Connected and Automated Vehicles Investment and Smart Infrastructure in Tennessee

Research Final Report from University of Tennessee | Asad Khattak, Iman Mahdinia, & Mina Sartipi | May 30, 2022

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This project has developed a series of five (5) reports that support intelligent mobility strategies, which are critical to achieving economic development, safety, mobility, energy, environmental, and equity goals. These supplementary reports are available on the sponsoring agency's website.

16. Abstract
Sponsored by the Tennessee Department of Transportation, this project aims to assist the State of Tennessee prepare for future intelligent mobility strategies that encompass connected and automated vehicles, electric vehicles, multimodal personal and freight movements, all done in a safe, secure, and equitable way. The project has developed a series of five (5) supplementary reports that support intelligent mobility strategies—critical to achieving economic development, safety, mobility, energy, environmental, and equity goals. Intelligent mobility is enabled by large-scale data, tools for transportation modeling and artificial intelligence, simulation and visualization, multi-scale connectivity, and high-performance computing. Partnerships between government agencies, industry, and academic institutions are deemed critical to successfully deploying intelligent mobility strategies, as is workforce development. To assess the value of intelligent mobility strategies in Tennessee, the supplementary reports provide a framework by exploring different focus areas, including physical infrastructure, digital/smart infrastructure, electric vehicles and charging infrastructure, policies and regulations, and associated public knowledge and acceptance. Specific topics covered in the reports and summarized below in this final report include fact-based research on readiness and investments in connected and automated vehicle technologies, infrastructure and vehicular communications, a review of smart corridor projects across the US, establishing an ecosystem for CAV data, data collection, data analytics, and simulations, and intelligent mobility readiness. The project informs policy and provides recommendations for TDOT on future developments of emerging technologies and contributes to the enhancement of intelligent mobility readiness in Tennessee.

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Table of Contents

List of Tables

List of Figures

Glossary of Key Terms and Acronyms

ARC-IT - Cooperative and Intelligent Transportation
AV – Automated Vehicle
BSM – Basic Safety Message
CACC - Cooperative Adaptive Cruise Control
CARLA - Car Learning to Act
CAV – Connected and Automated Vehicle
CDP - Connected Data Platform
CMAQ - Congestion Mitigation and Air Quality
CV – Connected Vehicle
C-V2X - Cellular Vehicle-to-Everything
DSRC - Dedicated Short-Range Communication
EV – Electric Vehicle
FCC – Federal Communication Commission
FHWA - Federal Highway Administration
HIP - Highway Infrastructure Program
HOV - High-Occupancy Vehicle
HSIP-Highway Safety Improvement Program
IIJA - Infrastructure Investment and Jobs Act
INC-ZONE - Incident Scene Work Zone Alerts for Drivers and Workers
IOOs - Infrastructure Owners and Operators
LED - Light-Emitting Diode
LTE – Long-Term Evolution
MA3T - Market Acceptance of Advanced Automotive Technologies
NHPP-National Highway Performance Program
OBU – Onboard Unit
ODD - Operational Design Domain
OEMs - Original Equipment Manufacturers
ORNL - Oak Ridge National Laboratory
OTA - Over-The-Air
PROTECT - Promoting Resilient Operations for Transformative, Efficient, and Cost-saving Transportation
PVMS - Portable Variable Message Signs
Q-WARN - Queue Detection/Warning
RDS - Radar Detection System
RR - Refuge Roads
RSU – Roadside Unit
SCorE - Safe Corridor Enhancement
SPaT - Signal Phasing and Timing
SUMO - Simulation of Urban MObility
TDEC - Tennessee Department of Environment and Conservation
THEA-Tampa Hillsborough Expressway Authority
TIM - Traveler Information Message
TMC - Traffic Management Center

TVA - Tennessee Valley Authority
UM - University of Michigan
UTC - University of Tennessee at Chattanooga
US DOE - US Department of Energy
US DOT - US Department of Transportation
V2I - Vehicle-to-Infrastructure
V2V – Vehicle-to-Vehicle
V2X – Vehicle-to-Everything
WAS - Worker Alert System
WAVE - Wireless Access in Vehicular Environments

Chapter 1 Introduction

> *The goals of TDOT's smart infrastructure project are to provide:*
> - *A complete picture of relevant research, development, and deployment (RDD)*
> - *Discuss key research findings and investment opportunities*
> - *Provide recommendations for investments in intelligent mobility*

Transportation innovations captured through intelligent mobility strategies are critical to achieving economic development, safety, mobility, energy, environmental, and equity goals. Intelligent mobility is broadly defined to encompass connected and automated vehicles, electric vehicles, multimodal personal and freight movements, all done safely and securely. Intelligent mobility is enabled by large-scale data, tools for transportation modeling and artificial intelligence, simulation and visualization, multi-scale connectivity, and high-performance computing.

For the State of Tennessee, it is critical to assess investments in the future of intelligent mobility from a statewide perspective. In this regard, partnerships between government agencies, industry, and academic institutions are critical to the success of intelligent mobility strategies, as is workforce development (Figure 1-1). To assess intelligent mobility strategies in Tennessee, this and the accompanying supplementary reports provide a framework by exploring different focus areas, including physical infrastructure, digital/smart infrastructure, electric vehicles and charging infrastructure, policies and regulations, and associated public knowledge and acceptance. Tools that can support the diffusion of emerging technologies include engineering and planning approaches to solutions, large-scale data, modeling, simulation, visualization, and artificial intelligence. Specific topics covered in this and supplementary reports include readiness and investments in Connected and Automated Vehicle (CAV) technologies in Tennessee, infrastructure and vehicular communications, a review of smart corridor projects across the US, establishing an ecosystem for CAV data, data collection, data analytics, and simulations, and intelligent mobility readiness. Note that readiness assessment of intelligent mobility strategies is critical to move the needle, with participation by all stakeholders. The project provides recommendations for the Tennessee Department of Transportation (TDOT) on future developments of emerging technologies and enhancement of intelligent mobility readiness in Tennessee.

> *Establishing a secure cyber-physical ecosystem is critical, which also entails the collection, processing, management/storage, and harnessing of Connected and Automated Vehicle (V2X) communications data.*

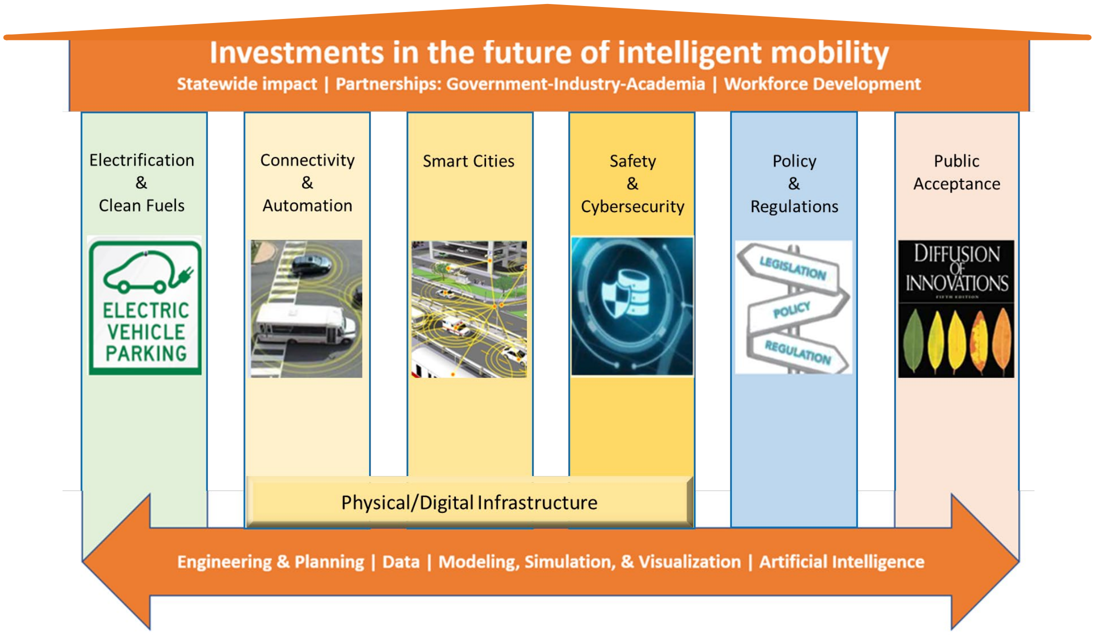

Figure 1-1 Components of investments in the future of intelligent mobility

1.1 Readiness and Investments in CAV Technologies in Tennessee

Connected and automated vehicles are increasingly diffusing through the transportation system. Characterized by Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications, CAVs can mitigate some of the problems that come with growth, including mobility in Tennessee (especially traffic congestion, costing an estimated $4.2 billion in 2020), safety (1,325 lives lost in 2021 and $25 billion annual economic cost and societal harm from crashes), and energy/environmental issues (with associated potential for non-conformity). CAV technologies can impact a wide range of transportation functions in public agencies. Specifically, several divisions of TDOT may be impacted, including Traffic Operations, Strategic Transportation Investments, Maintenance, Asset Management, Environmental, Long Range Planning, Multimodal Transportation Resources, and Occupational Health and Safety. Partners of TDOT may also be impacted, especially the infrastructure owners and operators (IOOs), which include public agencies working locally.

TDOT and IOOs, together, they can facilitate CAV deployment and operation through collaboration and enhanced readiness in terms of roadway infrastructure, digital infrastructure, and electric vehicle infrastructure. New regulations, policies, programs, and partnerships are needed to prepare TDOT for new forms of safe and reliable transportation. Specifically, research, development, and deployment of emerging technologies are critical going forward, as is the management and harnessing of big data from new sensors, e.g., communication of data between roadside units and onboard units. This research project is meant to support TDOT's future efforts in terms of readiness for emerging technologies, focusing on investments in smart infrastructure and intelligent mobility strategies. Baseline information is provided to assist with the development of future strategic plans that can guide TDOT in the deployment of CAV technologies, especially smart infrastructure enablers.

