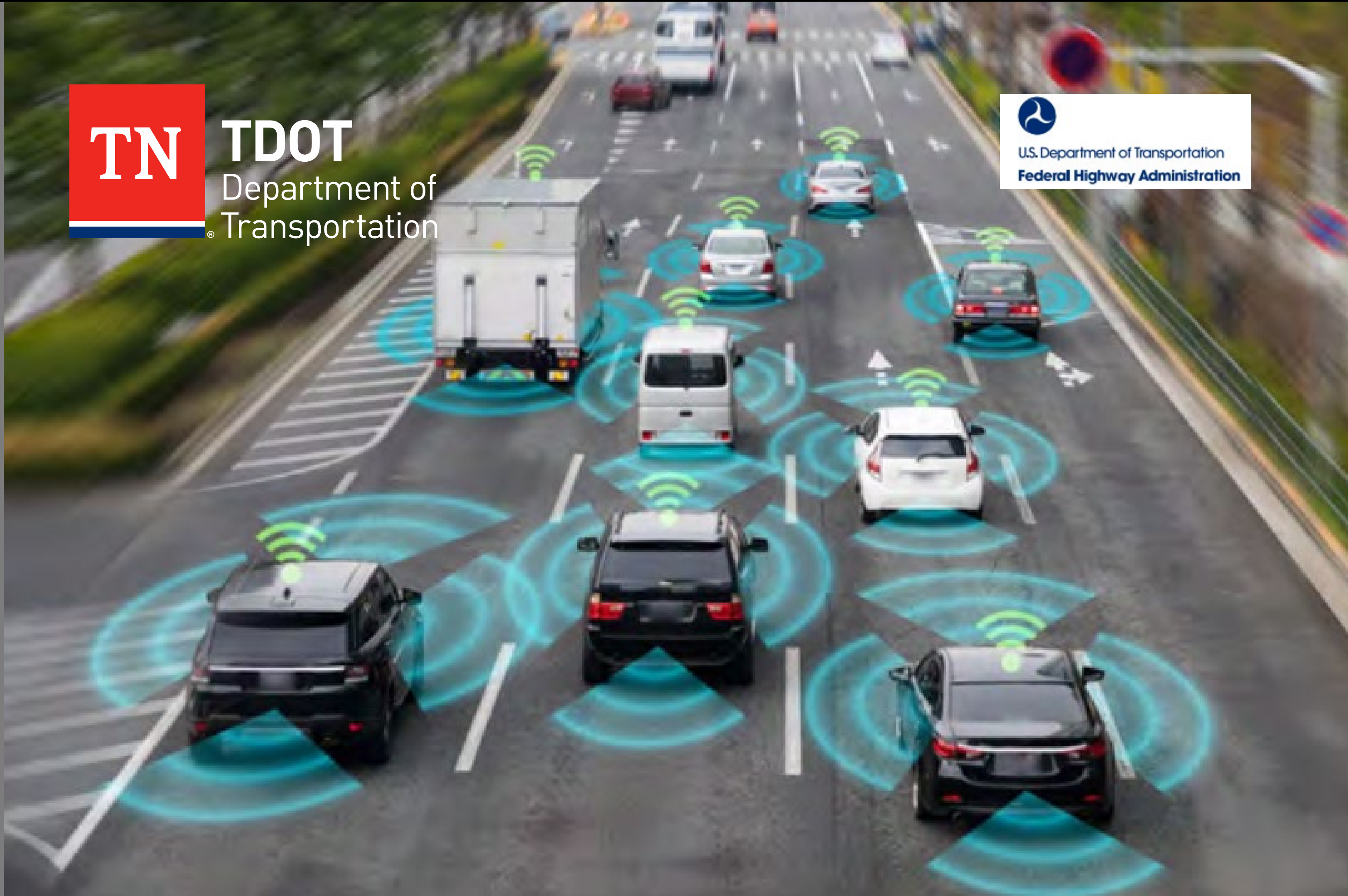

I-24 Smart Corridor V2X Roadmap

Tennessee Department of Transportation

Research Report from Kimley-Horn & Associates, Inc. | Terrance Hill, P.E.; Matthew Smith, P.E.; Paul Bonner; Jack Stockhausen | April 14, 2025

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16. Abstract

The I-24 SMART Corridor takes a comprehensive approach to improving the safety and travel time reliability along the corridor utilizing existing infrastructure and emerging technology. Vehicle-to-Everything (V2X) technologies are a key initiative of TDOT by aligning with several strategic goals of TDOT including safety, mobility, sustainability, and consistent customer experience. To achieve the benefits of successfully applied V2X technologies along the I-24 SMART Corridor, a clearly defined direction of V2X deployments needs to be established. The path towards applying V2X technologies throughout the I-24 SMART Corridor is described within the I-24 SMART Corridor V2X Roadmap. The I-24 SMART Corridor Roadmap provides an evaluation of the existing Intelligent Transportation Systems (ITS) infrastructure along the corridor as well as an implementation plan for V2X applications that meet the goals of the I-24 SMART Corridor. The initial deployment locations for V2X applications were based on several safety factors including existing traffic volumes, crash history, and re-occurring congestion. These safety factor hotspots led to the specific V2X application needs along the I-24 SMART Corridor. Along with the hotspots, geometric factors were included in determining which specific V2X applications were most applicable at each hotspot location. In addition to identifying and locating where specific V2X applications should be provided along the I-24 SMART Corridor, the Roadmap provides the costs associated with implementing these applications. These costs include software, physical integration, vehicular integration, and annual operations and maintenance costs.

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Executive Summary

The Tennessee Department of Transportation (TDOT) has a mission to provide a road system that is valued by their customers as being safe and reliable, while supporting national mobility and commerce. Over the past 20 years, intelligent transportation systems (ITS) including road weather information systems (RWIS), dynamic message signs (DMS), closed-circuit television (CCTV), and smartphone-based motorist information applications have expanded TDOT's capabilities to improve traffic operations, incident management and customer travel experience. In the coming years, TDOT will further leverage existing and future technology to support and enable the next generation of ITS devices: Connected Vehicles (CV) and Vehicle-to-Everything (V2X).

V2X technologies are a key initiative of TDOT by aligning with several agency values including safety, development, innovation, collaboration and consistency for the driving experience. To fully realize the benefits of successfully applied V2X technologies along the I-24 SMART Corridor, a clearly defined application deployment strategy needs to be established. TDOT has deployed ITS technology along the I-24 SMART Corridor, including the deployment of connected vehicle Roadside Units (RSUs) along I-24, US-41, and several connecting routes between those two corridors. These deployments are aimed at improving traffic management and setting up infrastructure for V2X applications. The deployments TDOT currently has along the I-24 SMART Corridor are as follows:

- 67 Lane Use Gantries
- 269 Lane Control DMS Signs
- 67 Shoulder Signs
- 10 DMS Walk-In Signs
- 14 Emergency Pull Off Detection Systems
- 31 CCTVs
- 60 Radar Detection Units
- 130 Network Switches
- 254 Advanced Radar Detection Units
- 135 Vehicle Detection Units
- 2 Network Hub Buildings
- 226,750 feet 144F Fiber
- 150 V2X Roadside Units

Part of the overall technology improvements along the I-24 corridor includes the I-24 Mobility Technology Interstate Observation Network (I-24 MOTION). The I-24 MOTION project equipped a four-mile section of I-24 with nearly 300 ultra-high-definition cameras. I-24 MOTION provides an environment for testing advanced traffic management and automated vehicle technologies under real world freeway traffic, giving researchers an idea of how traffic flows and drivers behave.

The path towards deploying V2X applications throughout the I-24 SMART Corridor is described within this document, the I-24 SMART Corridor V2X Roadmap. The Roadmap goals are provided in Table ES-1 below.

Table ES-1. I-24 SMART Corridor V2X Roadmap Goals

I-24 SMART Corridor V2X Roadmap Goals
• Prioritize V2X applications to leverage the I-24 Roadside Unit (RSU) deployment. • Develop an implementation strategy for V2X technologies along the I-24 SMART Corridor. • Detail a fiscally realistic conceptual deployment plan for the I-24 SMART Corridor.

The I-24 SMART Corridor V2X Roadmap represents a grounded deployment plan that minimizes risk while simultaneously building the knowledge, skills, and abilities of the I-24 SMART Corridor. Considerations such as measured traffic operations or crash hot-spots, stand-alone capability," back-end" IT system complexity, backhaul network capability, roadside unit (RSU) density, and equipped vehicle density allowed TDOT to create a risk matrix to aid decision making in the appropriate V2X applications to pursue.

Connected Vehicle Application Deployment Projects

The identified Vehicle to Infrastructure (V2I) application deployment projects were developed with consideration towards anticipated Market Penetration Rate (MPR) growth of CV equipped public and private vehicles.

Connected Vehicle Fleet Integration

The MPR of fleet and private vehicles equipped with V2X technologies will significantly influence the capabilities of the V2X applications. TDOT can strategically retrofit fleet vehicles (maintenance or motorpool) with aftermarket safety devices to pilot CV applications that coincide with the natural MPR of equipped vehicles. This is detailed in Section 4.3 of this report.

I-24 SMART Corridor V2X Program Costs

The national vision for V2X technology is to have the capabilities seamlessly deployed as an integral part of all vehicles and the transportation infrastructure, allowing transportation agencies to deliver a safer, more reliable, and greater customer-valued road system that continues to support national mobility and commerce. It is expected that an approximate investment of approximately $1.8 million to replace the Dedicated Short-Range Communications (DSRC) roadside units with C-V2X units should be completed initially. While on-board units and specific V2X applications can be implemented over the next few years to fully allow TDOT to fully realize the capabilities of V2X benefits along the I-24 corridor.

Key Findings

- Federal Communications Commission (FCC) rulings will "sunset" DSRC technology over the next 2 years; all V2X direct communications will need to use C-V2X standards by December 14, 2026.
- There is a defined set of V2X applications that are ideal for the freeway segments of the corridor. These include Basic Safety Messaging, Queue Warning, Spot Weather Warning, Curve Speed Warning, Reduced Speed / Lane Closure Warning, Emergency Vehicle Alert, Road Maintenance Reporting, and Distress Notification.
- There is a defined set of V2X applications that are ideal for the arterial roadway segments of the corridor. These include Emergency Vehicle Pre-Emption, Intelligent Traffic Signal System, Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk, Red Light Violation Warning, Emergency Vehicle Alert, Road Maintenance Reporting, and Distress Notification.

Key Recommendations

- Program replacement of DSRC RSUs with C-V2X-capable RSUs.
- Retrofit vehicle fleets with on-board units
- Build in application deployments for freeway segments into the transportation program.
- Work with local agency partners on building in application deployments for arterial segments into the transportation program.
- Include Roadmap recommendations into larger agency plans.

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Glossary of Key Terms and Acronyms

ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
ASD	Aftermarket Safety Device
ASP	Authorized Service Providers
AV	Automated Vehicles
CCTV	Closed-Circuit Television
CSW	Curve/ramp Speed Warning
CV	Connected Vehicles
C-V2X	Cellular Vehicle to Everything
DMS	Dynamic Message Signs
DSRC	Dedicated Short-Range Communications
FCC	Federal Communications Commission
FOBN	Fiber Optic Broadband Network
GIS	Geographic Information Systems
IT	Information Technology
ITS	Intelligent Transportation Systems
ITS JPO	Intelligent Transportation Systems Joint Program Office
KSA	Knowledge, Skills, and Ability
MPR	Market Penetration Rate
O&M	Operations and Maintenance
OBU	Onboard Unit
OEM	Original Equipment Manufacturer
OTA	Over the Air
NIST	National Institute of Standards and Technology
ROM	Rough Order of Magnitude
RSU	Roadside Unit

RSWZ	Reduced Speed Zone Warning
RWIS	Road Weather Information Systems
SCMS	Security Credential Management System
SPR	State Planning and Research
SWIW	Spot Weather Impact Warning
TDOT	Tennessee Department of Transportation
THP	Tennessee Highway Patrol
TITAN	Tennessee's Integrated Traffic Analysis Network
TOC	Traffic Operations Center
USDOT	United State Department of Transportation
V2X	Vehicle-to-Everything

Chapter 1 Introduction

TDOT embarked on the journey towards realizing the benefits of V2X with a robust deployment of connected vehicle Roadside Units (RSUs) within the I-24 SMART Corridor.

The Tennessee Department of Transportation (TDOT) has a mission to provide a safe and reliable transportation system to support economic growth and quality of life which the I-24 Smart Corridor project aims at achieving. Over the past 20 years, intelligent transportation systems (ITS) including road weather information systems (RWIS), dynamic message signs (DMS), close-circuit television (CCTV) and smartphone-based motorist information applications have expanded TDOT's capabilities to improve traffic operations, incident management and customer travel experience. Over the next 20 years, TDOT can further leverage existing and future technology to support ITS devices: Connected Vehicles (CV) and Vehicle-to-Everything (V2X).

V2X-based transportation solutions enable communication between a vehicle and any entity that may interact with it. V2X is the combination of Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N) deployments. By integrating these components through the development and deployment of specialized applications, V2X technology creates a connected transportation ecosystem to improve road safety, optimize traffic flow, and enhance the driving experience by providing real-time information and facilitating coordinated responses to road and traffic conditions.

The United States Department of Transportation (USDOT) has led efforts nationally to develop initiatives and promote technology that combats the negative safety and congestion related impacts occurring on our roadways. According to USDOT statistics, from 2019 through 2022, there have been an average of 40,000 fatalities across the nation each year. In addition to the cost of human life, resulting injuries, and loss of property, motorists are faced with congestion related system inefficiencies, costing the U.S. $200 billion in wasted time and fuel each year. In total, the fuel consumed in moving people and goods, or sitting idle in traffic, contributes nearly 28% of the total Greenhouse Gas Emissions throughout the country. While it is true that existing transportation technologies are successful in reducing these statistics, the USDOT and industry leaders feel that emerging technologies will drastically affect those statistics. The emergence and documented value of V2X technologies, through early testing and deployment, indicate that V2X technologies will create a substantial positive impact on safety, mobility, and environmental quality of our nation's roadways, once deployed.

TDOT embarked on the journey towards realizing the benefits of V2X with a robust deployment of connected vehicle Roadside Units (RSUs) within the I-24 SMART Corridor. The next step to leveraging the benefits of V2X technology is to determine the safety, mobility and agency information applications that can be deployed to leverage the benefit of this RSU investment. The path towards deploying V2X applications within the I-24 SMART Corridor is described within this document, the *I-24 Smart Corridor V2X Roadmap (Roadmap)*. The Roadmap reviews the key areas of focus for V2X technology use, literature review, a potential list of prioritized V2X applications and the next steps to implement potential projects.

TDOT has deployed ITS technology along the I-24 via Phase I and Phase II of the I-24 SMART Corridor program. These deployments are aimed at improving traffic management and setting up infrastructure for V2X applications. The deployment TDOT currently has along the I-24 SMART Corridor are as follows:

- 67 Lane Use Gantries
- 269 Lane Control DMS Signs
- 67 Shoulder Signs
- 10 DMS Walk-in Signs
- 14 Emergency Pull Off Detection Systems
- 31 CCTVs
- 60 Radar Detection Systems
- 130 Network Switches
- 254 Advanced Radar Detection
- 135 Vehicle Detection
- 2 Network Hub Buildings
- 226,750 feet 144F Fiber
- 150 Roadside Units (RSU)

The 150 RSUs that TDOT has deployed include a mixture of mostly Dedicated Short-Range Communications (DSRC) and C-V2X units on the I-24 and US-41 corridors between Nashville and Murfreesboro. The deployments also include routes that connect I-24 and US-41. Of the 150 RSUs, 25 are C-V2X capable, and 125 are DSRC. The I-24 SMART Corridor V2X Roadmap provides an evaluation of the existing RSUs and provides recommendations of V2X applications TDOT can implement using these existing RSUs.

1.1 Guiding Documents

Several documents and previous efforts were used as a basis for developing the Roadmap.

I-24 SMART Systems Engineering Management Plan

The *I-24 SMART Corridor Systems Engineering Management Plan* (SEMP) serves as a guideline throughout the course of the project. The SEMP identifies proposed tasks, details the schedule of the tasks, and identifies who is responsible for completing the tasks. The SEMP has enabled TDOT and project partners to manage the project using systems engineering principles and methods to maximize the quality of the system being implemented, while minimizing the budget and schedule required for its completion. The primary objectives of the SEMP are as follows:

- To provide modern, state of the art project management requirements and process for the design, procurement, construction, integration, testing, and maintenance of technical systems.
- To limit and reduce proliferation of management documentation and to implement relevant aspects of applicable standards.
- To identify relevant directives and references.
- To provide evidence that control points during the planning, design, procurement, installation, integration, testing and support are being completed in a logical fashion.
- To ensure that inspections demonstrate acceptability of material and services according to the original project objectives.
- To provide emphasis on a discipline integrated systems development approach.
- To establish overarching goals and objectives for the project, including performance metrics for how the benefits will be measured and demonstrated.
- To inform stakeholders with concepts of systems engineering management and techniques.

Other Guiding Documents

The following documents published by TDOT help to guide the development of new TDOT programs and initiatives and are referenced as part of the V2X Roadmap:

- I-24 SMART Corridor Phase I & II Project Plans
- I-24 SMART Corridor Systems Engineering Analysis Report

- I-24 SMART Corridor Concept of Operations
- I-24 SMART Corridor Field Data Collection Summary
- I-24 & US-41 RSU Assessment Report

1.2 Business Case

TDOT wishes to leverage V2X technologies to create comprehensive, intelligent, and integrated systems that improve the operational environment, providing travel time reliability, for all I-24 SMART Corridor users, allowing motorists to execute well-informed decisions as they navigate the roadways. These applications, when combined and leveraged appropriately, will have the potential to vastly improve roadway operations and most importantly, customer safety, allowing TDOT to reduce crashes and fatalities through more proactive operation and management of the roadway network. A summary of the ways in which V2X technologies can support each strategic goal is provided in Table 1-1.

Table 1-1. Benefits of V2X Technologies Based on Goals for I-24 SMART Corridor (From I-24 SMART Corridor Concept of Operations)

I-24 SMART Corridor Concept of Operations Goals	Support of V2X Technologies
Increase travel time reliability	Improve awareness of road conditions (e.g., congestion, lane closure, weather, etc.).
Increase mobility of all modes	Improve the travel time reliability and safety of all modes of transportation.
Reduce concentration of collisions	Provide a facility with improved mobility and safety performance factors for all road users.
Develop agency coordination	Remain engaged with other state, local agency, research, and industry leaders in the planning, design, and deployment of V2X projects and continue collaboration with organizations in the strategic advancement of V2X deployments across jurisdictions.

1.3 Roadmap Goals

This Roadmap will allow TDOT to better leverage existing and future investments in ITS and connected vehicle infrastructure within the I-24 corridor that supports the overall Concept of Operations, and the next steps for deploying specific V2X applications. The specific purpose and goals of the Roadmap are detailed in Table 1-2.

Table 1-2. I-24 SMART Corridor V2X Roadmap Goals

I-24 SMART Corridor V2X Roadmap Goals
• Assess the current capabilities of the I-24 V2I Network • Prioritize V2X applications for implementation. • Develop an implementation strategy for V2X applications along the I-24 Corridor. • Detail a conceptual implementation plan.

1.4 Roadmap Approach

The Roadmap was developed using the systematic approach shown in Figure 1-1. This process allows for the optimal use of existing roadside infrastructure and creates an actionable plan to guide the I-24 SMART Corridor V2X program over the next several years.

