and Safety Engineering, Design Build, Snow & Ice, and the Planning Office. It is recommended that MassDOT conduct an annual briefing (e.g., via a one-day workshop) to keep MassDOT staff aware of the technology developments and make informed decisions (e.g., be cautious when investing in new control devices, as those may not be appropriate for CAVs and may become obsolete soon after installation).

Additionally, the MassDOT Traffic Operations Division may wish to consider taking a lead to monitor or conduct research on the following key issues:

- CAV-compatible traffic control devices (particularly for work zones), pavement markings, and signage that will enhance CAVs operations and reduce MassDOT liability.
- Safety and roadway maintenance practices in inclement weather conditions to minimize MassDOT liability.
- Safety applications of CAVs such as collision avoidance systems (MassDOT should also assist in their deployment in Massachusetts).
- CAV-enabled solutions for improving operational efficiency, such as smart traffic signal control strategies, AV-only lanes, Cooperative Adaptive Cruise Control, and truck platooning.
- Identify CAV-enabled traffic management strategies that are both economically feasible and environmental policy–compliant, with emphasis on integrated vehicle routing (guidance) and traffic signal control, eco-driving, managed lanes, and advanced signal priority strategies, as well as innovative mobility solutions (e.g., SAVs).
- In cooperation with the Design & Engineering and the Maintenance divisions, identify various MassDOT design and maintenance manuals and standards that might be impacted by CAVs.

State DOTs should also consider taking the lead to monitor research on:

- Impacts of total VMT changes caused by CAVs.
- Impacts of CAVs on land use, travel behavior, and freight.
- Impacts of CAV-enabled new mobility solutions on public transportation.
- CAV-enabled tolling and transportation financing strategies, travel demand management strategies, etc.

4.2.2 Mid-Term (6–10 Years)

It is expected that in this time frame, MassDOT may have to make many strategic decisions on CAV deployments, including technology types, implementation scale, and investment mechanisms. Following these decisions, there might be extensive implementations.

The authors recommend that in this period, MassDOT may wish to consider:

1. Expanding the size of the CAV working group and its mission to include:
   - Coordinating state agencies and offices, local cities and towns, the private sector, and the public during the CAV planning and implementations.
   - Monitoring CAV implementations in Massachusetts, and providing an annual report on the statewide CAV implementation status.
   - Continuing to monitor major CAV research and deployments in other states and countries, and providing an annual report on CAV development trends.

2. Developing the workforce for CAV implementations. This may involve the training of existing staff, hiring new staff with data science and cybersecurity backgrounds, and creating co-op and internship opportunities in related areas.

3. Creating a designated office to handle data issues of CAVs, including establishing and updating standards for data collection, storage, and sharing; data privacy and integrity; data analysis; and facilitating data utilization.

4. Strengthening a state DOT's research capacity to address the challenges and embrace the opportunities presented by CAV technologies, particularly in the areas of planning, safety, operations, maintenance, data analysis, and construction. This can be achieved by:
   - Increasing the state research budget and adding new research staff.
   - Enhancing a state DOT's research partnership with state universities, UMTC, and NETC (see Section 3.3).

In addition, the MassDOT Highway Division may wish to consider:

- Conducting research to identify and address issues related to the safe operation of CAVs under a wide variety of situations, such as adverse weather conditions, work zone operations, special events, emergencies, etc.
- Updating standards and manuals on traffic control devices, roadway design, and traffic operation to facilitate CAV deployments in Massachusetts. Ensure that the updates reflect the unique driver, roadway, and environmental characteristics of Massachusetts and their impacts on CAV operations.
- Working with the RMV to develop and/or revise the regulations for registering, testing, and operating CAVs on public roads in Massachusetts.
- Implementing CAV-enabled safety technologies.
- Implementing CAV-enabled efficiency improvement strategies (e.g., advanced traffic signal control, dedicated lanes for AVs, dynamic speed limits, smart routing, and VMT- and congestion-based pricing).

- Continuing to explore innovative applications of CAV data, such as infrastructure inspection based on crowd-sourcing CAV data and automatically generating traffic signal and highway performance measures using CAV trajectories.

The MassDOT Transportation Planning Division may wish to consider:

- Developing procedures to quantify the impacts of CVs, AVs, and SAVs on different travel modes, particularly public transportation, and develop strategies to take advantage of such impacts (e.g., using the mobility service of CAVs to complement or even replace short-distance transit services).
- Incorporating the impacts of CAVs into transportation planning practices, particularly travel demand modeling and land-use modeling.
- Developing CAV-enabled advanced transportation financing strategies, such as mileage-based road user charges, rather than fuel taxes.

4.2.3 Long Term (11–20 Years)

In this time frame, it is expected that CAV technologies will be mature and a majority of the vehicles on the roads will be connected or automated. In this period, MassDOT may wish to consider:

1. Expanding the CAV working group to a single agency within MassDOT to coordinate all CV/AV related issues. The new agency will continue fulfilling the missions of the original CAV working group. It will also be responsible for handling new problems that will surface as CAV technologies evolve and their implementations progress.

2. Implementing innovative mobility solutions that seamlessly integrate various transportation modes (e.g., heavy rail, automated cars, SAVs, and shuttle buses).

3. Developing procedures that fully utilize the data from CAVs and other sources, with the ultimate goals of accurately modeling traveler behavior; designing highly efficient, safe, and sustainable transportation systems; and provide satisfactory mobility services to all passengers and freight customers.

4. Utilizing the data generated by CAVs to develop procedures to accurately model the relationship between land use and transportation systems.

5. Developing and implementing procedures for data sharing, data analysis, privacy protection, security, etc.

More specifically, the Mass DOT Highway Division may wish to consider:

- Developing data-driven models to improve highway design, infrastructure, and vehicle maintenance practices: traffic control, traffic state prediction, etc.
- Developing sophisticated simulation, analytical, or hybrid models based on crowdsourcing data generated by CAVs to accurately estimate and predict transportation system performance, and develop proactive and multimodal transportation management plans.

4.3 Immediate-Term Plan: Development of MA SPaT Corridor

As a short-term recommendation, MassDOT may wish to consider deploying a CAV pilot project to gain knowledge of current CV deployment, lay the groundwork for implementing more advanced CAV applications, and prepare MassDOT for future large-scale CAV implementations. This pilot study is also in response to the AASHTO SPaT Challenge [*18*]. The UMass Lowell research team is in discussions with MassDOT and other stakeholders to develop a plan to establish an MA (Massachusetts) SPaT Corridor. The section below outlines some key components of the project.

4.3.1 Pilot Site

The pilot site consists of a segment of State Route 9 from Lake Avenue in Worcester to I-95 (see **Figure 4.1**). It has 31 signalized intersections, and the Commonwealth owns all these signals. Five of the signals are newly installed SynchroGreen adaptive signals.