For more details about the readiness and investments in CAV technologies within Tennessee, please refer to the supplementary report “Readiness and Investments in Connected and Automated Vehicles Technologies in Tennessee: A Baseline” [1].

1.2 Infrastructure and Vehicular Communications

Using the five levels of automation suggested by the Society of Automotive Engineers and the US Department of Transportation (US DOT), the operation of higher-level CAVs is enabled by the exchange of data between smart infrastructure and equipped vehicles. A vehicle can also share data with other nearby vehicles. Dedicated short-range communication vehicle-to-everything (DSRC V2X) and cellular vehicle-to-everything (C-V2X) are two technologies used for very high-speed and high-frequency data transmission (up to 10 times per second with millisecond latency). These technologies can provide travel information, rear-end crash warnings, red-light running notices, slippery roadways, critical weather warnings, and curve speed alarms.

To support TDOT decisions on communications technologies, the research team has compared different standards for vehicle communications (DSRC V2X and C-V2X technologies) and explored the transition from DSRC V2X technology to C-V2X, given the relatively recent safety band ruling by the Federal Communications Commission (FCC). Furthermore, research is needed to test communications technology to ensure their safe operation. Notably, C-V2X and DSRC V2X technologies have similarities, including sharing similar information such as location, acceleration, and speed, utilizing a digital signature, and using the same message sets. However, they have several differences, such as different spatial coverage and ranges, latency and packet drop rates, and different communication beds based on their different chipsets. Generally, smart infrastructure deployment in the US will require a successful transition from DSRC V2X to C-V2X communications, especially with roadside units. This transition might be costly and needs substantial time and effort. Despite the advantages and disadvantages of the two technologies (DSRC V2X and C-V2X), comprehensive testing that compares their performance is limited. Moreover, one of the critical aspects of C-V2X technology that encouraged the industry to move forward with the transition to this technology is the compatibility of mobile phone technology and increasingly low latency for safety applications. However, as C-V2X communication technology has not been tested at a large scale, the technology currently has substantial uncertainty, which can be hedged by using dual-mode C-V2X/DSRC V2X devices.

For more details about Tennessee's infrastructure and vehicular communications, please refer to the supplementary report “Infrastructure and Vehicular communications: From Dedicated Short-Range Communications to Cellular Vehicle-to-Everything” [2].

1.3 Investments in Smart Corridor Projects

The themes of CAV and smart infrastructure are reflected in the development of smart corridors. These often entail installing advanced and emerging traffic management, traveler information, and automation/connectivity technologies within a highway corridor. The goals of smart corridors are to provide improved mobility, safety, and the environment by improving and balancing traffic demand on a stretch of freeway or expressway and parallel arterial streets. As such, they are focused on improving performance in a specific geographic context. The research team has reviewed smart corridor projects across the US that have implications for intelligent mobility in Tennessee. Steps for evaluating performance included network performance analysis, traveler behavior, vehicle trajectories, and interviews with stakeholders and institutional participants. Notably, real-world evaluations of smart corridors cannot be conducted with the precision of laboratory experiments. In conducting natural experiments, some compromises may be needed ranging from the details of data collection to the framing of mutually agreeable goals and objectives by stakeholders. It is critical to emphasize the importance of evaluation plans for real-world smart corridors and the practical issues that can arise, such as establishing and agreeing on a basis for comparison of before and after criteria, defining data collection methods for vehicle trajectory and basic safety message data, assuring impartiality, and enhancing cooperation among stakeholders. The evaluation experiences gained from reviewing relevant smart corridor literature have provided insight into how to conduct successful smart corridor implementation and evaluations in Tennessee.

For more detail about the investments in smart corridor projects in Tennessee, please refer to the “A review of smart corridor projects across the US with implications for intelligent mobility in Tennessee” supplementary report [3].

1.4 Ecosystem for Connected and Automated Vehicles Data

Intelligent mobility technologies' research, development, and deployment are essential for improving transportation performance. It is critically important for any state Department of Transportation to lay the foundation for the smart technology infrastructure ecosystem. The infrastructure includes supporting 1) roadside and onboard devices for connected vehicles and new sensors, 2) selection of context-relevant applications and user services, i.e., delivering transportation service packages that meet the needs of a community, have clear benefits, and their risks (of non-use) are well-managed, 3) installing roadside cameras and dynamic message signs, 4) deploying fiber for fast communication of data, and 5) installing traffic control device improvements. Importantly, establishing the appropriate cyber-physical ecosystem is critical, which also entails the collection, processing, management/storage, and harnessing of CAV (Vehicle-to-Everything-V2X) communications data. For the operation of connected vehicles, such data are continuously being transferred (streamed) between roadside units and onboard units. The research team has worked on supporting TDOT's future efforts in terms of readiness for data collection, data analysis, and the use of simulation for emerging CAV technologies. Focusing on investments in smart infrastructure and intelligent mobility, actions and activities needed for supporting the CAV data collection, data analysis, modeling, and simulation efforts are provided. These are meant to assist in deploying the entire cyber-physical ecosystem for CAV technologies and smart infrastructure.

For more detail about the Ecosystem for CAV Data, please refer to the supplementary report “Eco-system for Connected and Automated Vehicles: Investments in Data Collection, Analytics, and Simulations” [4].

1.5 Intelligent Mobility in Tennessee

This report and supplementary reports further cover several topics to assess intelligent mobility strategies in Tennessee. They include 1) an overview of intelligent mobility in Tennessee, 2) a business case for intelligent mobility strategies by predicting their benefits and impacts, 3) results of a readiness survey and assessment based on the focus areas defined in the framework, and 4) benchmarking of aspirational states in the US with regards to intelligent mobility strategies.

Note that the readiness assessment results are based on an extensive survey of TennSMART consortium members (https://tennsmart.org/) that included government agencies, private sector companies, and universities. This report provides detailed recommendations on intelligent mobility readiness.

For more detail about the Intelligent Mobility in Tennessee, please refer to the supplementary report "A comprehensive plan for Intelligent Mobility in Tennessee" [5].

Chapter 2 Findings

2.1 Readiness and Investments-CAV Technologies in Tennessee

The project deals with intelligent mobility strategies and readiness for a range of emerging technologies that include automated, connected, and electric vehicles in Tennessee.

A strategic plan that accommodates the deployment of CAVs and related investments in physical and digital/technology infrastructure is needed to accelerate the diffusion of emerging technologies. Emerging technologies also require electrical vehicle infrastructure, policy and regulation, and public acceptance. To this end, focus on readiness and deployment plans in different US states are reviewed and compared, i.e., the strategies that these states are following are compared with Tennessee's activities in CAVs. Strategies that can enhance vehicle-to-everything interactions, leverage Tennessee resources, and provide strategic directions based on a review of statewide CAV readiness plans include:

Identifying emerging technology opportunities. Specifically identifying opportunities for CAV-related Intelligent Transportation Systems (ITS) architecture service packages in Tennessee. The selection of service packages can start locally with use-cases and whether the service addresses the community's need, and the capabilities of relevant technology. Proper planning and engineering can avoid costly mistakes. For example, placing roadside communication equipment without consideration of specific services, staffing needs, and users (who require on-board units to benefit from the information) can potentially lead to unused equipment.

Leveraging Tennessee-based resources. Successful implementation of tactical and long-range plans that will require TDOT to rely on the diverse resources available in Tennessee. The key resources that can be leveraged include: 1) TDOT owned and operated roadways with diverse urban, suburban, and rural characteristics, 2) TDOT capabilities in terms of data systems that include RDS, RITIS, ETRIMS, traffic volume data (TNTIMES), incident data from the Smartway Central Software, and TDOT-supported traffic operations centers that collect, process and disseminate data using advanced technologies, 3) a regulatory environment that facilitates testing and on-road deployment of CAVs, e.g., see Tennessee Automated Vehicles Act, 4) research, development and testing capabilities, available at universities and the Oak Ridge National Laboratory (ORNL), and 5) presence of industry, especially automobile manufacturers and associated industries such as automotive suppliers.

2.2 Infrastructure and Vehicular communications

The key findings from a review of recent US DOT guidance on vehicular communication and the literature highlight the issues below. Notably, C-V2X communication technologies are not yet approved for use by the USDOT. Currently, DSRC V2X is the only approved communication protocol, with FCC is ruling it out for future use. This has created uncertainty about the adoption of a specific protocol for the future.

Transition to C-V2X technologies. Agencies throughout the US that have deployed DSRC V2X roadside units are now transitioning to C-V2X technologies, which nevertheless involves uncertainty given the complexities of procuring and installing the software and hardware. Furthermore, technology, equipment, standards, and uses for C-V2X are evolving and agencies have found the transition from DSRC V2X to C-V2X challenging. While the transition undertaken by TDOT can be done by working with vendors, indeed this involves more than swapping DSRC V2X devices with LTE C-V2X devices or installing dual-mode devices that can perform both DSRC V2X and C-V2X communications. Notably, these devices and associated software are still in their infancy, have limited availability through vendors, and entail several complicated steps, with associated uncertainties, according to a recent NCHRP report [6]. This transition will involve more time and resources.