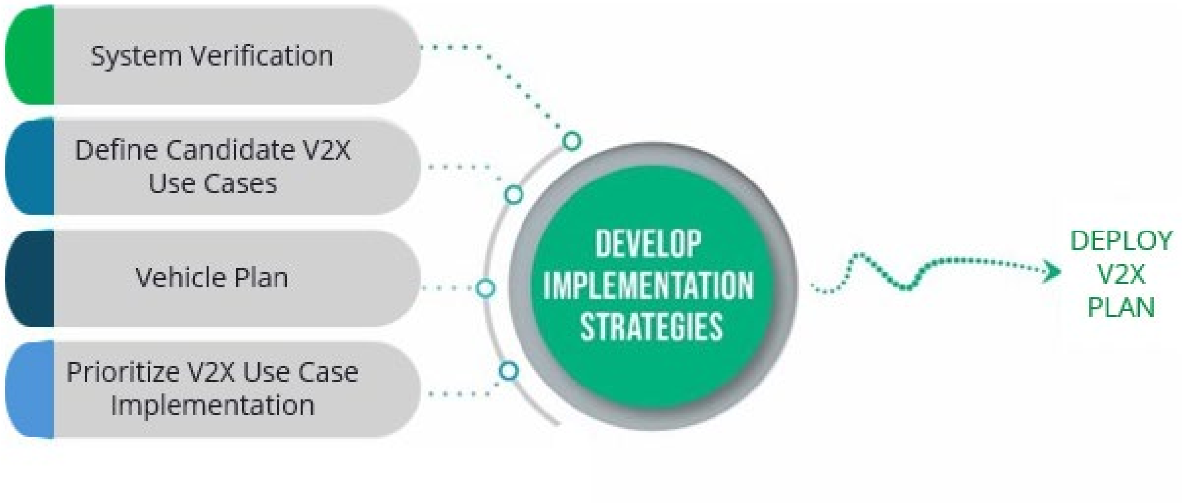

Figure 1-1. V2X Program Roadmap Approach

With V2X technologies advancing at a rapid pace, it is recommended to update the Roadmap at regularly scheduled intervals to account for changes in industry standards and the I-24 SMART Corridor strategic goals and to indicate the progress that has been made since the previous edition.

1.5 V2X Program Roadmap Assumptions

While there are many facts and guidance documents on which the Roadmap is based, it still remains necessary to note a few of the key assumptions that were made in its development. As the industry continues to move forward and policies are created and revised, the following assumptions may need to be revisited along with the associated impact to the Roadmap as originally defined. The key assumptions in developing the V2X Program Roadmap are as follows:

- The upper portion on the 5.9 GHz bandwidth has been reserved for C-V2X communication as laid out in the Federal Communications Commission (FCC) rulemaking First Report and Order and Second Report and Order will remain largely unchanged from published intent, with associated requirements and standards developed

- FCC rules sunset DSRC-based communications in the 5.9 GHz by November 2026; V2X communications in the 5.9 GHz band must use C-V2X protocols for direct communication.
- The development of V2X applications will continue at the infrastructure owner and operator, equipment, and vehicle manufacturer levels.
- USDOT guidance will continue to be refined for public agencies to create seamless V2X environments.
- Initial deployments of V2X applications will likely leverage smaller fleets of agency or partner vehicles and may provide limited benefits until publicly equipped vehicles begin to interact with the system.
- Further development of federal and "industry" standards will determine V2X communication requirements.
- TDOT has several existing deployments that are complementary to V2X needs, such as upgraded fiber along the I-24 corridor, overhead lane closure and speed limit gantries, and upgraded vehicle detection.

1.6 References

Table 1-4 lists national reference documents and websites that were specifically used in the creation of this document.

Table 1-3. References

#	Document (Source, Title, Date)
1	Connected Vehicle Reference Implementation Architecture, http://local.iteris.com/cvria/, May 2020 (Since replaced by ARC-IT)
2	Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT), January 2024
3	Tennessee Traffic Information Management and Evaluation System, June 2024
4	Pennsylvania Turnpike Connected and Automated Vehicles Program Roadmap, May 2022

#	Document (Source, Title, Date)
5	Tennessee’s Integrated Traffic Analysis Network (TITAN)
6	WeGo Murfreesboro Corridor Quarterly Performance Indicator Report
7	I-24 SMART Corridor Phase I Plans, August 2020
8	I-24 SMART Corridor Phase II Plans, March 2023
9	I-24 SMART Corridor System Engineering Analysis Report, July 2018
10	I-24 SMART Corridor Concept of Operations, May 2018
11	I-24 SMART Corridor Systems Engineering Management Plan, November 2017
12	I-24 SMART Corridor Field Data Collection Summary, December 2024
13	I-24 & US-41 RSU Assessment Report, November 2024
14	ITS Deployment Evaluation Executive Briefing – Vehicle-to-Everything Technology, 2024

Chapter 2 Literature Review

V2X technologies are rapidly transforming transportation systems. In the state of Tennessee and beyond, research is underway to understand not only how these vehicles will be adopted by the public but also what infrastructure and policy changes are required to support their safe and efficient operation. This review examines four key documents:

1. *Impacts and Adoption of Connected and Automated Vehicles in Tennessee*
2. *Connected and Automated Vehicles Investment and Smart Infrastructure in Tennessee*
3. *I-24 SMART Corridor Systems Engineering Management Plan*
4. *Pennsylvania Turnpike Commission Connected and Automated Vehicles Program Roadmap*

Each section below discusses one document, summarizing its objectives, methodologies, key findings, and implications for future research and policy.

2.1 Impacts and Adoption of Connected and Automated Vehicles in Tennessee

This report examines the factors influencing the acceptance of Connected and Autonomous Vehicle (CAV) technology among Tennessee residents. The study draws on a large-scale survey, covering more than 4,600 residents, to gather detailed information on individual's familiarity with automated systems, their perceptions of potential benefits and risks, and the extent to which social influences play a role in their decision making. One of the report's key contributions is its focus on the interaction between personal attitudes and broader social attitudes and networks. For example, it highlights how individuals who perceive a higher social status benefit from owning an automated vehicle or who are surrounded by peers enthusiastic about the technology are significantly more inclined to adopt CAVs.

The report uses a hybrid choice model that integrates traditional discrete choice analysis with laten variables capturing the more subtle attitudinal components of decision making. The model evaluated residents' inclination to adopt five different CAV based travel modes: privately owned, carpool, public transport, and ride-hailing service with and without the human backup driver. The model used two different parts, structural equation modeling and discrete choice modeling. The structural equation modeling evaluated the attitudinal constructs associated with the acceptance of CAVs and their relationship with peer-to-peer intersection. Six attitudinal constructs were: social status, social influence, CAV benefits, CAV barriers, CAV purchase, and media influence. Discrete choice evaluated residents' likelihood of adopting various CAV based travel modes based on attitudinal constructs, travel behavior, and peer-to-peer interaction attributes. This approach allows for a richer understanding of how observable factors, such as income and age, interact with intangible influences, such as trust and perceived safety. Additionally, the study incorporates an agent-based simulation to model the diffusion of CAVs over time. This simulation accounts for peer-to-peer interactions, demonstrating that even moderate annual price reductions could result in exponential increases in adoption rates. The findings are not only valuable for academic understanding but also carry practical implications.

The study suggests that policies aimed at reducing financial barriers, combined with efforts to build public confidence in automated technologies, could significantly accelerate CAV uptake in Tennessee. This report provides a detailed picture of how social, economic, and behavioral factors converge to influence CAV adoption. It underscores that while cost remains a critical factor, the influence of social networks and individual perceptions cannot be underestimated. The insights derived from this study lay the groundwork for targeted interventions such as financial incentives and public awareness campaigns that can help overcome barriers to adoption, thus paving the way for a more connected and automated transportation future in Tennessee.

2.2 Connected and Automated Vehicles Investment and Smart Infrastructure in Tennessee

This report shifts focus from individual consumer behavior to the broader infrastructural readiness needed to support CAV technologies in Tennessee. It provides an in-depth baseline assessment of the state's current investments in both physical and digital infrastructure, with an emphasis on how these investments can be aligned with the future demands of connected and automated vehicles. The themes of CAVs and smart infrastructure are reflected in the development of smart corridors, with the goals of providing improved mobility, safety, and the environment by improving and balancing traffic demand. The study reviewed smart corridor projects across the United States that have implications for intelligent mobility in Tennessee. The performance evaluation included network performance analysis, traveler behavior, vehicle trajectories, and interviews with stakeholders and institutional participants.

The report details the current landscape of smart infrastructure in Tennessee, describing existing digital networks, roadside communication systems, and electric vehicle (EV) charging facilities. A major theme is the transition from older Dedicated Short-Range Communication (DSRC) systems to the more advanced Cellular Vehicle-to-Everything (C-V2X) technology. The report explains that while DSRC has been the standard for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, recent federal guidance and technological developments suggest that C-V2X offers benefits such as lower latency, wider coverage, and better compatibility with modern mobile devices. However, the transition is not without its challenges. The document discusses issues such as the higher cost of C-V2X equipment, the need for extensive vendor coordination, and the critical importance of upgrading cybersecurity measures to safeguard the vast amounts of data generated by these systems.

One of the strengths of this study is its benchmarking of Tennessee's infrastructure against that of other leading states. By drawing comparisons with regions that have advanced further in their smart infrastructure investments, the report makes a case for increased public-private partnerships and additional funding for ITS upgrades. It identifies the timeframe in which different levels of automation can realistically be implemented while understanding that higher levels of automation will require additional time and research. It also identifies gaps, most notably in EV charging networks, and recommends targeted strategies to address these shortcomings. The report's conclusions stress that the future success of CAVs in Tennessee depends not only on consumer readiness but also on a robust, integrated infrastructure that can support advanced communication and data analytics. The practical recommendations provided in this document serve as a roadmap for state agencies to ensure that investments in infrastructure are strategically aligned with emerging technology trends.

2.3 I-24 SMART Corridor Systems Engineering Management Plan

The I-24 SMART Corridor Systems Engineering Management Plan (SEMP) is a practical document that serves as both a blueprint and an operational guide for transforming a critical stretch if I-24 into a "smart corridor". This corridor is envisioned as a real-world testbed where a variety of ITS technologies can be deployed and evaluated under actual operating conditions. The I-24 SEMP document is intended to be a living document. As information is gathered through the life cycle of the project, document content will be updated to reflect the most current direction.

The systems engineering process used in the document follows an interdisciplinary approach that helps to enable the realization of successful systems that focus on defining customer needs and required functionality early in the development cycle. The process is used to identify the project's needs and constraints and lay out the activities, resources, budget, and timeline for the project. The document provides guidance for the activities and plans that will act as controls on the project's System Engineering activities, these include plans to manage the project, plans developed during project planning phase, plans developed during project development and design phase, and plans developed during project construction and integration phase. These guidance plans provide detailed information on key items throughout the project's life cycle to build consensus among the stakeholders of the project. The process is applicable at all stages of the project, from initial system planning through final operations and maintenance of the system.

In addition to identifying tasks to be completed, details of the schedule of the tasks, and identifying who is responsible for completing the tasks, the SEMP also provides the process followed for achieving ITS Architecture consistency/compliance and recommended ITS standards for the I-24 SMART Corridor project. The SEMP has enabled TDOT and project partners to manage the project using systems engineering principles and methods to maximize the quality of the system being implemented, while minimizing the budget and schedule required for its completion.

2.4 Pennsylvania Turnpike Commission Connected and Automated Vehicles Program Roadmap

The Pennsylvania Turnpike Commission's (PTC) CAV Program Roadmap represents a comprehensive strategic framework for integrating CAV technologies along one of the nation's busiest toll highways. The Roadmap is designed specifically for large-scale deployment in a high-traffic corridor and reflects the unique challenges and opportunities that come with such an environment. The Roadmap outlines a phased approach that begins with pilot programs aimed at testing and refining emerging technologies. Early phases are dedicated to gathering real-world data under controlled conditions. These pilots serve as critical experiments, providing feedback on performance metrics such as latency, reliability, and data accuracy, which are essential for ensuring safety in automated operations.

One significant aspect of the PTC CAV Roadmap is its emphasis on infrastructure upgrades. The document details how existing systems must be evaluated and enhanced to support the demands of CAVs. Upgrading RSUs, installing advanced sensors, and integrating high-speed communication networks are presented as foundational steps. The Roadmap emphasizes that the successful deployment of CAV technology hinges on the ability to collect and process large volumes of data in real time. The document does not overlook the challenges involved in the transition to these infrastructure upgrades. It discusses the need for extensive testing, vendor coordination, and the development of robust cybersecurity measures to protect against potential threats. These discussions are grounded in both theoretical considerations and practical lessons learned from previous pilot projects and deployments.

The PTC CAV Roadmap offers a detailed, phased strategy that blends technical, operational, and regulatory elements to guide the rollout of CAV technologies on a major toll road system. Its focus on pilot projects, infrastructure upgrades, and multi-stakeholder collaboration provides a practical template for addressing the complex challenges of deploying advanced transportation technologies on a large scale. The Roadmap not only highlights the technical and logistical requirements for successful implementation but also reinforces the importance of ongoing research, data integration, and standardization in building a resilient and efficient transportation network for the future.

Chapter 3 V2X Program Overview

3.1 Recent Projects

I-24 SMART Corridor

The I-24 SMART Corridor project was initiated in 2018 to develop and implement a comprehensive approach to managing the existing infrastructure and improving travel time reliability between Rutherford and Davidson counties. The project includes approximately 28 miles along I-24 from Exit 53 (I-440) in Metro Nashville-Davidson County to Exit 81 (SR-10/US -231) in the City of Murfreesboro, approximately 28.5 miles along US-41 from I-24 in Metro Nashville-Davidson Country to SR-10/US-231 in the City of Murfreesboro, and approximately 30 miles of connector routes between I-24 and US-41. The project included some physical improvements along the existing I-24 corridor including extending ramp lengths and adding emergency pull-offs. ITS features were also deployed to upgrade signal infrastructure and optimize signal timings on US-41 and the connector routes and to provide dynamic message signs (DMS) on both I-24 and US-41.

Phase 2 of the I-24 SMART corridor included the construction of overhead gantries as part of the new ITS developments throughout the corridor between mile markers 53 and 70. These gantries enable active traffic management of the freeway during congested times and during incidents. Additionally, the project incorporated advanced traffic management systems, including real-time monitoring to optimize traffic flow along the corridor. Multiple communication technologies such as CCTV cameras, fiber optic networks, wireless interconnect, RSUs were deployed to gather data and enable seamless communication between devices and the central control system.

3.2 Strategic Goals & Objectives

V2X technologies have the capability to address a wide variety of transportation related concerns on the roadway. The core focus of the Roadmap is to address those concerns through emerging transportation technologies by aligning the overall mission of the I-24 SMART Corridor with the national best practices, guidance documents, and architectures, defined through the Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT).

Discussions within TDOT regarding near-term capital improvement projects led to the identification of “safety”, “mobility”, and “reliability” as overall goals of the I-24 SMART Corridor V2X Program.

Clear objectives were also identified as pertinent to each defined goal that TDOT could independently evaluate. The evaluation of the individual objectives allows for a more in-depth investigation into the value obtained from V2X deployments and a direct correlation to the impact and effectiveness achieved by the overall I-24 SMART Corridor goals.

3.3 Core Focus Areas

The core focus areas are linked to the defined corridor goals and objectives and identify specific components for which TDOT desires positive outcomes in their operations and maintenance sectors. Below, the Core Focus Areas are described in further detail, demonstrating TDOT envisioned the impact of V2X technology, applications to their business, and derived values for both TDOT and its customers.

3.3.1 Safety

Work Zone Safety – Leverages V2X applications to improve work zone safety and operation for both motorists and workers by providing warning of lane restrictions and backlog and warning of mobile and long-term construction and maintenance patterns.

Roadway Safety – Supports communication regarding hazardous conditions, such as slowed or stopped traffic, restricted geometry (tight curves), or unplanned incidents throughout the entire corridor or at specified locations.

Road Weather Safety – Supports alerts and advisories for Connected Vehicles regarding adverse weather conditions at specific locations or corridor wide, provides road weather information to assist in adjusting posted speed limits, and supports connected snowplows to provide weather data.

Traffic Incident Management – Leverages V2X applications to improve safety for the first responders and motorists by warning drivers of lane closures and reduced speeds when approaching incident zones and warning on-scene responders of vehicles approaching the incident zone at speeds or in lanes that pose a high risk to their safety.

3.3.2 Mobility

Traveler Information – Leverages V2X applications and data sets to improve I-24 SMART Corridor operations that lead to increases in reliability and capacity while also improving the traveler information data that is ultimately disseminated from TDOT to motorists.

Traffic Network – Supports the integration and utilization of new data streams, stemming from CVs and the I-24 SMART Corridor infrastructure, to support the operation of traffic management systems and V2X applications.

3.3.3 Customer Experience

Freight – Supports the transmission of freight-specific traveler information, based upon historical and near real-time based V2X data sets, to improve overall reliability and efficiency of travel on the roadway system. In addition, supports notification of truck parking availability, provides warning of oversize restrictions, and provides warning of winter restrictions. Also, it supports truck platooning.

3.4 Program Summary

Table 3-1 provides a summary of the Strategic Objectives and Core Focus Areas used to guide the development of the V2X Roadmap.

Table 3-1. I-24 SMART Corridor Strategic Objectives and Core Focus Areas

SAFETY	MOBILITY	CUSTOMER EXPERIENCE
Objectives		
Reduce the number and severity of: ▶ All crashes ▶ Crashes in work zones ▶ "On-the-job" injuries to employees	Increase mobility and reliability in travel time.	Improve customer experience by complementing existing ITS communications for consistency.
Core Focus Areas		
▶ Work Zone Safety ▶ Traffic Incident Management ▶ Roadway Safety ▶ Road Weather Safety	▶ Traveler Information ▶ Traffic Network	▶ Freight

Chapter 4 V2X Project Prioritization

The goal of this section is to identify the projects and applications that TDOT prioritized to advance the V2X program to the next level of success. In addition to connected and automated vehicle applications themselves, this section of the document identifies ongoing foundational investments and preliminary planning, design, and procurement projects to support the long-term communications, security, and data management requirements of future full-scale deployments. The result is a list of V2X Program efforts that identify Foundational Investments, CV Preliminary Projects, and prioritized V2X applications.

4.1 Foundational and Initial Project Investments

The I-24 SMART Corridor leverages technology to improve business operations and customer travel experiences along the system. V2X technologies will rely on several current and recent efforts to enhance the performance, capabilities, and effectiveness of V2X applications.

Fiber Optic Broadband Network (FOBN) – The upgraded fiber optic network significantly enhances the communications capabilities among the devices, the devices and the traffic management center and between traffic management centers. Although there are some missing links in the network along the I-24 SMART Corridor, the existing network should be capable of accommodating communication needs for the foreseeable future.

Dedicated Short-Range Communications (DSRC) and Cellular Vehicle to Everything (C-V2X) Roadside Units (RSU) – TDOT has deployed a mixture of 150 DSRC and C-V2X RSUs along the I-24 SMART Corridor. These RSUs connect all entities on the road, allowing them to communicate with one another and share critical information regarding the status of each road user, potential hazards, and the condition of the road and traffic flow.

Overhead Gantries – TDOT has constructed 67 overhead gantries along the I-24 SMART Corridor. These overhead gantries provide overhead message boards that display variable speed limits and lane control signs to warn of incidents, construction, or congestion ahead. The goal of the overhead gantries is to improve the safety of the corridor and make the average commute time more consistent.

4.2 Define Candidate V2X Use Cases

V2X applications using roadside communications are only effective if they are specifically aimed at solving a problem. While communications infrastructure is critical and indeed the backbone of a V2X network, the value is not in the infrastructure itself, the value is in the applications that the infrastructure supports. V2X applications will be successful when they address a defined problem either along the corridor or at a spot location. Approximately 30 FHWA identified applications were reviewed to determine their feasibility and relevance to the I-24 SMART Corridor. These include, but are not limited to, multimodal ITS system/Transit Signal Priority (TSP) and emergency vehicles, curve speed warning, red light violation warning, and traffic incident management specific applications.