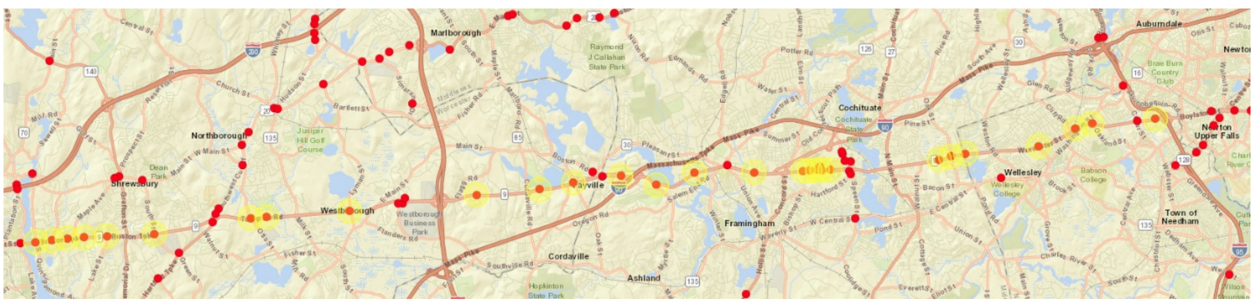

Figure 4.1: Pilot site for Mass. SPaT Corridor

4.3.2 Applications

The proposed CV applications for this pilot project are grouped into four categories as follows.

4.3.2.1 Transit Signal Priority (TSP)

This includes occupancy-based and schedule-based TSPs for local and inter-city buses, and signal coordination for transit.

1. Occupancy-based and schedule-based TSPs for local and inter-city buses
    - Occupancy-based TSP will be activated only when there are a significant number of passengers on the bus.
    - Schedule-based TSP will be activated only when a bus is behind the schedule.
    - Both TSPs can be planned more efficiently ahead of time, not necessarily when a bus is very close to an intersection.
    - By tracking the locations of multiple buses, their TSPs can be coordinated for improved efficiency, avoiding one TSP immediately after another. This can minimize the negative impacts of TSP on non-transit vehicles.

2. Signal coordination for transit
   Route 9 is a suburban inter-city corridor with two unique features: (i) the distance between adjacent intersections varies from a few hundred feet to more than one mile, and (ii) is a high-speed corridor. The closely spaced signals can be coordinated, while those isolated ones can be controlled by adaptive strategies. In both cases, the real-time trajectories of transit vehicles will be used to fine-tune signal control parameters in either real time or offline. For example, transit trajectories can be used to improve signal offsets and to evaluate signal coordination performance. For adaptive signal control, the real-time locations of buses can be used to optimize signal phase sequences and durations.

4.3.2.2 Effective and Green Freight via V2I and V2V

This project will use V2I to provide SPaT information to the many freight carriers traveling along this corridor to enable eco-driving. It can lead to significant fuel consumption savings and emission reductions (e.g., greenhouse gas and critical pollutants like NOx). This could be achieved by modifying the MMITSS-California Model (an open source project) developed in an Arizona and California CV pilot study, for example, to derive an optimal truck speed profile based on the SPaT information. Another example is to provide signal priority to freight trucks during non-peak hours to reduce stops and idling of trucks and therefore reduce their emissions.

4.3.2.3 Intelligent Traffic Signals for Safety

- **Red-light violation warning**. Broadcast SPaT information to all vehicles to warn about an upcoming red light.
- **Dilemma zone warning.** Inform vehicles about an upcoming signal change when they are approaching the dilemma zone.
- **Pedestrian detection and warning**. Detect and share pedestrian crossing information with vehicles, particularly buses and trucks, to warn them "pedestrians are crossing." Detection of pedestrians can be achieved by installing low-cost pedestrian sensors.
- **SPaT for all.** Increase the penetration rate of connected vehicles by enabling V2I via cell phones. In this case, drivers can receive critical traffic information through cell phones (i.e., these are cell-phone based CVs). For example, the three applications listed previously, red-light violation warning, dilemma zone warning, and pedestrian warning, can be implemented via a smartphone application. This will significantly increase the number of users who can benefit from SPaT.

4.3.2.4 Emergency Vehicle Priority

When an emergency vehicle determines its destination and best route, the information can be broadcast to drivers and traffic controllers along the route to clear the route ahead of time and improve the safety of first responders. Particularly, if the route involves sensitive areas, like school zones or work zones, drivers in these areas can receive the alert in advance to avoid potential collision. In addition, signals along the route can be adjusted in real time to clear standing queues so that emergency vehicles can pass with minimum delay.

4.3.3 Partnership

State DOTs, including MassDOT, could serve as the lead agency and could engage various stakeholders in this project, including:

- **Freight carriers**: FedEx, UPS, and other carriers. Note that FedEx has a shipping center in Framingham, MA, and UPS has a freight center in Southborough, MA. Both centers are near the pilot corridor and generate a significant amount of freight traffic.
- **Transit authorities and carriers**: Metrowest Regional Transit Authority has buses running on Route 9, and regional transit operators, including Greyhound and Peter Pan, have inter-city bus lines across Route 9.
- **Auto manufacturers**: Audi.
- **Academic and consulting partners**: UMass Lowell will help to conduct the before-and-after study to evaluate the pilot project, and consulting partners will help to design, procure, and set up the hardware and software and other support systems.

4.3.4 Funding

This pilot project can leverage funding from existing federal sources, including the Accelerated Innovation Deployment (AID) Demonstration program, and the Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) program.

5 APPENDIX A: List of State Government Activities

A large number of studies have recently been funded by state DOTs to investigate the impacts of CAVs and the new roles for state DOTs so they can be prepared for such impacts in the near future. These studies are summarized in this Appendix.

A.1 Oregon

Oregon created an Oregon Intermodal Leadership Team CAV Initiative, aiming to "increase ODOT's (Oregon Department of Transportation) level of preparedness for an uncertain future" [*50*]. The objective of the CAV initiative was to help ODOT participate early in CAV deployment and to focus on aspects that will result in the maximum benefits for the state. The CAV team reached out to ODOT personnel and eventually developed a strategic framework titled "Oregon Connected and Automated Vehicles Strategic Framework."

The CAV team helped ODOT understand the technologies by placing "Oregon in the national conversation about connected and automated vehicles." This included having ODOT staff seize leadership roles on ASSHTO's subcommittees, participate in an NCHRP panel on CV deployment, and attend CAV-related conferences (e.g., ITS America and national symposium on vehicle automation).

The team was also involved in identifying CV applications with the greatest benefits to Oregon. Based on that, they identified three categories of applications and prioritized seven entries (**Figure 5.1** [*47*]):

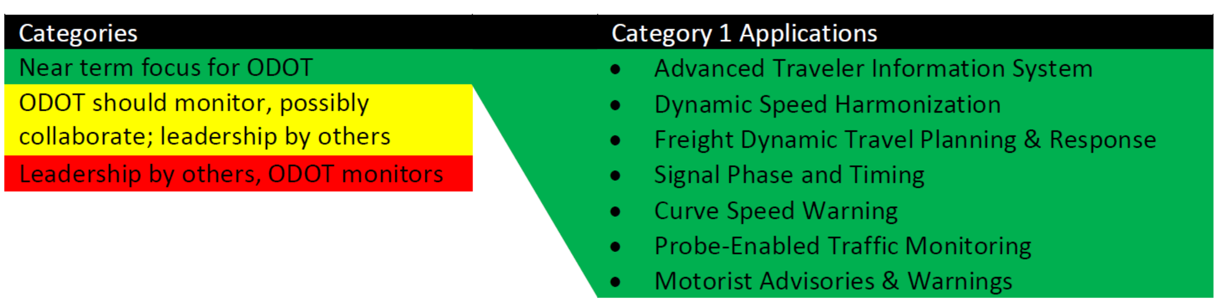

Figure 5.1: Categories of applications for CVs

Lastly, they also developed a "CAV Business Investment Map that identifies how ODOT can prepare for these emerging technologies" [*47*]. A detailed CV Application Roadmap was developed later in 2016 [*51*]. The initial CAV Business Investment Map consists of seven broad areas: "Transportation System Planning, Culture and Workforce Readiness, Transportation Data, Strategic Investment, System and Technology, Legal and Regulatory Implementation, and Collaboration" [*47*]. To help implement and adopt CAVs at ODOT, the team included three elements in a proposed strategic framework: a CAV business investment map, a policy advisor, and a steering team.