Issues in C-V2X transition. Complicating the migration to C-V2X is TDOT's role in traffic signal operations and maintenance, which is limited to funding and designing/constructing traffic signals. However, local agencies (infrastructure owners and operators-IOOs) operate and maintain signals, and TDOT works and assists local agencies in the smooth operation of signals. Hence local agencies will work with TDOT to deploy, operate, and maintain C-V2X technology. A further complication comes from LTE C-V2X interference from unlicensed devices and channel congestion, adversely affecting safety-critical applications. Since there are substantial uncertainties in transitioning to these emerging technologies, discussions with IOOs about the operation and maintenance of C-V2X may have to wait to resolve these issues, while TDOT can invest in limited experimentation with dual-mode devices. Since there are substantial uncertainties in transitioning to these emerging technologies, IOOs in Tennessee can examine the operation and maintenance of dual-mode C-V2X. Notably, TDOT has recently issued guidance recommending a transition to dual-mode C-V2X devices if IOOs are in planning or design stages. Meanwhile, it will be prudent to develop investment plans to experiment with dual-mode C-V2X devices.

Smart infrastructure deployment. In Tennessee, smart infrastructure deployment will require a successful transition from DSRC V2X to C-V2X communications, especially with roadside units, e.g., installed at traffic signals or on freeways. This transition has a relatively high opportunity cost in terms of changing communication devices and delaying the deployment of safety-critical applications through the available DSRC V2X devices. Specifically, researchers at the University of Michigan Transportation Research Institute [7] point out that the cost of delaying the deployment of safety-critical applications through the available DSRC V2X can be measured in terms of tens of thousands of lives lost over five years.

Connected vehicle applications and needed research. Connected vehicle applications in Tennessee have relied on the DSRC V2X communication platform for applications such as Transit Signal Priority and Emergency Vehicle Preemption. CAV data collection, use, security, and storage are critical aspects going forward. Notably, 4G LTE-based C-V2X communication technology is being tested by the US DOT. Early results of data analysis indicate that there can be congestion issues during operation compared with DSRC V2X. However, presently there is not enough evidence to confirm or contradict whether LTE C-V2X will scale up to the safety issues. More research is needed on several aspects of communication technology. While the FCC has provided a transition plan for moving from DSRC V2X into the new C-V2X spectrum, the shift will nevertheless be costly.

2.3 Investments in smart corridor projects across the U.S.

Future investments in smart corridors are critical for improving transportation system performance. Information on the conceptual and practice-oriented issues involved in designing and implementing smart corridors is critical. The smart corridor reports and studies reviewed show that:

- Connectivity supporting lower levels of automation (up to Level 2) can be implemented in the short term (about 3 to 5 years).
- Realistically, support for higher levels of automation (Levels 3 and 4) will require more time, given the current state-of-the-art and practice, based on the reviewed studies.
- The analysis of specific strategies separately and in combination can help TDOT know which strategies are impactful for safe mobility and identify strategies for broader deployment as well as strategies that should be tested in future smart corridors in Tennessee. For instance, a deep and comprehensive evaluation of the I-24 Smart Corridor can help determine how smart corridors will be deployed in the future.

2.4 Ecosystem for Connected and Automated Vehicles

Focusing on smart infrastructure, the findings of investments in a CAV ecosystem are summarized in three areas:

Collection of CAV data. The whole CAV system is based on the fast movement of data over wireless networks, and hence a critical component of operating CAV systems is data collection. Data transfer in real-time enables 1) the applications and user services that improve traffic operations, 2) archived data helps improve planning and related models for the future, and 3) assists with an independent evaluation of emerging technologies. CAV data refers to the continuous streaming of Basic Safety Messages (BSMs), Traveler Information Messages (TIMs), Signal Phase and Timing (SPaT) messages, and logs of alerts or warnings, most of which are transmitted over wireless networks. For example, if alerts or warnings are given, then event logs can be created from BSM, TIM, and SPaT messages in a vehicle before and after the alert or warning was issued to the driver. Such data can be stored on Aftermarket Safety Devices (ASD) at the time of collection and pushed Over-The-Air (OTA) from the ASD to the roadside unit (RSU), from where it can be archived on a secure server. Notably, CAV data can be collected, archived, and harnessed in different ways. Details are provided about CAV and non-CAV data sources, data archival, processing, and sharing, with specific use case examples from Tennessee (MLK smart corridor and Shallowford Road in Chattanooga) and around the country covering the implications for smart infrastructure technology deployments in the future.

Data analytics and modeling are needed to use the CAV data effectively. This can include visualization of the collected data to measure system performance in real-time and for tactical/strategic planning. CAV data are increasingly being shared through dashboards, data hubs, and data lakes. The analytics include visualization of CAV data. Specifically, CAV user services such as red-light running alerts or curve-speed warnings use standardized BSMs, which are data packets related to a vehicle's position, heading, speed, acceleration, state of control, and predicted path. These data can be transmitted from one vehicle to other vehicles via V2V and V2I communications, collectively known as V2X communications. In a real-life application, they are analyzed by the receiving onboard unit (OBU) to determine the presence of hazardous situations and alert the driver of the host vehicle accordingly. Storing and analyzing these messages can provide insights into whether the alerts were given appropriately and if they were effective in avoiding hazardous situations. Similarly, TIM provides drivers with information about traffic incidents, major events, and even evacuations. These messages typically utilize V2I communications and are sent to vehicles by RSUs. Furthermore, SPaT messages contain data about the state of signal phases at an intersection and related information. SPaT messages are processed by vehicles to support driver/vehicle decision-making at an intersection, e.g., whether to stop or go at a signalized intersection. The point is that these data are analyzed to improve the transportation system's performance, e.g., in terms of safety and mobility, as well as these messages can be analyzed for their effectiveness and harnessed more generally to improve system performance. Modeling the data and applications of Artificial Intelligence have gained momentum in this realm.

- Case studies highlight the experience with V2I technologies in the Chattanooga MLK smart corridor, analysis of BSM and alert data from bus drivers with access to “Enhanced Pedestrian Collision Warning Systems,” analysis of data on cooperative merging systems at on-ramps, and application of Artificial Intelligence techniques for smart traffic signal control strategies at intersections. New performance measures based on BSM data for safety (e.g., driving volatility and time to collision), energy, and emissions have also emerged.
- Case studies also feature experiences with specific CAV applications such as adaptive cruise control that utilized V2V technologies.
- Case studies further highlight how CAV data can be more generally harnessed for proactive planning without a specific CAV application or user service.

The application of a key set of tools for CAVs is simulations. Several simulation tools are available for envisioning CAV scenarios, sensitivity testing, and identification of edge cases. Simulations can range from 1) using tools such as Simulation of Urban MObility (SUMO) and Car Learning to Act (CARLA) for insights about CAV performance at the levels of transportation network or vehicle sensors (LiDAR, radar, and cameras), 2) hardware-in-the-loop simulations, e.g., the Rototest driving simulator for a realistic representation of vehicle (drivetrain) components, 3) multi-user virtual reality simulators for understanding driver behavior at different levels of automation and connectivity, and 4) digital twins to represent a real-time digital counterpart of an operating transportation system. Simulations can provide a system or vehicle-level testing and analysis of vehicle sensors and components. Together, the tools can be viewed as "virtual testbeds" for developing and testing emerging technologies. Moreover, the toolsets can be integrated (e.g., combining SUMO and CARLA) to expand and enhance their capabilities. Generally, simulations are needed as part of the CAV ecosystem because they can envision future strategic planning scenarios, e.g., mixtures of conventional vehicles and CAVs, anticipate the operation of high-level automated vehicles' that are merging at on-ramps and intersections, as well as explore "edge-cases" where extreme situations can be anticipated and addressed proactively. Case studies of simulations are provided in the detailed report [4], e.g., studies using SUMO to anticipate future safety and CARLA to identify edge cases, and the digital twin using a representation of the transportation system in Chattanooga, Tennessee. The highlighted work represents a collaboration between The University of Tennessee and ORNL.

2.5 Intelligent Mobility in Tennessee

Readiness for emerging technologies is relatively high in electric vehicle infrastructure, followed by digital infrastructure, roadway infrastructure, and modest levels of public knowledge and acceptance.

The findings on intelligent mobility strategies are structured in terms of intelligent mobility overview, expected benefits, readiness, and benchmarking.

Overview of intelligent mobility in Tennessee. The detailed report [5] first summarizes intelligent mobility in Tennessee, with a statewide review focusing on available digital infrastructure. While Tennessee faces physical infrastructure challenges in terms of roads needing repair and improving structurally deficient bridges (4.4%), innovative solutions are needed for growth-related congestion in major cities, evidence-based safety countermeasures, and environmentally friendly technologies. Relevant information on innovative intelligent transportation system inventories across Tennessee comes from several sources, including ITS architecture reports for 11 cities in Tennessee (from Bristol to Memphis) and the statewide ITS architecture report. Other TDOT sources include the integrated ITS Smartway systems and the Tennessee Department of Environment and Conservation (TDEC) for electric vehicle charging infrastructure. Additionally, summaries of national-level inventories for transportation infrastructure technologies are presented.

Traffic Management Centers (TMCs) are the backbone of intelligent transportation systems in Tennessee. They operate in different regions of Tennessee to monitor traffic operations and communications. The TMCs in Tennessee have sufficient equipment and resources to enable the diffusion of emerging technologies. These resources include TMC operators, HELP vehicles and operators, IT technicians, CCTV cameras, speed detectors, dynamic message signs, highway advisory radio (HAR) transmitters, and portable variable message signs (PVMS). However, inventories are either low or non-existent for changeable speed limit signs, dynamic message signs and over lane signs for active lane management, roadside and onboard devices for connected vehicles and new sensors, software for context-relevant applications/user services, fiber for fast communication of data, and latest traffic control devices (e.g., traffic signal upgrades to cabinets, communication devices that can perform edge computing, new signal controllers that can communicate with roadside units, radar detection sensors, and 360-degree cameras for detection and traffic surveillance.