In order to undertake the prioritization activity for determining which of the FHWA-identified V2X applications were applicable to the I-24 corridor (See Section 4.4), a comprehensive overview of traffic and operational conditions along the corridor is required. The following documents were used to provide this overview of existing and future corridor conditions:

- Five (5)-Year Crash History[1]
- Recurring Congestion History on I-24[2]
- Recurring Congestion History on Arterials and at Signalized Intersections within the I-24 SMART Corridor project limits[3]
- Ten (10)-Year Traffic Volume History[4]
- Projected Traffic Growth
- Vehicle Travel Times[5]
- Geometric Constraints[6]
- Transit Vehicle On-Time Performance[7]
- Long-Range Transportation Plans
- I-24 Smart Corridor Systems Engineering Management Plan
- I-24 SMART Corridor Concept of Operations
- I-24 SMART Corridor Design Plans

[1] Crash Data from TDOT AASHTOWare

[2] Congestion Data from RITIS/INRIX

[3] Congestion Data from RITIS/INRIX

[4] Traffic Volumes from ETRIMS

[5] Travel Times from RITIS/INRIX

[6] Road Geometrics from ETRIMS

[7] Transit OTP provided by WeGo

Data for the congestion and crash locations along the I-24 SMART Corridor were compiled into heat maps to illustrate locations where V2X applications should be investigated. Figures 4-1 through 4-4 provide an overview of the congestion hotspots along the freeway and arterial segments within the I-24 Smart Corridor. The figures show the average travel speed (mph) of vehicles per hour on the I-24 corridor. Areas in yellow, orange, or red show when and where there is congestion, as average vehicle speeds fall significantly under the posted speed limit for a particular section of roadway. Note that along US-41, the average travel speeds of most time periods/sections fall under the posted speed limit due to the presence of traffic signals manipulating the average speed. The posted speed limit is mostly 70 MPH but is 55 MPH from I-440 to just East of Briley Parkway (SR 155) and 65 MPH from Briley Parkway (SR 155) to just east of Harding Place. This data was gathered using the Regional Integrated Transportation Information System (RITIS) and the INRIX Roadway Analytics tools, which provide current and historical congestion data through calculating average vehicle speeds.

Direction	Intersection	12:00 AM	1:00 AM	2:00 AM	3:00 AM	4:00 AM	5:00 AM	6:00 AM	7:00 AM	8:00 AM	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM	6:00 PM	7:00 PM	8:00 PM	9:00 PM	10:00 PM	11:00 PM
WB	US-231/EXIT 81	68	68	68	68	69	70	70	69	69	69	70	70	69	69	69	69	69	69	70	70	69	68	68	68
WB	US-231/EXIT 81	68	68	68	68	69	70	69	70	70	70	70	70	70	70	69	69	69	70	70	70	69	67	68	68
WB	TN-96/EXIT 78	68	68	68	68	69	70	69	68	69	69	69	68	69	69	69	68	69	69	69	70	69	66	67	68
WB	TN-96/EXIT 78	67	66	67	67	68	68	68	67	68	68	68	68	68	68	68	68	68	68	67	67	68	66	66	67
WB	TN-840/EXIT 74	69	68	68	69	70	71	69	69	70	70	70	70	70	70	69	70	70	69	68	69	69	67	68	68
WB	TN-840/EXIT 74	67	67	67	68	69	70	67	66	68	68	68	68	69	68	67	67	67	67	67	69	68	66	66	67
WB	TN-102/ALMAVILLE RD/EXIT 70	69	68	69	69	71	71	67	68	70	70	71	71	71	70	70	70	70	70	70	71	70	70	70	69
WB	TN-102/ALMAVILLE RD/EXIT 70	69	68	68	69	70	71	62	66	68	70	70	70	70	70	70	70	70	69	70	70	70	70	70	69
WB	TN-266/SAM RIDLEY PKWY/EXIT 66	68	68	68	69	70	70	60	61	65	68	69	69	69	69	68	69	68	67	68	69	69	69	69	69
WB	TN-266/SAM RIDLEY PKWY/EXIT 66	68	68	68	69	70	70	51	48	57	67	68	68	69	68	66	67	66	65	67	69	68	68	69	68
WB	WALDRON RD/EXIT 64	68	67	68	68	70	70	46	34	43	63	66	67	67	67	66	66	65	63	65	67	67	68	68	68
WB	WALDRON RD/EXIT 64	68	68	68	69	70	71	42	26	34	59	66	68	69	69	68	67	65	64	66	67	67	68	69	68
WB	TN-171/OLD HICKORY BLVD/EXIT 62	68	67	67	68	69	69	42	26	32	55	63	65	66	66	66	65	63	61	64	66	66	65	67	68
WB	TN-171/OLD HICKORY BLVD/EXIT 62	67	67	67	68	69	69	43	26	32	53	61	63	64	65	65	64	63	61	64	68	67	61	63	66
WB	HICKORY HOLLOW PKWY/EXIT 60	66	66	67	68	69	69	39	25	31	51	59	61	62	62	62	61	61	59	62	66	65	58	58	62
WB	HICKORY HOLLOW PKWY/EXIT 60	66	67	68	69	69	68	34	21	27	47	57	60	60	61	61	59	60	59	62	66	65	59	60	62
WB	TN-254/BELL RD/EXIT 59	66	67	68	68	69	66	34	23	28	46	56	60	59	61	60	58	59	57	60	64	64	59	59	63
WB	TN-254/BELL RD/EXIT 59	65	67	67	68	69	67	35	24	29	44	54	59	59	59	58	56	57	56	58	62	63	58	60	63
WB	HAYWOOD LN/EXIT 57	66	66	67	67	69	67	47	37	41	53	59	63	63	63	62	61	62	61	62	65	65	63	64	65
WB	HAYWOOD LN/EXIT 57	67	66	67	68	69	67	50	38	46	57	63	66	66	65	65	64	65	64	65	67	67	66	66	67
WB	TN-255/HARDING PL/EXIT 56	68	68	68	68	69	68	46	31	36	51	61	66	67	64	64	63	66	66	67	68	68	67	67	68
WB	TN-255/HARDING PL/EXIT 56	68	68	68	68	69	68	44	31	34	47	58	64	65	63	62	61	65	66	67	69	69	68	67	67
WB	TN-155/BRILEY PKWY/EXIT 54	67	66	66	66	68	67	56	50	48	56	61	64	63	62	62	62	63	63	65	67	67	66	66	66
WB	TN-155/BRILEY PKWY/EXIT 54	66	66	66	66	67	68	61	51	46	58	63	66	65	65	65	64	63	63	66	67	66	67	67	67
WB	I-440/EXIT 53	66	65	65	66	67	67	62	51	47	56	63	65	65	65	64	63	62	62	65	67	66	66	66	66
WB	I-440/EXIT 53	65	64	64	65	66	66	59	57	45	46	54	59	59	59	56	51	47	46	56	64	62	61	61	63

Figure 4-1. I-24 Westbound Congestion Between I-440 Exit and US-231 Exit

Direction	Intersection	12:00 AM	1:00 AM	2:00 AM	3:00 AM	4:00 AM	5:00 AM	6:00 AM	7:00 AM	8:00 AM	9:00 AM	10:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM	6:00 PM	7:00 PM	8:00 PM	9:00 PM	10:00 PM	11:00 PM
EB	US-231/EXIT 81	68	68	68	68	68	69	69	68	68	67	64	63	64	66	66	64	63	66	68	68	67	68	68
EB	US-231/EXIT 81	69	68	68	68	69	70	70	70	70	68	65	64	64	66	68	66	65	68	70	69	69	69	69
EB	TN-96/EXIT 78	68	68	68	69	69	70	70	69	69	69	67	65	65	66	68	67	66	68	70	69	67	67	68
EB	TN-96/EXIT 78	69	68	68	69	69	70	71	70	70	70	69	69	69	68	69	66	64	68	69	69	67	67	68
EB	TN-840/EXIT 74	68	69	68	69	69	70	70	70	70	70	69	69	69	69	69	66	64	67	70	70	69	69	68
EB	TN-840/EXIT 74	68	69	69	69	69	70	71	70	71	71	70	70	70	70	69	68	67	67	70	69	68	68	67
EB	TN-102/ALMAVILLE RD/EXIT 70	67	69	69	69	69	70	71	70	70	71	70	71	70	69	69	67	66	68	70	67	65	66	66
EB	TN-102/ALMAVILLE RD/EXIT 70	69	69	69	69	69	70	71	70	70	71	70	70	70	70	68	65	64	68	69	69	68	68	69
EB	TN-266/SAM RIDLEY PKWY/EXIT 66	69	69	69	69	69	70	70	70	69	69	69	69	70	69	68	65	64	68	69	69	69	69	69
EB	TN-266/SAM RIDLEY PKWY/EXIT 66	69	68	68	68	68	69	70	68	68	68	68	68	68	67	65	62	61	65	67	67	68	67	68
EB	WALDRON RD/EXIT 64	69	68	68	68	68	69	69	68	68	68	67	68	68	66	64	61	60	64	66	67	68	68	69
EB	WALDRON RD/EXIT 64	69	68	68	68	69	69	69	67	68	68	67	66	67	65	62	57	56	61	65	67	68	69	69
EB	TN-171/OLD HICKORY BLVD/EXIT 62	69	69	69	69	69	70	70	68	69	69	67	67	67	65	62	55	53	60	65	68	69	69	69
EB	TN-171/OLD HICKORY BLVD/EXIT 62	67	67	67	67	68	69	69	67	68	68	67	66	65	63	61	55	54	59	63	66	65	66	67
EB	HICKORY HOLLOW PKWY/EXIT 60	65	66	65	66	66	67	67	66	66	67	67	64	63	60	56	47	47	55	62	64	63	63	65
EB	HICKORY HOLLOW PKWY/EXIT 60	65	65	66	66	66	67	67	66	66	67	67	64	64	62	58	49	48	56	62	64	63	64	65
EB	TN-254/BELL RD/EXIT 59	64	66	66	67	67	68	67	64	64	67	67	65	64	62	58	51	50	56	63	64	61	61	62
EB	TN-254/BELL RD/EXIT 59	60	64	66	67	68	68	67	65	64	66	66	63	61	58	52	45	43	48	58	57	53	55	56
EB	HAYWOOD LN/EXIT 57	60	66	66	67	68	68	67	65	63	65	64	59	57	53	41	30	27	37	55	55	51	52	53
EB	HAYWOOD LN/EXIT 57	60	65	66	67	67	68	68	66	65	65	65	61	58	55	44	32	29	40	58	59	55	55	55
EB	TN-255/HARDING PL/EXIT 56	62	65	66	67	67	68	69	67	65	66	66	62	59	55	45	31	29	42	59	61	56	56	58
EB	TN-255/HARDING PL/EXIT 56	64	65	65	66	66	67	67	65	63	65	65	60	56	47	34	28	27	33	51	61	57	57	62
EB	TN-155/BRILEY PKWY/EXIT 54	64	64	64	65	65	66	65	63	61	64	64	59	55	41	23	18	17	23	47	61	57	60	64
EB	TN-155/BRILEY PKWY/EXIT 54	65	65	65	65	65	66	66	65	64	64	64	60	58	44	22	16	15	22	50	62	61	64	64
EB	I-440/EXIT 53	61	62	62	62	62	63	62	60	59	59	58	55	54	45	24	17	15	22	48	57	57	58	59
EB	I-440/EXIT 53	59	60	60	60	60	60	59	56	55	54	53	52	51	45	27	21	18	24	47	53	52	54	56

Figure 4-2. I-24 Eastbound Congestion Between I-440 Exit and US-231 Exit

Direction	Intersection	12:00 AM	1:00 AM	2:00 AM	3:00 AM	4:00 AM	5:00 AM	6:00 AM	7:00 AM	8:00 AM	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM	6:00 PM	7:00 PM	8:00 PM	9:00 PM	10:00 PM	11:00 PM
WB	ASH ST	32	32	32	32	33	34	33	30	29	29	28	27	27	26	27	26	25	26	28	29	31	32	32	32
WB	US-231/S CHURCH ST	33	33	33	33	35	35	33	29	28	29	28	27	26	26	27	27	27	28	30	31	32	33	33	33
WB	W MAIN ST	33	33	33	33	35	36	32	29	28	28	27	25	24	25	26	25	26	28	29	31	32	33	33	33
WB	US-231/TN-96/OLD FORT PKWY	30	31	31	32	33	33	30	27	26	27	26	25	24	25	25	24	24	26	26	28	29	29	29	30
WB	W LOKEY AVE	34	35	35	35	36	37	36	31	30	30	29	28	27	26	27	26	25	27	29	31	33	34	34	34
WB	US-231/TN-96/OLD FORT PKWY	30	31	32	32	33	33	34	32	31	31	30	29	29	29	29	29	29	30	29	30	31	31	29	30
WB	W CLARK BLVD	37	37	37	38	38	40	40	35	34	35	35	34	32	33	33	33	33	34	35	37	37	38	37	37
WB	W NORTHFIELD BLVD	38	39	39	39	40	41	38	35	35	35	35	35	34	34	35	34	34	34	36	36	37	38	38	38
WB	N THOMPSON LN	40	40	40	40	41	40	33	32	34	35	34	34	32	32	32	30	25	20	34	36	36	38	39	39
WB	TN-840	49	48	49	49	51	52	51	50	50	50	50	49	49	49	49	48	48	48	49	50	50	50	50	49
WB	TN-840	52	51	51	51	53	55	55	56	55	55	55	55	56	55	55	56	56	56	56	56	55	55	53	52
WB	FLORENCE RD	50	50	49	49	51	52	47	49	49	50	50	50	50	49	49	49	49	50	50	50	50	51	50	49
WB	GEORGE FRANKLIN RD	47	47	47	47	49	50	47	47	47	48	48	48	47	47	47	47	47	47	47	47	47	48	48	47
WB	TN-102/NISSAN DR	44	44	44	44	45	45	38	41	45	45	45	44	44	44	43	44	44	44	45	45	44	45	45	44
WB	TN-102/NISSAN DR	46	46	46	46	46	47	48	48	48	48	48	48	49	48	48	48	48	48	48	48	48	48	47	46
WB	ENON SPRINGS RD	40	39	39	39	40	40	38	36	37	37	37	36	36	36	35	34	34	34	36	37	37	38	39	39
WB	TN-266/SAM RIDLEY PKWY	36	36	36	36	37	38	37	34	34	33	33	32	31	31	31	31	31	31	32	33	33	34	35	36
WB	TN-266/SAM RIDLEY PKWY	43	43	43	43	44	45	45	45	45	45	44	44	44	44	43	43	43	42	43	44	43	43	43	43
WB	OLD NASHVILLE HWY/MADISON SQUARE BLVD	40	40	40	40	40	40	38	37	38	38	38	37	36	36	35	34	33	32	35	37	38	39	38	39
WB	PARTHENON BLVD	33	33	33	34	35	34	25	21	29	30	30	29	27	26	25	24	22	20	24	28	30	31	32	33
WB	TN-171/OLD HICKORY BLVD/HOBSON PIKE	39	39	40	40	41	41	33	22	29	36	36	36	35	35	33	31	32	32	33	34	36	37	38	38
WB	TN-171/OLD HICKORY BLVD/HOBSON PIKE	30	30	31	32	32	32	26	23	23	24	24	24	24	24	24	24	25	25	25	24	25	26	28	29
WB	MT VIEW RD	39	39	39	40	41	40	34	26	26	32	33	33	32	32	31	28	29	29	30	32	34	35	37	38
WB	HAMILTON CHURCH RD	41	40	41	42	43	42	38	35	35	36	36	36	35	35	34	32	32	32	33	34	35	36	38	39
WB	TN-254/BELL RD	35	35	36	37	38	36	31	28	27	29	28	28	27	26	24	24	24	24	25	27	29	31	32	33
WB	TN-254/BELL RD	29	31	32	33	32	31	26	23	22	24	24	23	22	22	20	20	20	21	21	23	24	26	27	28
WB	RURAL HILL RD	33	34	35	36	36	35	28	24	22	26	27	26	25	24	22	22	22	22	23	25	27	29	30	31
WB	NASHBORO BLVD/UNA ANTIOCH PIKE	36	37	38	39	39	38	29	21	21	28	28	27	27	26	25	26	26	26	27	28	30	32	34	35
WB	NASHBORO BLVD/UNA ANTIOCH PIKE	32	34	35	35	35	32	22	16	18	22	22	21	20	20	19	19	20	21	21	22	24	26	28	29
WB	FRANKLIN LIMESTONE RD	36	37	38	39	38	35	27	23	23	27	27	26	26	25	24	24	25	25	27	28	30	31	33	34
WB	SMITH SPRINGS RD	38	39	39	40	40	39	34	31	32	35	36	35	34	33	31	30	30	31	32	35	36	37	37	37
WB	SMITH SPRINGS RD	40	40	41	42	41	41	37	34	35	38	39	38	38	37	35	34	34	34	35	38	39	39	39	39
WB	TN-255/DONELSON PIKE	43	43	43	44	44	43	36	25	31	38	40	40	39	39	39	38	38	37	39	40	41	42	42	42
WB	TN-255/DONELSON PIKE	33	35	35	35	32	31	28	26	26	26	26	26	25	25	25	24	24	24	25	27	28	30	30	31
WB	TN-155/BRILEY PKWY	44	44	44	44	43	43	39	36	37	38	38	38	38	38	38	38	38	38	39	41	42	43	44	44
WB	TN-155/BRILEY PKWY	34	35	36	35	36	34	31	29	28	29	29	29	28	29	29	28	28	28	29	29	31	32	33	33
WB	THOMPSON LN/THOMPSON PL	36	37	38	38	39	39	35	32	31	31	31	30	29	29	30	29	28	28	29	30	31	33	34	35
WB	I-24	33	34	35	35	36	35	30	23	23	28	29	28	27	27	26	25	25	25	27	28	30	31	32	33
WB	I-24	36	36	36	36	37	37	35	32	31	32	33	33	33	33	33	33	33	34	34	35	35	36	36	35