A.2 Texas

In a research project titled "Preparing Texas' Road Map for Automated and Connected Vehicle Deployment" [*52*],Texas Department of Transportation (TxDOT) examined the question of "What strategies can transportation agencies begin implementing to help them function effectively regardless of what the future brings?" [*49*] for state and local agencies in general (not specific to Texas). It considered two scenarios for future AV and CV deployments—evolutionary and revolutionary—and interviewed representatives from state DOTs (representing over 15 states) and staff from different regions and cities. In the end, the project recommended a list of robust strategies to prepare agencies for future deployments, regardless of the future scenarios.

This project resulted in some key takeaways that will be useful for other states as well:

- Two scenarios for future AV and CV deployments considered: the "revolutionary" path and the "evolutionary" path:
    - "Revolutionary path: Automotive manufacturers (OEMs) and suppliers make aggressive and substantial R&D investments that accelerate progress in AV and V2V technologies; federal and state policies do not hinder development to reach significant numbers of fully self-driving vehicles on roads by 2025" [*49*].
    - "Evolutionary path: OEMs and suppliers achieve step-wise improvements in advanced driver assistance systems. However, making the leaps from Level 2 to Level 3 automation, and then Level 3 to Level 4, proves very challenging even for technology firms like Google. This slows deployment even for the less complex driving environments such as limited access highways or simpler applications like truck platooning, and it delays reaching significant numbers of fully self-driving vehicles on roads to 2050." [*49*]
- A slight majority of state DOT interviewees believed the evolutionary path is more likely and also preferred, while most local and regional agencies favored a revolutionary path and expected more financial resources.
- State and local agencies surveyed had the following expectations on AV/CV deployments: (1) CV: "more like the ITS model of implementation; public sector has more responsibility and control"; (2) AV: "AV technology deployment—whether evolutionary or revolutionary—is driven by the OEMs and the technology firms"; and (3) uncertainties: "There was uncertainty about if and how V2I would deploy mainly because of the cost implementation." [*49*]
- The robust strategies for states to prepare for future deployments regardless of the future scenarios include "a review of legislation and policies in place that could potentially impact the implementation of AV/CV technologies," and "the establishment of an internal group made up of people in affected groups across the transportation agency organization in order to develop a strategic plan or roadmap for implementation." [*49*]

Texas also created an Accelerate Texas Center, which was a public-private collaboration aiming to make Texas the leader in the commercialization of CAV technologies.

In 2016 alone, TxDOT funded nine projects directly related to CAV:

1. TxDOT 0-6836: Commercial Truck Platooning [*53*]
2. TxDOT 0-6838: Bringing Smart Transport to Texans: Ensuring the Benefits of a Connected and Autonomous Transport System in Texas [*54*]
3. TxDOT 0-6845: Guidelines on CV Networking Information Flow Optimization for Texas [*55*]
4. TxDOT 0-6847: An Assessment of Autonomous Vehicles: Traffic Impacts and Infrastructure Needs [*56*]
5. TxDOT 0-6848: Transportation Planning Implications of Automated/Connected Vehicles on Texas Highways [*57*]
6. TxDOT 0-6849: Implications of Automated Vehicles on Safety, Design and Operation of the Texas Highway System [*58*]
7. TxDOT 0-6867: Wrong-Way Driving Connected Vehicle Demonstration [*59*]
8. TxDOT 0-6875: Autonomous and Connected Vehicle Test Bed to Improve Transit, Bicycle, and Pedestrian Safety [*60*]
9. TxDOT 0-6877: Communications and Radar-Supported Transportation Operations and Planning (CAR-STOP) [*61*]

In the "Commercial Truck Platooning" project, TxDOT aimed to gain full understanding of the technical, operational, and legislative challenges for implementing truck platooning through system design, development, implementation, data collection, and engineering analysis. TxDOT also plans to investigate strategies to mitigate risks involved in truck platooning, and to identify truck platooning scenarios that are technically and economically sound and can be legally implemented on Texas highways The final results of this project include identifying two potential corridors for truck platooning implementation and the demonstration of platooning using two commercial trucks. In addition to this project, TxDOT also funded several CAV studies that are focused on very specific safety topics, including wrong-way driving warning [*56*], improving transit, bicycle, and pedestrian safety [57], and collision avoidance with radar [*58*].

In the project entitled, "Bringing Smart Transport to Texans: Ensuring the Benefits of a Connected and Autonomous Transport System in Texas," the authors conducted a comprehensive study of CAVs and their impacts. It covered CAV related policies, public opinions, simulation of transportation network dynamics with CAVs, CAV-enabled micro-tolling, safety and environmental benefits, impacts on regional transportation planning, potential applications in various areas, two technology demonstrations, economic impact analysis, and concepts of operations. In the end, the authors concluded that there was much uncertainty in the federal and state laws regarding CAV adoption.

They suggested that TxDOT should:

- "Create a single agency point person, situated within TxDOT, who has authority and credibility to coordinate among various state and local agencies within Texas. This would also assist in 'preparing government' for the transition to this new driving paradigm.

- Set standards for testing and development of CAVs.
- Legally define the "operator" of a CAV.
- Establish rules for intensive use of truck platooning.
- Address privacy and security questions stemming from CAV use.
- Answer liability questions that arise from CAV adoption.
- Advance broader public goals in CAV innovation." [*51*]

The authors also provided specific short-, medium-, and long-term practice recommendations to TxDOT.

In the project entitled "Guidelines on CV Networking Information Flow Optimization for Texas," DSRC and LTE technologies were compared. The author further investigated the security challenges faced by connected vehicles. At the end, a CV-enabled variable speed limit case study was conducted.

In "An Assessment of Autonomous Vehicles: Traffic Impacts and Infrastructure Needs," the authors discussed the driving forces, barriers, mainstream adoption, traffic impact, and infrastructure needs of CAVs. They included an extensive survey to forecast the adoption of CAVs. Although infrastructure needs are highlighted in the title of this report, this study mainly focused on the traffic impacts of CAV, including the impacts on planning, link and node traffic models, microscopic simulation, and shared mobility.

In "Transportation Planning Implications of Automated/Connected Vehicles on Texas Highways," the authors first summarized the current and future states of CAVs.

