Connected and Automated Vehicles Investment and Smart Infrastructure in Tennessee

Part 1: A review of smart corridor projects across the US with implications for intelligent mobility in Tennessee

Research Final Report from University of Tennessee | Asad Khattak & Iman Mahdinia | May 1, 2022

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16. Abstract

The development of a smart corridor entails the installation of existing and emerging technologies for traffic management within a highway corridor. The goal is to improve traffic conditions on interstates/expressways and parallel arterials. Using text mining, this report discusses investments in smart corridor projects across the United States and performance measures used in smart corridor studies nationwide. The report focuses on issues in developing evaluation plans for smart corridors. These can include establishing a basis for comparison, defining data collection methods, assuring impartiality, and gaining cooperation. The report provides insights on evaluating existing and future smart corridors in Tennessee. Based on an analysis of relevant reports, the concept of smart corridors and the steps for evaluating smart corridor performance are discussed. A fundamental premise of the smart corridor evaluation methodology is that physical infrastructure, digital infrastructure, electric vehicle charging infrastructure, and cooperation among stakeholders are needed for effective implementation. The evaluation steps typically include the analysis of network performance, vehicle movements, traveler response, interviews with stakeholders and participants, and direct measurements of system elements. The report discusses the nature of natural experiments and the practical issues that come into play, from data collection mechanisms to the framing of agreeable goals and objectives.

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Executive Summary

Background

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*

The themes of Connected and Automated Vehicles (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.

Key Findings

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.

Recommendations

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 aims to improve 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 roadside unit (RSU) and onboard unit (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 (EV) 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 using 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 cellular vehicle-to-everything (C-V2X) communication equipment, partnerships with stakeholders, especially infrastructure owners and operators (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 EV fast-charging network to enhance electrification across Tennessee. Notably, the "Fast Charge TN Network" has prioritized corridor infrastructure gaps, and coordination with the Tennessee Department of Environment and Conservation (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, including 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 more significant 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 original equipment manufacturers 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 Federal Communications Commission ruling on opening dedicated short-range communication 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 connected vehicle (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 Basic Safety Message (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 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, and 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 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 vital to invest in evaluating the potential benefits/costs and impacts of emerging technologies and associated strategies in smart corridors within Tennessee.

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Glossary of Key Terms and Acronyms

ACC - Adaptive Cruise Control
ADMS - Arterial Dynamic Message Signs
ADS - Aftermarket Safety Devices
AV – Automated Vehicle
BRT - Bus Rapid Transit
BSM – Basic Safety Message
CACC - Cooperative Adaptive Cruise Control
CAV – Connected and Automated Vehicle
CCTV - Closed-Circuit Television
CV – Connected Vehicle
C-V2X - Cellular Vehicle-to-Everything
DOT - Department of Transportation
DSRC - Dedicated Short-Range Communication
EV – Electric Vehicle
FCC – Federal Communication Commission
FCW - Forward Collision Warning
FHWA - Federal Highway Administration
HIP - Highway Infrastructure Program
I2V - Infrastructure-to-Vehicle
INC-ZONE - Incident Scene Work Zone Alerts
IOOs - Infrastructure Owners and Operators
LED - Light-Emitting Diode
LTE – Long-Term Evolution
NHTSA - National Highway Traffic Safety Administration
OBU – Onboard Unit
ORNL - Oak Ridge National Laboratory
OTA - Over-The-Air
QDA – Qualitative Data Analysis
RDS - Radar Detection System
RSU – Roadside Unit
TDEC - Tennessee Department of Environment and Conservation
THEA-Tampa Hillsborough Expressway Authority
TSMO - Transportation Systems Management and Operations
TVA - Tennessee Valley Authority
UM - University of Michigan
US DOT - US Department of Transportation
V2I - Vehicle-to-Infrastructure
V2V – Vehicle-to-Vehicle
V2X – Vehicle-to-Everything
WAS - Worker Alert System

Chapter 1 Introduction

The evaluation experiences gained from reviewing relevant smart corridor literature provide insight into how to conduct successful smart corridor implementation and evaluations in Tennessee.

The development of smart corridors often entails installing advanced and emerging traffic management, traveler information, and automation/connectivity technologies within a highway corridor. The goal is to provide improved mobility and safety by improving and balancing traffic demand on a stretch of freeway or expressway and parallel arterial streets. This report reviews smart corridor projects across the US that have implications for intelligent mobility in Tennessee. Steps for evaluating performance are discussed. They include analysis of network performance, 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. This report emphasizes 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 provide insight into how to conduct successful smart corridor implementation and evaluations in Tennessee.

Based on the literature reviewed, this research finds that future investments in smart corridors are critical for improving transportation system performance.

1.1 Framework

One of the most significant developments in transportation is the management of the transportation system through the design and implementation of connectivity and automation for integrated freeway and arterial control. Such corridors are often termed "Smart Corridors" and are intended to provide improved mobility and safety by managing traffic flows. Broadly speaking, Transportation Systems Management and Operations (TSMO) elements can include:

- Connected and Automated Vehicle (CAV) technology deployment that includes roadside units (RSUs) and onboard units (OBUs).
- Ramp metering, with rates that dynamically respond to dynamic traffic conditions and incidents.
- Adaptive signal systems that include alternate signal plans for unexpected events such as incidents.

- Changeable message signs to direct travelers and advise travelers on and off the corridor of traffic conditions and incidents.
- Media services, including highway-advisory radio, to further inform travelers.
- Crews and freeway service patrols to speed the clearance and investigation of traffic incidents.
- Work zone management.
- Improved pedestrian and bicycle movements, e.g., when crossing arterials.
- Electric vehicle (EV) fueling support.
- Mobility on-demand services.

Although new technologies promise substantial benefits, it is still unclear whether these benefits justify the cost of smart corridor implementation and operation costs. Smart corridor projects often cost tens of millions of dollars and the benefits in terms of time savings or safety improvements must be substantial, e.g., in terms of thousands of fewer hours of vehicle delay per day over a relatively long time horizon to justify costs.

Evaluating the effectiveness of smart corridors is complex, requiring a robust framework and a plan that accounts for practical issues in the execution. To the extent possible, the evaluation framework should be quantitative while accounting for the institutional environment in which large-scale technology testing and deployment evaluations are performed.

As the move toward information and communication technology applications in transportation continues, many State Departments of Transportation are preparing for the incoming technologies to be implemented on US roadways. This portion of the research project reviews existing smart corridors, smart corridor investment plans, smart corridors that are being studied, and statewide connected vehicle (CV) pilots. To accomplish this, 22 technical reports from 12 smart corridor/CV pilot projects were identified and reviewed. Critical information for these projects includes their locations, type of roads, project objectives, the technology used, including RSUs and OBUs, applications used in the projects, and their status. The selected smart corridor projects are structured along the lines of a comprehensive framework for investments in 1) roadway and physical infrastructure, 2) digital infrastructure, 3) electric vehicle infrastructure along with investments focusing on 4) public awareness and education, and 5) discussion of policies and regulations for the diffusion of emerging technologies, shown in Figure 1-1.

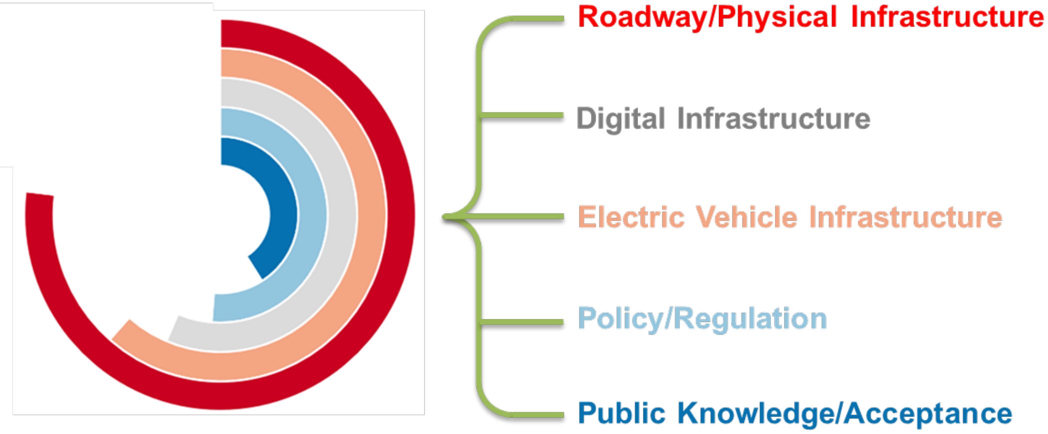


Figure 1-1 Five main areas of investment (Circles depict level of readiness by stakeholder)