Figure 4-3. US-70S Congestion Between I-24 and Ash Street

Direction	Intersection	12:00 AM	1:00 AM	2:00 AM	3:00 AM	4:00 AM	5:00 AM	6:00 AM	7:00 AM	8:00 AM	9:00 AM	10:00 AM	11:00 AM
EB	ASH ST	34	34	33	33	33	33	33	31	30	29	28	28
EB	US-231/S CHURCH ST	34	34	34	33	34	34	34	30	30	28	28	27
EB	W MAIN ST	32	32	32	32	32	32	31	28	27	27	26	24
EB	US-231/TN-96/OLD FORT PKWY	29	30	30	30	29	28	26	27	27	26	25	25
EB	US-231/TN-96/OLD FORT PKWY	35	36	36	35	35	34	32	32	32	30	30	29
EB	W LOKEY AVE	37	37	37	37	37	37	36	33	33	32	30	28
EB	W CLARK BLVD	40	40	39	39	39	41	41	39	38	38	36	34
EB	W NORTHFIELD BLVD	41	40	40	40	40	41	40	38	37	38	37	36
EB	N THOMPSON LN	48	48	48	48	48	48	49	43	45	47	47	46
EB	TN-840	56	56	56	56	56	56	58	58	58	58	58	58
EB	TN-840	49	49	49	48	49	50	49	47	48	48	48	47
EB	FLORENCE RD	49	49	49	49	49	49	47	39	46	47	47	47
EB	GEORGE FRANKLIN RD	46	46	46	46	47	46	45	45	47	47	47	47
EB	TN-102/NISSAN DR	46	46	45	45	45	45	47	47	47	47	47	47
EB	TN-102/NISSAN DR	40	40	39	39	40	40	40	38	38	38	37	36
EB	ENON SPRINGS RD	37	37	37	37	37	37	37	34	33	33	32	31
EB	TN-266/SAM RIDLEY PKWY	43	43	43	43	44	44	43	43	42	43	43	42
EB	TN-266/SAM RIDLEY PKWY	41	41	40	40	40	40	39	37	37	37	37	36
EB	OLD NASHVILLE HWY/MADISON SQUARE BLVD	35	35	36	35	35	35	34	32	31	31	31	29
EB	PARTHENON BLVD	42	42	41	41	42	41	38	35	36	37	37	35
EB	TN-171/OLD HICKORY BLVD/HOBSON PIKE	28	28	28	28	28	27	25	23	23	26	26	26
EB	TN-171/OLD HICKORY BLVD/HOBSON PIKE	39	40	40	40	40	40	37	33	34	35	35	33
EB	MT VIEW RD	42	43	43	43	42	43	39	36	37	39	38	37
EB	HAMILTON CHURCH RD	36	37	37	37	36	35	32	30	30	30	30	28
EB	TN-254/BELL RD	30	31	32	32	31	29	26	24	24	25	25	24
EB	TN-254/BELL RD	32	33	34	34	33	30	27	25	25	26	26	25
EB	RURAL HILL RD	35	37	37	37	37	36	33	31	30	30	29	27
EB	NASHBORO BLVD/UNA ANTIOCH PIKE	28	29	31	32	30	27	23	22	22	23	23	21
EB	NASHBORO BLVD/UNA ANTIOCH PIKE	34	36	36	37	36	35	31	28	27	28	27	24
EB	FRANKLIN LIMESTONE RD	36	37	39	39	38	38	35	32	31	33	33	30
EB	SMITH SPRINGS RD	37	38	39	40	39	39	36	33	33	34	34	32
EB	SMITH SPRINGS RD	41	42	42	42	41	41	40	39	39	40	40	39
EB	TN-255/DONELSON PIKE	30	31	32	32	30	29	28	26	26	26	26	24
EB	TN-255/DONELSON PIKE	43	43	43	42	40	40	39	38	39	39	39	38
EB	TN-155/BRILEY PKWY	32	33	35	35	34	31	29	26	26	28	28	27
EB	TN-155/BRILEY PKWY	35	36	38	37	37	35	32	30	30	32	32	31
EB	THOMPSON LN/THOMPSON PL	35	35	36	36	36	35	32	29	28	30	30	28
EB	I-24	34	34	35	34	33	32	29	27	27	30	30	30
EB	I-24	34	34	35	35	34	32	30	28	28	28	28	28

Direction	Intersection	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM	6:00 PM	7:00 PM	8:00 PM	9:00 PM	10:00 PM	11:00 PM
EB	ASH ST	27	27	26	25	24	24	28	28	29	31	33	34
EB	US-231/S CHURCH ST	25	25	23	22	22	23	28	29	30	32	33	34
EB	W MAIN ST	23	23	23	22	21	22	26	28	30	31	31	32
EB	US-231/TN-96/OLD FORT PKWY	24	24	24	23	21	22	25	26	27	27	27	28
EB	US-231/TN-96/OLD FORT PKWY	28	28	28	28	26	26	29	31	32	33	33	34
EB	W LOKEY AVE	27	27	28	28	28	28	29	33	35	36	36	36
EB	W CLARK BLVD	33	34	35	35	35	35	36	38	39	39	40	39
EB	W NORTHFIELD BLVD	36	36	36	34	34	33	36	38	39	39	40	41
EB	N THOMPSON LN	46	46	44	39	33	27	40	47	47	47	48	48
EB	TN-840	59	58	58	58	59	58	58	58	57	56	57	57
EB	TN-840	48	48	47	46	46	46	48	49	49	49	50	49
EB	FLORENCE RD	47	46	43	40	32	31	46	48	48	48	49	49
EB	GEORGE FRANKLIN RD	47	47	45	43	43	44	46	47	47	47	47	47
EB	TN-102/NISSAN DR	48	47	47	47	47	47	48	47	47	47	47	46
EB	TN-102/NISSAN DR	36	36	36	35	35	35	36	38	38	39	40	40
EB	ENON SPRINGS RD	31	30	30	29	28	29	32	33	33	34	36	36
EB	TN-266/SAM RIDLEY PKWY	42	42	41	40	39	40	42	43	43	43	44	43
EB	TN-266/SAM RIDLEY PKWY	36	36	35	34	33	33	35	37	37	39	39	40
EB	OLD NASHVILLE HWY/MADISON SQUARE BLVD	29	29	29	28	26	27	28	30	32	33	34	35
EB	PARTHENON BLVD	34	32	29	27	23	20	24	33	37	39	40	41
EB	TN-171/OLD HICKORY BLVD/HOBSON PIKE	26	25	23	22	24	25	25	24	25	25	25	26
EB	TN-171/OLD HICKORY BLVD/HOBSON PIKE	32	32	31	28	28	29	30	32	34	36	37	38
EB	MT VIEW RD	36	35	33	32	29	27	30	34	36	39	40	41
EB	HAMILTON CHURCH RD	27	26	25	24	23	23	23	25	28	30	32	34
EB	TN-254/BELL RD	24	23	23	22	20	21	21	22	24	26	27	28
EB	TN-254/BELL RD	24	24	23	22	20	20	21	23	25	27	28	30
EB	RURAL HILL RD	26	26	25	25	24	24	24	25	28	31	33	34
EB	NASHBORO BLVD/UNA ANTIOCH PIKE	20	20	20	20	20	19	19	19	22	24	25	26
EB	NASHBORO BLVD/UNA ANTIOCH PIKE	23	22	21	18	16	16	17	20	25	28	30	32
EB	FRANKLIN LIMESTONE RD	29	28	27	19	15	14	16	24	30	32	33	34
EB	SMITH SPRINGS RD	31	30	29	21	15	14	16	25	31	33	34	35
EB	SMITH SPRINGS RD	37	37	36	29	20	17	21	32	37	39	40	40
EB	TN-255/DONELSON PIKE	23	23	21	20	17	16	18	23	26	27	28	28
EB	TN-255/DONELSON PIKE	38	38	36	34	31	29	33	39	41	42	42	42
EB	TN-155/BRILEY PKWY	27	27	27	27	26	27	28	30	30	31	31	31
EB	TN-155/BRILEY PKWY	30	30	30	29	29	29	30	31	32	33	34	34
EB	THOMPSON LN/THOMPSON PL	27	27	26	23	21	20	23	28	30	32	33	34
EB	I-24	30	29	28	25	25	25	27	31	31	32	33	33
EB	I-24	28	28	28	25	23	25	32	34	34	35	35	35

Figure 4-4. US-70S Eastbound Congestion Between I-24 and Ash Street

Crash data for the I-24 Freeway, US-41, and connector routes were collected. The crash data and congestion hotspots were combined to create an overview of where V2X applications would likely help the most from a traffic mobility and safety standpoint. This resultant "hot spot" map can be found in Figure 4-5.

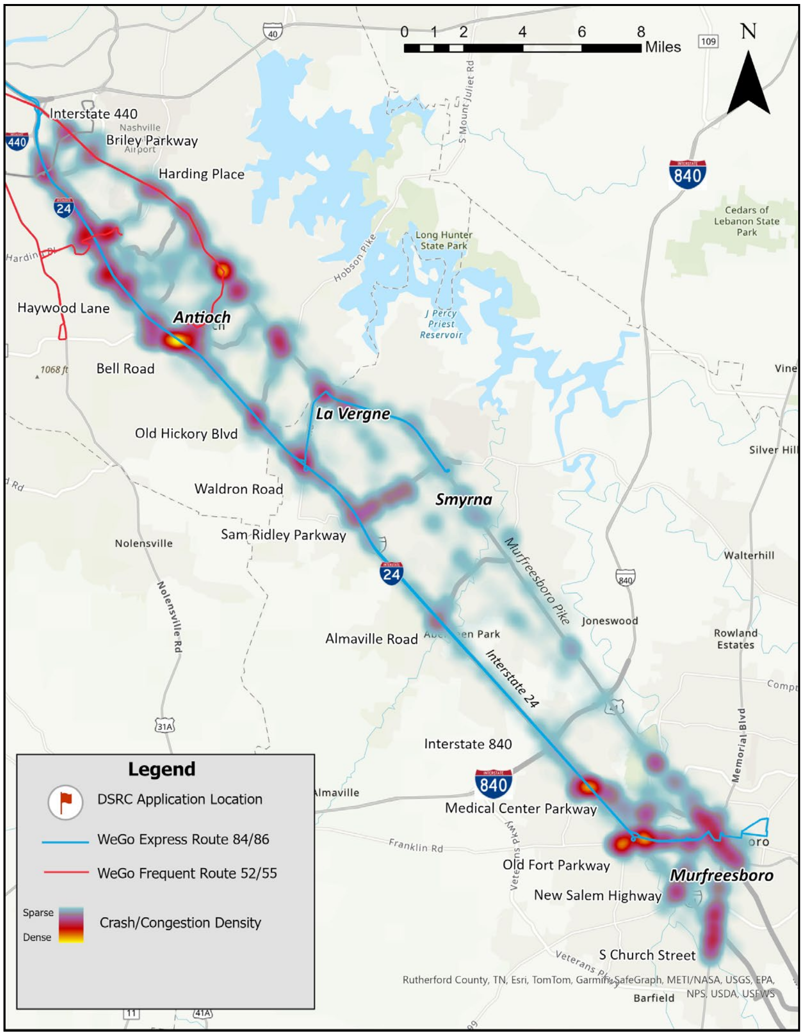

Figure 4-5. I-24 Corridor Crash/Congestion Density Heat Map

4.3 Vehicle Plan

Without vehicles, CV systems cannot function as intended. Benefits from any V2X application can only be realized with vehicles equipped and able to support the applications. Many industry experts predict that it may be many years before OBUs are installed and required as equipment on new vehicles coming off the assembly line. Optimistic experts indicate that vehicles will become equipped with OBUs within the next five years and will take at least 10 more years to start realizing the benefits of some V2X applications. By then, deployed CV infrastructure systems run the risk of being obsolete.

To jump-start the benefits of V2X applications and more quickly realize application benefits, a vehicle plan that points to “seeding” the network with equipped vehicles is recommended. Identifying a fleet of vehicles that can communicate with the field devices is essential for the RSUs to function as intended. Where captive fleet vehicles typically travel along the I-24 SMART Corridor is an important input into the V2X application prioritization process as well as ensuring that these fleet vehicles frequently travel the corridor.

TDOT Fleet Vehicles – This could include statewide or regional maintenance vehicles or passenger vehicles owned and/or operated by TDOT. Typically, these vehicles are the easiest to access and equip with OBUs. This is likely the most cost-effective means of boosting equipped vehicle Market Penetration Rate (MPR) and testing of pilot and early development applications. In the areas surrounding the I-24 SMART Corridor, TDOT employs 419 fleet vehicles. Equipping these vehicles with OBU’s can help increase the penetration rate of vehicles, which can advance the maturity and utility of deployed V2I applications.

TDOT HELP Vehicles – These vehicles are the freeway service patrol vehicles that provide incident management, motorist safety, and congestion prevention services within the I-24 SMART Corridor. In the Nashville area, TDOT employs ten (10) of these vehicles. Having these vehicles equipped with OBU’s can help increase the penetration rate of vehicles, which can advance the maturity and utility of deployed V2I applications.

Partner Public Fleet Vehicles – These vehicles could include transit vehicles, state and local emergency vehicles, local maintenance vehicles, and passenger vehicles of partner state, county, and local agencies. Typically, these vehicles require intergovernmental agreements to equip and maintain. TDOT could then utilize these devices to pilot various V2X applications through the partnerships.

Partner Private Fleet Vehicles – These vehicles could include fleets owned and/or operated by private entities, such as UPS, FedEx, or other delivery services. Significant coordination is typically required to work with these fleet vehicles; however, these fleets usually have the most geographically diverse footprint.

General Privately Owned Vehicles – While privately owned vehicles generally cover the most geographically diverse footprint, the level of effort, coordination, and responsibility for actively recruiting privately owned personal vehicles generally are not supported by the benefits received. It may be more appropriate to wait for the manufacturers to install OBUs in new vehicle from the factory.

4.4 Prioritize V2X Use Case Implementation

The United States Department of Transportation has previously sponsored the planning of dozens of V2X applications over five (5) major categories. As part of the Roadmap development, TDOT evaluated Vehicle-to-Infrastructure (V2I) specific applications for priority use along the I-24 SMART corridor, listed below in Table 4-1.

Table 4-1. V2I Applications

Application Group	Freeway	Arterial
Safety	• Distress Notification • Curve Speed Warning • Wrong-way Driving • Railway Crossing • Reduced Speed / Lane Closure Warning • Queue Warning • Incident Zone Warning • Work Zone Warning • Work Zone Intrusion Warning	• Red Light Violation Warning • Intersection Movement Assist • Emergency Vehicle Pre-Emption • Emergency Vehicle Alert • Distress Notification • Curve Speed Warning • Pedestrian in Signalized Crosswalk • Wrong-way Driving • Railway Crossing • Reduced Speed / Lane Closure Warning • Queue Warning • Incident Zone Warning • Work Zone Warning • Work Zone Intrusion Warning

Application Group	Freeway	Arterial
Mobility and Environment	• Oversize Vehicle Warning • Speed Harmonization • Road/Lane Use Restriction • Spot Weather	• Mobile Accessible Pedestrian Signal • Oversize Vehicle Warning • Eco Approach and Departure • Intelligent Traffic Signal System • Speed Harmonization • Road / Lane Use Restriction • Spot Weather
Commercial Vehicle Operations	• Commercial Vehicle Wireless Inspection • Truck Parking Information System	• Commercial Vehicle Wireless Inspection
Traveler Information	• Probe-Enabled Traffic Monitoring	• Probe-Enabled Traffic Monitoring
Data Collection and Asset Management	• Road Maintenance Reporting	• Road Maintenance Reporting

Not all of these applications are applicable to the I-24 SMART Corridor. Additionally, some of the applications that may address conditions relevant to the I-24 SMART Corridor may not yet be deployable and may require significant additional development and implementation costs and timelines that could extend beyond the vision of TDOT. To filter through these applications and determine what could be realistically within the vision of TDOT, a collaborative prioritization assessment was performed.

The assessment of V2X applications began with input from TDOT staff, who were asked to objectively rank the priority of twenty-four (24) V2X applications for deployment along the I-24 SMART Corridor. TDOT was guided through a general process of determining which applications, as defined in ARC-IT, were applicable and of specific interest in supporting roadway operations. TDOT evaluated the applications using the following criteria:

- **Readiness/Maturity –** This factor is the result of a subjective assessment of a V2X application's readiness for deployment. Has the application been deployed elsewhere? Was the deployment successful? Does the application still require development? The scoring is on a scale of 1-5, with a scoring of 1 indicating significant development is still needed, while a score of 5 would indicate the application has been used and is successful elsewhere.
- **Applicability –** Based on the results of the previous corridor condition evaluation, this scoring is an assessment of a specific application's usability throughout the I-24 SMART Corridor. This scoring is on a scale of 1-5, with a scoring of 1 indicating the application is not pertinent to the corridor, and a scoring of 5 indicating the application is appropriate for the corridor conditions.
- **Ease of Deployment/Support Systems Needed –** This factor assesses the complexities of deploying a specific V2X application, including the amount of "back-end" systems and infrastructure needed to support the application. This scoring is on a scale of 1-5, with a scoring of 1 indicating the application requires significant and/or complex back-end supporting systems, and a scoring of 5 indicating the application needs minimal supporting systems.
- **Vehicle Assessment –** This factor assesses the accessibility of the vehicles that would benefit the most from the application. In general, V2X applications that require broader deployment of personally owned vehicles will take longer to realize benefits than applications requiring "captive fleet" vehicles. As such, applications benefiting "captive fleet" vehicles would score higher. This scoring is on a scale of 1-5, with a scoring of 1 indicating the application requires general deployment of fleet and personally owned vehicles to realize benefits, and a scoring of 5 indicating the application will realize benefits with captive fleet vehicles.

This process is summarized graphically in Figure 4-6.

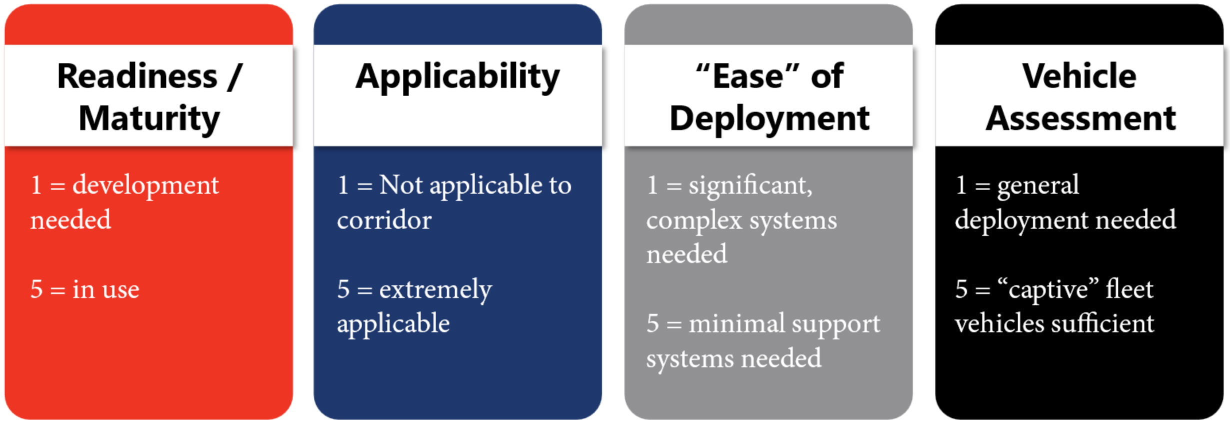

Figure 4-6. V2X Application Prioritization Process

Each application was individually evaluated based on the criteria listed above and assigned an overall priority ranking. These rankings represent the overall perception of the application to the TDOT staff members surveyed. The prioritized rankings can be found in Table 4-2.

Table 4-2. I-24 SMART Corridor V2I Application Prioritized Ranking

Application	Applicability	Ease of Deployment	Vehicle Assessment	Readiness / Maturity	**TOTAL**
Emergency Vehicle Pre-Emption	5	3	4	4	**16**
Reduced Speed / Lane Closure Warning	5	4	2	4	**15**
Intelligent Traffic Signal System	5	2	3	4	**14**
Emergency Vehicle Alert	5	3	2	3	**13**
Mobile Accessible Pedestrian Signal System	5	2	4	2	**13**
Queue Warning	5	4	2	2	**13**
Spot Weather Warning	4	3	2	4	**13**
Road Maintenance Reporting	4	3	2	4	**13**
Distress Notification	5	3	1	3	**12**
Curve Speed Warning	2	5	1	4	**12**
Pedestrian in Signalized Crosswalk	5	3	1	3	**12**
Red Light Violation Warning	2	4	1	4	**11**
Truck Parking Information Systems	1	3	3	4	**11**
Eco-Approach and Departure	5	2	1	3	**11**
Speed Harmonization	5	3	1	2	**11**
Work Zone Instrusion Warning	5	3	1	2	**11**
Railway Crossing Warning	2	4	1	3	**10**
Oversize Vehicle Warning	1	4	2	2	**9**
Road / Lane Use Restriction	2	3	2	2	**9**
Intersection Movement Assist	3	2	1	2	**8**
Left Turn Across Path	3	2	1	2	**8**
Wrong-Way Driving	5		1	2	**8**
Commercial Vehicle Wireless Inspection	1	2	3	2	**8**
Probe-Enabled Traffic Monitoring	2	3	1	1	**7**

Freeway Related | Arterial Related | Freeway and Arterial Related

The design, deployment, and testing of a V2I application is intensive, with a considerable investment of time and money required. As such, it is impractical to expect that each application can reasonably be deployed within the I-24 SMART Corridor comprehensively.