Following that, they investigated the impacts of CAVs on transportation planning from four perspectives:

- **Personal Travel Behavior**: shared mobility, vehicle ownership, trip length, urban form, etc.
- **Freight Transportation**: driver availability/hours of service, automation in freight logistics, etc.
- **Travel Forecasting**: changes in vehicle miles traveled, mode shift, etc.
- **Transportation Planning Process**

In "Implications of Connected and Automated Vehicles on the Safety and Operations of Roadway Networks," the authors discussed the national and Texas opinions on CAV technologies. They included separate sections on the safety, operational, emission, and planning implications of CAVs. The authors focused on discussing the safety strategies that TxDOT should take to fully embrace the benefits of CAV.

At the end, the authors provided short-, medium-, and long-term best strategy and practice recommendations to TxDOT for adopting CAV. The recommended strategies are:

- **Short-term**: Fixing pavement markings and traffic signs in poor conditions and developing legislative policies on CAVs.

- **Medium-term**: Providing scheduled construction activity information to CAVs, creating CAV-only lanes and nighttime safety rules for CAVs, regulating empty CAV driving, updating roadway design manuals, and exploring CAV-enabled tolling and travel demand management strategies.
- **Long-term**: Updating roadway design and maintenance standards to accommodate CAVs and automated construction and maintenance vehicles, upgrading rural infrastructure for CAVs, and smart intersection traffic control.

A.3 Pennsylvania

The Pennsylvania Department of Transportation (PennDOT) has created a CAV Working Group, consisting of multiple stakeholders. In 2014, the CAV working group developed a "Connected and Autonomous Vehicles 2040 Vision to assess the implications of CAV on the management and operation of the state's surface transportation system." It "evaluated the implications on highway infrastructure within the Pittsburgh region," "explored the impacts of CAV on several aspects related to PennDOT," and created a timeline for action items and recommendations. Currently, the group is working toward the development of a Connected/Automated Vehicle Strategic Plan for Pennsylvania [*62*].

In December 2016, the PennDOT Autonomous Vehicle Policy Task Force published an Autonomous Vehicle Testing Policy [*63*].

This document covers six main policy topics:

- **Minimum approval for Highly Automated Vehicles (HAV) testers**: This describes the minimum qualifications an HAV tester has to demonstrate in order to test HAVs on Pennsylvania highways.
- **Who is the driver?** This policy defines who the driver is and how to determine the driver's liability when an accident happens.
- **Operation of HAVs**: This policy describes when, where, and under what circumstances HAVs can be tested.
- **Vehicle characteristics, capabilities, and security:** This policy defines the minimum requirements that an HAV has to meet in order to be tested on Pennsylvania highways.
- **Data collection:** This policy defines what data can and should be collected.
- **Testing approval and renewal:** This policy describes the procedure to review and approve a HAV on-road test request, to ensure that all PennDOT concerns are properly addressed and the approval process will not be unnecessarily long.

A.4 Florida

In 2012, Florida passed laws to allow testing AVs on public roads, which made Florida the second state to do so. These laws were further updated in 2016. Currently in Florida, vehicle manufacturers are not liable for the damage or injuries that are attributed to the conversion from a regular vehicle into an autonomous vehicle by the owner. In addition, Florida legislation requires the Florida Department of Transportation (FDOT) and Department of Highway Safety and Motor Vehicles to study the safety and operation of truck platooning technology.

The Florida Transportation Secretary has established an FDOT AV/CV/ITS Steering Committee to coordinate and provide leadership direction over FDOT's AV/CV/ITS initiatives. The committee is responsible for developing a strategic plan, drafting design standards for major infrastructure investments, initiating additional testing facilities, forming new non-traditional partnerships, and prioritizing investment locations. Since 2016, AV/CVs are included in all state planning documents.

Recently, FDOT has funded the following studies on CAV [*64*]:

- Florida State University: Enhanced Mobility for Aging Population Using Automated Vehicles
- University of Florida: Surveying Florida MPO Readiness to Incorporate Innovative Technologies into LRTPs
- Embry-Riddle Aeronautical University: Autonomous Service Vehicle Project
- Florida Atlantic University: Unmanned Surface Vessel (USV) Systems for Bridge Inspection
- Florida State University: Envisioning Florida's Future: Transportation and Land Use in an Automated Vehicle World
- University of Central Florida: Investigation of Connected Vehicles to Inform Design of Automated Vehicle Systems
- Bishop Consulting/HNTB: Applications of Connected-Automated Vehicles for Movement of Freight

A.5 Colorado

Colorado Department of Transportation (CDOT) proposed a RoadX plan [*65*]. Its vision was to have "crash-free, injury-free, delay-free and technologically transformed travel in Colorado" through public and industry partnerships. To achieve this goal, CDOT planned to invest $20 million each year during 2016 and 2017 in foundational technology projects. It also planned to reallocate CDOT's annual $1.4 billion budget to support technology projects. In November 2016, CDOT announced a partnership with Panasonic to build a Connected Transportation Program that provides V2V and V2I communications. This program is expected to provide critical safety data for generating safety warnings (e.g., low visibility, sun glare), mobility applications (e.g., smart truck parking, variable speed limits), road planning, and winter maintenance.

A.6 Michigan

The Michigan CAV technology strategic plan was developed in 2013 [*66*]. Michigan developed this plan to align the Michigan Department of Transportation's (MDOT) long-term plan with recent advances in technology and policy regarding CAVs, particularly the update on new technologies in digital cellular communications and vehicle-embedded automated systems. This is more at a planning level that outlines a strategic philosophy to guide specific programming directions and investment decisions. It consists of six strategic areas of focus: (1) leadership, (2) safety, (3) customer service, (4) partnership, (5) system linkages, and (6) efficiency. Michigan has other research and decision-support guidance on more specific areas, such as the MDOT ITS investment plan, connected vehicle info-structure plan, use of ITS technologies for transit and freight assets, mode-specific ITS strategies, and ethics of government use of ITS data.

Regarding the development of connected vehicles, Michigan focuses on five areas:

- **Infrastructure**: MDOT believes that "CV infrastructure investment is key to creating an environment supportive of V2I testing, and to understand the complexities of managing a large CV infrastructure deployment" [*67*]. The current infrastructure includes the connected vehicle environment (with vehicles equipped with communication devices), CV test beds, Tier 1 automotive suppliers, major OEM facilities, and MDOT roadway ITS coverage.
- **V2I applications**: MDOT focuses on V2I applications such as red light violation, road weather system, work zone warning and operations, and pavement condition monitoring. MDOT has been developing the truck parking information and management system using a $3 million federal TIGER (Transportation Investment Generating Economic Recovery) grant.
- **Data management**: MDOT has created the Data Use Analysis and Processing (DUAP) program.
- **Partnership**: The department aims to collect and fuse CV data from various sources.
- **Talent development**: MDOT focuses on training employees on various V2I applications.