Notably, establishing the appropriate cyber-physical ecosystem is critical, which also entails the collection, processing, management/storage, and harnessing of CAV (Vehicle-to-Everything) communications data. Providing web-based platforms for vehicle location and geo-referencing, signal phasing and timing, MAP data, traveler information message, and message authentication are important considerations for readiness. Additionally, software applications from the ITS architecture can be beneficial in different contexts. There is a need to identify connected vehicle mobility and safety applications/user services, e.g., lane management and control system or work zone alerts, in different regions of Tennessee.

Business case for intelligent mobility strategies: Expected benefits. The business case for intelligent mobility readiness should cover the expected benefits from intelligent mobility solutions. The intelligent mobility report covers a review of ongoing research on the impact of intelligent mobility strategies, which is a composite of research done at the national and State levels [5]. Information about the extent of problems and impacts of innovative transportation solutions in terms of economic growth, safety, mobility, energy, and environment is provided in Tables 2-1 and 2-2. There is a strong case for adopting emerging technologies, given their benefits. To achieve the benefits, investments are needed in readiness of roadway, digital, and electric vehicle infrastructure, and increasing emerging technology (e.g., CAV, EV) awareness across Tennessee, broader testing of new technologies through pilot projects, establishing business processes to support future CAV and EV deployment and dedicating new workforce to CAV and EV implementation.

TABLE 2-1 TRANSPORTATION IMPACTS IN TENNESSEE

Economic Costs	*Safety*	*Traffic flow & congestion*	*Energy and Efficiency*	*Health and Environment*
• *Congestion cost the economy $4.2 billion in 2020* • *$25 billion annual economic cost and societal harm from crashes*	• 1,325 lives were lost in 2021 on TN roadways • Estimated 66,000 people were injured in crashes in 2021 • Vulnerable road user/bike and ped crashes (177 pedestrian deaths in 2021)	• 225 million hours spent in delays annually	• 83 million gallons of fuel are wasted annually • $0.29 trillion in goods shipped by truck each year	• Greenhouse gases • Public health impacts

TABLE 2-2 ESTIMATED BENEFITS IN TENNESSEE WITH FULL AUTOMATION AND ELECTRIFICATION ADOPTION

Economic Costs	*Safety*	*Traffic flow & congestion*	*Energy and Efficiency*	*Health and Environment*
• *Savings in congestion can be $2 billion* • *Reduction of $8 billion annual economic cost and societal harm from crashes* • *Savings in the environmental cost of damage by $70 million* • *Higher GDP due to redevelopment of real estate by about $4.3 billion*	• 430 lives can be saved per year on TN roadways • Estimated 21,500 reductions in people injured in crashes annually • 20% reduction in vulnerable road user/bike and ped crashes	• About 48% reduction in hours spent in delays annually	• Increase in energy efficiency due to adoption of hybrid vehicles by about 50% more MPG • 40% reduction in fuel wasted annually • $0.6 trillion in goods shipped by truck each year	• Reduction in greenhouse gases due to electrification by about 33% • Public health impacts

Intelligent mobility funding. Tennessee is poised to receive $6.2 billion (2021 to 2026) through the Infrastructure Investment and Jobs Act (IIJA), which can be a critical source of funds for intelligent mobility projects. Among other objectives, the act encourages investments in new and emerging technologies such as CAVs and associated broadband deployment, electric vehicle infrastructures such as charging stations; safety for all road users, particularly vulnerable road users; addressing environmental impacts of transportation, especially emissions; and equity and inclusion of disadvantaged and under-represented groups in CAV accessibility, planning and project selection. Notably, IIJA prioritizes projects that advance choices across all modes and are sustainable. The sources of funds for intelligent mobility can include core programs (NHPP-National Highway Performance Program, STBG-Surface Transportation Block Grant, HSIP-Highway Safety Improvement Program, RR-Refuge Roads, CMAQ-Congestion Mitigation and Air Quality, Metropolitan Planning, and Freight), as well as new programs related to electric vehicle infrastructure, carbon and green initiatives, protection and resiliency of infrastructure, bridge rehabilitation, and ferry transportation. For Tennessee, there is new funding of $139 million for carbon reduction, $88 million for electric vehicle infrastructure, $302 million for bridge rehabilitation, and $158 million for Promoting Resilient Operations for Transformative, Efficient, and Cost-saving Transportation (PROTECT). Notably, some of the IIJA funds are grants that will need resources to prepare proposals and plans. TDOT can take steps to adopt the broader zero-emissions vehicles mandate and envision electric vehicle infrastructure in smart corridors to increase the chances of success in competitive grants.

Intelligent mobility readiness survey. As mentioned, a framework to study intelligent mobility across Tennessee was developed. The framework focuses on physical roadway infrastructure, electric vehicle infrastructure, digital infrastructure, policy/regulation, and public knowledge/acceptance. Each area contains a series of subcategories to broadly explore intelligent mobility readiness across TennSMART members, including representatives from cities, agencies, a national lab, the private sector, and academia. A questionnaire was developed to assess intelligent mobility readiness and score it. After its distribution to TennSMART members, 22 responses were analyzed. The framework assesses readiness on a scale of 0 (no activity – 0% Readiness) to 3 (strong activity – 100% Readiness) in terms of physical infrastructure, digital infrastructure, electric vehicle infrastructure, public knowledge and acceptance, and policy/regulation awareness. The survey asked respondents whether their organization had researched, developed, or deployed roadway improvements or any emerging technologies. The answers were Yes (coded as 3), No, but we have a specific plan for it (coded as 2), No, but we expect to have a specific plan for it in the future (coded as 1), No, and we have no plan for it (coded as 0), and don't know/ not sure/ not applicable is excluded from the readiness index calculation. A set of questions was developed and administered through a structured survey for each area of interest. For example, physical roadway infrastructure was divided into roadway structures, signage and markings, and design standards.

The results range from the relatively high activity and readiness in electric vehicle infrastructure, followed by digital infrastructure, roadway infrastructure, and modest levels of public knowledge and acceptance (Figure 2-1).

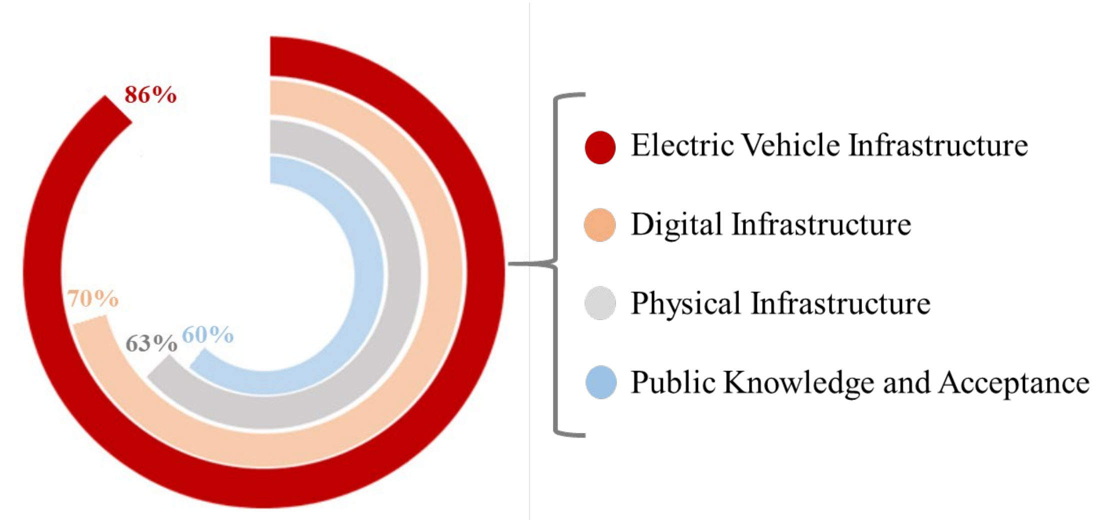

Figure 2-1 Readiness index for each area

To support electrification, the transportation system needs "a network of EV charging stations" with different charging levels, i.e., Level 1, Level 2, and DC Fast charging. Despite the substantial potential for improvement in charging infrastructure, the results show high levels of readiness in terms of installing charging stations and electricity generation and distribution, assessing future demand for charging infrastructure and expanding charging stations.

Notably, CAV technologies can exchange information with digital infrastructure, e.g., C-V2X capable roadside units can warn drivers for red-light running or high speeds on curves. Within this category, low readiness in C-V2X communication is quite apparent, showing 44% on the readiness scale (this may also be due to the fact that this question applies more to agencies than the entire spectrum of TennSMART members). The next category that has readiness improvement potential is harnessing the C-V2X data to improve mobility and safety. Furthermore, cybersecurity also ranked relatively low in terms of readiness. More attention is needed on C-V2X communication and the secure collection and harnessing of CAV data.

Within physical infrastructure, the least readiness is observed for the ability of CAVs to detect pavement markings at 42%, followed by road sign improvements at 49%, truck platooning readiness (56%), and expanding operational design domain (ODD) at 69%. Clearly focusing on improving pavement markings and road signs for CAVs, expanding ODDs, and facilitating truck platooning can improve physical infrastructure readiness.

The area that shows more significant potential for improvement is public knowledge and acceptance reflected in information about automation and electrification in passenger travel by personal vehicles, transit, and freight. Informing the public about automation in passenger vehicles and the freight industry (e.g., truck platooning) has the lowest index among all, which can receive attention in the future.