With the landscape of the connected vehicle infrastructure still evolving, it is recommended that TDOT focus their investment strategy on low-risk projects. From an application perspective, low-risk projects are those that can be deployed as standalone projects or have low requirements for centralized IT systems complexity, backhaul infrastructure, and RSU density. Additionally, applications that have low to medium equipped vehicle requirements are considered feasible for short-term deployments. These applications are reflected in Table 4-2, as the top 12 applications.

Early deployment of V2X applications, while low in complexity and infrastructure requirements, will still have a one-to two-year lead time for planning (such as Concept of Operations documentation), implementation, and testing. As such, it is not expected that all of the applications listed would be implemented immediately. TDOT could continue deployments of low-risk applications or could build upon work completed during early deployments with more complex applications.

It is not feasible at this time to recommend applications for the long-term timeframe (+10 years) due to the rapidly evolving technology surrounding V2X applications. This Roadmap should be revisited and updated on a regular basis to adapt to changes in the state of the industry. An interim review should be conducted after 3 years to evaluate the Roadmap based on current technology and trends.

Chapter 5 Implementation Strategy

The V2X Roadmap implementation strategy focuses on the key actions and processes TDOT will need to accomplish to build a successful V2X Program within the I-24 corridor. The key areas of focus are providing successful program launches and delivering value to TDOT as each project is selected to move forward into deployment. In general, the systems engineering process is noted as the best practice and a required step for deploying complex technology solutions. The systems engineering process uses a prescriptive approach to identify project specific goals, develop concepts of operation, determine stakeholder roles, and derive system requirements that are foundational to the final system design. Upon completion of each application's deployment, the systems engineering process verifies that the system meets all requirements and validates that the system meets all user goals.

5.1 Planning-Level Costs

Typical rough order of magnitude (ROM) costs of V2X applications are detailed in Table 5-1 and Table 5-2. These costs were derived from NCHRP 289: *Business Models to Facilitate Deployment of Connected Vehicle Infrastructure to Support Automated Vehicle Operations*. Cost projections for the OBUs and RSUs were adjusted from the NCHRP data to reflect recent deployments in the Nashville area and based on updated information provided by our equipment team partner, Brand Motion. It should be noted that not all applications listed in the tables below are applicable to the I-24 SMART Corridor. These tables provide us with a general guideline to follow for planning-level application deployment costs.

Table 5-1 provides details on several V2X applications, laying out the minimum deployment size for each application (i.e., curve speed warning can be applied at a singular curve), initial cost associated with the application, and the annual operations and maintenance cost required to keep the application operable. Table 5-2 provides details on the costs associated with the equipment that is necessary for these applications to function, It should be noted that the cost estimates for OBUs and RSUs were adjusted from the NCHRP data to match recent estimates in the area.

Table 5-1. Planning-Level Costs for Various V2X Investments (Source NCHRP)

V2I Application	Minimum Deployment Size	Initial Capital Cost	Annual Operations and Maintenance Cost
Curve Speed Warning (CSW)	1 location	$110,000	$11,500
Pedestrian in Signalized Crosswalk Warning	1 intersection	$120,000	$11,500
Railroad Crossing Violation Warning (RCVW)	1 intersection	$11,500	$11,500

Table 5-1. Planning-Level Costs for Various V2X Investments (Source NCHRP) (continued)

V2I Application	Minimum Deployment Size	Initial Capital Cost	Annual Operations and Maintenance Cost
Red Light Violation Warning (RLVW) - hub architecture	10 intersections	$230,000 to $430,000	$11,500
Reduced Speed Zone Warning (RSZW)	1 location	$110,000	$11,500
Incident Scene Work Zone Alerts for Drivers and Workers	1 location	$110,000	$11,500
Queue Warning (Q-WARN)	1 bottleneck	$400,000	$43,000
Eco-Traffic Signal Timing / Transit Signal Priority	3 arterials (15 intersections)	$280,000 to $580,000	$16,500
Intelligent Traffic Signal System (I-SIG)	30 intersections	$660,000 to $1,060,000	$82,000
Speed Harmonization (SPD-HARM)	1 bottleneck	$400,000	$43,000

Table 5-2. Planning-Level Equipment Costs Reference (Source NCHRP)

<table>
<tr><th></th><th>Equipment (per unit unless indicated otherwise)</th><th>Design/Systems Engineering, Deployment, Integration, Testing</th><th>Annual O&M</th><th>Note</th></tr>
<tr><td colspan="5">Roadside Systems</td></tr>
<tr><td>RSU Hardware (RSU, mounting hardware, cabling, connection to traffic signal/ITS cabinet)</td><td colspan="2">$14,500</td><td>$250</td><td>Adjusted based on recent local deployments</td></tr>
<tr><td colspan="5">Support Systems</td></tr>
<tr><td>Security Credential Management System (SCMS)</td><td>-</td><td>-</td><td>$15,000 - $50,000</td><td>Assumed to be developed by others and purchased as a subscription on an annual basis</td></tr>
<tr><td>CV Back Office System</td><td colspan="2">$50,000 - $800,000</td><td>N/A</td><td>Varies considerably based on existing systems, application(s), and extent. Low end - 50 RSU SPaT deployment High end - Small urban region test bed environment</td></tr>
</table>

Table 5-2. Planning-Level Equipment Costs Reference (Source NCHRP) (continued)

	Equipment (per unit unless indicated otherwise)	Design/Systems Engineering, Deployment, Integration, Testing	Annual O&M	Note
V2I Application Software	-	$100,000 - $200,000	10% maintenance, support, and enhancement per year	Per discrete app. Projects may deploy multiple apps and net economies of scale.
	-	$500,000	N/A	UDOT modification of MMITSS software to implement TSP
In-Vehicle Systems				
OBU Hardware (after market)	$7,000		$1,200	Provided by recent local deployment vendor

Chapter 6 Conceptual Deployment Plan

This section details the conceptual deployment plan proposed for the I-24 SMART Corridor along with the associated Capital Plan investment costs. Based on the corridor conditions assessment and "hot spot" analysis, and the V2I application prioritization exercise, a comprehensive picture of where along the corridor V2I applications should be deployed and an associated planning-level cost of each deployment can be developed.

6.1 V2X Preliminary Projects

DSRC to C-V2X

The FCC recently promulgated an order dictating that DSRC as a communications standard is going to be sunset by December 14, 2026. Any roadside unit currently broadcasting using DSRC will not be permitted to operate under a license within that timeframe, and transition to C-V2X protocols. Under the new rules C-V2X is still permitted, and encouraged, to operate within the 5.9 GHz spectrum within and beyond the timeframe leading up to November 21, 2026.

The V2X applications in this Roadmap are dependent on operating 5.9 GHz RSU infrastructure. As such, the priority for TDOT should be to convert all existing DSRC-based RSUs to C-V2X units. This would require upgrading existing DSRC-based RSUs with new units, although all other supporting infrastructure can remain in place.

Along the I-24 SMART Corridor, TDOT has 150 RSUs installed. Of these, 25 are C-V2X capable. The remaining 125 RSUs should be replaced and upgraded to allow for C-V2X operation. The United States Department of Transportation (USDOT) provided in 2024 (*ITS Deployment Evaluation Executive Briefing*) a summary of some recent RSU deployment costs. Using these costs, a new RSU would cost within a range of $900-$5,250 for purchasing the equipment, with a range of $1,000 - $8,000 for the configuration, integration and testing of each RSU. Since TDOT would be replacing existing DSRC RSUs with C-V2X-capable units, it would be appropriate to use planning-level costs in the middle of these ranges, rather than using a conservative "maximum" cost.

Planning-level costs for replacing each DSRC RSU with a C-V2X RSU so the entire corridor is C-V2X capable would be:

125 units x ($3,100 (purchase) + $4,500 (integration/testing/verification)) = $950,000

Using the values provided by NCHRP, each RSU would require a $250 annual O&M cost, which includes security certificates, power, and equipment maintenance.

6.2 V2X Fleet Integration

The MPR of equipped public and private vehicles will significantly influence the capabilities of V2X applications. As detailed in Section 4.3, there are several approaches to increasing equipped vehicle MPR on the I-24 SMART Corridor:

1. I-24 SMART Corridor Fleet (TDOT maintenance and passenger vehicle fleet)
2. Strategic Partners (THP, Fire and EMS vehicle fleet)
3. Partner Private Fleet Vehicles (UPS, FedEx, and other delivery services)
4. General Privately Owned Vehicles

For early deployment, it is not recommended to invest in equipping strategic partners for V2X communications. Rather, the lower-risk strategy would be to retrofit the I-24 SMART Corridor's TDOT fleet with an aftermarket safety device (ASD), specifically around the locations of the V2X Deployment Projects listed in Section 6.3. These units will allow TDOT to test the operations of V2X applications along the system. In the areas surrounding the I-24 SMART Corridor, TDOT currently employs 419 vehicles.

Capital costs for C-V2X vehicle on-board units (OBU) can cost up to $5,000 each, depending on the unit manufacturer. For this Roadmap document, we used this value to develop planning-level costs. Similarly, the installation, integration and verification of an OBU can cost up to $2,200 each, depending on the vehicle type. We used this value to develop the planning-level costs in this Roadmap.

6.3 V2X Deployment Projects

Incorporating the I-24 SMART Corridor V2X Implementation Strategy, as identified in Section 5, the process for prioritizing locations and subsequently developing conceptual buildouts for the initial deployment of V2X application across the I-24 SMART Corridor took place. Building a V2X program from localized, small-scale use-cases to larger and more complex applications will take time and an investment strategy that capitalizes on the short-term benefits of the application while considering the scalability of the infrastructure over time for long-term V2X applications.

6.3.1 Application Location Determination

As detailed in Section 4.2 the I-24 SMART corridor was evaluated based on the following information from other sources:

- Mainline Curve Warning
- Road Weather Hotspots
- Re-occurring Congestion
- Reduced Speed Limits
- Crash History
- AADT
- Existing/Planned ITS Devices
- Interchanges

This data was combined with the prioritized applications to determine the appropriate locations and application approach. A total of 49 locations would be integrated into one or more V2I applications. Information regarding the location screener and prioritization is further detailed in Appendix C: V2X Application Deployment Locations. Figure 6-1 summarizes the application deployment locations.

6.3.2 V2X Application Deployments

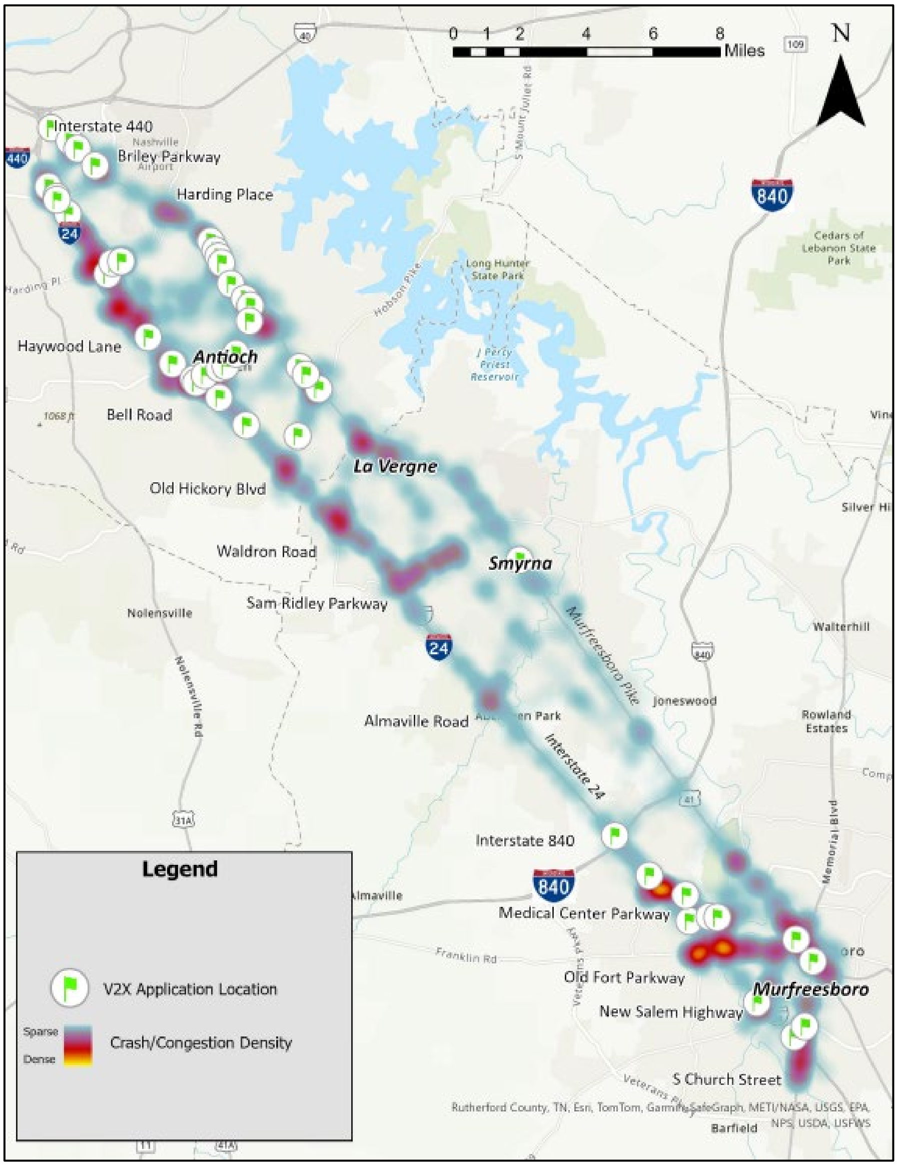

Figure 6-1. V2X Deployment Locations with Average Congestion Heat Map

These 45 locations were selected to develop a conceptual build-out of V2X applications. The recommended application location for each service package is illustrated in Figure 6-1 and listed below:

- I-24 WB Off ramp and signal at Thompson Lane/Briley Parkway
- US-41 at Plus Park Boulevard
- US-41 at Millwood Drive
- US-41 at Thompson Drive
- US-41 at Glengarry Drive
- US-41 at Franklin Limestone Road
- US-41 at British Woods Drive
- US-41 at Ransom Place
- US-41 at Nashboro Blvd
- US-41 at Edge 'O Lake Drive
- US-41 at Rural Hill Road
- US-41 at Bell Road
- US-41 at Summercrest Boulevard
- US-41 at Hobson Pike
- US-41 at KPP Antioch College Prep Elementary School
- US-41 at Washington Street
- US-41 at Old Fort Parkway
- US-41 at US-231
- Harding Place at Perimeter Park Drive
- Harding Place at Antioch Pike
- Bell Road at Hickory Hollow Parkway
- Bell Road at Mt View Road
- Bell Road at Hickory Hollow Terrace
- Bell Road at Zelida Avenue
- Bell Road at Morris Gentry Boulevard
- Old Hickory Boulevard at Cane Ridge High School
- Medical Center Parkway at Gresham Park Drive
- Medical Center Parkway at Robert Rose Drive
- Medical Center Parkway at Livy Dearing Place
- US-231 at Rutherford Boulevard
- I-24 at Harding Place
- I-24 lane reduction at Hickory Hollow Parkway
- I-24 lane reduction between I-840 and Fortress Boulevard
- I-24 lane reduction between Fortress Boulevard and Old Fort Parkway
- I-I-24 WB on ramp at US-231
- I-24 EB at Harding Place
- I-24 between Haywood Lane and Blue Hole Road
- I-24 EB at Bell Road off ramp
- I-24 at Hickory Hollow Parkway
- I-24 at Old Franklin Road
- I-24 between I-440 and Thompson Lane/Briley Parkway
- I-24 WB between Thompson Lane and Antioch Pike
- I-24 over Mill Creek
- I-24 at I-840 interchange ramps
- I-24 off ramps at New Salem Highway

*US-41 = Murfreesboro Pike

Vehicle On-Board Units (OBUs)

One of the variables of projecting the cost of the development of any V2X application is the ability to equip vehicles with On Board Units. Historically, pilot V2X deployments across the country have used a combination of partner agency fleets, such as those at transit agencies or emergency services, commercial vehicle fleet partners, or incentivized general public vehicles. For a transportation agency such as TDOT that is looking gradually implement and leverage V2X systems, it is appropriate to be able to equip “captive fleet vehicles”; e.g., fleet vehicles that are owned and operated by the agency. Using information provided by TDOT, it is expected that up to 419 agency fleet vehicles could regularly travel along the I-24 and US-41 corridor, and thus most likely to benefit from V2X applications in the short-term.

For planning cost purposes, the Kimley-Horn team developed a “per-vehicle” cost to fully equip a vehicle with a C-V2X OBU and extrapolated that value to the 419 vehicles currently identified as potentially available within the corridor. It should be noted that this was done using a “straight-line” extrapolation, and that the costs for installing and integrating OBUs will be directly proportional to the per-vehicle cost.

In practice, a vehicle would only need to be equipped with one OBU and undergo an initial integration and testing period. These integration costs are captured in Table 6-0, below, and would only be incurred once for each vehicle. As each V2X application is deployed, the vehicle OBUs will need to be integrated and verified with that application; however, that cost is captured in the “Integration” planning cost item for each application and is separate from the initial OBU set up and integration.

Table 6-1. Vehicle OBU Costs

Item	Unit Cost	Units	Total	Annual O&M **
On Board Unit	$7,000 ea.	1	$7,000	$700
On Board Units	$7,000 ea.	419	$2,933,000	$293,300

** O&M Includes firmware upgrades, licensing, security certificates, equipment calibration.

Intelligent Traffic Signal System

This application uses both vehicle location and movement information from OBU-equipped connected vehicles, as well as infrastructure measurement of non-equipped vehicles, to improve the operations of traffic signal control systems. This application can use OBU-generated vehicle data vehicle information to help adjust signal timing for an intersection or group of intersections in order to improve traffic flow, including allowing platoon flow through intersections.

An Intelligent Traffic Signal System also allows for the implementation of ***Emergency Vehicle Pre-Emption, Vulnerable Road User Safety, Pedestrian in Signalized Crosswalk, and the Mobile Accessible Pedestrian Signal System*** applications.