Michigan conducted the Connected Vehicle Safety Pilot in 2012 and has maintained the test bed since the pilot. In addition, Michigan passed legislation for AVs in 2013, which allows the state to test prototype AVs on public roads, given that they are registered with a special license plate (M-plate) [*68*]. The Governor of Michigan, Rick Snyder, signed four laws related to AVs, which provide a framework for testing and deploying AV technologies. Notably, for M-plates, Michigan does not require a detailed description of technology; thus, the detailed testing activities are unknown. Michigan has issued M-plates to several companies to allow testing of AVs, including Autoliv Electronics America and Valeo.

Michigan created a CAV Working Group in 2016, with the mission to "cooperatively pursue projects and other activities that are best accomplished through partnerships between multiple agencies, companies, universities, and other organizations and that ultimately advance Michigan's leadership position in connected and automated vehicle research, deployment, and operations."

A 2016 report funded by Michigan Department of Transportation (MDOT) reviewed the international deployment efforts of CAVs [*69*]. In May 2017, MDOT announced a partnership with 3M [*70*] to modernize a 3-mile work zone on I-75 to accommodate connected and autonomous vehicles. With new all-weather pavement markings, retroreflective signs, and DSRC devices, the new work zone is intended to significantly improve the safety of both human drivers and CAVs.

A.7 Louisiana

Louisiana Department of Transportation and Development (LDOTD) recently sponsored two projects on CAV. In a report entitled, "Investigation into Legislative Action Needed to Accommodate the Future Safe Operation of Autonomous Vehicles in the State of Louisiana" [*71*], the authors reviewed CAV legislation status of different states. Based on their review, the authors summarized issues that should be considered in CAV legislation, which includes safety, public acceptance, progression, infrastructure, permit and license requirements, regulation, liability, cost, and platooning.

In the LDOTD report, it was concluded that "the review of bills and regulations related to autonomous vehicles developed by individual states show considerable similarity. The general format of the legislation is to define an autonomous vehicle, address who is responsible for issuing licenses to operate an autonomous vehicle, who is authorized to provide training to operate an autonomous vehicle, what facilities may be used to operate autonomous vehicles on and what weather conditions (if any) should prevail while autonomous vehicles are operated, and whether certified operators are restricted to testing vehicles or permission is granted to operate autonomous vehicles for general purposes. They also generally include the necessity to report any crashes or malfunctions, require that an event recording device be installed in the vehicle, that an operator be present in the vehicle and be able to regain control of the vehicle at all times, and that liability insurance of $5M be provided for each vehicle tested on public roads." [*68*]

In the "Louisiana Statewide ITS Architecture" [*72*] published in 2016, the authors recommended that both vehicle connectivity and automation technologies be continuously developed and refined. The role of LDOTD in autonomous vehicle development and implementation is undetermined and depends on what kind of technologies will eventually be used for autonomous vehicle operations (e.g., machine vision, digital mapping).

For connected vehicles, the authors suggested that LDOTD should focus on:

- Data capture and sharing (broadcast, multicast, and unicast)
- Security and credentialing management system
- Compatibility and interoperability with on-board equipment
- Performance measures

In May 2017, LDOTD announced a $2 million multi-year contract [*73*] to investigate the impacts of CAVs and to develop a strategic plan for CAV implementation.

A.8 Rhode Island

Together with the World Road Association (WRA), Rhode Island Department of Transportation (RIDOT) cohosted an international forum on CAVs in April 2017 [*74*]. This forum focused on the impacts of CAVs on future highway and urban planning and design.

In June 2017, RDOT announced a request for information [*75*] to seek technical support in the following areas related to CAV:

- "Opportunities for partnerships
- Impact on the state's capital planning and execution process
- Regional safety programs (including law enforcement and security)
- Environmental conditions
- State laws and regulation
- Workforce and professional training needs within the state" [*72*]

A.9 Nevada

Nevada was the first state that passed legislation to permit on-road AV testing. In September 2016, Nevada issued the nation's first AV driver's license [*76*].

In November 2016, Nevada DOT (NDOT) initiated a project to establish a CAV policy framework, which covers the following activities [*77*]:

- "Leveraging state infrastructure and real estate to further promote CAV testing and ultimate ubiquity in Nevada.
- Promoting collaborative policies, standards, and programs to highlight CAV innovations that expand economic growth and create jobs in Nevada.
- Identifying, vetting, and forming private sector partnerships where capabilities and offerings can be used to enhance CAV initiatives.
- Identifying an "innovation incubator" between public and private sector partners that explores and nurtures new ideas and companies focused on CAV.
- Expanding transportation innovation and connecting Nevada's residents through advanced mobility options.
- Modernizing and improving freight mobility throughout Nevada and its neighboring states.
- Connecting Nevada through smart infrastructure and using transportation as the launching point for Smart Cities, Smart Regions, and Smart States." [*74*]

A.10 Maryland

Maryland established an Autonomous and Connected Vehicle Working Group [*78*] in 2015 to coordinate the development and deployment of CAVs. The group consists of a policy subcommittee and a technical subcommittee. The policy subcommittee focuses on policy and legislative issues, while the technical subcommittee oversees technical, operational, and testing issues. Members of the working group include elected officials, representatives from relevant state and local agencies, traffic safety organizations, as well as private sector stakeholders (e.g., from the automotive industry). Maryland welcomes companies to test CAVs and has created a one-stop shop for interested companies.

A.11 North Carolina

In 2016, the North Carolina Department of Transportation (NCDOT) formed a steering committee [*79*] to investigate the impacts of CAVs with stakeholders from Department of Motor Vehicles, Governor's Highway Safety Program (GHSP), NC Department of Health and Human Services, Department of Insurance, Attorney General's Office, Universities, Trucking Association, Manufacturers, NC Division of Blind, Law Enforcement, and others. The main purpose of this committee is to review state laws and policies and identify what North Carolina needs to do in order to be prepared for the future transportation with CAVs.

Two key objectives of this committee are:

- Assess the state's conditions for CAV testing and operations, which include:
  - Vehicle code
  - Liability/tort
  - Road owner operations and maintenance
  - Surface transportation planning
  - University research and development
  - Industrial research, development, and collaboration
  - Regional (e.g., multi-state) coalitions and efforts
- Recommend action items to state agencies and other stakeholders and identify issues that may impact North Carolina's readiness for autonomous vehicle testing and deployment.

A.12 Minnesota

The Minnesota Department of Transportation (MnDOT) has been focusing on the following areas of CAV research: snowplow operation, work zone, traveler information, and transit [*80*]. In a recent study, MnDOT is exploring the use of autonomous buses in cold weather [*81*]. Phase 1 of this project started in February 2017, which is mainly focused on defining the project scope, performing preliminary study, and soliciting partners. Phase 2 will be a controlled demonstration of autonomous bus to identify risks and challenges in future deployments.

A.13 Virginia

The Virginia Department of Transportation (VDOT) established the Virginia Connected Corridor in 2014, which deployed CV technologies along I-66, I-495, US-29, and US-50. In addition, VDOT's FY16 Business Plan called for the development of a statewide connected vehicle program plan to "develop a statewide connected vehicle program plan to maximize the safety and operational benefits of these emerging technologies" [*82*].