CAV readiness of cities in Tennessee. To further enhance understanding of readiness in Tennessee cities, the study explored infrastructure elements required to accommodate CAVs. Several measures are used to evaluate readiness for CAVs, based on cities' readiness in terms of digital and physical infrastructure. Analysis of cities' ITS architecture reports was conducted. The research team first identified several variables that can promote CAV diffusion. The

Tennessee cities analyzed include Clarksville, Nashville, Memphis, Knoxville, Johnson City, Jackson, Bristol, Kingsport, Chattanooga, Cleveland, and Lakeway. The physical infrastructure measures used include quality of road signage and markings, CAV-compatible parking facilities, sensor-equipped cones and beacons, and CAV-only pick-up and drop-off areas. Digital infrastructure encompasses infrastructure to vehicle communication devices, high-resolution maps of the road network, and infrastructure-based pedestrian detection technologies [8]. Generally, larger cities with more population are likely to have more resources, though smaller cities may be able to leapfrog more quickly as they are likely nimbler with less inertia. Cities across Tennessee vary in terms of their readiness for CAV adoption. Memphis, Chattanooga, and Nashville have received relatively high readiness ratings based on the information contained in the Tennessee Regional ITS Architecture reports analyzed in this study. Whereas Knoxville, Clarksville, and Johnson City received relatively low readiness ratings. At the same time, larger cities that have encouraged innovation in transportation seem more prepared than smaller and medium-size cities; relatively modest infrastructure investments in such cities, as appropriate, can significantly enhance their readiness.

Analysis of ITS architecture plans for cities in Tennessee shows Tennessee's focus on a set of strategies. These include 1) installing digital infrastructure, especially fiber optic networks and field sensors, 2) responding to emergencies—planning, operation, and routing of emergency vehicles when responding to incidents, traffic signal preemption and emergency traffic control, area alerts, evacuation if needed, and traffic incident management, 3) enhancing safety, especially reducing deaths and injuries and damages to TDOT property—through a collection of information (e.g., CCTV cameras) and dissemination of information through dynamic message signs and radio transmitters, and 4) workforce development.

A key opportunity is to integrate inventories for electric vehicle infrastructure, e.g., a fast-charge network to enhance the diffusion of EVs in Tennessee by reducing barriers to electrification. Based on the analysis of Tennessee inventory data, substantial efforts are needed to increase the inventory of digital infrastructure to enhance readiness for emerging technologies.

Benchmarking of aspirational states. The team has identified the leading states in emerging technologies (CAV and EV) research and development, summarizing their progress and success stories. A vital aspect of this research is that the holistic approach developed in this study gives insights into planning for the future of emerging technologies. TDOT seeks to boost readiness for intelligent mobility solutions, encompassing physical infrastructure, digital infrastructure, electric vehicle infrastructure, policies, and public acceptance. Initial information about benchmarks for Tennessee's readiness relative to aspirational agencies in other states is provided. Notably, TDOT has not previously conducted such a readiness benchmarking project. The research team provides information that can be used by a TDOT benchmarking team to enhance readiness further. The performance measures relevant to the goals include safety, mobility, energy, and environment to reduce the costs associated with these goals, e.g., reducing the costs of crashes, injuries, and death. The aspirational agencies selected for use case analysis include Michigan, Florida, California, and Minnesota. They were selected due to their leadership in developing, testing, and deploying emerging technologies. The research team collected and analyzed information from the four states to identify innovative readiness strategies, approaches, and best practices that may be adopted in Tennessee to boost readiness. The results for consideration in Tennessee are discussed as follows:

- *Physical infrastructure.* Regarding changes to physical infrastructure, TDOT can consider improving signs and pavement markings, upgrading traffic signals to absorb new technologies, and in the long-term, the creation of CAV park-and-ride facilities.
- *Digital infrastructure.* More research, development, and pilot testing are needed for CAV technologies, including truck platooning and autonomous shuttles. For example, truck platooning can be tested to examine fuel economy improvements and capacity enhancements along freight corridors. This will require coordination between several stakeholders, including TDOT divisions—Traffic Operations, Freight and Logistics, and Long Range Planning. Generally, TDOT can adopt pilot testing as a near-term goal. Additionally, more efforts and resources can be allocated to workforce development in digital infrastructure/emerging technologies and enhancing cybersecurity.
- *Electric vehicle infrastructure.* TDOT can consider adopting the Zero-Emission Vehicle concept and mandate, which is broader than electric vehicles, e.g., they include fuel-cell vehicles that use hydrogen and associated infrastructure. Besides increasing their coverage, TDOT can consider innovative strategies for charging stations, e.g., solar energy charging at stations. Consideration can be given to incentives for EVs to use High Occupancy Vehicle (HOV) lanes, assuming that HOV lanes are strictly enforced and enhance the availability of EV charging throughout the network and destinations, e.g., activity centers, hotels, vacation spots, and parks. It is noteworthy that currently, TDOT and TDEC are collaborating to develop the "Tennessee Electric Vehicle Infrastructure (TEVI) Deployment Plan" to receive funds from the National Electric Vehicle Infrastructure Formula Program (NEVI Formula).
- *Public knowledge and acceptance.* TDOT can consider conducting stakeholder meetings to increase awareness of intelligent mobility strategies. TDOT can design a campaign to send information through various media, e.g., text messages, to inform the public about the benefits of intelligent mobility strategies that include adopting and using CAVs and EVs. Public knowledge strategies can be implemented in the near term.

Ultimately, TDOT Division Directors and staff should select the relevant best practices from these aspirational states that can be adopted in Tennessee. Over time, the transportation system's performance should be monitored to assess the effectiveness of the new practices and processes, realizing that improvements can take multiple years to show results.

Unintended consequences. Emerging transportation technologies will automate some tasks and thereby make some of the workforces (e.g., delivery workers, ambulance drivers, and plumbers) more productive, lowering the cost of providing the services. Also, automation technologies can lower crash costs, which are their clear benefits. However, the repair costs may be higher if such vehicles with more sensors and technologies are involved in crashes. The sensors and other technology components that enable automation may be damaged during collisions and they are typically more expensive to repair.

> *To reduce unintended consequences of emerging technologies, such as job losses in specific sectors, use collaborative approaches to coordinate mitigation solutions.*

On a broader scale, automation may be disruptive to manufacturing employment in Tennessee, with potential job losses in car manufacturing. While factory automation itself can reduce the number of tasks performed by workers [5], vehicle support industries may be affected directly as demand for many support services can be significantly reduced, e.g., fewer crashes can eliminate much of the need for repair. Vehicle intensive-use occupations can see substantial impacts, e.g., automated vehicles can dramatically eliminate motor vehicle operators and other on-the-job drivers (e.g., taxi drivers, rideshare drivers, and truck drivers).

Another disruptor is the shift from the conventional internal combustion engines with a lot more moving parts than electric vehicles. This shift can affect a variety of jobs. Specifically, electric vehicles have substantially fewer parts and require less time to manufacture, assemble, and maintain, reducing the need for jobs in these industries. Given Tennessee's automobile manufacturing focus, the shift to electrification can mean job losses in manufacturing, assembly, and maintenance service industries. Additionally, workforce development may be needed to support the growth in the battery industry and battery recycling.

Thus, anticipating some of the unintended consequences, especially negative social impacts on labor, the insurance industry, and equity in access to automated vehicles is crucial as they may disproportionately and negatively affect different strata of the society, creating equity issues. Additionally, vehicle electrification creates instability in manufacturing, assembly, and vehicle maintenance jobs. In addition to the clear benefits of intelligent mobility, the business case should also consider collaborative approaches and strategies for mitigating the disruptive consequences of innovation adoption.

Chapter 3 Conclusions and Recommendations

3.1 Readiness and Investments in CAV Technologies in Tennessee

Investments are needed in innovative solutions that encompass physical infrastructure, digital and smart infrastructure, electric vehicles, and charging infrastructure.

Investments are needed in innovative solutions that encompass physical infrastructure, digital and smart infrastructure, electric vehicles, and charging infrastructure. For instance, to realize the full potential of intelligent mobility benefits focusing on smart infrastructure, investments in C-V2X equipment installation solutions are critical for TDOT. A key question is how to best plan for readiness in emerging technologies and work with IOOs when TDOT does not own or operate traffic signals in the state. Options include i) using TDOT Traffic Design Manual and TDOT standard specifications (modified by cities to fit their local needs) and statewide ITS architecture, ii) updating TDOT DSRC V2X guidance, and iii) supporting local agencies and, in some cases, TDOT operating and controlling traffic signals. The State of Georgia provides a good use case of DOT and IOO cooperation. Specifically, TDOT can create a program similar to the "SigOps program" by Georgia DOT. Under this program, traffic signal operations will be divided into regions supported by a separate consultant contract and dedicated funding. This shift will enable all signals to be remotely monitored automatically. In order to prioritize operational needs and resources, TDOT can use a tiered approach to define the level of remote monitoring and field presence required for each intersection. Critical and bottleneck intersections will require a higher level of monitoring and field presence than other locations. Furthermore, staff will be needed for this program. They will include remote signal engineers, field signal engineers, signal technicians, data analysts, and maintenance inspectors. The stakeholders will include TDOT Traffic Operations, TDOT district signal staff, and traffic engineering staff in counties and cities. To summarize, TDOT can consider a SigOps type approach or establish a way that fits with the current structure in Tennessee by supporting local agencies wishing to implement connected vehicle technologies.

Besides installing equipment, readiness also involves CAV data solutions. In this regard, options include i) city TMCs themselves or universities serving as repositories of new CAV data; the Tampa connected vehicle (CV) pilot deployment can serve as a relevant use case of new databases needed and it resides at the Center for Urban Transportation Research, University of South Florida. ii) TDOT's regional TMCs serve as repositories (data lakes); e.g., in TDOT's case, data coming from freeway CAV devices can be handled first by regional TMCs. For cities, regional centers can be used as data repositories for CAV data, requiring connectivity between the regional and city-based TMCs, especially for traffic signals. Currently, in Tennessee, regional TMCs are not well-connected with city TMCs, except there seems to be some movement along the I-24 smart corridor and surrounding cities.