A brief description of these areas is as follows:

- **Roadway/Physical Infrastructure:** Physical infrastructure includes all physical assets associated with roads (i.e., the roadway, markings, signage, safety barriers, earthworks, drainage, and structures). Also included are public transit systems as well as pedestrian and bicycle facilities.
- **Digital Infrastructure:** Digital infrastructure provides the information technology foundation for operating the transportation system. It includes transportation sensors (e.g., cameras, loops, and radars), cable, information dissemination equipment (e.g., radio transmitters and message signs), communication devices, traffic signal controllers, and transportation management centers with associated data centers and equipment. Digital infrastructure also includes cloud-hosted services, data centers, security credentialing, and in-vehicle devices/systems (Onboard units and sensing systems).
- **Electric Vehicle Infrastructure:** Electric vehicle infrastructure includes structures, machinery, and equipment needed to support electric vehicle charging, as well as electricity generation and distribution.
- **Policy/Regulation:** Policy and regulation comprise transportation system goals (e.g., mobility and safety), mechanisms for transportation investments, and relevant regulations (e.g., safety standards of CAVs on public roads).
- **Public Knowledge and Acceptance:** Public knowledge and acceptance signify communication and dissemination of scientifically based knowledge to the public to educate them about transportation issues (e.g., safe mobility). This is often done through media (e.g., smart devices and the internet).

While these elements are fundamental, additional application areas include cybersecurity, freight efficiency, and multimodal travel.

1.2 Organization of the Report

The report is organized into the following sections:

Chapter 2 - Review of Related Evaluation Projects. This chapter reviews and discusses the smart corridors in different states.

Chapter 3 - Performance Measures Found in Different Smart Corridor Projects. This chapter discussed the performance measures suggested in different smart corridor projects, e.g., travel time reliability, congestion, delay, environment, and safety.

Chapter 4 - Text Analysis of Smart Corridors Across the United States. This chapter utilizes artificial intelligence text analysis to synthesize information containing smart corridor project reports.

Chapter 5 - Opportunities and Compromises for Smart Corridors in Tennessee. This chapter discusses Tennessee's technical and institutional opportunities and challenges for smart corridors evaluations.

Chapter 6 - Conclusions and Recommendations. The findings are summarized along with the contributions of the reported work. A discussion of recommendations is provided.

Chapter 2 Review of Related Evaluation Projects

As mentioned earlier, smart corridors strive to: (1) continuously monitor and control traffic flows, manage traffic incidents and work zones, (3) provide information to motorists, and (4) dynamically control traffic signals and increasingly use CAV and electrification technologies, along with mobility on demand services. The investments in the five areas for the studied cases are presented in TABLE 2-1. Note that the findings are restricted to the contents of the selected reports only and may be subject to change. Clearly, EV infrastructure is not frequently addressed in smart corridors and policies and regulations are addressed to a limited extent.

TABLE 2-1 SMART CORRIDORS AND CONNECTED VEHICLE PILOT PROJECT INVESTMENTS

Smart Corridor/CV Pilot	***Roadway/Physical Investments***	***Digital Investments***	***Electric Vehicle infrastructure***	***Public Awareness and Education***	***Policies and Regulations***
THEA CV Pilot	✓	✓	✗	✓	✓
Missouri I-70	✓	✓	✗	✗	✗
California I-80 & I-880	✓	✓	✗	✓	✓
Iowa I-80	✓	✓	✗	✗	✓
Main Street, Buffalo, NY	✓	✓	✓	✓	✓
Virginia Avenue, Georgia	✓	✓	✓	✓	✗
North Avenue, Georgia	✓	✓	✗	✓	✗
Pennsylvania I-76 (Schuylkill Expressway)	✓	✓	✗	✗	✗
US 33 Smart Mobility Corridor, Ohio	✓	✓	✗	✓	✓
Wyoming CV Pilot, Wyoming	✓	✓	✗	✓	✓
CV Pilot, New York City	✓	✓	✗	✓	✓

The findings are summarized and synthesized to overview the current deployment and practices regarding Connected and Automated Vehicles and Smart infrastructures in the US, which can subsequently guide similar initiatives in Tennessee. Next, text-mining techniques are applied to these documents to systematically extract key topics of smart corridors, smart infrastructures, and CV pilots. Word cloud and co-occurrences maps are developed to understand and visualize which areas have been emphasized and prioritized in these projects, which will help develop similar projects for Tennessee.

2.1 Summary of Selected Smart Corridor Projects Across the US

Major smart corridor projects are multi-agency and utilize emerging technologies, including traffic management through information and communication technologies. The purposes of the smart corridor projects are to address the problems of corridor mobility and safety and reduce energy consumption and emissions. A variety of geographically dispersed smart corridor projects are presented below with the intent of providing insight into their locations, objectives, and technologies tested and implemented.

2.1.1 THEA Connected Vehicle Pilot, Tampa, Florida

Description: This pilot project is in the city streets of downtown Tampa, Florida [1] [2].

Objectives: 1) Crash prevention, 2) traffic flow enhancement, 3) transit trip time improvement, and 4) greenhouse gas (GHG) emission reduction.

Technologies: This project equipped OBUs in more than 1000 private cars, ten transit buses, and eight streetcars and equipped 47 RSUs throughout downtown. Dedicated short-range communications (DSRC) and satellite communications are used to communicate between the connected vehicles and RSUs. THEA uses Honda, Hyundai, and Toyota vehicles to test and deploy CV technology. Safety and mobility applications used in this project include End of Ramp Deceleration Warning, Forward Collision Warning, Emergency Electronic Brake Light Warning, Wrong-Way Entry, Intersection Movement Assist, Pedestrian Collision Warning, Transit Signal Priority, Vehicle Turning Right in Front of Transit Vehicle, Intelligent Signal System, and Probe Data-Enabled Traffic Monitoring.

2.1.2 Wyoming Connected Vehicle Pilot, Wyoming

Description: This project is located on Interstate 80 (I-80), a 402-mile-long road along the southern edge of Wyoming. Applications used in this project are Forward Collision Warning (FCW), Infrastructure-to-Vehicle (I2V) Situational Awareness, Work Zone Warning, Spot Weather Impact Warning, and Distress Notification. This is an ongoing project [3] [4].

Objectives: 1) Safety improvement, 2) increasing mobility and productivity of travelers on this road.

Technologies: This pilot uses Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and I2V connectivity using DSRC-based applications. This project equipped 75 RSUs on I-80's crash hotspots and installed OBUs on 400 fleet vehicles and commercial trucks. The 75 roadside units receive and broadcast messages using DSRC V2X along various sections of the I-80. In this project, a combination of fleet vehicles and 150 commercial trucks, with OBUs that are expected to be regular users of I-80 are deployed. OBUs have the functionality to broadcast Basic Safety Messages (BSMs) and collect environmental data through mobile weather sensors.

2.1.3 California I-80 and I-880 Smart Corridors, California

Description: The Interstate 80 Smart Corridor is an intelligent transportation system designed to improve safety, travel time reliability, and reduce congestion by implementing different traffic operations strategies. The segment of Interstate Highway 80 (I-80) in California runs east from San Francisco across the Bay Bridge to Oakland, where it turns north and crosses the Carquinez Bridge before turning back northeast through the Sacramento Valley. The speed limit is at most 65 miles per hour along the entire route because most of the route is in either urban areas or mountainous terrain. I-80 in California is about 205.07 mi (330.03 km). Notably, the California I-80 Smart Corridor aims to improve travel time reliability by measuring expected travel time and communicating those times to motorists so they can plan their trips. To that end, some corridor management devices, such as variable message signs and information display boards, are deployed. Furthermore, lane-use signs communicate with drivers that the lane is blocked ahead due to a stalled vehicle or incident. Variable advisory speed signs are deployed to slow down vehicles ahead of the queue to avoid secondary accidents [5].

Active traffic management is implemented to monitor traffic operations using closed-circuit television cameras and traffic detection devices to reduce traffic congestion. The I-80 incident management component provides real-time information to motorists in the event of an incident. The information is specific enough to reduce unexpected lane changes, provide easier access for emergency response vehicles, and reduce secondary accidents and congestion associated with such incidents. Moreover, deploying adaptive ramp metering devices on I-80 help to keep traffic flowing more smoothly and reduce greenhouse gases.