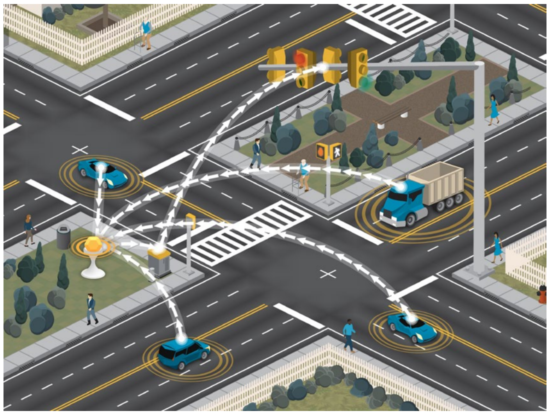

Figure 6-2. Intelligent Traffic Signal System (Source: USDOT)

Locations proposed for an Intelligent Traffic Signal System V2I application follow. These locations were identified due to vehicle crash totals within a coordinated traffic signal system (See Section 4.2):

- I-24 WB off ramp and signal at Thompson Lane/Briley Parkway
- US-41 at Plus Park Boulevard
- US-41 at Millwood Drive
- US-41 at Thompson Lane
- US-41 at Glengarry Drive
- US-41 at Franklin Limestone Road
- US-41 at British Woods Drive
- US-41 at Ransom Place
- US-41 at Nashboro Blvd
- US-41 at Edge O Lake Drive
- US-41 at Rural Hill Road

- US-41 at Bell Road
- US-41 at Summercrest Boulevard
- US-41 at Hobson Pike
- US-41 at KPP Antioch College Prep Elementary School
- US-41 at Washington Street
- US-41 at Old Fort Parkway
- US-41 at US-231
- Harding Place at Perimeter Park Drive
- Harding Place at Antioch Pike
- Bell Road at Hickory Hollow Parkway
- Bell Road at Mt View Road
- Bell Road at Hickory Hollow Terrace
- Bell Road at Zelida Avenue
- Bell Road at Morris Gentry Boulevard
- Old Hickory Boulevard at Cane Ridge High School
- Medical Center Parkway at Gresham Park Drive
- Medical Center Parkway at Robert Rose Drive
- Medical Center Parkway at Livy Dearing Place
- US-231 at Rutherford Boulevard

Table 6-2. Intelligent Traffic Signal System Planning Level Costs

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$500,000 per application	4 *	$1,250,000	$80,000
Integration	$50,000 per intersection per application	30	$1,500,000	N/A
TOTAL			**$2,750,000**	**$80,000**

- Four applications would be provided simultaneously; the first would be $500,000, followed by $250,000 for the subsequent 3.

** O&M Includes operating software, firmware upgrades, licensing, security certificates.

Reduced Speed Zone Warning / Lane Closure

This application provides OBU-equipped connected vehicles that are approaching a reduced speed zone with information on the zone's posted speed limit and/or if the configuration of the roadway is altered (e.g., lane closures, lane shifts). Reduced speed zones include (but are not limited to) construction/work zones, school zones, pedestrian crossing areas, and incorporated zones (e.g., rural towns). The OBU-equipped connected vehicle uses the revised speed limit along with any applicable changed roadside configuration information to determine whether to provide an alert or warning to the driver.

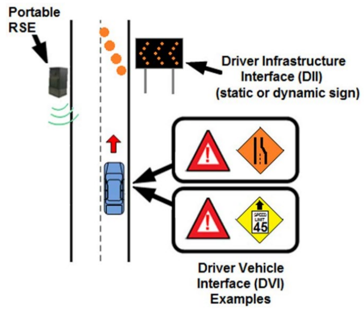

Figure 6-3. Reduced Speed Zone / Lane Closure Warning (Source: USDOT)

Locations proposed for a Reduced Speed zone Warning / Lane Closure / Lane Reduction Warning follow. These locations were identified as congested-related hotspots along the I-24 freeway (See Section 4.2).

- I-24 EB at Harding Place
- I-24 lane reduction at Hickory Hollow Parkway
- I-24 lane reduction between I-840 and Fortress Boulevard
- I-24 lane reduction between Fortress Boulevard and Old Fort Parkway
- I-24 WB on ramp at US-231
- I-24 EB at Harding Place
- I-24 between Haywood Lane and Blue Hole Road
- I-24 EB at Bell Road off ramp
- I-24 at Hickory Hollow Parkway
- I-24 at Old Franklin Road

Table 6-3. Reduced Speed Zone / Lane Closure Planning Level Costs

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$200,000	1	$200,000	$20,000
Integration	$110,000 per location	10	$1,110,000	N/A
TOTAL			**$1,310,000**	**$20,000**

** O&M Includes operating software, firmware upgrades, licensing, security certificates.

Emergency Vehicle Alert

Under this concept, OBU-equipped vehicles would receive alerts of oncoming emergency vehicles responding to incidents. From a V2I perspective, this application is best implemented using established third-party systems and applications; this would be much more cost effective than deploying a location-specific application. Deploying such a system or application would be a collaborative effort between TDOT and partner agencies. In the Roadmap analysis, a planning-level cost for a sample third-party system is included. The HAAS Alert is a private third-party system that provides drivers with a digital alert to slow down and move over when an emergency vehicle is approaching or when the driver is approaching an emergency on the side of the road. This digital alert notifies the driver of a nearby emergency vehicle allowing the driver to safely maneuver around the emergency vehicle, reducing the risk for a crash. While this is proprietary third-party application, it is included as one example that could address this identified priority. This type of application would be an "area-wide" application, and not specific to a segment of arterial or freeway.

Table 6-4. Emergency Vehicle Alert Planning-Level Costs (Sample Vendor)

HAAS Alert	$700 / year/ vehicle

Queue Warning

This application allows an infrastructure-based system to detect vehicle queues in order to minimize or prevent rear-end or other secondary collisions. The infrastructure system will broadcast out this information via the RSUs to OBU-equipped vehicles. The OBU-equipped vehicles would be able to determine whether a warning to avoid a collision is warranted; if so, the OBU would generate an immediate action-required warning to the driver.

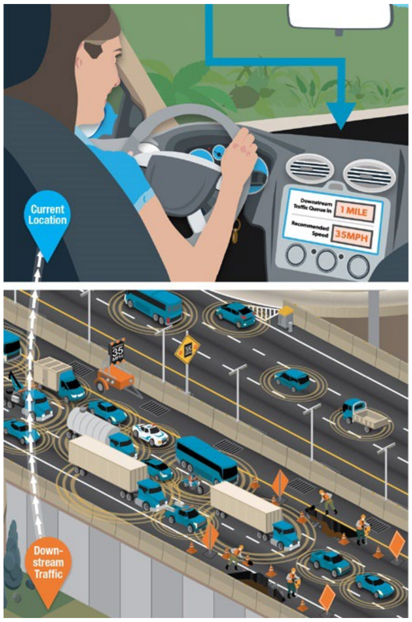

Figure 6-4. Queue Warning (Source: USDOT)

Locations proposed for a Queue Warning V2I application follow. These locations were identified based on a history of crashes along the I-24 freeway (See Section 4.2).

- I-24 between I-440 and Thompson Lane/Briley Parkway
- I-24 WB off ramp at Thompson Lane/Briley Parkway
- I-24 WB between Thompson Lane/Briley Parkway and Antioch Pike

Table 6-5. Queue Warning Planning-Level Costs

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$200,000	1	$200,000	$20,000
Integration	$400,000 per location	3	$1,200,000	N/A
TOTAL			**$1,400,000**	**$20,000 ***

** O&M Includes operating software, firmware upgrades, licensing, security certificates.

Spot Weather Warning

This application provides alerts and warnings to drivers of OBU-equipped vehicles of unsafe conditions due to weather-related impacts, which include, but are not limited to, high winds, flood conditions, ice, fog, dust storms, snow drifts and rock falls. This application uses real-time weather information collected from fixed environmental sensor stations, weather services, and advisory systems. The information is processed by an approaching OBU-equipped vehicle to determine whether to issue an alert or warning to the driver.

Figure 6-5. Spot Weather Warning (Source: USDOT)

Locations proposed for a Spot Weather Impact Warning V2I application follow. This location was identified based on the potential of roadway icing-related conditions on the bridge segment.

- I-24 over Mill Creek

Table 6-6. Spot Weather Warning Planning-Level Costs

Item	Unit Cost	Units	Total	Annual O&M **
Environmental Sensor Equipment	$35,000	1	$30,000	$2,250
Application Software	$200,000	1	$200,000	$20,000
Integration	$110,000 per location	1	$110,000	N/A
TOTAL			**$340,000**	**$22,250**

** O&M Includes operating software, firmware upgrades, licensing, security certificates.

Curve Speed Warning

This application allows OBU-equipped connected vehicles to receive information that it is approaching a curve along with the recommended speed for the curve. This capability allows the OBU-equipped vehicle to provide a warning to the driver if the vehicles speed and performance characteristics would exceed the recommended safe speed through the curve.

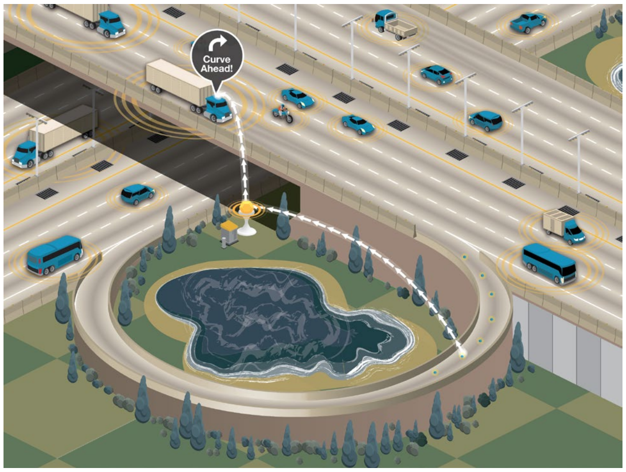

Figure 6-6. Curve Speed Warning (Source: USDOT)

Locations proposed for a Curve Speed Warning V2I application follow. Thes locations were identified based on curve geometrics requiring speed reduction warnings and crash rates along the I-24 freeway.

- I-24 WB between Thompson Lane/Briley Parkway and Antioch Pike
- I-24 at I-840 interchange ramps
- I-24 off ramps at New Salem Highway
- I-24 EB ramps at Bell Road

Table 6-7. Curve Speed Warning Planning-Level Costs

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$200,000	1	$200,000	$20,000
Integration	$110,000 per location	4	$440,000	N/A
TOTAL			**$640,000**	**$20,000**

** O&M Includes operating software, firmware upgrades, licensing, security certificates.

Road Maintenance

This application uses on-board vehicle equipment, such as internal instruments or cell phones, to collect data on pavement conditions. This data can be shared with TDOT and local agency partners on a real-time, or near-real-time, basis. This application doesn't require V2X RSUs to operate; it can leverage existing cellular and wi-fi network connections. There are third-party systems and equipment that can be installed in vehicles to facilitate this application. This would be an area-wide application, and not specific to an arterial or freeway segment.

Table 6-8. Road Maintenance Planning-Level Costs

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$500,000	1	$500,000	$50,000
TOTAL			**$500,000**	**$50,000**

** O&M Includes operating software, firmware upgrades, licensing, security certificates.

Distress Notification

This application provides for the capability for drivers or collision detection sensors to report an emergency and summon assistance. This application is largely provided by vehicle manufacturers, cellular phone services, and other third-party systems, without the need for TDOT infrastructure. The costs for these services are borne by the vehicle or device owners; as such, there are no costs to TDOT or other infrastructure owners and operators. TDOT and partner agencies are encouraged to work with these third-party providers to promote this capability along the I-24 SMART Corridor.

Red Light Violation Warning / Intersection Safety Warning and Collision Avoidance

This application allows OBU-equipped connected vehicles to receive information from the infrastructure regarding the signal timing and intersection geometry. The OBU-equipped vehicle will be able to make a determination, based on the vehicle's speed, heading and acceleration, along with the signal timing and geometry information, whether the vehicle will travel through the intersection on a red indication. The OBU-equipped vehicle would then generate a warning for the driver to take immediate action.

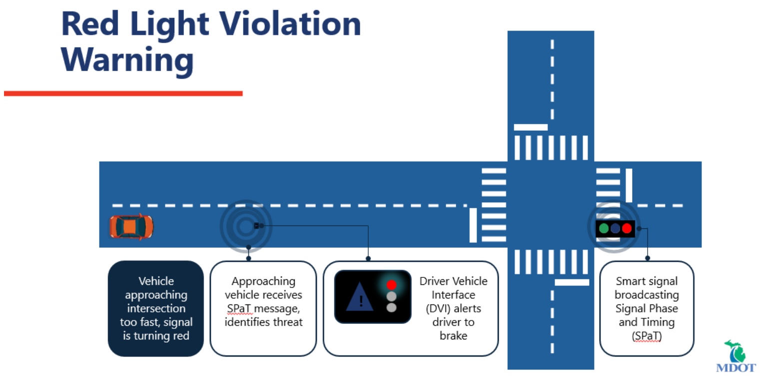

Figure 6-7. Red Light Warning V2I Application (Source: MDOT)

The location for a proposed Red Light Violation Warning V2I application follows. This location was identified based on historical signalized intersection crashes within the corridor.

- I-24 WB off ramp and signal at Thompson Lane/Briley Parkway

Table 6-9. Red Light Violation Warning Planning-Level Costs

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$200,000	1	$200,000	$20,000
Integration	$250,000 per location *	1	$250,000	N/A
TOTAL			**$450,000**	**$20,000**

** O&M Includes operating software, firmware upgrades, licensing, security certificates.

Note that although this location would benefit most from this application due to crash history, it could be included at any location that would be part of an *Intelligent Traffic Signal System* application.

Table 6-10 provides a summary of each of the applications within the corridor, including planning-level costs.

Table 6-10. Planning-Level Cost Summary

Application	# Locations	Initial Cost	Annual O&M Cost
RSU C-V2X Upgrade	125	$950,000	$31,250
On-Board Units	419	$2,933,000	$293,300

Intelligent Traffic Signal System	30	$2,750,000	$80.000
Reduced Speed / Lane Closure Warning	10	$1,310,000	$20,000
Queue Warning	3	$1,400,000	$20,000
Spot Weather Warning	1	$340,000	$22,250
Curve Speed Warning	4	$640,000	$20,000
Road Maintenance	N/A	$500,000	$50,000
Red Light Violation Warning	1	$450,000	$20,000

6.3.3 Application Deployment Project Process

A functional V2I application requires roadside infrastructure (RSUs), a communications network, vehicle-based equipment (onboard units [OBU]), a back-end data and IT system, and a process for integrating each component into a working application. The RSUs are already deployed along the I-24 SMART Corridor, although 125 need to be replaced with units that have C-V2X functionality. This Roadmap assumes that the communications network and back-end data and IT systems are in place and compatible with the individual application needs. The time and cost for each application are borne with any specific data management systems that need to be in place, vehicle on-board equipment that is necessary, the integration of all components into a functioning application, and recurring application-specific operations and maintenance costs.

It is recommended that a Systems Engineering process is undertaken for each of the applications that will be deployed (although some of the systems engineering processes for multiple applications can be done concurrently). Part of the Systems Engineering process should include:

Feasibility & Concept of Operations (ConOps) – Determine the feasibility, operational needs, desires, and vision of the V2I application.

Requirements – Define the functions that the V2I application system must perform at a technical level. These usually include data collection, data analysis, security, data transfer, and commanding/controlling devices within the system. Requirements should also define technical and performance-related constraints on the system.

Design & Procurement – Confirm that centralized IT systems and backhaul communication capabilities are in place along the corridor. If additional equipment, or on-board vehicle equipment is required, procure these components.

Deployment & Integration – Deploy any new V2X components and integrate into the overall ITS / Connected Vehicle environment.

Operations & Maintenance – Establish operations and maintenance roles, responsibilities, and methods. Monitor system activity and manage software and hardware configuration to ensure the system is working properly.

Chapter 7 Results and Discussion

A field system verification was conducted by the project team to verify RSU V2X messages comprising MAP, signal phase and timing (SPaT), traveler information messages (TIM), and, if available, signal status messages (SSM) / signal request messages (SRM). TDOT deployed 150 RSU units along both I-24, SR 1, and the connecting routes. TDOT and their on-call consultant provided status information for each unit before verification began. It should be noted that a number of the devices were still in the process of being configured. Additionally, the OBUs were unable to be enrolled in TDOT's security credential management system (SCMS), and as a result, it is possible that units at signals that have priority or preemption may have ignored any SRM sent by the OBUs. However, the OBUs could still receive secured or unsecured messages from the RSU.

7.1 Testing Procedure

The field verification was performed in two stages with a vehicle equipped with a Commsignia OBU. During the first stage, DSRC and C-V2X onboard units were utilized in the field to capture and visualize V2X messages—primarily MAP, SPaT, and any observed traveler information messages (TIM), and an attempt was made to request signal priority/preemption at intersections that supported it. The second stage included analyzing packet capture logs from the OBUs for both the DSRC and C-V2X units. An effort was made to ensure that the verification process was as thorough as possible; each RSU was passed multiple times and in both directions of travel to help ensure data was captured. Appendix B includes more detailed information on testing procedures and the routes taken during the week in which field verification occurred.

7.2 System Verification Results

150 units are currently deployed along the I-24 Smart Corridor, and as of the week in which verification occurred, the OBU only received messages from 29 of the units (two of the units were outside of the I-24 Smart Corridor project limits on Fortress Boulevard in Murfreesboro). Twelve of the 29 units were C-V2X units primarily along Medical Center Parkway in Murfreesboro and 17 were DSRC units, more than half were also located in Murfreesboro. The following are verification testing items of note:

<u>C-V2X RSUs</u>

- Lane alignment or the ability of the OBU to identify what lane it occupies failed or partially failed at all but six intersections. This could be attributed to the OBU's GPS and the MAP data that was configured in the RSU.

- Seven of the twelve units were broadcasting unsecure messages. There were also three intersections that were broadcasting a combination of secure and unsecure messages.
- All twelve C-V2X units broadcasted MAP, but only 8 of them broadcasted SPaT.
- TIM were only received for two units and although those units were not located near one another, they were broadcasting the same message.

DSRC RSUs

- Lane alignment could not be verified as DRSC limits the data can be collected with the OBU. Lane alignments were approximated using basic safety message GPS coordinates
- 16 of the 17 units were broadcasting unsecure messages
- 13 of the 16 locations were broadcasting SPAT while 12 of the 13 were broadcasting SPaT.
- TIM was not detected at any of the DSRC locations.

7.3 Verification Summary

Testing revealed that only 18% (or 27 of the 150 units) of the units could be verified to be sending messages that the OBU could receive. This indicates that some updates and changes should be considered to improve the operation and messages/information collected and broadcasted from the devices. Two additional devices adjacent to the I-24 Smart Corridor, but not technically within its boundaries) also communicated with the OBU. It is recommended that TDOT perform a diagnostic review of all devices to ensure that they are operating as intended and are configured consistently with other devices. Eventually, TDOT will need to update the DSRC units to C-V2X units.

Chapter 8 Conclusion & Recommendations

The field system verification process in conjunction with the review and prioritization of C-V2X applications reveals that TDOT has the opportunity to build upon the framework that has been deployed along the I-24 Smart Corridor. Much of the required infrastructure is in place, and an emphasis can be placed on configuring/reconfiguring the devices to operate the way in which they are intended. One of the key components to a successful connected vehicle environment is the need for vehicles to be retrofitted with OBUs so that they can communicate with the RSUs by both sending and receiving messages. An investment in OBU devices, a determination as to which vehicles or fleets to install those devices on, as well as intentionality of having those vehicles operate align the I-24 Smart Corridor network will assist TDOT is future deployments around the state.

Additionally, we recommend that TDOT develop specific verification procedures to be followed every time a V2X deployment is undertaken. This includes RSU / Messaging verification, OBU verification, and application verification. We recommend this as an initial step prior to the deployment of any specific applications.