To further prepare for CAVs in Tennessee, strategies to consider include:

- ***Research, develop and deploy CAV technologies*.** TDOT and partners are demonstrating the capabilities and benefits of CAVs through testbeds, e.g., I-24 Smart Corridor. The Chattanooga

MLK Smart City Corridor testbed and other statewide initiatives are also underway. Expansion of such initiatives should be considered.

- ***CAV readiness plans.*** Monitor and understand the current practices of statewide CAV readiness plans in other states, lessons learned, and recommendations while tracking emerging technology advances.
- ***Developing a roadmap.*** Develop a roadmap for physical and digital infrastructure, electric vehicle infrastructure, regulation and policy, user acceptance, partnerships with stakeholders, and workforce development.
- ***Smart infrastructure technologies.*** Identify improvements in roadway, digital, and electric vehicle infrastructure technologies through ITS architecture service packages for implementation. A wide range of CAV service applications includes emergency vehicle preemption, broadcast traveler information, queue warning, work zone management, connected vehicle traffic signal system, personalized traveler information, road weather motorist and warning, pedestrian and cyclist safety, and electric charging stations management. Also, TDOT can identify opportunities in terms of connected, automated, and electric transportation systems that are multimodal, i.e., include freight, transit, pedestrians, and bicycles. TDOT can integrate CAV strategies into long-term planning and programming processes by anticipating the impacts of their increased diffusion; developing data collection and harnessing capability from new sensors, e.g., basic safety messages and traveler information messages; and conducting research on specific issues related to CAV data, harnessing the data, and investing in modeling/simulation capabilities that can directly deal with complexity and fragility of the transportation system when operating in a mixed-mode, where some vehicles are high-level CAVs while others are human-driven.
- ***Future research on CAV readiness*****.** Future CAV research can focus on readiness for emerging technologies. In this regard, it is important to invest in conducting interviews/surveys of various stakeholders, including TDOT Division Directors and staff in terms of their readiness for CAV and synergistic technologies, including electric vehicles.

Additionally, TDOT can consider the following actions:

- Accelerate the integration of CAV technologies in TDOT's plans, programs, and projects.
- Consider creating positions for TDOT-based program managers to test and deploy CAVs (their responsibilities can be similar to ITS managers).
- Develop an external stakeholder coordination strategy, especially with IOOs, vehicle manufacturers, information technology companies, and the TennSMART consortium.

3.2 Infrastructure and Vehicular communications

The recommendations regarding communications are structured around three main themes, the transition, data, and research/testing:

- ***Managing the transition to dual-mode C-V2X and DSRC V2X devices.*** Given that C-V2X technology is still being examined for large-scale deployment, the transition will include testing and using dual-mode DSRC V2X and C-V2X radio devices. Furthermore, strategies can include investing in reliable installation of software updates for C-V2X (e.g., updates that address security vulnerabilities within signal controllers, so they can communicate securely with C-V2X devices in the future), recruiting volunteers from the general public and/or fleet vehicles (owned by TDOT, or other agencies) for installing onboard units, and exploring automotive/Original Equipment Manufacturer (OEM) industry's acceptance of C-V2X technologies. Importantly, experimentation with dual-mode devices by the University of Tennessee, Chattanooga, has shown promising results for dual-mode devices. Specifically, early experimentation in the Chattanooga MLK smart corridor shows that LTE 4G provides relatively stable performance compared with DSRC V2X when considering packet loss and range in an urban environment.

- ***Managing and harnessing connected and automated vehicle data.*** It is important to identify CAV data needs and types of data (e.g., basic safety messages, SPaT messages, and vehicle trajectories). Equally important are data analytics and cybersecurity investments for streaming data generated by CAVs. Data management plans are also needed. Harnessing the data is an opportunity to improve traffic operations and performance evaluation. TDOT, with private sector partners, could collect high-resolution data from traffic signals and vehicle probe data, allowing engineers to track traffic trends at an intersection, corridor, and programmatic level as well as visualize maintenance problems. In this regard, TDOT could in the future expand its role in traffic signals through owning and/or operating traffic signals in the state. (This would represent a major expansion of TDOT's role in traffic signals and infrastructure, given that TDOT does not currently own and operate traffic signals.) If a program similar to GDOT's SigOps was developed, TDOT could use Automated Traffic Signal Performance Measures (ATSPM) software to oversee real-time and historic functionality at individual intersections. All intersections communicating with TDOT could be configured in ATSPM. ATSPM can find faults and errors, thereby saving staff field inspection time. There are several use cases for this software, including Utah DOT, Virginia DOT, and Georgia DOT. In addition, TDOT can consider using a software named TEAMS (Traffic Engineering and Asset Management Software) to track traffic signal equipment, including signs, Americans with Disabilities (ADA) compliance, and overall rating of intersections. For equipment maintenance updates, if the equipment is not performing correctly, it is noted as a task in TEAMS and updated as needed.
- ***Future research on communication technologies.*** Conducting future research can entail testing the performance in terms of latency and packet drop of C-V2X technologies and the impacts of (user) congestion and interference in communication networks. Also, assessing TDOT's tolerance for latency and packet loss in safety-critical applications is important. Furthermore, investments in addressing the uncertainty of C-V2X in terms of the scale (number of vehicles) will be valuable, along with testing the longevity and compatibility of C-V2X technology performance in different environmental conditions within Tennessee. Noting that the current 30 MHz for communication may not be sufficient, there is a need to investigate how the 5.9 GHz communication band can support C-V2X. More generally, for TDOT to deploy C-V2X technologies, transportation system readiness should be assessed. Overall, substantial and comprehensive testing and research are needed before fully transitioning to C-V2X.

3.3 Investments in smart corridor projects

Smart corridors are manifestations of emerging technology deployments. TDOT investments in the following initiatives can be considered:

- ***Invest in the successful operation of smart corridors.*** The I-24 Smart Corridor is an example of improving capacity and operations to manage congestion and improve safety in Tennessee. Accordingly, TDOT is forming much-needed partnerships with local authorities to implement the I-24 Smart Corridor initiative. This initiative proposed various deployment goals, such as increasing travel time reliability and reducing crashes on the I-24 Smart Corridor. The deployed I-24 smart corridor technologies and improvements can potentially mitigate problems caused by rapid growth in Tennessee, including traffic congestion, fatalities, injuries, and environmental issues. As these strategies are being deployed, TDOT should consider operating the system smoothly by deploying emerging technologies and ensuring that they can operate effectively, e.g., have enough RSU and OBU devices in the field, collect, process and use new forms of CAV data to fully utilize new applications, and evaluate the impacts of these improvements to inform future transportation projects.
- ***Invest in evaluation plans for smart corridors.*** A substantial effort by TDOT and supporting partners can be devoted to the conceptual design and practical issues involved in evaluating the effectiveness of smart corridor demonstration projects in Tennessee, with the I-24 Smart Corridor project as the first test case. Efforts should focus on producing a completely specified and implementable evaluation plan and include methods for data collection, reduction, analysis, scheduling, budgeting, and creating deliverables. The evaluation plans should consider physical infrastructure, digital infrastructure, electric vehicle infrastructure, user acceptance, policy, and regulatory issues. Multi-faceted evaluation elements should be addressed, including changes in transportation network performance, traveler behavior, vehicle trajectories, and institutional issues. TDOT and partners should plan to evaluate the impacts of emerging technologies in the corridor. This entails designing experiments around the deployment of emerging technologies and collecting and analyzing relevant data for the different phases of the project. Specifically, the project should identify appropriate performance metrics and develop a framework to utilize the performance metrics and the necessary data to quantify the impacts based on a before-and-after study. Furthermore, TDOT should conduct a benefit-cost comparison for each strategy deployed, which entails the use of emergency pull-offs, ramp extensions, connected vehicle infrastructure, and the implementation of dynamic lane use control, variable speed limits, and queue warning. Support of these activities will require installing RSUs and OBUs on personal and state vehicles, installing dual-mode C-V2X communication equipment, partnerships with stakeholders, especially IOOs, given that TDOT does not own or operate traffic signals on parallel arterials, CAV data storage, transmission, and analysis considerations, and staffing needs associated with the I-24 infrastructure deployment. More generally, as more testbeds come online in Tennessee, they can be supported with solid experimental designs and evaluation plans that cover issues related to the operation of smart technologies, e.g., partnerships with stakeholders and collection/use of CAV data and TDOT staffing needs.
- ***Synergize transportation infrastructure with electric vehicle infrastructure*.** A key gap in almost all smart corridor studies is the lack of focus on electric vehicle infrastructure. This can

be considered in future strategies for smart corridors. As electric vehicles become more widely adopted in Tennessee and nationwide, the transportation networks should be ready for their arrival. TDOT can pay particular attention to deploying EV infrastructure, including installing cutting-edge electric vehicle charging stations. In fact, locations of future smart corridors can be synergized with the Tennessee statewide electric vehicle (EV) fast-charging network to enhance electrification across Tennessee. Notably, the "Fast Charge TN Network" has prioritized corridor infrastructure gaps, and coordination with TDEC and the Tennessee Valley Authority (TVA) can help identify new opportunities for implementing smart corridors. Furthermore, about a dozen states have adopted the broader zero-emission vehicles program that includes a range of alternative fuel technologies. TDOT can consider adopting the zero-emissions vehicle program and coordinate efforts with TDEC to develop alternative fuel technologies and related infrastructure plans.