Regarding automated vehicles, Virginia Gov. Terry McAuliffe made a 2015 Governor's Proclamation that "allows the testing of any automated vehicle on Virginia roads under the guidance of the Virginia Tech Transportation Institute (VTTI). The Virginia Department of Motor Vehicles (DMV) will support research efforts performed by VTTI in accordance with the proclamation" [*83*]. Responding to the proclamation, the Virginia Automated Corridors initiative was created, aiming to "provide an automation-friendly environment that government agencies, original equipment manufacturers, and suppliers can use to test and certify their systems, providing a system migration path from test-track to real-world operating environments." An Automated Vehicle demo was held October 19–20, 2015 [*84*]. The Virginia Automated Corridors initiative is a partnership between VDOT, DMV, HERE (a high-definition mapping business), Transurban, and VTTI (the lead).

Currently, VDOT is developing the "Virginia Automated Strategic Plan", which is expected to be finalized in August 2017 [*85*]. The purpose is "to create a strategic policy framework for transitioning autonomous vehicles into the Virginia transportation network, and associated Autonomous Vehicle program, by which [the] Office of the Secretary can position Virginia to be a national leader in the rapidly advancing field of self-driving, connected mobility." The primary focus of the plan is to develop "a set of robust strategies for implementation in near-term (now), mid-term (within three years), and longer term (between five and seven years)," each of which has a clearly defined owner, supporting agencies, performance measurements, and timeline.

A.14 Utah

Utah Department of Transportation (UDOT) completed a CAV study [*86*] in October 2016. In the report entitled "Best Practices for Regulation of Autonomous Vehicles on Utah Highways," the authors concluded that as the CAV technologies continue to evolve rapidly, it might be premature to pass any laws or implement new policies now. However, they recommended that a committee should be formed to consider the following issues related to CAVs: vehicle safety, data and personal security, infrastructure preparation, training and licensing, vehicle registration, enforcement, and regional and national consistency.

Additionally, the authors recommended that some policy issues should also be investigated, including:

- Should Utah consider leveraging CAV growth for economic development a high priority?

- Should Utah take a conservative approach and learn from other states' experience of implementing CAV?

A.15 Indiana

Indiana recently hosted its 2017 Indiana Connected and Autonomous Vehicle Summit [*87*].

The Indiana Department of Transportation (INDOT) has two ongoing CAV projects and two planned projects [*88*]:

- "Strategic and Tactical Guidance for the Connected & Autonomous Vehicle Future" (to be completed in June 2018).
- "Synthesis of Autonomous Vehicle Legislation" (to be completed in December 2017).
- "Autonomous Vehicle Test Track Feasibility Study" (planned): To study the feasibility of a test track to stimulate AV related technology and economic development opportunities.
- "Connected Corridor Implementation" (planned): To test CAVs on US-31 and US-30.

A.16 Ohio

Ohio has been investing heavily in CAVs. In November 2016, Ohio announced a $15 million plan to turn a 35-mile segment of US-33 near Columbus into a "Smart Mobility Corridor" [*89*]. In the same month, Otto, an autonomous truck developer, tested its self-driving truck on this US-33 segment. As the winner [*90*] of the 2016 USDOT Smart City Challenge, Ohio will obtain around $140 million from the USDOT, Paul G. Allen's Vulcan Inc., and other private partners for the proposed smart city plan. With smart mobility being a central part of this Smart City Challenge award, the Smart Mobility Corridor and the USDOT Smart City Challenge projects will complement each other.

On top of these efforts, Ohio has formed a Smart Belt Coalition with Pennsylvania and Michigan in January 2017, involving both public and private sector partners. One focus area of this coalition is commercial freight automation (e.g., truck platooning) [*91*].

A.17 Georgia

Not much information related to CAV has been identified for Georgia through this literature review. One notable item is that Georgia passed a law in May 2017 to allow self-driving cars with proper insurance and registration to drive on Georgia roads [*92*]. Outside of state efforts, the City of Atlanta is planning a smart corridor [*93*] near its midtown to facilitate CAV research, testing, and deployment, according to an October 2016, news article. This smart corridor will connect vehicles with traffic lights, various traffic sensors, parking meters, etc.

6 APPENDIX B: Pilot Test Sites and Implementation Issues

There is a growing number of test sites for connected, autonomous, and automated vehicles in the United States, as well as abroad. Some of these sites are operational, but many are still in the development phase. The following section describes several of these sites.

B.1 Connected Vehicle Testbeds

The USDOT has established a number of connected vehicle testbeds in Southeast Michigan, California, New York, and elsewhere. These testbeds are available to DSRC technology and application developers. As of November 2016, the USDOT had 87 agreements with public, private, and academic organizations.

The testbeds can provide the following applications:

- Signal Phase and Timing (SPaT).
- Geometric Intersection Description (GID) data broadcast.
- Available vehicle awareness devices (VADs), aftermarket safety devices (ASDs), in-vehicle safety devices (ISDs), and roadside units (RSUs).
- USDOT preliminary Security Credentials Management System (SCMS).

Additionally, the USDOT funded three sites. Three sites have been selected to design, deploy, and conduct preliminary tests: Wyoming, New York City, and Tampa. These three sites have significantly different characteristics, aiming to cover a different range of issues for the successful deployment of CVs using a variety of V2V and V2I applications [*21*].

B.1.1 Wyoming (WYDOT Pilot)

The Wyoming pilot will be deployed along I-80 (see **Figure 6.1**), a heavily trafficked freight corridor, at multiple points across the state. The primary goal is to improve safety and reduce delays caused by adverse weather-related incidents. About 75 RSUs (with receiving and broadcasting capability) will be deployed. This project will also equip a 400-vehicle fleet with OBUs. The fleet will have at least 150 heavy trucks that will regularly use I-80, and 100 WYDOT fleet vehicles, snowplows, and highway patrol vehicles. The WYDOT pilot will emphasize “DSRC for advisories, roadside alerts, parking notifications, and dynamic travel guidance to commercial and fleet vehicles.” [*94*]

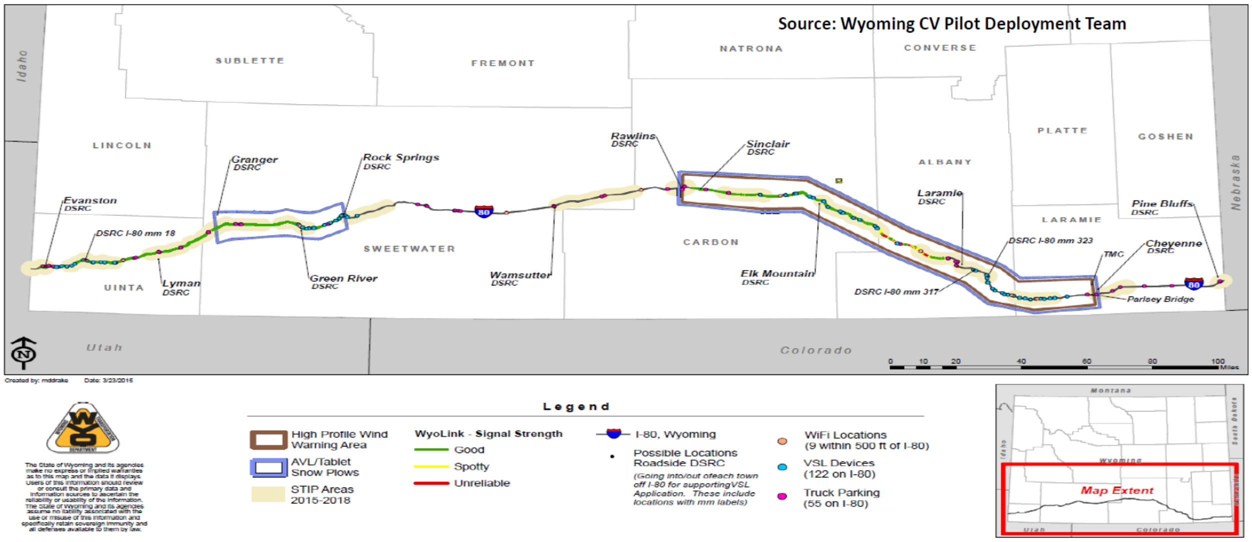

Figure 6.1: Wyoming I-80 Corridor—connected vehicle map [*94*]