8.1 Existing RSU Recommendations

The majority of the units that have been deployed by TDOT are currently DSRC-only units. Although this technology is still operational, under FCC rules, RSUs must cease broadcasting by November 21, 2026. It is recommended that TDOT begin migrating toward C-V2X units as soon as practicable. Replacement can be completed in a variety of ways such as when a DSRC unit fails, replace that device with a C-V2X unit or methodically replace units in locations where C-V2X applications are deemed a priority to implement. TDOT may also elect to replace all units at one time to ensure that no disruptions occur due to the FCC rules. Special emphasis needs to be placed on configuration of the devices to ensure that they are able to broadcast the appropriate information. Each unit should be able to remotely communicate with the TDOT Region 3 TMC. The units should all be individually tested with an OBU to ensure that they are broadcasting MAP, SPaT, TIM, SSM/ SRM and receiving pertinent information from the OBU. In order for SPaT messaging to be broadcast, TDOT must ensure that the signal controllers are compatible with the RSUs and the controllers themselves are configured correctly. Below is a list of specific recommendations that were observed during field verification:

- Enable local transmission PCAP logging on RSUs and / or use of native RSU diagnostic utilities to confirm what the RSU self-reports to be broadcasting;
- Use of network utilities to confirm (on the RSU directly or using a temporary stand-in computer with the same IP) whether the RSU is receiving SPaT messages from the controller on the correct UDP port
- Confirm DSRC RSUs are configured to broadcast all messages on channel 180

- Confirm C-V2X RSUs are configured to broadcast all messages on channel 183
- Investigate the physical antenna connections on the RSUs
- Update MAP message PSIDs to 0x204097 instead of 0x8002 to reflect new PSID convention standards distinguishing MAP from SPaT
- Update MAP message lane definitions to reflect intersection geometries and / or define more accurate lanes. Use of LiDAR imagery to generate MAP messages has proven to be a highly accurate and reliable way to produce MAPs compared to hand-wheeling or the use of online satellite imagery tools

Additional recommendations are outlined in Appendix B of this report for RSUs

8.2 OBU Retrofit Recommendations

Besides the RSUs themselves, one of the most critical components is a vehicle network in which vehicles are able to communicate with the RSUs. The higher the saturation of equipped vehicles, the more effective the applications supported by the RSUs will be. Very few existing vehicles within the state of Tennessee (or across most of the country) are able to communicate with RSUs, and most new car manufactures are still developing their strategy for integrating OBUs as part of their new-build vehicles. Given this fact, TDOT will have to make a concerted effort to equip a fleet of vehicles to utilize the RSUs. Based on the frequency with which TDOT HELP vehicles travel along I-24, those vehicles may be the most appropriate vehicle fleet to begin retrofitting with OBUs. However, the HELP trucks primarily operate along I-24 which leaves a gap along the arterial and collector roads with the I-24 Smart Corridor network.

TDOT also operates a sizeable fleet of vehicles that regularly drive through the metropolitan Nashville area (419 vehicles, as provided by TDOT), and by default, the I-24 SMART Corridor. Prioritizing equipping these vehicles with OBUs will allow TDOT to receive near-term benefits of RSU and associated V2X application deployments.

Engaging partner local agencies can be another method for increasing the amount of OBU-equipped vehicles along the I-24 SMART Corridor and hence enhancing the near-term benefits of the V2X application supported by corridor RSUs. TDOT could look to assist local agencies with retrofitting their vehicles; nationally, much success with this approach has been realized with these partnerships in pursuing federal grants that are specifically geared towards encouraging deployment of safety technology solutions.

Local transit agencies regularly have buses and other vehicles travelling through the I-24 SMART Corridor; transit vehicles can both improve the penetration rate of OBU-equipped vehicles, while benefiting directly from some V2X applications, such as the Intelligent Traffic Signal System. Retrofitting local emergency vehicles may make the most sense because they typically travel throughout the cities during the day, and their OBUs would interact with signals;

these vehicles would also benefit directly from many of the V2X applications recommended in this study,

8.3 Connected Vehicle Pilot Deployment

Once the RSUs are updated and configured to work in a C-V2X environment, TDOT could explore pilot V2X application deployments. Pilot deployments allow deploying agencies to gain institutional knowledge in the V2X environment while determining methods and means to integrate V2X applications into existing TDOT systems and practices. Frequently, successful V2X pilots see several transportation agencies partnering together with an interjurisdictional deployment. In the case of the I-24 SMART Corridor, partnering with local municipalities in a pilot deployment is going to be essential to realize the complete benefits of signal and arterial-based applications.

Retrofitting agency or partner-agency vehicles can occur as part of a pilot deployment, and doesn't have to occur separately; in fact, equipping vehicles as part of a pilot deployment can allow for efficiencies of scale in verifying and integrating V2X applications.

To encourage use of the connected vehicle potential within the I-24 SMART Corridor, TDOT should consider establishing a multi-agency partnership group with the municipalities and local agencies within the corridor. This corridor partnership group can explore the benefits of a V2X environment and applications, share lessons learned (and benefits) in developing and deploying V2X applications, and apply for grant and funding opportunities for pilot deployments.

Federal funding and grant opportunities frequently favor interjurisdictional and muti-partner technology deployments, in order to promote and develop interoperable connectivity between agencies. One of the primary goals of a Corridor partnership could be to pursue grant and funding opportunities for a pilot deployment and V2X system enhancement.

The US Department of Transportation (USDOT) and US Department of Energy (USDOE) have regularly provided technology-focused implementation grant programs that can be used to support V2X application development and deployment. While these grant programs and funding sources may change titles and have some requirement shifts with the changing of federal administrations, since 2015 there have been continuous programs to support pilots and deployments. We would recommend investigating these programs as they become available at the federal level and prepare to submit for grant and funding opportunities. Successful past awardees always have at least one quality in common; a comprehensive, well-thought-out plan for the deployment, and how such a deployment fits into the overall local and regional transportation ecosystem. TDOT can work together with their partner agencies along the I-24 corridor to leverage existing investments, and position for funding opportunities.

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Appendices

Appendix A: Recommended V2I Application Descriptions

Appendix B: Field Verification Summary

Appendix C: V2X Application Deployment Locations

Appendix A: Recommended V2I Application Descriptions

V2X Applications

SAFETY

Emergency Electronic Brake Lights Warning
Forward Collision Warning
Blind Spot Warning/Lane Change Warning
Intersection Movement Assist
Left Turn Assist Warning
Red Light Violation Warning
Emergency Vehicle Preemption
Emergency Vehicle Alert
Distress Notification (Mayday Alert)
Curve Speed Warning
Reduced Speed Warning
Pedestrian in Signalized Crosswalk Warning
Wrong Way Entry Warning
Railroad Crossing Warning
Oversize Vehicle Warning

COMMERCIAL VEHICLE

Commercial Vehicle Wireless Inspection
Truck Parking and Other Information

MOBILITY & ENVIRONMENT

Traffic Signal Optimal Speed Advisory (or Control)
Intelligent Traffic Signal Systems (I-SIG)
Signal Priority
Mobile Accessible Pedestrian Signal System
Speed Harmonization
Queue Warning
Cooperative Adaptive Cruise Control / Vehicle Platooning

TRAFFIC ADVISORIES & WARNINGS

Incident and Road Closure Advisories and Warnings
Road Weather Advisories and Warnings
Work Zone Advisories and Warnings
Work Zone Worker Advisories and Warnings

DATA COLLECTION

Road Weather Data Collection
Probe-enabled Traffic Monitoring
Probe-based Pavement Maintenance

V2X Use Case Implementation Prioritization Assessment

- In September 2024, there was a collaborative prioritization assessment with TDOT Staff and Stakeholders to determine most applicable applications using the following criteria:

Readiness / Maturity	Applicability	"Ease" of Deployment	Vehicle Assessment
1 = development needed	1 = Not applicable to corridor	1 = significant, complex systems needed	1 = general deployment needed
5 = in use	5 = extremely applicable	5 = minimal support systems needed	5 = "captive" fleet vehicles sufficient

*Each application was individually evaluated based on the criteria listed above and assigned an overall priority ranking.

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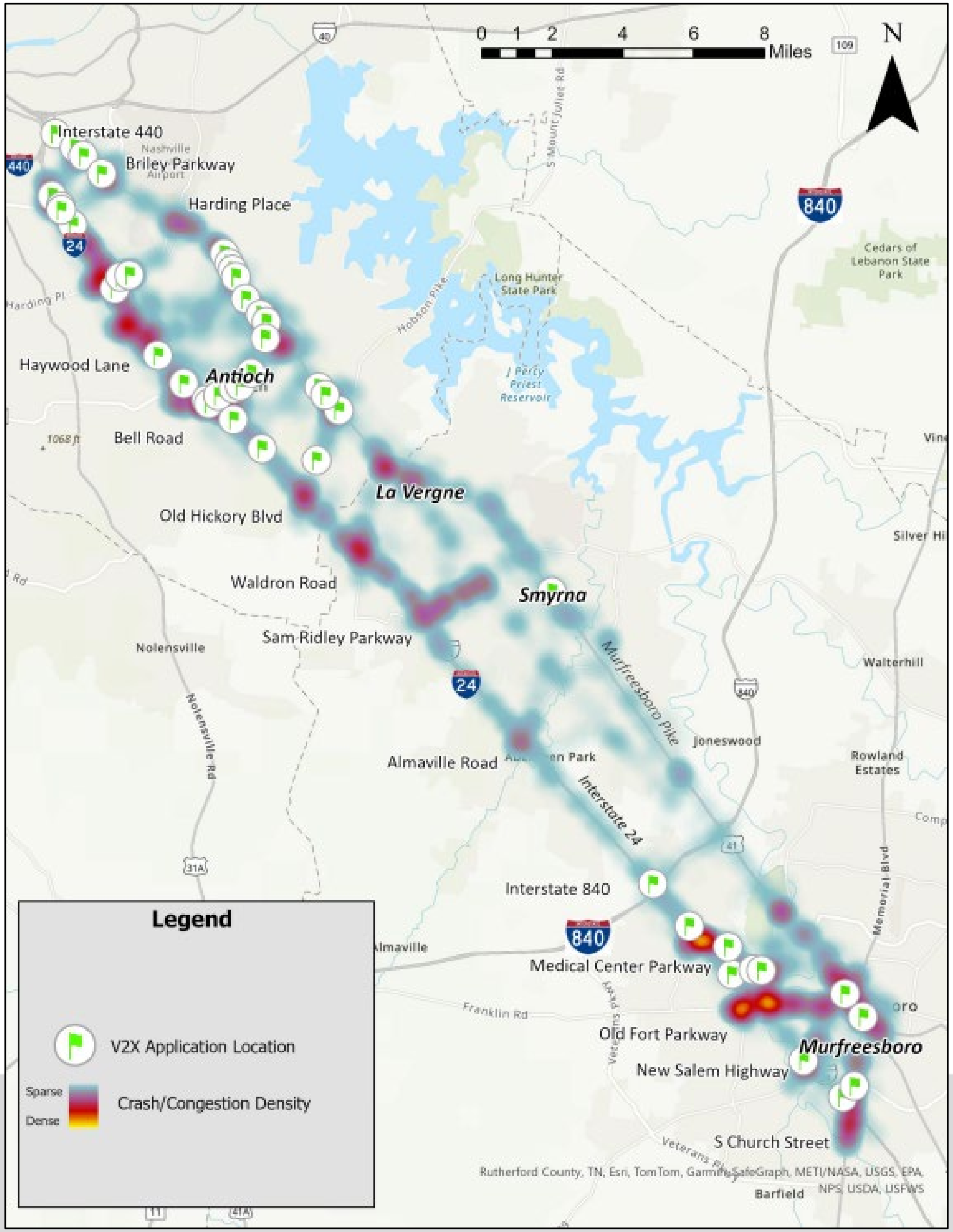
V2X Use Case Implementation Prioritization Rankings

- Rankings represent the overall perception of each application based on criteria.
- Top ranked applications assessed on the Corridor:

Application	Applicability	Ease of Deployment	Vehicle Assessment	Readiness / Maturity	TOTAL
Emergency Vehicle Pre-Emption	5	3	4	4	**16**
Reduced Speed / Lane Closure Warning	5	4	2	4	**15**
Intelligent Traffic Signal System	5	2	3	4	**14**
Emergency Vehicle Alert	5	3	2	3	**13**
Mobile Accessible Pedestrian Signal System	5	2	4	2	**13**
Queue Warning	5	4	2	2	**13**
Spot Weather Warning	4	3	2	4	**13**
Road Maintenance Reporting	4	3	2	2	**11**
Distress Notification	5	3	1	2	**11**
Curve Speed Warning	2	5	1	4	**12**
Pedestrian in Signalized Crosswalk	5	3	1	3	**12**
Red Light Violation Warning	2	4	1	4	**11**
Freeway Related		Arterial Related		Freeway and Arterial Related	

V2X Conceptual Deployment Plan Application Locations



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V2X Implementation Strategy
Planning-Level Unit Costs

	Equipment (per unit unless indicated otherwise)	Design/Systems Engineering, Deployment, Integration, Testing	Annual O&M
	Roadside Systems		
RSU Hardware (RSU, mounting hardware, cabling, connection to traffic signal/ITS cabinet)	$14,500		$250
	Support Systems		
Security Credential Management System (SCMS)	-	-	$15,000 - $50,000
CV Back Office System	$50,000 - $800,000		N/A
V2I Application Software	-	$100,000 - $200,000	10% maintenance, support, and enhancement per year
	-	$500,000	N/A
	In-Vehicle Systems		
OBU Hardware (after market)	$7,000		$1,200

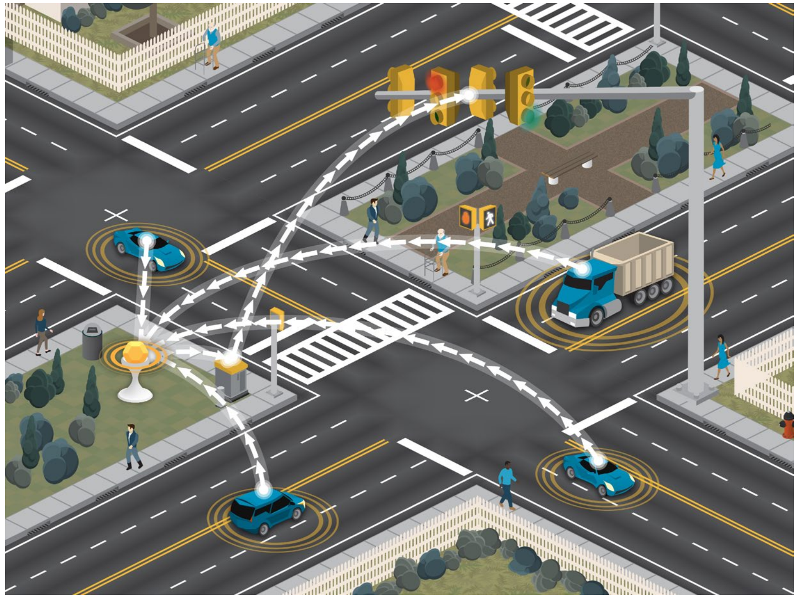
Equipment Costs Reference (Source NCHRP, Local Deployment)

V2X Implementation Strategy Planning-Level Costs

V2I Application	Minimum Deployment Size	Initial Capital Cost	Annual Operations and Maintenance Cost
Red Light Violation Warning (RLVW) - hub architecture	10 intersections	$230,000 to $430,000	$11,500
Reduced Speed Zone Warning (RSZW)	1 location	$110,000	$11,500
Incident Scene Work Zone Alerts for Drivers and Workers	1 location	$110,000	$11,500
Queue Warning (Q-WARN)	1 bottleneck	$400,000	$43,000
Eco-Traffic Signal Timing / Transit Signal Priority	3 arterials (15 intersections)	$280,000 to $580,000	$16,500
Intelligent Traffic Signal System (I-SIG)	30 intersections	$660,000 to $1,060,000	$82,000
Speed Harmonization (SPD-HARM)	1 bottleneck	$400,000	$43,000
Curve Speed Warning (CSW)	1 location	$110,000	$11,500
Pedestrian in Signalized Crosswalk Warning	1 intersection	$120,000	$11,500
Railroad Crossing Violation Warning (RCVW)	1 intersection	$11,500	$11,500

ROM Costs for Various V2X Investments (Source NCHRP and Local Deployment)

V2X Conceptual Deployment Plan: Intelligent Traffic Signal System



An Intelligent Traffic Signal System also allows for the implementation of:

- Emergency Vehicle Pre-Emption
- Vulnerable Road User Safety
- Pedestrian in Signalized Crosswalk
- Mobile Accessible Pedestrian Signal System applications

Key Locations (30 total):

- I-24 WB off ramp and signal at Thompson Lane/Briley Parkway
- US-41 at Thompson Lane
- US-41 at Ransom Place
- US-41 at Nashboro Blvd
- US-41 at Bell Road
- US-41 at Summercrest Boulevard
- US-41 at Hobson PikeUS-41 at Old Fort Parkway
- US-41 at US-231
- Medical Center Parkway at Gresham Park Drive
- Medical Center Parkway at Robert Rose Drive
- Medical Center Parkway at Livy Dearing Place

Potential Costs:

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$500,000 per application	4 *	$2,000,000	$80,000
Integration	$50,000 per intersection per application	30	$1,500,000	N/A
TOTAL			**$3,500,000**	**$80,000**

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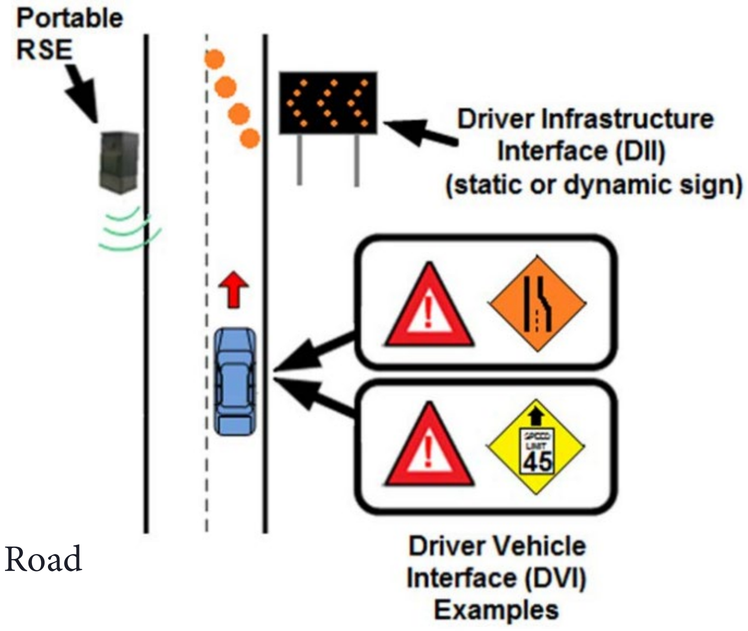
V2X Conceptual Deployment Plan: Reduced Speed Zone Warning / Lane Closure



OBU-equipped connected vehicles approaching a reduced speed zone with information on the zone's posted speed limit and altered configuration of the roadway (lane reduction).

Locations:

- I-24 EB at Harding Place
- I-24 lane reduction at Hickory Hollow Parkway
- I-24 lane reduction between I-840 and Fortress Boulevard
- I-24 lane reduction between Fortress Boulevard and Old Fort Parkway
- I-24 WB on ramp at US-231
- I-24 EB at Harding Place
- I-24 between Haywood Lane and Blue Hole Road
- I-24 EB at Bell Road off ramp
- I-24 at Hickory Hollow Parkway
- I-24 at Old Franklin Road

Potential Costs:

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$200,000	1	$200,000	$20,000
Integration	$110,000 per location	10	$1,110,000	N/A
TOTAL			**$1,310,000**	**$20,000**

** O&M Includes operating software, firmware upgrades, licensing, security certificates.

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V2X Conceptual Deployment Plan: Emergency Vehicle Alert

- OBU-equipped vehicles would receive alerts of oncoming emergency vehicles responding to incidents.
- Using third-party systems and applications (HAAS Alert).
- Collaborative effort between TDOT and partner agencies.