- ***Establish regional or city pilots and testbed corridors.*** Similar to the successful MLK Smart Corridor testbed in Chattanooga, Tennessee, urban testbeds can be envisioned for smart city infrastructure applications in other cities, e.g., Clarksville, Nashville, Memphis, Knoxville, Johnson City, Jackson, Bristol, Kingsport, Chattanooga, Cleveland, and Lakeway. Such testbeds will provide greater opportunities to explore CAV impacts on diverse road users, especially vulnerable road users, i.e., pedestrians, bicyclists, scooters, and motorcyclists. TDOT can plan for connected vehicle regional pilot projects and deploy CAV RSUs targeting the busy downtowns of its cities. Notably, having a sufficiently large number of OBUs on personal vehicles and fleet vehicles (state vehicles) is also needed for the RSUs to be helpful. Several smart corridor studies reviewed show that substantial effort is devoted to OBU implementation. TDOT should explore how a sufficiently large number of OBUs can be provided to the users of the smart corridor (in hundreds or even thousands of OBUs on personal and state vehicles) in coordination with local agencies and jurisdictions, transit agencies, and automobile manufacturers. Coordination efforts are needed with automotive OEMs to get a clearer sense of what connectivity technologies will be used by vehicle manufacturers to support and improve operations through infrastructure technologies. Broadly speaking, TDOT can carefully test and deploy RSUs to improve safety, enhance traveler and freight mobility, e.g., at entry points to interstates, and move Tennessee as a leader in C-V2X and CAV programs. Given that many smart corridor projects focus on infrastructure and vehicle communication at urban traffic signals, it is also recommended that TDOT explore coordination with cities and counties or localities (i.e., IOOs) that control the intersections when installing roadside units.
- ***Test communication technologies and applications.*** Given the focus on CAVs, TDOT should consider equipping smart corridors with OBUs (supplying OBUs on personal and state vehicles) and RSUs for communicating basic safety messages and providing warnings to drivers. It is vital to test the 5G C-V2X technology, given the FCC ruling on opening DSRC V2X bandwidth and the emergence of 5G C-V2X communication. This requires establishing and supporting pilots and testbeds to explore CAV impacts. Moreover, TDOT can undertake one or more CV pilot projects on crash-prone interstates to improve safety and mobility on such roadways. The information collected by CVs potentially can help safety practitioners better understand driving behavior and target countermeasures after uncovering crash risk factors.

- ***Collect new forms of data-Basic Safety Messages.*** While TDOT collects and stores data from several sources that include camera feeds, radar detection systems, RITIS, ETRIMS, and SmartWay Central Software, equipping fleet vehicles with DSRC V2X or C-V2X devices (OBUs) and collecting microscopic level BSM data from CAVs can be very helpful in evaluating the performance and effectiveness of user service applications such as curve warning or red-light violation warning. Furthermore, TDOT should consider coordinating the implementation of OBUs with in-state automobile manufacturers. With the emergence of such high-frequency CAV data, data analysis can provide helpful information about the extent of improvements in safety and mobility. BSM data can be broadly analyzed at the driver/vehicular level or aggregated to the system level. Several performance measures have been introduced at the system level and are being utilized to evaluate traffic performance. Specifically, novel driver/vehicle level measures such as time-to-collision, driving volatility, energy consumption, and emission measures can be quantified using BSM data. Quantifying performance measures can help evaluate and monitor driver, vehicle, and roadway performance. Analytics can provide valuable insights to improve safety, mobility, reduce energy consumption, and benefit the environment.
- ***Test CAV technologies in mixed traffic.*** TDOT can investigate the impact of CAVs in mixed traffic by developing testbed experiments or developing digital twin experiments. As the market penetration of automated vehicles (AVs) is increasing, the interactions between conventional vehicles and AVs are inevitable but by no means clear. It is necessary to understand behavioral changes caused when conventional human-driven vehicles interact with AVs and investigate the impact of these changes (if any) on traffic performance.
- ***Test and deploy cutting-edge technologies.*** TDOT can test and analyze cutting-edge technologies such as Cooperative Adaptive Cruise Control (CACC) and encourage truck platooning by using fleet vehicles. Additionally, eco-traffic signal timing/priority, Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG), Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE), queue detection/warning (Q-WARN), eco-lane management, eco-adaptive ramp metering, and curve speed warning can be considered. These and other technologies identified in the Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) provide a framework for planning, defining, and integrating intelligent transportation systems. These cutting-edge technologies can be tested and analyzed first in smart corridor testbeds to provide a clear and realistic vision of their potential impacts and then deployed in Tennessee. As an enabler, TDOT can establish fiber-optic networks along important highways and ensure fully integrated transportation systems along these routes.
- ***Future research on smart corridors.*** In terms of future CAV research, it is important to invest in evaluating the potential benefits/costs and impacts of emerging technologies and associated strategies in smart corridors within Tennessee.

3-4 Ecosystem for Connected and Automated Vehicles Data

Associated with the selection of context-relevant connected vehicle user services is creating an effective ecosystem. A set of actions include the following:

- ***Invest in collecting CAV data.*** This entails developing a CAV data management system, given the large scale of such streaming data, and identifying the types of CAV data that can support core TDOT functions, including operations, maintenance, planning, and the required workforce for data collection and management. Data collection also comes with investments in cybersecurity, given the potential for adversarial attacks on the large-scale streaming data generated by CAVs. Notably, cybersecurity is a national challenge, and, in this regard, TDOT can follow the guidelines provided by the National Highway Traffic Safety Administration (NHTSA). Some of the best practices in cybersecurity in the automotive industry are gathered and discussed in the NHTSA cybersecurity best practices report [9]. Importantly, TDOT should consider developing CAV data sharing procedures within TDOT and a sharing policy with external partners that include other agencies, industry, research institutions, and the general public. Such policies can enhance traffic operations and freight supply chains and support smart city initiatives.
- ***Invest in CAV data analytics and modeling.*** Procedures are needed that fully utilize data from CAVs and other sources to successfully operate CAV user services and understand/improve transportation system performance. Data analytics, modeling, and artificial intelligence techniques are critical in designing highly efficient, safe, and sustainable transportation systems and providing smart mobility services to passengers and freight customers. TDOT should consider creating CAV data dashboards to monitor the performance of the transportation system and the deployed CAV technologies. Specifically, to manage data, TDOT can create and maintain a CAV data dashboard through centralized servers. Such dashboards can provide information that helps oversee operations and inventory and assists stakeholders in tracking resources and activities across the state. TDOT can emulate the connected data platform (CDP), similar to the Georgia DOT use case, to begin integrating diverse data sources. Specifically, CDP can overlay road inventory, WAZE data, CAV device information, highway patrol data, traffic, and crash data in a user-friendly interface.
- ***Innovative uses of CAV data.*** TDOT can use new data sources related to CAVs to support planning activities and assess modeling tools and the methodology they are applied to reflect future uncertainty about CAV adoption. This includes developing transportation models based on CAV data and other data (e.g., crowdsourcing) to accurately estimate and predict transportation system performance and develop proactive and multimodal transportation management plans. Another use of data is providing short-term traffic performance predictions and locating hazardous sites. The data can further be harnessed to improve traffic signal performance by incorporating new performance measures such as driving volatility of the CAV trajectories and using CAV data in high-uncertainty situations such as incidents and special events for lane recommendations and determining dynamic speed limits. The data can also be used by TDOT's partner agencies, such as Fire and Emergency Medical Services. Further, CAV data can fill data gaps for various functions provided by TDOT, e.g., by Maintenance or Environmental divisions. All the potential uses will require analysis of the CAV and related data, with some requiring research.
- ***Invest in simulations to create virtual testbeds and digital twins to enhance transportation system performance.*** More investments in "virtual testbeds" through simulation methodologies such as digital twins and the use of software SUMO and CARLA simulations can be valuable for CAV data integration and processing, anticipating future scenarios, doing

sensitivity analysis, as well as identifying Tennessee-specific "edge" (fringe) cases. Additionally, simulations can evaluate operational and planning strategies across large-scale networks. Notably, TDOT can further leverage modeling and simulation capabilities available in Tennessee through the universities and ORNL. This can involve leveraging high-performance computing, data science, and advanced sensors and communications protocols to develop, test and deploy emerging technologies and algorithms for vehicle-to-everything communications (including, of course, the infrastructure and the grid) that enable applications for smart routing, smooth and safe traffic flow, and higher operational efficiency of the network. TDOT investments in applied research should be considered, e.g., using big data and machine learning to improve traffic signals' delay and safety performance in Tennessee or harnessing basic safety message data from CAV.

- ***Future research on data collection, processing, analysis, and dissemination.*** In terms of future CAV research, it is important to invest in:
    - Developing sophisticated visualizations of CAV data. Specifically, TDOT can invest in creating a data visualization platform that will process real-time data and show different performance metrics. For instance, the visualization may include throughput, arrivals on green, progression ratio, and travel time index on signalized arterials.
    - Using modeling, artificial intelligence, and simulation capabilities based on data generated by CAVs and smart infrastructure enablers to enhance the diffusion of higher automation levels.
    - Accurately estimate and predict transportation system performance and develop proactive and multimodal transportation management systems.

3.5 Intelligent Mobility in Tennessee

The application of new tools, large-scale data, modeling, simulation, visualization, and artificial intelligence can help Tennessee plan for the future of intelligent mobility.

Successful implementation of intelligent mobility strategies requires that TDOT and partners rely on the diverse resources available in Tennessee, as mentioned previously. To prepare for intelligent mobility in Tennessee, recommendations are partly based on rankings received in the readiness survey of TennSMART consortium members. The recommendations are structured based on physical, digital, and electric vehicle charging infrastructure and public knowledge and acceptance.