The Next Generation Simulation program collected detailed vehicle trajectory data on southbound US 101 and Lankershim Boulevard in Los Angeles, CA, and eastbound I-80 in the San Francisco Bay area in Emeryville, CA, on April 13, 2005. The detailed, high-quality traffic datasets support the development of microscopic driver behavior algorithms.

Objectives: 1) Reduces traffic congestion, 2) improves travel time reliability, 3) speeds up incident clearances, and 4) reduces greenhouse gases.

Technologies: The overall Smart Corridor Program includes using Intelligent Transportation System elements, including directional signs, fixed and pan-tilt-zoom closed-circuit television (CCTV) cameras at intersections and midblock locations, arterial dynamic message signs (ADMS), center-to-center communications between all local agencies, blocked lane signs, variable advisory speeds, real-time ramp metering, traffic information boards, incident management, local street improvements, and vehicle detector stations.

2.1.4 Iowa I-80 Smart Corridor, Iowa

Description: Interstate Highway 80 (I-80) is the longest Interstate Highway in Iowa. It extends from west to east across the state's central portion through the population centers of Council Bluffs, Des Moines, and the Quad Cities. Most of the highway runs through farmland, yet roughly one-third of Iowa's population lives along the I-80 corridor. The length of I-80 in Iowa State is 306.268 mi (492.891 km) [6].

Objectives: 1) Leverage existing automated vehicle (AV) knowledge, 2) help understand AVs and other transformative shifts in transportation, 3) prepare for AV impacts on safety, mobility, and travel time reliability in Iowa, and 4) plan for the future by considering the impact of AVs in the design of the proposed improvements.

Technologies: To achieve these goals, some infrastructure should be provided. In fact, one aspect of this study is to identify the impacts on required and recommended infrastructure due to the emergence of AVs. AV-supportive infrastructure includes:

- Communications infrastructure: Advanced cellular and fiber
- Detection: Cameras, sensors, and processed data from AVs

Infrastructure elements include physical elements such as fiber and cameras and virtual elements, such as HD mapping, which provide additional sensing capabilities that work beyond the range of AV sensors and functions in all-weather scenarios. AV-supported infrastructure will transition I-80 to a corridor that provides connected and cooperative information between vehicles and the roadway and roadway operator.

2.1.5 Missouri I-70 Smart Corridor, Missouri

Description: Interstate 70 (I-70) in Missouri is parallel to the Missouri River. This section of the transcontinental Interstate begins at the Kansas state line on the Lewis and Clark Viaduct, concurrent with US Routes 24, 40, and 169, and the east end is on the Stan Musial Veterans Memorial Bridge in St. Louis. In total, the I-70 Highway traverses 250 mi (402 Km) across the Missouri state [7].

Objectives: 1) Reduce traffic-related fatalities, injuries, and property damage; 2) minimize and manage traffic congestion and improve travel time reliability; 3) optimize system performance through agile incident management; and 4) improve access to transportation innovations for low- and medium-income populations that do not use smartphones or own DSRC-enabled vehicles.

Technologies: This project has considered the following innovative technologies to achieve the goals:

- Integrated Model for Road Condition Prediction
- Dedicated Short-Range Communications systems and variable message signs
- Real-time traffic operations using vehicle probe data
- Autonomous truck-mounted attenuator vehicles
- Mesh networking platform for V2X communications using 4G LTE and DSRC V2X
- Predictive analytics and machine learning for incident management
- Mobile edge computing system supporting highway Internet of Things applications

2.1.6 Ohio 33 Smart Corridor, Ohio

Description: Ohio 33 Smart Corridor is a 35-mile highway between Dublin, Maryville, and East Liberty in Ohio. This highway is being developed as a proving ground for CAVs and smart mobility technologies [8] [9] [10].

Objectives: The objective of developing such a test ground is to show that even smaller cities can adapt to the growing transportation technologies and have congestion-free safer roads.

Technologies: The corridor has been equipped with a fiber-optic network, 62 RSUs, and 45 connected intersections. The corridor is planned to use DSRC V2X for communication. Traffic signals will be connected to DSRC detectors that communicate directly with connected vehicles. Honda is testing their 200 CVs in this corridor to test its V2X technology that will increase safety and fuel efficiency. Later the testbed will test higher levels of automation. This is an ongoing project and plans to deploy a pool of up to 1200 test vehicles. The test vehicles will be installed with OBUs and displays for communication with RSUs through DSRC V2X.

The Ohio DOT and Honda are working closely with the City of Marysville to develop AV/CV testing in an urban environment. DSRC V2X units will be installed in up to 1200 vehicles to test connected and automated vehicle technology and applications. It is stated in this project that Honda will use its purchasing and acquisition processes to procure and install the DSRC V2X units on their vehicles for testing.

2.1.7 I-76 (Schuylkill Expressway) corridor, Pennsylvania

Description: This project area is located along Interstate-76 (I-76) between King of Prussia and Philadelphia. The project is part of the Integrated Corridor Management initiative [11] [12].

Objectives: 1) Maximizing road capacity; 2) optimizing traffic flows on adjacent roadways; and 3) regionwide promotion of walking, biking, and transit use.

Technologies: According to the TSMO guidebook, such corridors should have dynamic solutions that support efficient transportation facilities and incorporate other TSMO strategies. For instance, this project has installed 72 variable speed limit signs and an end-to-end Queue Detection and Warning system along eastbound and westbound I-76 (Schuylkill Expressway) from the Pennsylvania Turnpike in Montgomery County to the US 1 North (Roosevelt Expressway) Interchange in Philadelphia. Other considered strategies for this I-76 corridor include Dynamic Signal Management, Ramp Metering, Junction Control, Part-Time Shoulder Use, and Smart Parking. This is an ongoing project.

2.1.8 Main Street Smart Corridor Plan, Buffalo, New York

Description: The main street smart corridor is between Goodell Street and Ferry Street in Buffalo, NY [13].

Objectives: The ultimate objective of the Buffalo main street-smart corridor plan is to create a corridor to pilot smart city transportation projects that can be expanded after an initial testing period.

Technologies: The technologies for the corridor plan are divided into three phases.

- Phase 1: Installation of smart city communications (e.g., wi-fi enabled traffic signal boxes, and public wi-fi routers), smart city sensors, smart cycle track utilizing existing sensor technology that gives intersection priority to cyclists and micro-mobility users, EV charging stations, smart mobility hubs.
- Phase 2: Development of the systems architecture, regional Smart Operating System responsible for data storage, processing, and distribution to collaborative entities.
- Phase 3: Integration of real-time data to display available spaces, dynamic pricing for parking spaces, dynamically controlled traffic signals, creating a universal design testing

intersection to pilot new and emerging universal design technology, ready corridor with AV/CV infrastructure for pilot testing.

2.1.9 Virginia Avenue Smart Corridor, Georgia

Description: The 2-mile Virginia Avenue Smart Corridor from US 29 main street in Atlanta, Georgia, is the study area of this project [14].

Objectives: The overall goal is to assess the potential of new and emerging transportation technologies and their ability to address safety, walkability, and mobility along the Virginia Avenue Smart Corridor.

Technologies: Thirty-three (33) technology applications were evaluated in this project. The applications are broadly on traffic signals, bike/pedestrian, street lighting, pavement/sidewalks, wayfinding, transit, parking, EV charging, vehicle surveillance, wi-fi, curbside, phone apps, and data exchange. Notably, DSRC V2X and 5G-NR C-V2X communications solutions are recommended for the project. As part of this project, there has been extensive research to understand better the differences between DSRC V2X and C-V2X based on 5G-NR. The conclusions were that some technology applications might be better suited for DSRC V2X and some for C-V2X (4G LTE or 5G-NR), while many can use either.

Transit signal priority, emergency vehicle signal preemption, transit-pedestrian warning system, CV-based adaptive signal control technologies, and bike signal detection are some of the mentioned technologies to move forward in this project.

2.1.10 North Avenue Smart Corridor, Georgia

Description: North Avenue Corridor is a 2.3-mile stretch of roadway. It includes multiple transit operators and routes and intersects with important bicycle routes. It also comprises 26 signalized intersections from Northside Drive to Freedom Parkway. A significant portion of the corridor is also a US and state route [15].

Objectives: The project's long-term goal is to improve safety and better manage multimodal traffic flow for special events and normal traffic conditions.

Technologies:

- Real time response based on advanced video detection systems.
- A combination of thermal imaging and video cameras continuously detects pedestrians and bicycles for adaptive control of the traffic signals.
- Smart alert for cyclists and pedestrians through a smartphone app.
- All mobility users are connected to each other and the technology on the street (V2I).