B.1.2 New York City (NYCDOT Pilot)

The NYCDOT pilot mainly aims to improve safety and mobility of travelers through CV technologies. It will deploy V2V technology in Midtown Manhattan (in up to 8,000 vehicles) and V2I technology along arterials with high accident rate.

The NYCDOT CV Pilot involves three distinct areas in Manhattan and Brooklyn (see **Figure 6.2**). It will deploy CV technology in about 5,800 cabs, 1,250 MTA buses, 400 commercial delivery trucks, and 500 city vehicles. NYCDOT will equip 310 signalized intersections with V2I technology via DSRC, install 8 RSUs on FDR Drive (to test applications for short-radius curves, weight limit, and minimum bridge clearance), and install 36 RSUs strategically to enable system management functions. The pilot also aims to reduce vehicle-pedestrian conflicts, which will deploy in-vehicle pedestrian warnings and equip pedestrians with personal devices to improve the safety of street crossing. [*95*]

Figure 6.2: New York City pilot deployment site map

B.1.3 Tampa (THEA Pilot)

The THEA pilot focuses on a variety of CV applications, including relieving congestion, reducing collisions, preventing wrong-way entry at the reversible express lanes (REL) exit, enhancing pedestrian safety, and reducing conflicts between streetcars, pedestrians, and passenger cars. The THEA CV Pilot will deploy DSRC to enable the V2V/V2I applications for "1,600 cars, 10 buses, 10 trolleys, 500 pedestrians (through smartphone), and approximately 40 RSUs" [*96*]. See **Figure 6.3** for a map of the CV Pilot deployment.

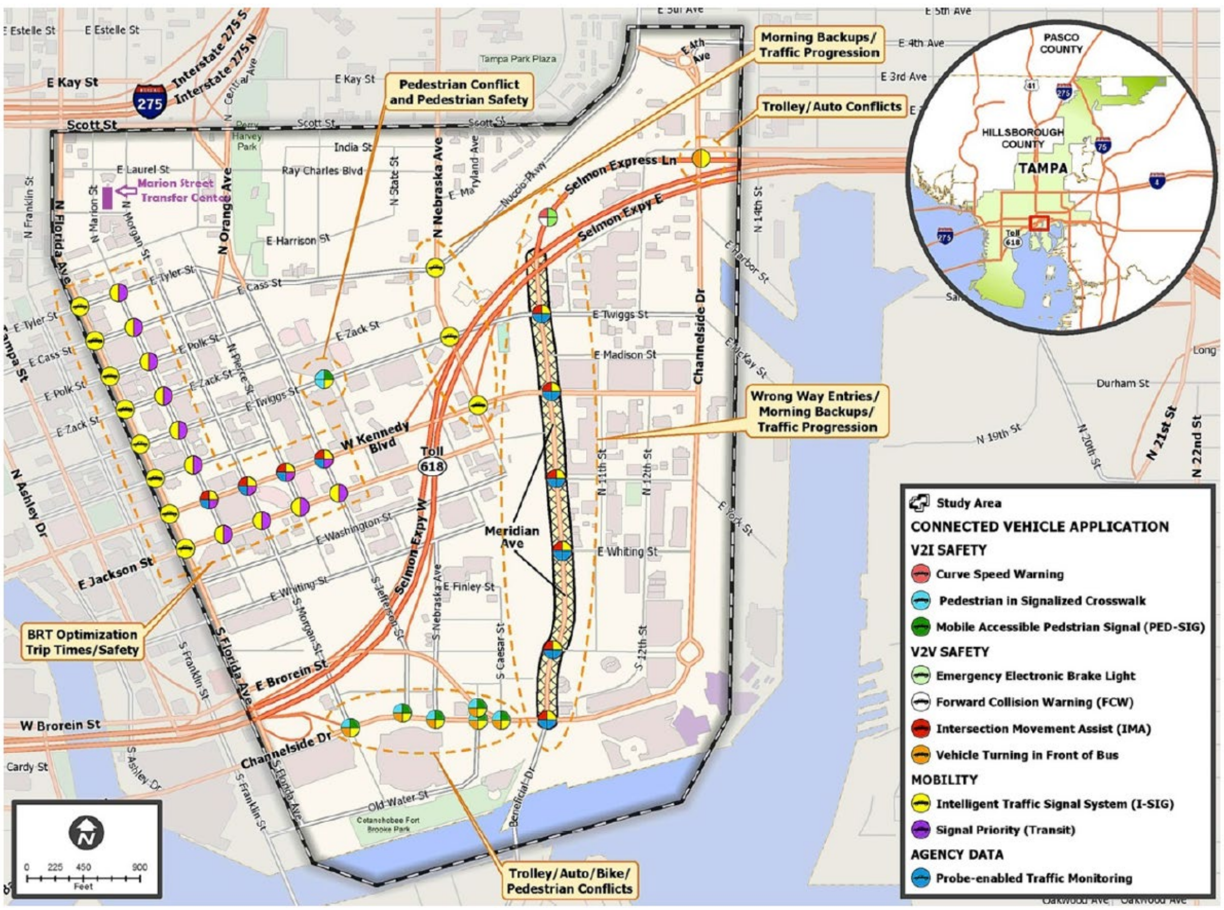

Figure 6.3: Connected Vehicle Pilot deployment—Downtown Tampa [*96*]

B.2 The Smart City Challenge

The Smart City was initiated by USDOT. It awarded $40 million to Columbus, OH. Columbus proposed to equip buses and public safety vehicles with DSRC for signal priority and deploy a fleet of "last-mile" automated transit vehicles equipped with DSRC as well [*97*].

B.3 Automated Vehicle Testbeds

In addition to the connected vehicles, automated vehicle technologies are emphasized in the "USDOT ITS Strategic Plan." NHTSA provided an extensive "Federal Automated Vehicles Policy" document in September 2016 [*98*]. Though still uncertain, the document suggests that NHTSA is seriously considering rulemaking related to AVs.

The USDOT has identified 10 sites as an automated vehicle proving ground pilot to "encourage testing and information sharing around automated vehicle technologies."