- ***Enhancing readiness in physical roadway infrastructure.*** Several aspects need to be considered by TDOT, including 1) identifying road sign issues and addressing them so that CAVs can read the signs properly. 2) The use of smart cameras to detect different object types on the roadway that may need consideration to enhance safety (e.g., identifying trending risky behaviors among all road users and implementing mitigation measures before collisions occur) and improve mobility by reducing congestion on roadways (e.g., detecting vehicles, pedestrians, and cyclists to ensure demand is being serviced and signal timing plans are being used effectively). 3) Designing and increasing the width of pavement markings and improving signs, where needed, for CAV deployment to enhance their visibility throughout Tennessee (noting that TDOT is already in the process of doing this, with appropriate staffing and funding). Also, as mentioned, consider creating CAV park-and-ride facilities in the long-term and upgrading traffic signals to absorb new technologies to make the CAV deployment in Tennessee smoother. 4) Partner with organizations, e.g., TennSMART and academic institutions, to hold workshops addressing many individual aspects of intelligent mobility, e.g., roadway design changes and physical infrastructure needs, and offer courses in intelligent mobility. 5) While larger cities that have encouraged innovation in transportation seem more prepared than smaller and medium-size cities, relatively modest infrastructure investments in such cities, as appropriate, can significantly enhance their readiness. 6) Conduct research on cooperative driving automation and scenario generation to expand operational demand domains for highly automated vehicles.

- ***Enhancing readiness in digital infrastructure.*** TDOT can allocate more resources to workforce development in emerging technology and enhancing cybersecurity. Furthermore, cooperation with data science experts from different organizations such as universities can be enhanced and resources for harnessing C-V2X data should be considered. Real-time traffic and CAV data dashboards can be developed to improve the ability of TMC operators to access and harness the data. TDOT can work in conjunction with universities and the private sector to deploy a field solution for C-V2X communications and conduct research projects such as testing new OBUs and RSUs in both laboratory settings and on-road.
- ***Enhancing readiness in electric vehicle infrastructure.*** TDOT should consider adopting the zero-emission vehicle program, which includes several types of alternative fuel vehicles. Regarding support for transportation electrification, TDOT, TDEC, and diverse stakeholders such as TVA and private sector companies can partner to 1) develop a deployment plan for EV charging stations along interstates and key routes in Tennessee (effort underway through Tennessee Electric Vehicle Infrastructure, or TEVI). 2) Develop and use an infrastructure location planning tool for creating a network of charging stations based on the future demand for EVs in Tennessee and undertake other supportive actions related to EV charging. The plan can guide the efficient deployment of charging stations by considering the development of partnerships that can help prepare communities for locating DC fast charging. Also, constructing electric vehicle parking facilities through partnerships with public building authorities can be pursued.
- ***Strategies for readiness in public knowledge and acceptance.*** TDOT can improve public knowledge and acceptance using either internal resources or through the participation of universities, especially centers or institutes that focus on technology transfer activities and public awareness. Strategies to consider can include educating travelers about CAV capabilities, re-engaging AVs in complex situations when driver attention is needed and communicating the intent of CAVs to conventional vehicle drivers. Also, knowledge about alternative fuel vehicles (including EVs) can be disseminated through the Tennessee Clean Fuel Coalition, which is a DOE Clean City program (an initiative that TDOT's Long Range Planning can coordinate and pursue). TDOT can seek and incorporate public feedback into intelligent mobility policies and programs. TDOT can cooperate with other private or public

organizations to study EV/CAV adoption based on their specific models. One example is the ORNL Market Acceptance of Advanced Automotive Technologies (MA3T) model.

To deploy smart infrastructure enablers for intelligent mobility strategies, such as automated and electric vehicles, all stakeholders need to be fully engaged in an open process.

- ***General strategies for enhancing intelligent mobility.*** The strategies mentioned below can be adopted by TDOT, with some of them supporting TDOT's Transportation System Management and Operations Program Plan. The strategies include several action items that can be easily implemented to show demonstrable progress.

1) **Creating Roadmaps.** TDOT can develop roadmaps for physical and digital infrastructure, electric vehicle infrastructure, regulation and policy, user acceptance, partnerships with stakeholders, and workforce development. To deploy smart infrastructure enablers for intelligent mobility strategies, such as automated and electric vehicles, all stakeholders need to be fully engaged in an open process. For example, intelligent transportation systems and broadband/fiber roadmaps can be developed with stakeholder input by the Traffic Operations Division in coordination with the Information Technology Division (responsible for computerized information resources) and transportation consultants. Currently, the Transportation Systems Management and Operations Program Plan development is underway at TDOT, which outlines the vision and strategies for intelligent mobility. Furthermore, TDOT and TDEC are collaborating to develop the Tennessee Electric Vehicle Infrastructure Deployment Plan. Such activities can be expanded to achieve the broader impact of intelligent mobility technologies and cover other areas mentioned above e.g. physical infrastructure.
2) **Benchmarking.** Efforts can be undertaken to understand the current state of practice of statewide intelligent mobility readiness plans in other states, lessons learned, and recommendations while tracking emerging technology advances.
3) **Intelligent Transportation Systems.** Improvements in roadway, digital, and electric vehicle infrastructure technologies through ITS architecture service packages for implementation can be envisioned. A wide range of CAV service applications can be considered for implementation in Tennessee, including emergency vehicle preemption, broadcast traveler information, queue warning, work zone management, personalized traveler information, road weather motorist and warning, pedestrian and cyclist safety, and electric charging stations management.
4) **Multimodal transportation.** TDOT can identify opportunities in terms of connected, automated, and electric transportation systems that are multimodal, i.e., including freight, transit, pedestrians, and bicycles. For example, the TDOT Traffic Operations Division staff can work with the Multimodal Transportation Resources Division staff to conceive and implement projects that deal with transit systems detecting pedestrians to increase safety or coordinate with private sector logistics companies to improve freight movement and delivery.

5) **Planning.** Intelligent mobility strategies can be integrated into long-term planning and programming processes. This activity can involve coordination between the Traffic Operations Division and Long Range Planning Division staff for the various plans created at TDOT, e.g., the TSMO Program Plan and the TEVI plan.

6) **Data collection.** TDOT can develop data collection and harnessing capability from new sensors, e.g., OBUs and RSUs that transmit basic safety messages and alerts or warnings. However, this will require investments of significant resources to handle CAV-related activities, including equipment deployment and data collection. Notably, CAV data collection, processing, and use are particularly challenging, given the uncertainties associated with communication technologies (i.e., DSRC V2X technology), CAV data storage and analysis, data sharing, the requirement to have a sufficient number of OBUs on vehicles, and TDOT not owning or operating traffic signals.

7) **Conduct Interviews and Surveys.** Technology readiness surveys were designed and conducted for members of the TennSMART consortium by the research team. TDOT can further conduct interviews and surveys of various stakeholders, including TDOT Division Directors and staff in terms of their readiness for CAV and synergistic technologies, including electric vehicles.

8) **Workforce.** TDOT can consider creating positions for TDOT-based program managers to test and deploy CAVs (their responsibilities can be similar to ITS managers). This activity will be clearly resource intensive.

9) **Coordination.** Develop an external stakeholder coordination strategy, especially with IOOs, vehicle manufacturers, information technology companies, and the TennSMART consortium.

10) **Research Development and Deployment.** TDOT can further research, develop and deploy intelligent mobility technologies. TDOT is demonstrating the capabilities and benefits of CAVs through testbeds, e.g., I-24 Smart Corridor. Additionally, the Chattanooga MLK Smart City Corridor testbed and other statewide initiatives are exemplars. More comprehensive testing and deployment of these technologies will help achieve transportation system improvement goals.

- ***Future research on intelligent mobility strategies.*** TDOT can conduct research on specific issues related to CAV data, harnessing the data and investing in modeling/simulation capabilities that can directly deal with the complexity and fragility of the transportation system when operating in a mixed-mode, where some vehicles are high-level CAVs while others are human-driven. Currently, TDOT is researching the I-24 Mobility Technology Interstate Observation Network (I-24 MOTION) to understand how different types of vehicles interact with each other and the State's infrastructure to advance congestion management across Tennessee. Also, TDOT's Research Program is able to address short-term research needs. However, more investments in research activities to synergize various aspects of intelligent mobility strategies are needed. TDOT should continue to invest in several aspects of intelligent mobility strategies. These would include research on the efficacy and broader impacts of intelligent mobility strategies and the potential for disruption in terms of job losses in Tennessee due to vehicle automation, e.g., taxi and large truck driver jobs. Further, there is a need to explore how rural areas will be impacted by access to CAV and broadband technologies, how transit agencies can use CAV technologies to address first mile/last mile issues, and how to address equity and inclusion of disadvantaged and under-represented groups in the accessibility of emerging technologies, and what are the impacts of intelligent mobility strategies on land use in the long term.

Overall, this report and supplementary reports highlight investments needed in intelligent mobility strategies from a statewide perspective. In this regard, it is critical to nurture partnerships between stakeholders, i.e., government agencies, industry, and academic institutions, as is workforce development. Specifically, investments are needed in innovative solutions encompassing physical infrastructure, digital and smart infrastructure, electric vehicles, and charging infrastructure. Furthermore, state policies and regulations are needed to guide the safe development, deployment, and adoption of new technologies, considering federal policy guidance. The application of new tools, large-scale data, modeling, simulation, visualization, and artificial intelligence can help Tennessee plan for the future of intelligent mobility.

The supplementary reports highlight more details about use-cases that can be helpful in the deployment of smart infrastructure in Tennessee. For instance, these include 1) installing RSUs and OBUs on personal and state vehicles, 2) funding opportunities in IIJA, 3) options for installing communications equipment when TDOT does not own or operate traffic signals, 4) communications considerations associated with connected vehicle equipment, 5) use cases showing CAV data storage/transmission considerations, and 6) staffing needs associated with smart infrastructure deployments.

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