2.1.11 CAV Corridor, Michigan

Description: Michigan DOT has envisioned developing a 40-mile-long smart corridor consisting of lanes fully dedicated for CAV operations. This corridor will connect Detroit and Ann Arbor by encompassing Michigan Avenue and Interstate 94 in Wayne County and Washtenaw County. Critical destinations of this corridor will be various opportunity zones like universities, automotive companies, and businesses. The project is under study [16] [17].

Objectives: Some of the key objectives of this project are safety improvement, open data accessibility, cyber security, replicability, and co-existence of CAVs, transits, freight, cars, and shared mobility on the same road.

Technologies: Phase one of the project will examine CAV technology and different financial models to achieve a viable project plan. The subsequent phases will consist of constructions and deployments.

2.1.12 CV Pilot Deployment Program, New York City, New York

Description: This CV pilot project encompasses three study areas in Manhattan and Brooklyn. Area one consists of a 4-mile segment of Franklin D. Roosevelt drive in Manhattan's Upper East Side and East Harlem neighborhoods. Area two covers four one-way corridors in Manhattan. Area three includes a 1.6-mile segment of Flatbush Avenue in Brooklyn [18].

Objectives: The main objectives of the pilot are reducing crash frequency and severity, managing the speed of the vehicles, and assessing the benefits of CV deployment in a dense urban environment.

Technologies: The initial plan mentions installing OBUs in 5800 cabs, 1250 MTA buses, 400 commercial fleet delivery trucks, and 500 city vehicles. Using DSRC V2X technology, the pilot also establishes 353 RSUs at approximately 310 signalized intersections of Manhattan and Brooklyn. Three connectivity applications are considered.

- V2V safety application includes Forward Collision Warning, Emergency Electronic Brake Lights, Blind Spot Warning, Lane Change Warning, Intersection Movement Assist, and Vehicle Turning Right in Front of Bus Warning.
- V2I safety applications include Speed Compliance, Curve Speed Compliance, Speed Compliance in Work Zone, Red Light Violation Warning, Oversize Vehicle Compliance, and Emergency Communications and Evacuation Information.
- V2I pedestrian application includes Pedestrian in Signalized Crosswalk and Mobile Accessible Pedestrian Signal System.

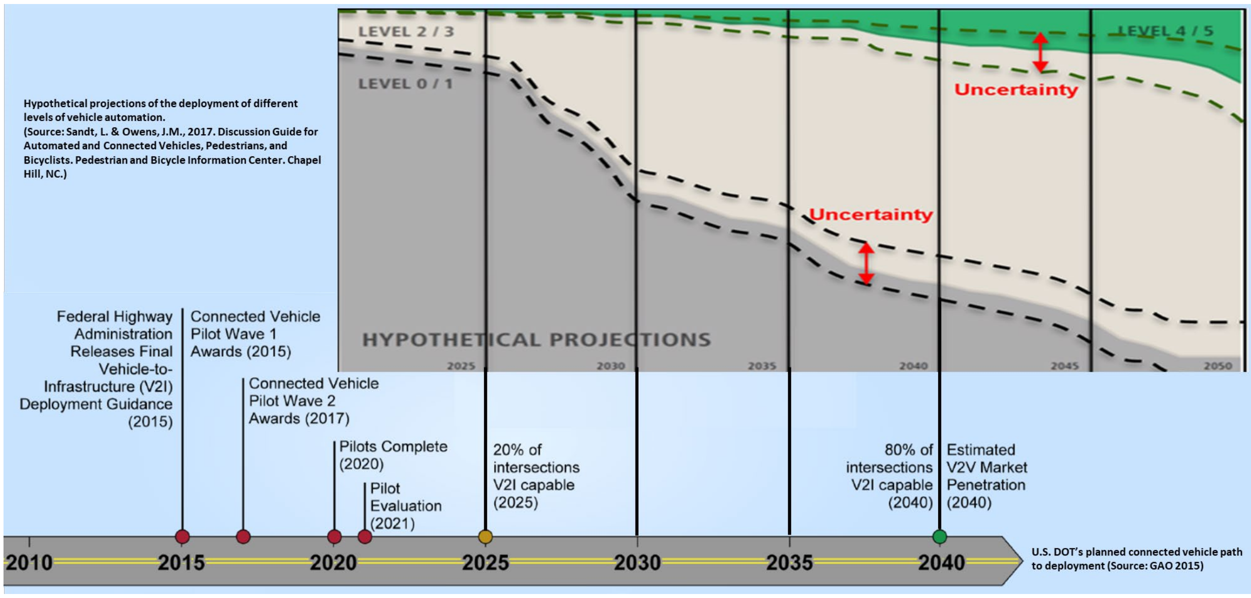
2.2 Synthesis

Based on a review of the projects mentioned above, most smart corridors and cities focus on connectivity that supports technology at low levels of automation up to National Highway Traffic Safety Administration (NHTSA) Level 2. However, some aspire to achieve higher levels of vehicle automation, i.e., Levels 3 and 4. A few projects have studied the feasibility of deploying necessary infrastructure and vehicles with higher levels of automation. For instance, the I-70 Ohio-Indiana Truck Automation Corridor was awarded $4.4 million to advance the adoption of truck

> …the deployment of CV technologies to support lower levels of vehicle automation is likely in the near future (5 years or so), while supporting higher levels of AV technologies (Level 3 or 4) especially in complex environments such as urban areas will take longer.

automation technologies. Progressively more complex deployments will include Level 1 platooning technology while the driver is in control, Level 2 driver assist capabilities, such as longitudinal and lateral control, and finally, Level 4 highly automated truck deployments. However, the exact timeline for Level 4 automation in this project is unclear. Furthermore, in the Indianapolis automation of the Red-Line eBRT (Bus Rapid Transit) system project, the Indianapolis Smart City initiative is planning to identify and finance the support and infrastructure needed to implement and operate NHTSA Level 4 automated and electric BRT system. Also, the Airport Shuttle Automation project in Indianapolis is under the immediate implementation of NHTSA Level 4 automation using an electric autonomous shuttle system. While most smart corridors are working on testing and implementing Level 1 and 2 automation, depending on the Operational Design Domain in rare and selected situations, higher levels of automation can be envisioned and tested.

Figure 2-1 demonstrates hypothetical projections of the US vehicle fleet composition with different levels of automation. The figure shows that lower levels of automation will dominate for quite a long period of time, while higher levels of automation will not be available widely for some time. Notably, the graph is a hypothetical projection and differing opinions exist in agencies, industry, and academia about when specific levels of automation will diffuse through the transportation system. Nevertheless, this timeline for different CAV technologies is meant to convey that widespread adoption of high automation levels is likely to take time, given the uncertainties associated with decisions made by stakeholders such as the Federal Communication Commission (FCC) and the current state of automation enabling technologies, including data science and artificial intelligence techniques (e.g., predicting edge cases may be the Achilles' heel). To reiterate, the deployment of CV technologies to support lower levels of vehicle automation is likely in the near future (5 years or so), while supporting higher levels of AV technologies (Level 3 or 4), especially in complex environments such as urban areas will take longer.



Hypothetical projections of the deployment of different levels of vehicle automation.
(Source: Sandt, L. & Owens, J.M., 2017. Discussion Guide for Automated and Connected Vehicles, Pedestrians, and Bicyclists. Pedestrian and Bicycle Information Center. Chapel Hill, NC.)

U.S. DOT's planned connected vehicle path to deployment (Source: GAO 2015)

Figure 2-1 CV/AV hypothetical paths to deployment

Chapter 3 Performance Measures Found in Different Smart Corridor Projects

Broadly speaking, the core questions in a smart corridor evaluation include:

- Does the smart corridor project improve the distribution of traffic across the network reducing both recurrent and non-recurrent congestion, resulting in more effective use of corridor capacity?
- Does the smart corridor improve the network's capability to serve large traffic volumes with an acceptable level of service?
- How effective is the smart corridor’s multi-agency arrangement and cooperation in responding to the corridor's traffic problems?
- Does the smart corridor improve overall safety in terms of reducing the number of crashes and fatalities?