The 10 sites are: [*99*]

- City of Pittsburgh and the Thomas D. Larson Pennsylvania Transportation Institute
- Texas AV Proving Grounds Partnership
- U.S. Army Aberdeen Test Center
- American Center for Mobility (ACM) at Willow Run
- Contra Costa Transportation Authority (CCTA) and GoMentum Station
- San Diego Association of Governments
- Iowa City Area Development Group
- University of Wisconsin-Madison
- Central Florida Automated Vehicle Partners
- North Carolina Turnpike Authority

B.4 U.S. State and Local Efforts

Besides the test beds and proving grounds supported by the USDOT, a growing number of states and large metropolitan areas participate in public-private partnerships for the development of connected and automated vehicle technologies. Some examples of these partnerships are listed as follows.

B.4.1 Michigan Connected Vehicle Environment

Southeast Michigan started DSRC testing in 2007. It has over 100 RSUs installed [*100*]. The Michigan Connected Vehicle Environment consists of a couple projects, including the Southeast Michigan testbed (50 RSUs in multiple locations in Oakland County and 17 RSUs in downtown Detroit [*101*]), and the Ann-Arbor Connected Vehicle Environment (this project has collected data from over 2,800 vehicles and 25 RSUs). With the support of USDOT, it is transitioning to be a connected and eventually automated vehicle environment [*102*]) and American Center for Mobility (a decommissioned General Motors plant converted into a CAV testing facility [*103*]).

B.4.2 Florida

In 2011, Florida created the Connected-Vehicle Test Bed in Orlando, which is a 25-mile roadway on I-4. In addition, Florida has conducted a number of pilot projects (without deployment) on CAVs, which were under the Florida Automated Vehicles (FAV) program, aiming to help "educate the public by engaging stakeholders, developing research and pilot projects, and creating awareness of the technologies and how they support FDOT's vision statement" [*104*].

B.4.3 Ohio Smart Mobility Corridor

The Ohio Department of Transportation (ODOT) will install high-capacity fiber optic cable on a 34-mile US 33 segment to link researchers and traffic monitors with data from embedded and wireless sensors. It will also conduct autonomous vehicle research by upgrading the facilities [*105*].

B.4.4 Pennsylvania

PennDOT is involved in the development of two testbeds that have been equipped with DSRC: the CMU Cranberry Township (11 signals) and Pittsburgh (24 signals) testbed; and the ongoing PennDOT Ross Township testbed "to deploy innovative technologies, including adaptive traffic control signals and DSRC." This is funded through an FHWA Accelerated Innovations Deployment (AID) grant [*106*].

B.4.5 Texas

TxDOT funded an I-35 Connected Work Zone (CWZ) project, which expanded existing I-35 traveler information to include in-vehicle messages for commercial vehicles. Texas also has several CV demonstrations, including over-height vehicle detection and warning, and enhancing work zone safety with connected automation. In addition, TxDOT has sponsored a number of research projects to understand, plan, and demonstrate the applications of connected vehicle technologies.

B.4.6 City of Boston

The Cambridge, MA-based startup NuTonomy is testing autonomous vehicles in the Seaport District and Fort Point (see **Figure 6.4**). Tests will first take place in daytime and fair weather conditions and will gradually include nighttime and other conditions [*107*]. Optimus Ride has also been testing their driverless vehicles in Raymond L. Flynn Marine Park [*108*].

Figure 6.4: Autonomous vehicle testing area for NuTonomy vehicles in Boston

B.5 Europe

The European Commission has established a Cooperative Intelligent Transportation Systems (C-ITS) platform [*109*] to create a common vision on CAVs across the European Union. The role of C-ITS is to coordinate several complementary efforts for connected and automated vehicles deployment, to address legal, organizational, administrative, technical and implementation issues. It created a trans-European transport network (TEN-T) in 2013, which set a framework for CAV development until 2030 [*110*]. Additionally, a CAV working group has been created to advise the commission on potential regulatory actions and investments of CAV [*111*]. Currently there are a number of sites spread throughout the EU designated for the deployment of CV/AV technologies. These include the following.

B.5.1 The Austria/Germany/Netherlands C-ITS ECo-AT Corridor

A corridor starting from Rotterdam to Frankfurt and ending at Vienna will be used to phase in various ITS applications over time. In the first phase of the project, there are two initial applications implemented, due to their expected early impact, even with low penetration of technology: (a) road work warning and (b) traffic management by exploiting probe data [*112*].

B.5.2 France

There are two initiatives in France for the deployment of CAVs: the SCOOP@F project and the NAVLY project.

- The SCOOP@F project plans to equip 3,000 with V2X capability and deploy RSUs along 2,000 km of roads. The V2X will be used to detect and share events like wheel-slip and

emergency braking maneuvers. Also, road operators can send warnings to drivers via V2I communications. Phase 2 will span from 2016 to 2018, which involves Austria, Spain, and Portugal [*113*].
- The NAVLY Pilot: The transit operator of the city of Lyon, KEOLIS, in partnership with Navya, launched the Navly service to experiment with automated electric public transit [*114*].

B.5.3 Germany A9 Motorway Test bed

The Digital Motorway Test Bed is on the A9 federal motorway between Munich and Nuremberg and enables the automotive industry, suppliers, the telecommunication and software industries, and research centers to field test their systems under development in mixed traffic. The focus is on automated driving, C2X communications and sensor technologies, high-precision digital maps and real-time communications, and road equipment for the determination of vehicle position on the motorway [*115, 116*].

B.5.4 Switzerland

PostBus has partnered with École Polytechnique Fédérale de Lausanne to test two Navya automated shuttles. The test is on a fixed route in public areas but at low speed (up to 12 mph) [*117*].

B.5.5 NordicWay

As part of C-ITS, NordicWay is a corridor across Finland, Sweden, Norway, and Denmark. The project will focus on testing cellular 3G and 4G/LTE communication, which is to involve 2,000 vehicles. It will explore applications of safety-related traffic information and others enabled by probe-vehicle data [*118*].

B.5.6 Netherlands

There are two pilot projects in the Netherlands:

- A 2-km public roadway in Helmond is instrumented for real-world testing [*119*].
- The town of Wageningen used EasyMile EZ10 self-driving mini-buses to shuttle passengers between Wageningen University and the Ede-Wageningen railway station. The WEpods were taking passengers by invitation. This project concluded at the end of 2016 [*120*].

B.5.7 United Kingdom

The UK Department for Transport began allowing the testing of driverless vehicles in 2015 [*121*].

Three deployment-pilot projects are currently ongoing:

- GATEway: In Greenwich, this project plans to test and validate different use cases, including driverless shuttles and automated urban deliveries [*122*].

- UKAutodrive: Deployed in the towns of Milton Keynes and Coventry to demonstrate CAV technologies [*123*].
- **UK Venturer**: Will focus on the interactions between driving automation systems and their human users (e.g., the "hand-over" process) [*124*].

B.5.8 Finland

The SOHJOA Easymile trial project deployed two EZ10 shuttles on public roads in Helsinki with low volume and pedestrians [*125*].

B.5.9 Sweden

Volvo is working with the City of Gothenburg, Sweden, to deploy 100 automated vehicles (Volvo XC90s Volvo's "IntelliSafe Autopilot" automated driving system) operating on public roads in Gothenburg [*126*].

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