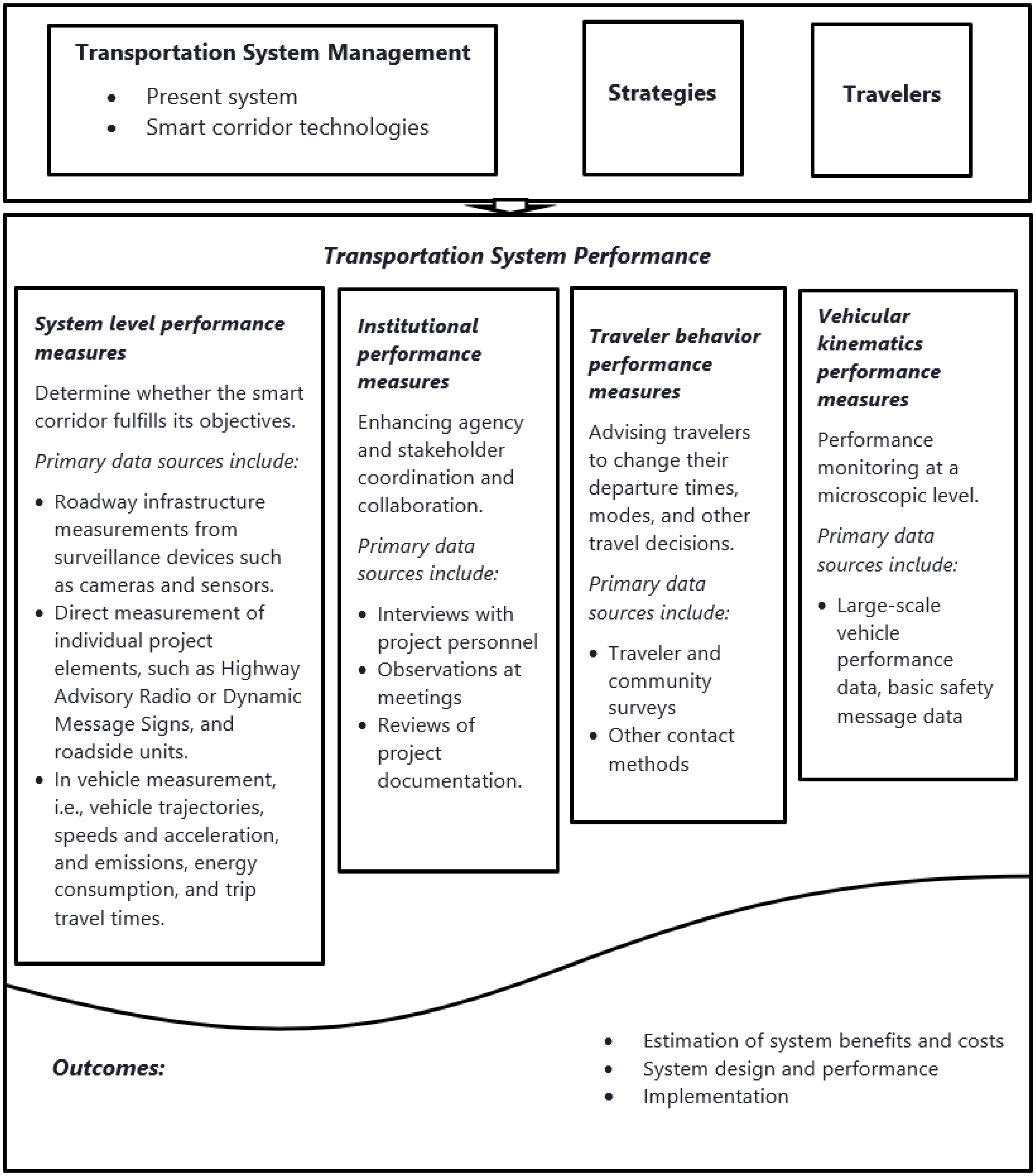
Performance measurement can be broadly divided into system or network level performance, traveler behavior and vehicle movements, and institutional issues. This section identifies performance measures used in studies to determine the impacts of the smart corridors' strategies and technologies. Key elements for smart corridor performance evaluation are shown in Figure 3-1.

3.1 System Level Performance Measures

Relevant data must be collected within the corridor to determine whether the smart corridor fulfills its objectives. Primary data sources include:

- Roadway infrastructure measurements from surveillance devices such as cameras and sensors.
- Direct measurement of individual project elements, such as Highway Advisory Radio or Dynamic Message Signs and roadside units.
- In vehicle measurements, i.e., vehicle trajectories, speeds and acceleration, and emissions, energy consumption, and trip travel times.

The data can effectively measure changes in throughput and speeds and might be used to infer changes in travel time, energy consumption, and emissions. The data also helps evaluators determine whether elements operate as expected, and in-vehicle data might be used for various purposes. Spanning all evaluation elements, it is also essential to include financial analysis to ascertain whether the benefits are cost-justified. This includes auditing costs incurred in all implementation phases and estimation of future operating and maintenance costs over the project's entire life cycle. The following measures were used in selected projects at a macroscopic system level to evaluate smart corridor performance.



Transportation System Management

- Present system
- Smart corridor technologies

Strategies

Travelers

Transportation System Performance

System level performance measures

Determine whether the smart corridor fulfills its objectives.

Primary data sources include:

- Roadway infrastructure measurements from surveillance devices such as cameras and sensors.
- Direct measurement of individual project elements, such as Highway Advisory Radio or Dynamic Message Signs, and roadside units.
- In vehicle measurement, i.e., vehicle trajectories, speeds and acceleration, and emissions, energy consumption, and trip travel times.

Institutional performance measures

Enhancing agency and stakeholder coordination and collaboration.

Primary data sources include:

- Interviews with project personnel
- Observations at meetings
- Reviews of project documentation.

Traveler behavior performance measures

Advising travelers to change their departure times, modes, and other travel decisions.

Primary data sources include:

- Traveler and community surveys
- Other contact methods

Vehicular kinematics performance measures

Performance monitoring at a microscopic level.

Primary data sources include:

- Large-scale vehicle performance data, basic safety message data

Outcomes:

- Estimation of system benefits and costs
- System design and performance
- Implementation

Figure 3-1 Key elements for smart corridor performance evaluation

California I-80 Smart Corridor Performance Measures [5]**:**

- Reduction in measured congestion
- Reduction in system travel time
- Reduction in queue clearance duration
- Reduction in amount of traffic filtering through local network

- Average time after an incident when Caltrans notifies local agencies
- Average time to activate alternate routes
- Average time required for traffic signals to transition to flush plan
- Percentage of time that the use of smart corridor devices provides satisfactory traffic flow
- Number of resources expended for managing traffic on local streets during freeway incidents
- Percentage of incidents that do not require active traffic monitoring on local streets
- Results of user surveys on the use of the Smart Corridor

Measures of Effectiveness-Smart Corridor I-80 in IOWA [6]**:**

- Density
- Capacity (maximum achievable traffic volume)
- Demand-to-capacity ratio
- Travel time and speed

Ohio State, US 33 Smart Corridor Performance Measures [9]**:**

- Reduce traffic-related fatalities and injuries
- Reduce traffic congestion
- Improve travel time reliability
- Reduce transportation-related emissions
- Improve public access to real-time integrated multimodal transportation information.

Buffalo NY, Main Street Smart Corridor Performance Measures [19]**:**

- Number of car, bicycle, and pedestrian accidents (looking for reduction/improvement to safety with smart city applications)
- Emergency Response Times
- Number of kilowatts per hour (kW/hr) saved from lighting (with use of smart/ LED street lighting)
- Reduction in vehicle emission through more efficient travel/mode choices
- Number of hours used at electric vehicle charging stations
- Number of new users
- Number of accessible data sets produced
- Number of smart infrastructure and roadside units installed

While smart corridors are beneficial in reducing recurrent congestion, they are likely to be most helpful in reducing non-recurrent congestion. Additional criteria typically include improvements in safety, energy, and emissions. Smart corridors employ an increasingly wide array of technologies and tools to address goals, e.g., quickly remove incidents, adjust signal settings on arterials and ramps to provide capacity where it is needed most (through extended cycles and adjusted phases), and stimulate changes in traveler behavior, to better utilize existing capacity. As a whole, smart corridors augment and utilize capacity more effectively.

3.2 Traveler behavior performance measures

Capacity utilization entails directing or advising travelers to divert to under-saturated routes to expedite their own travel and free up capacity for travelers who absolutely must use more congested routes. Behavioral strategies may entail advising travelers to change their departure times, modes, and other travel decisions. Unlike network management strategies such as signal control, information dissemination strategies are challenging to quantify and measure. However, by controlling information dissemination along the dimensions of content and medium and ensuring quality, smart corridor operators can influence traveler response and system performance. The goal is to provide messages that induce the desired response. Travelers' response to information is often conditioned based on their trust in the information source. If messages are not consistent with travelers' observations or other sources of information (such as smartphones), users will ignore them or perhaps react opposite to the advice. It is critical for smart corridor projects to develop a consistent policy for information dissemination that builds trust among travelers.

Traveler responses to smart corridors often rely on measuring changes in individual travel patterns that result from the implementation of smart corridor technologies. The questions to be answered can include the user benefits, both tangible and intangible, from Dynamic Message Signs and Advisory Radio. The extent of change in motorist usage of these technologies over time. Smart corridors can benefit users in terms of

- Reduced travel time and travel costs (e.g., vehicle operating costs, including wear and tear).
- Supportive information for changes in travel patterns under incident, adverse weather, or otherwise congested conditions.
- Increased knowledge of travel options (e.g., about alternate routes that may facilitate route choice).
- Reduced anxiety (even if travelers do not change their travel decisions).
- Reduced likelihood of getting lost.
- Increased reliability, particularly for arrival at destination.
- Enhanced ability to reschedule activities (e.g., through mobile phones) when unexpected events occur.

Evaluation projects typically investigate traveler responses (such as route diversion and departure time changes) from the smart corridor. Through traveler and community surveys and other contact methods, it is vital to understand how various factors impact traveler behavior over time; changes in traveler behavior are an essential component in determining the degree of success of smart corridors.

Some of the key traveler behavior performance measures (at an aggregate level) found in smart corridor studies are listed below [19]**:**

- Reduction in vehicle emission through more efficient travel/mode choices
- Duration of use for smart corridor applications
- Number of new users who have access to smart corridor applications
- Size of areas where public wi-fi connectivity is provided to support vehicle automation
- Number of hours travelers use electric vehicle charging stations

3.3 vehicular kinematics performance measures

With CAVs, more microscopic-level data are becoming available, and one such data source is the availability of basic safety message data. To harness large-scale vehicle performance data, the concept of driving volatility and time-to-collision have been utilized in recent studies to quantify the safety performance and fuel consumption and emissions are calculated to measure the environmental impacts.

Driving Volatility Measures

Volatility measures are used to quantify driving variation. Volatility measures try to capture variations in longitudinal control of the vehicle. To this end, these measures can be applied to speed, acceleration/deceleration, and vehicular jerk. Higher driving volatility contributes substantially to crash risk [20].

Time-to-Collision Measures

Time-to-Collision is a surrogate safety measure which is generally defined as “the duration of time before two objects collide with initial certain conditions” [21]. This measure is used to assess the risk of the rear-end collision and evaluate safety [22] [23].

Vehicle Fuel Consumption

The model proposed by Kamal et al. [24] is used to calculate fuel consumption. Their proposed model takes advantage of the relationship between speed, acceleration, and fuel consumption. This model can calculate fuel consumption at a microscopic level.

Vehicle Emissions

The vehicle-specific power microscopic model can estimate emissions regarding vehicle second-by-second speed, acceleration, and terrain gradient [25] using vehicular BSM data.

These measures can be applied to connected and automated vehicle technologies, which have the potential to improve transportation system performance significantly. In particular, advanced driver-assistance systems, such as adaptive cruise control (ACC) and cooperative adaptive cruise control (CACC), can substantially improve performance by decreasing driver inputs and taking over control of the vehicle. In testing these systems within a smart corridor on personal or fleet vehicles, the impacts of these technologies on the vehicle- and system-level energy consumption, emissions, and safety can be quantified in field tests in mixed traffic containing conventional, ACC, and CACC vehicles. Adopting ACC and CACC systems may substantially reduce driving volatility and reduce the risk of rear-end collisions, which improves safety. Furthermore, decreases in fuel consumption and emissions are expected with the smoother flow by CACC and ACC systems compared with manually driven vehicles.

3.4 Institutional performance measures

An evaluation of a smart corridor project is needed to enhance agency and stakeholder coordination and collaboration. It may be targeted at: (1) the funding or sponsoring agency, (2) the management of agencies participating in the project, or the (3) project staff, which can include private sector consultants. In the first case, the performance measure can determine whether the money was well spent and whether similar projects should be funded elsewhere. This can be done through cost-benefit analysis and interviews with the sponsoring agency staff. In the second case, the performance measure includes determining whether participation was worthwhile and whether the staff properly administered the project. In the third case, the objective is to fine-tune the project and assess the project contractors' performance. Each audience invites a different type of evaluation, with different levels of stress on strategic versus operational objectives, as well as financial objectives. The assessment can include interviews with project personnel, observations at meetings, and reviews of project documentation.

Institutional issues can be complex; in some cases, organizations may effectively strengthen the partnership by establishing a clear and balanced vision for the stakeholders, e.g., public sector and private sector consultants. Clarity on public sector responsibility for data collection and operation/supervision of the databases and the private sector responsible for developing products and services can be part of the institutional evaluation. Institutional performance measures also entail the provision of forums for resolving issues such as delays, schedule non-adherence, rigidity in procurement structure, and obtaining approvals and permissions to conduct human subjects' evaluations.

Chapter 4 Text Analysis of Smart Corridors Across the United States

Text analysis is a powerful artificial intelligence tool that allows for insights into a body of literature that may not be achieved by simply reading and evaluating reference texts in reports. Using text analysis software allows for an unbiased, systematic review of a large body of literature, with valuable outputs such as word clouds and extracted topics in combination with statistical information about the collected corpus. Text analysis outputs include keyword frequency clouds and tables, key phrase frequency clouds and tables, a list of detected topics, and a co-occurrence map. The data used in the text analysis was completed on 22 technical reports using QDA Miner 8 in combination with WordStat 5.

The study provides content/text analysis of diverse reports that provide insights on key topics of smart corridors, smart infrastructures, and CV pilots. The outcomes of text analysis can not only highlight the main topics of the literature in the field. To perform content analysis, an "inclusion dictionary" is developed. Then, frequency analysis is applied to identify shared and the most frequently used keyword and phrases in the literature. After performing an initial analysis, an exclusion list is made to remove the words that carry little semantic value, such as propositions, conjunctions, or those frequently used words with little discriminative value. The "inclusion dictionary" is developed to merge different word forms (e.g., vehicles and vehicle) to consider them as a single word. To show the results, various visualization tools such as "word clouds" and "concept maps" of key concepts based on co-occurrences are used to display the results obtained from statistical analysis. Word cloud plots are used to demonstrate the frequency statistics of the word lists. In the word cloud, frequencies are converted to words of different sizes. The more frequently the word appears in the studies, the larger the word would be in the plot. Figure 4-1 demonstrates the word and phrase cloud plot based on the frequency statistics of the word list and phrase list regarding the smart corridor, smart infrastructures, and CV pilot reports in the US. The word cloud emphasizes the words "Data," "Information," "Mobility," Management," "AV (Automated Vehicles)," "Technology," and "Congestion." These are some of the most frequently used words. Likewise, the phrase "Smart Corridor," "Travel Time," "Connected Vehicle," "Automated Corridor," and "Real-Time" are the most frequent phrases listed. It can be inferred that the focus of the recent smart corridor and CV pilot projects is on improving travel time and congestion as well as vehicle connectivity and automation.

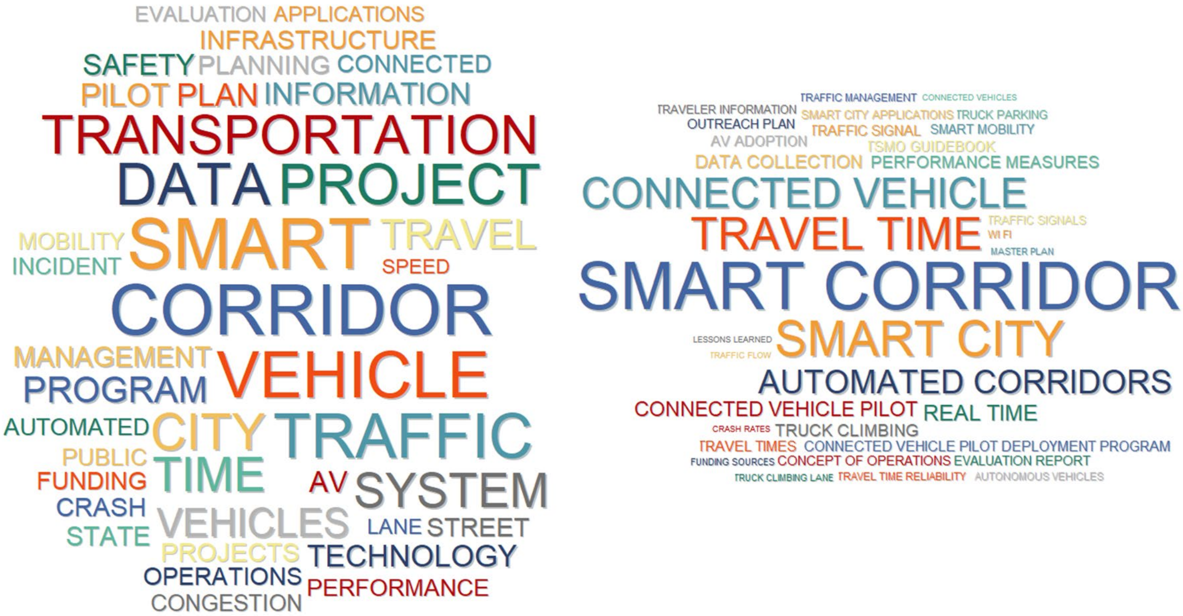


Figure 4-1 Word Cloud of High Frequency Words and Phrase Cloud of the High Frequent Phrases

TABLE 4-1 shows the results of topic extraction using the Factor Analysis method. Generally, higher Eigenvalues and coherence indicate higher variability explained by the topic. Having the highest eigenvalue, the topic of "Incident Management" appears 1308 times in 100 percent of the studies. The second highest eigenvalue belongs to "Automated Vehicle," with an eigenvalue of 3.39, which appeared 1229 times in 90.5 percent of the studies. Other topics of interest based on decreasing eigenvalues include: "Funding Sources," "Connected Vehicle," "Planning Process," "Smart City," and “Data Collection.”

Figure 4-2 illustrates the concept map of words across key concepts and topics. In this chart, words are plotted with a line between each pair of words showing a strong co-occurrence coefficient. Each cluster of words with a distinct color shows a topic or concept on the smart corridor and CV pilot. From the figure, the most important concepts/topics can be observed. There are some links between the words of different clusters showing the correlation between different concepts. For instance, there is a correlation between smart cities and traffic data. Similarly, there is a strong correlation between "Connected Vehicle" and "Traffic," "Data," and "DSRC." It indicates that traffic data is correlated with vehicle connectivity.

Figure 4-2 illustrates the concept map of words across key concepts and topics. In this chart, words are plotted with a line between each pair of words showing a strong co-occurrence coefficient. Each cluster of words with a distinct color shows a topic or concept on the smart corridor and CV pilot. From the figure, the most important concepts/topics can be observed. There are some links between the words of different clusters showing the correlation between different concepts. For instance, there is a correlation between smart cities and traffic data. Similarly, there is a strong correlation between "Connected Vehicle" and "Traffic," "Data," and "DSRC." It indicates that traffic data is correlated with vehicle connectivity.

TABLE 4-1 RESULTS OF TOPICS EXTRACTION

Topics	***Keywords***	***Eigenvalue***	***Freq.***	***% Cases***
Incident Management	Freeway; Streets; Incident; Agencies; Traffic; Major; TMC; Management; Control; Traffic Management; Incident Management; Traffic Signal; Freeway Incidents; Traffic Signals; Management Center; Traffic Flow	4.84	1308	100%
Automated Vehicle	AV; Adoption; Interstate; Crash; Speeds; AV Adoption; Crash Rates; AV Domination; Rise of The AVs; AV Technology; Crash Reduction; limited AV Adopters; Number of Crashes; Early AV Adopters	3.39	1229	90.5%
Funding Sources	Revenue; Funding; Tax; Federal; State; Percent; Rate; Sources; Projects; Year; Funding Sources; Federal Funding; Fuel Tax; Tax Rate; Funding and Legislative; Motor Fuel	2.97	1112	95.2%
Connected Vehicle	Pilot; Connected; Phase; Vehicle; Program; CV; Tampa; Connected Vehicle Pilot Deployment Program; Outreach Plan	2.7	1591	100%
Planning Process	Guidebook; Planning; Part; TSMO Guidebook; Planning Process; TSMO Solutions; TSMO Planning	2.49	718	85.7%
Smart City	Technology; Infrastructure; Applications; Corridor; Sensors; Smart City; Smart Corridor; Smart City Applications; Smart Mobility	2.27	1674	100%
Data Collection	Data; Speed; Real; Collection; Travel Time; Data Collection; Travel Time Reliability	2.19	1451	100%

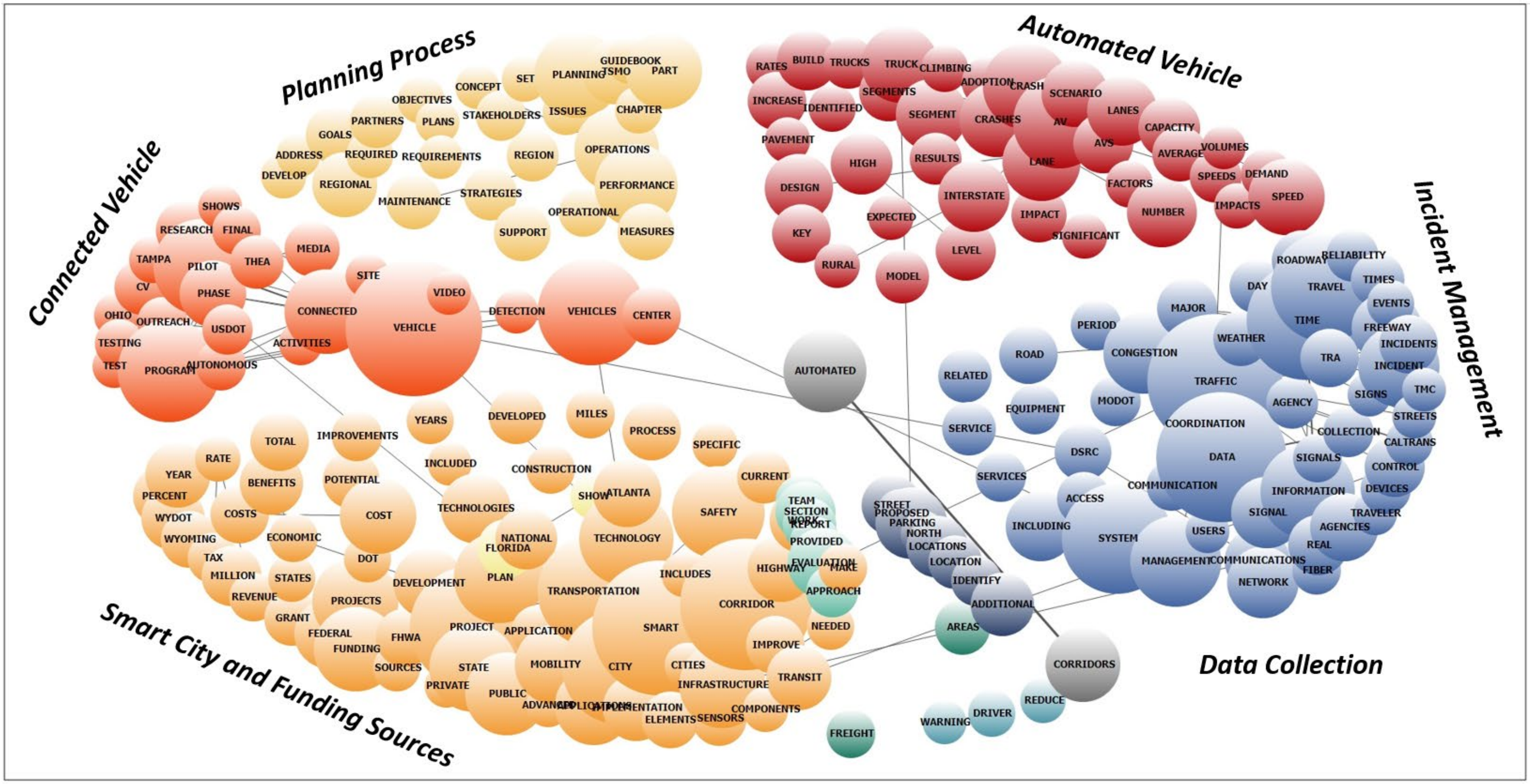


Figure 4-2 Concept Map of Words Across Key Topics

Chapter 5 Opportunities and Compromises for Smart Corridors in Tennessee

Smart corridors provide efficient use of facility resources using existing and emerging technology as well as coordination among agencies and stakeholders. Smart corridors are typically targeted toward mobility and safety improvement, including uncertainties caused by traffic incidents, adverse weather, and special events. Based on the literature, the application of connected and automated vehicles, electrification, and shared mobility services provide opportunities to move the needle on existing and emerging technologies in Tennessee. Concomitantly, the collection of big data, archival, and analytics, including artificial intelligence techniques, provides unprecedented opportunities. Strategies for testing and deployment in smart corridors include opportunities to:

- Enable vehicle and infrastructure communication for improved mobility and safety. This will entail deploying roadside units that can communicate with in-vehicle units and the collection as well as analysis of system performance using trajectories constructed from basic safety message data (5G C-V2X communication data) and high-resolution traffic surveillance camera data.
- Identifying hotspots along smart corridors in terms of congestion, safety, energy, and emissions.
- Designing experiments to test cutting-edge technologies such as ACC and CACC.
- Using simulations or digital twins to anticipate edge cases that can detract from safe mobility.

The I-24 Smart Corridor in Tennessee is an example of using new technologies to improve transportation performance. Specifically, the I-24 Smart Corridor Study has envisioned and evaluated multiple capacity and operational improvements to manage congestion and improve safety along the corridor. In this context, TDOT is forming partnerships with local authorities to implement the initiative. The objectives include increasing travel time reliability and reducing crashes on I-24. The proposed technological improvements deployed on the I-24 Smart Corridor include emergency pull-offs, ramp extensions, and connected vehicle infrastructure. Additionally, dynamic lane use control, variable speed limits, and queue warning applications are anticipated, along with ramp metering. Notably, these strategies are consistent with the contemporary reviewed literature. They reflect leadership in bringing together the emerging technologies at the core of intelligent transportation systems, especially automation and connectivity. Implementing these strategies requires a detailed evaluation and better understanding of the impacts of these improvements to inform future smart corridor transportation projects.

As mentioned, real-world smart corridor deployment projects are natural experiments that cannot be conducted with the scientific precision of laboratory experiments. Numerous compromises come into play at all levels, from the data collection mechanisms to the framing of goals and objectives in a manner that all stakeholders can agree on. Insights on how future current and future smart corridor projects might avoid.

5.1 Technical Obstacles to Evaluation of Smart Corridors

Defining Scope. By their nature, smart corridors test and deploy a collection of technologies that work cooperatively in an integrated fashion. These technologies may differ with respect to geographical and functional deployment. They may be new and never deployed in the corridor, or they may have limited functional deployment (e.g., DSRC V2X RSUs) with expanded coverage and upgrades during the project (e.g., upgrades to C-V2X RSUs). Other scenarios include current limited geographic deployment, with broader geographic coverage during the project; widespread existing deployment, with upgrades planned; and already deployed throughout the corridor, with no changes planned. As a complicating factor, some technologies may be viewed as enabling forces for others, e.g., new communication systems enable new applications, e.g., eco-traffic signal timing/priority, 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. The overall argument is that it may be impossible to isolate the effect of individual smart corridor improvements because some of the improvements may be in place in one form or another prior to the project or because several project technologies are implemented over a short time window. Simply determining the impacts on individual technologies, which ones are part of the smart corridor, and which elements can and should be evaluated can be challenging.

The Basis for Comparison and Design of Natural Experiments. A successful evaluation depends on the close coordination of the evaluation with technology testing and deployment. Ideally, project elements (e.g., signal upgrades and new incident management connected vehicle applications) would be introduced sequentially, with enough intervening time to support an evaluation of each key element's incremental contribution. Because traffic patterns are seasonal and fluctuate annually, an ideal spacing for major technology implementation may be over one year. Clearly, this is not feasible from the standpoint of smart corridor deployments, given the need for expeditious completion. An alternative would be to perform a before/after evaluation for the corridor. Data can be collected prior to implementing the first element and continue after implementing the final element. The problem here is that the period over which elements are deployed can be so long that general traffic conditions have changed appreciably. This is evident from the recent experiences with the COVID-19 pandemic and its non-linear impacts on traffic and safety. The second problem is that it will be impossible to identify which individual elements are more effective and which ones are less effective.

A third method would be to rely on a control group-another corridor within the region with similar traffic characteristics that does not benefit from smart corridor improvements. This could facilitate tracking differences in performance throughout the project and possibly identifying which smart corridor elements are effective. However, finding a truly comparable corridor may be challenging, especially since the instrumentation needed for data collection is closely tied to smart corridor implementation.

Data Collection Methods and Cost-Benefit Analysis. To quantify performance metrics, necessary data collection may involve measuring conditions for different phases of the project, measuring the after-conditions for the phases, and doing a cost-benefit analysis for each strategy/technology. However, a smart corridor may not have extensive surveillance capabilities before testing and deploying new technologies. This can be potentially problematic because data collection may be limited prior to installation, complicating before-after comparisons. While it may be possible to manually collect data in the before period, this can be expensive and not entirely comparable to automated data collection. Further obstacles include cooperating with project staff to perform manual data collection and retrieving historical data if the evaluation begins late in the project.

Measurable Effects. In some cases, it may be challenging to detect improvements at the system level in roadway performance against the background of normal variation in traffic conditions. Furthermore, improvements in roadway performance may dissipate once network equilibration effects are taken into account. Clearly, it is risky for an evaluation to rest on attributing changes in roadway conditions (such as speed or delay) entirely to the smart corridor strategies and technologies. Therefore, other measured effects, perhaps at the traveler or vehicle level, must also be assessed, such as whether travelers perceive an improvement in traveler information messages and whether they have responded to that information.

Furthermore, leading to institutional concerns, the evaluation team needs to be upfront about the limitations of the evaluation so that the project implementation team and sponsor are also realistic about expected improvements in terms of mobility and safety. Sometimes, it is possible that the empirical evidence for expected benefits is not found and a study may conclude that changes in network performance associated with a specific technology are statistically insignificant.

5.2 Institutional Obstacles to Evaluation

Given the aims of developing agency coordination and helping stakeholders work effectively, an evaluation project might logically target several audiences, as mentioned before.

Impartiality of the Evaluation. Invariably, the sponsor of evaluation projects demands an impartial evaluation. Nevertheless, sponsor staff must play an active role in evaluation design and execution to ensure accuracy and relevance. In this regard, a clear line should be drawn between the role of project monitor and evaluator. The staff have a legitimate role in ensuring that the evaluation is feasible and that the results are valid. They also play an essential role in facilitating cooperation. On the other hand, sponsor staff can sometimes be placed in a position to control the evaluation, which should be avoided. It is often challenging to execute a credible evaluation if the evaluator is not the ultimate decision-maker.

Competing Objectives. Implementation is bound to be the primary objective of any smart corridor project. When demands on project staff run high, they may be suddenly unavailable to support the evaluation. In addition, evaluation might not be viewed as an integral part of the project schedule, leaving little time to execute an analysis. It might also be impossible to schedule implementations to enable evaluation, e.g., two project elements/technologies, which need separate evaluations, to be implemented simultaneously.

Another aspect of competing objectives is that many smart corridor projects are governed by committees, given their large scope and financial commitments (tens of million dollars). Many evaluation projects are executed by multi-organization teams. In this environment, much of the effort can be consumed into understanding each other's position.

Cooperation. A critical concern is forming strong cooperation between the evaluation team and the project staff. The evaluation team can have obstacles to overcome: the perception of being outsiders and differences in work cultures. As a solution, the project staff needs to be involved in the evaluation. Ideally, the evaluation should begin during the project's planning phase and not come in late after making critical decisions. Furthermore, project staff could serve on an evaluation oversight committee, which helps define the evaluation's scope and objectives, and the staff can participate in the data collection process. Finally, the evaluation must proceed interactively, with mutual feedback along the way and an evaluation plan that evolves as the project proceeds.

Chapter 6 Conclusions and Recommendations

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 literature reviewed, this research finds that future investments in smart corridors are critical for improving transportation system performance. The report provides information on the conceptual and practice-oriented issues involved in designing and implementing smart corridors. Further, information is gleaned from smart corridor studies about automation levels, connectivity technologies, and data needed to evaluate improvement strategies. 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. Furthermore, 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. Recommendations include TDOT investments in the following initiatives:

- ***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 corridor. The deployed 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 using 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 EV fast-charging network to enhance electrification across Tennessee. Notably, the "Fast Charge TN Network" has prioritized corridor infrastructure gaps, and coordination with the Tennessee Department of Environment and Conservation (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, including 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 more significant 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 original equipment manufacturers to get a clearer sense of what vehicle manufacturers will use connectivity technologies 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 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 and 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 AV's market penetration 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 CACC and encourage truck platooning 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 vital to invest in evaluating the potential benefits/costs and impacts of emerging technologies and associated strategies in smart corridors within Tennessee.

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