<u>Potential Costs</u>:

HAAS Alert	$700 / year/ vehicle

V2X Conceptual Deployment Plan: Queue Warning

- Allows an infrastructure-based system to detect vehicle queues to minimize or prevent rear-end or other secondary collisions.
- System will broadcast out this information via the RSUs to OBU-equipped vehicles

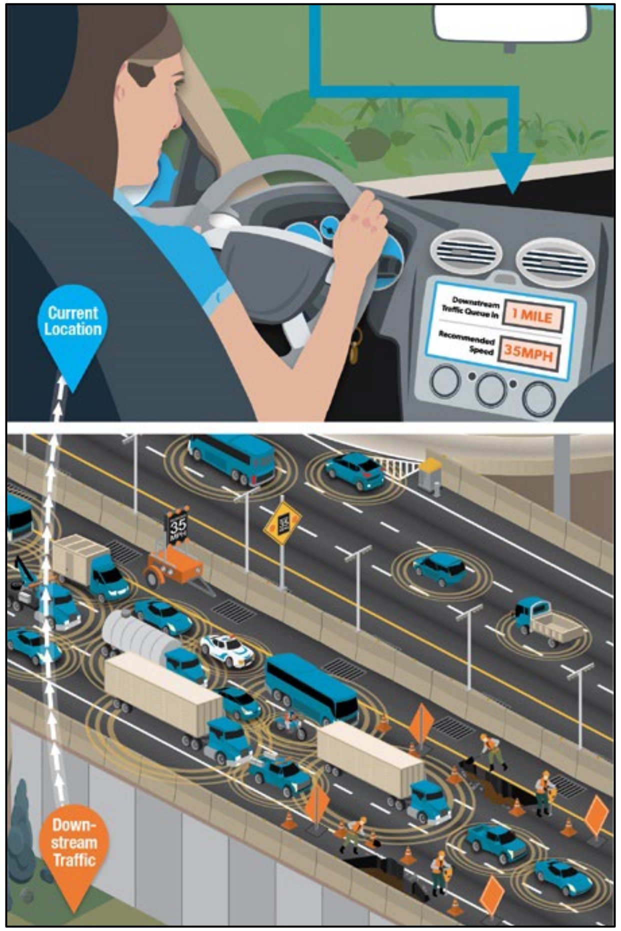
<u>Locations:</u>

- I-24 between I-440 and Thompson Lane/Briley Parkway
- I-24 WB off ramp at Thompson Lane/Briley Parkway
- I-24 WB between Thompson Lane/Briley Parkway and Antioch Pike

<u>Potential Costs</u>:

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$200,000	1	$200,000	$20,000
Integration	$400,000 per location	3	$1,200,000	N/A
TOTAL			**$1,400,000**	**$20,000 ***

** O&M Includes operating software, firmware upgrades, licensing, security certificates.



V2X Conceptual Deployment Plan
Spot Weather Warning

- Provides alerts and warnings to drivers of OBU-equipped vehicles of unsafe conditions due to weather-related impacts, which include, but are not limited to, high winds, flood conditions, ice, fog, dust storms, snow drifts and rock falls.
- Information is processed by an approaching OBU-equipped vehicle to determine whether to issue an alert or warning to the driver.

Location:

- I-24 over Mill Creek

Potential Costs:

Item	Unit Cost	Units	Total	Annual O&M **
Environmental Sensor Equipment	$35,000	1	$30,000	$2,250
Application Software	$200,000	1	$200,000	$20,000
Integration	$110,000 per location	1	$110,000	N/A
TOTAL			**$340,000**	**$22,250**

** O&M Includes operating software, firmware upgrades, licensing, security certificates.

V2X Conceptual Deployment Plan: Curve Speed Warning

- OBU-equipped vehicles receive information of approaching a curve with the recommended speed for the curve.
- Provides a warning to the driver if the vehicle would exceed the safe speed through the curve.

Locations:

- I-24 WB between Thompson Lane/Briley Parkway and Antioch Pike
- I-24 at I-840 interchange ramps
- I-24 off ramps at New Salem Highway
- I-24 EB ramps at Bell Road

Potential Costs:

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$200,000	1	$200,000	$20,000
Integration	$110,000 per location	4	$440,000	N/A
TOTAL			**$640,000**	**$20,000**

** O&M Includes operating software, firmware upgrades, licensing, security certificates.

V2X Conceptual Deployment Plan: Road Maintenance

- Uses on-board vehicle equipment, such as internal instruments or cell phones, to collect data on pavement conditions.
- Data can be shared with TDOT and local agency partners on a real-time, or near-real-time, basis.
- Doesn't require V2X RSUs to operate; it can leverage existing cellular and wi-fi network connections.

<u>Potential Costs</u>:

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$500,000	1	$500,000	$50,000
TOTAL			**$500,000**	**$50,000**

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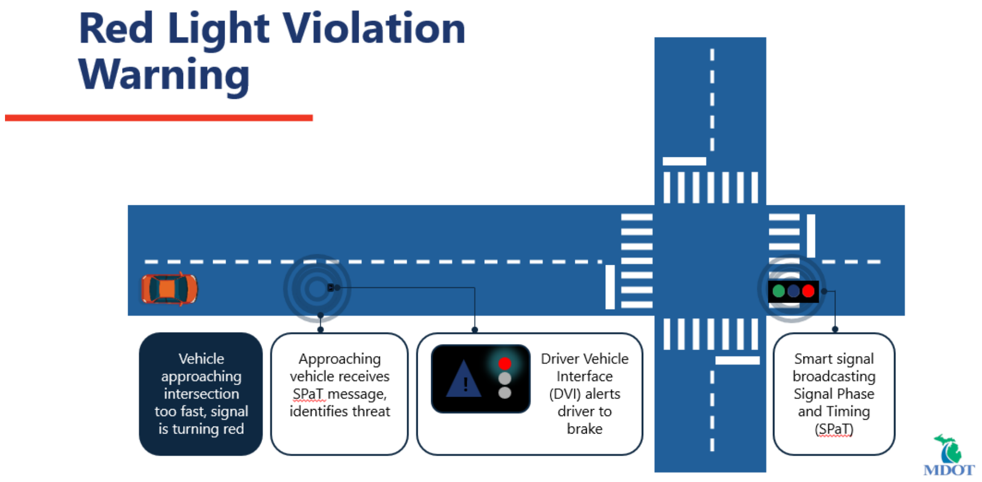
V2X Conceptual Deployment Plan: Distress Notification

- Capability for drivers or collision detection sensors to report an emergency and summon assistance.
- Largely provided by vehicle manufacturers, cellular phone services, and other third-party systems, without the need for TDOT infrastructure.
- Costs borne by the vehicle or device owners.

V2X Conceptual Deployment Plan: Red Light Violation / Intersection Safety Warning and Collision Avoidance



- OBU-equipped vehicles receive information from the infrastructure regarding the signal timing and intersection geometry.
- Vehicle determines, based on speed, acceleration, intersection geometry timing, whether it will travel through the intersection on a red indication.

Locations:

- I-24 WB off ramp and signal at Thompson Lane/Briley Parkway

Potential Costs:

Item	Unit Cost	Units	Total	Annual O&M **
Application Software	$200,000	1	$200,000	$20,000
Integration	$250,000 per location *	1	$250,000	N/A
TOTAL			**$450,000**	**$20,000**

** O&M Includes operating software, firmware upgrades, licensing, security certificates.

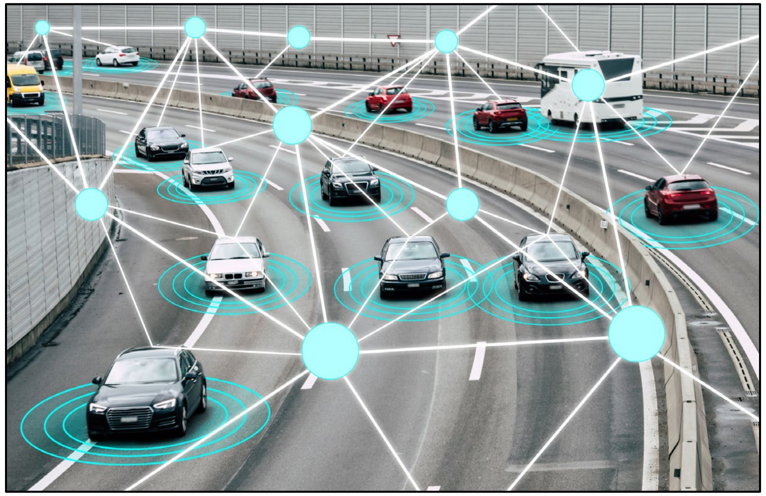
V2X Conceptual Deployment Plan: Fleet Integration

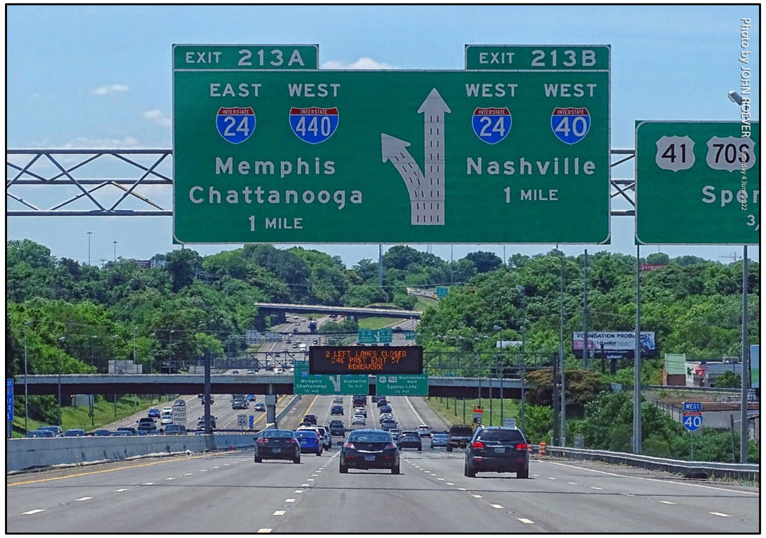
- Recommended that the lower-risk strategy would be to retrofit the I-24 SMART Corridor's personal fleet with an aftermarket safety device (ASD), specifically around the locations of the V2X Deployment Projects.
  - 419 total TDOT vehicles along the I-24 SMART Corridor

- Estimated Costs for TDOT Fleet OBUs:

Item	Unit Cost	Units	Total	Annual O&M **
On Board Unit	$7,000 ea.	1	$7,000	$700
On Board Units	$7,000 ea.	419	$2,933,000	$293,300

** O&M Includes firmware upgrades, licensing, security certificates, equipment calibration.





Appendix B: Field Verification Summary

Table of Contents

Introduction

The Tennessee Department of Transportation (TDOT) has deployed a mixture of Dedicated Short-Range Communications (DSRC) and Cellular Vehicle to Everything (C-V2X) Roadside Units (RSUs) on their I-24 and US-41 corridors between Nashville and Murfreesboro over the last several years, including on some arterial and surface streets between those parallel corridors. As part of an going project, TDOT contracted with Kimley-Horn and Associates, Inc. and Brandmotion Solutions to assess the current health and operation of these RSUs.

Brandmotion was provided with a list of 150 RSU locations and some preliminary health status information based on network monitoring. This list became the basis for the team's field assessment.

Attached to this report are the following appendices:

- Appendix A: Map of C-V2X Capture Routes and RSUs with Accompanying KMZ
- Appendix B: Map of DSRC Capture Routes and RSUs with Accompanying KMZ
- Appendix C: Matrix of TDOT Sites, Detected Messages, and Notes
- Appendix D: ZIP Archive of Field Capture PCAP Files

Testing Approach

Assessment of the RSUs was performed in two stages: first, DSRC and C-V2X Onboard Units (OBUs) were utilized in the field to capture and visualize V2X messages—primarily MAP, signal phase and timing (SPaT), and any observed traveler information messages (TIM)—and an attempt was made to request signal priority/preemption at intersections that supported it. Second, packet capture (PCAP) logs from the OBUs were analyzed offline. Due to the limitations of each OBU, the logs were analyzed in similar but slightly different ways:

1) C-V2X captures were made using a Commsignia OBU on channel 183 and an Android tablet application from Iteris named V2X Connect. V2X Connect supports visualizing live data or sideloading previously captured data to play it back in real-time or fast-forward. Because of Commsignia's proprietary PCAP generation method, this is currently the only way to analyze captures from their OBU after the fact. Each capture's "journey" was played back in the app, with the driven path traced in Google Maps and visualization used to identify received V2X messages. Note, the Commsignia OBU will send a Signal Request Message (SRM) for priority/preemption only if it is able to identify its occupied lane in the received MAP.

2) DSRC captures were made using a Danlaw OBU on channel 180 and an Android tablet application from Kapsch named V2X Insight. V2X Insight only supports visualizing live data and prompts the OBU to store PCAPs in a connected USB drive. The only way to analyze captures after the fact is to view them using Wireshark with an ASN.1 SAE J2375 decoding plugin. Each capture was opened in Wireshark; then, BSM GPS data was sampled to compile an approximate driving path for the capture; finally, the messages were filtered to exclude BSMs. Note, the Danlaw OBU will send an SRM for only if it receives a WAVE Service Advertisement (WSA) from the RSU that includes the SRM Provider Service Identifier (PSID) *and* is able to identify its occupied lane in the received MAP.

During analysis of the captures, the following assessments were made:

- Tracing of the vehicle's path in Google Maps for geographic context;
- Identification of MAP messages by intersection ID and GPS reference point;
  - GPS points were matched to intersection descriptions from TDOT's list.
- Identification of received SPaT messages by intersection ID;
  - SPaT intersection IDs were matched to a received MAP with the same ID.
  - In the absence of a matching MAP, or an invalid intersection ID, GPS coordinates were taken from Basic Safety Messages (BSMs) broadcast by the OBU at the same time the SPaT was received and used to approximate the intersection's location. That location was then matched against TDOT's list to identify the specific intersection.
- Identification of received TIM messages;
  - Any contained ITIS codes were translated to their human-readable meaning.
  - The TIM's anchor GPS reference point was used to identify the potential source RSU broadcasting the message.
- Observation of any sent SRM messages or Signal Status Messages (SSMs);
  - The OBU's occupied lane when it transmitted the SRM was identified.
  - Any SSM responses were identified and decoded.
  - Observations were made of any apparent signal timing changes.
- And, finally, for all messages:
  - Broadcast technology was identified (DSRC vs C-V2X).
  - Security certificate signatures (or lack thereof) were identified.

Note: Unfortunately, the testing OBUs were unable to be enrolled in TDOT's Security Credential Management System (SCMS) environment before field testing was performed. As a result, while the OBUs could still receive the secured (or unsecured) RSU messages, it is possible that RSUs operating priority/preemption applications may have ignored any SRMs sent by the OBUs because they were not secured.

Testing Pathways

To ensure that thorough assessment could be made of the target corridors, multiple passes were made through each, in multiple directions. Generally speaking, test runs followed one of the following patterns, with Nashville and Murfreesboro being the northern and southern limits of the testing area:

- Driving east/west on US-41
- Driving east/west on I-24
- Driving east/west on either US-41 or I-24 while also cutting back and forth across arterial roads:
    - TN-155 (Briley Parkway)
    - TN-255 (Harding Place)
    - TN-254 (Bell Road)
    - TN-171 (Old Hickory Boulevard)
    - TN-266 (Sam Ridley Parkway)
    - TN-102 (Lee Victory Parkway)
    - TN-96 (Old Fort Parkway)
    - TN-99 (New Salem Parkway)
    - US-231 (Shelbyville Highway / Church Street)
- Driving on select Murfreesboro surface streets:
    - Medical Center Parkway
    - South Rutherford Boulevard
    - North Thompson Lane
    - Fortress Boulevard
    - Middle Tennessee Boulevard
    - Wilkinson Pike

Test runs can be visualized in the map images and KMZ files provided in Appendices A and B.

Test Results

Summarized and detailed test results can be found below with specific recommendations in the following sections.

Summarized Results

Of the 150 sites in the list provided by TDOT, only 29 were producing receivable messages during the tests:

- 12 C-V2X RSUs
  - Primarily detected on Medical Center Pkwy and Fortress Blvd in Murfreesboro, with 2 also found on US-41 (Lowry St).
  - 2 intersections were not on TDOT's site list, both on Fortress Blvd.
  - All intersections had MAP but only 5 also had SPaT.
  - Of the ones broadcasting SPaT, 2 of them had SPaT with an ID of 0, not matching the ID of the associated MAP.
  - Only 5 RSUs had any kind of secure messaging, but some had MAP secured with unsecure SPaT and vice-versa.
  - SRMs were issued at 8 intersections but no SSMs were received and SPaT timing did not appear to be affected by the requests.
  - 2 RSUs appeared to be broadcasting the same test TIM message.

- 17 DSRC RSUs
  - Decently spread, but with most of them found in Murfreesboro.
  - 12 intersections had MAP, 8 had MAP+SPaT, and 5 only had SPaT.
    - Note: 3 RSUs were detected on I-24's mainline, and so are not at signalized intersections so SPaT would not be expected.
  - Only 1 RSU had security enabled, and it was only broadcasting SPaT.
  - 2 freeway RSUs on I-24 had very low MAP message transmit rates.
  - No SRMs were issued for any DSRC intersections, presumably because none of the received WSA messages had the PSID for SRM services.
  - No SPaT messages were detected with an ID of 0.
  - At least 1 intersection was broadcasting MAP with a PSID of 0x204097 instead of 0x8002. This is normal, but was an interesting inconsistency compared to the other sites.

Detailed Results: C-V2X

Most detected C-V2X RSUs were concentrated on Medical Center Pkwy in the Deerfield / Manson Park area just outside of Murfreesboro. This includes the 2 units on Fortress Blvd that were not identifiable on TDOT's site list (shown below with blue pin icons). Figures 1 and 2 below visualize the locations these RSUs were detected.

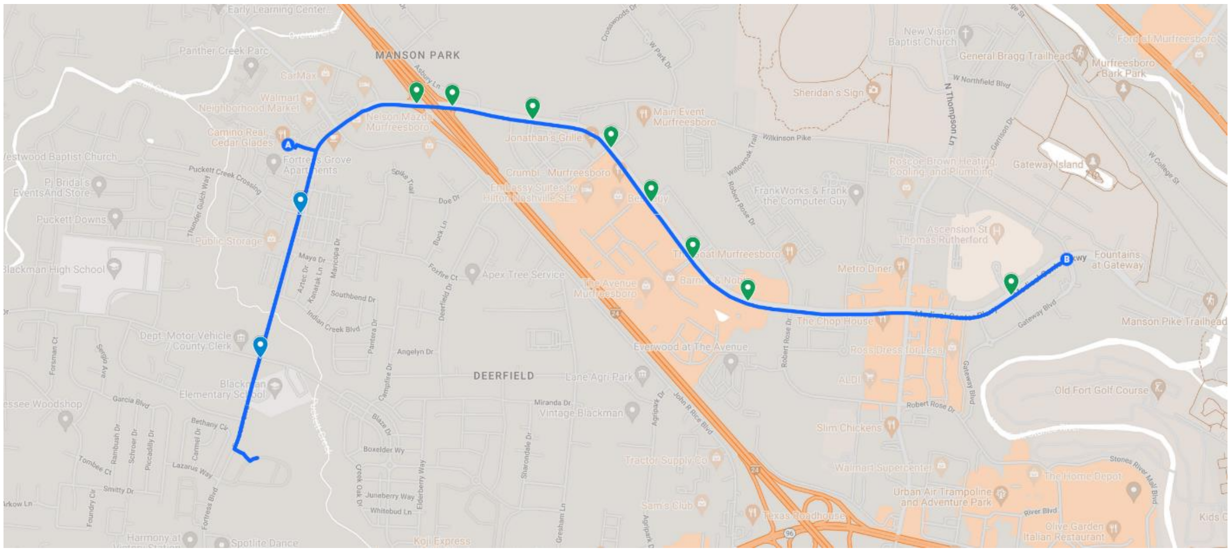


Figure 1 - C-V2X RSUs on Medical Center Pkwy and Fortress Blvd

The only other 2 units detected were on US-41 in Smyrna.

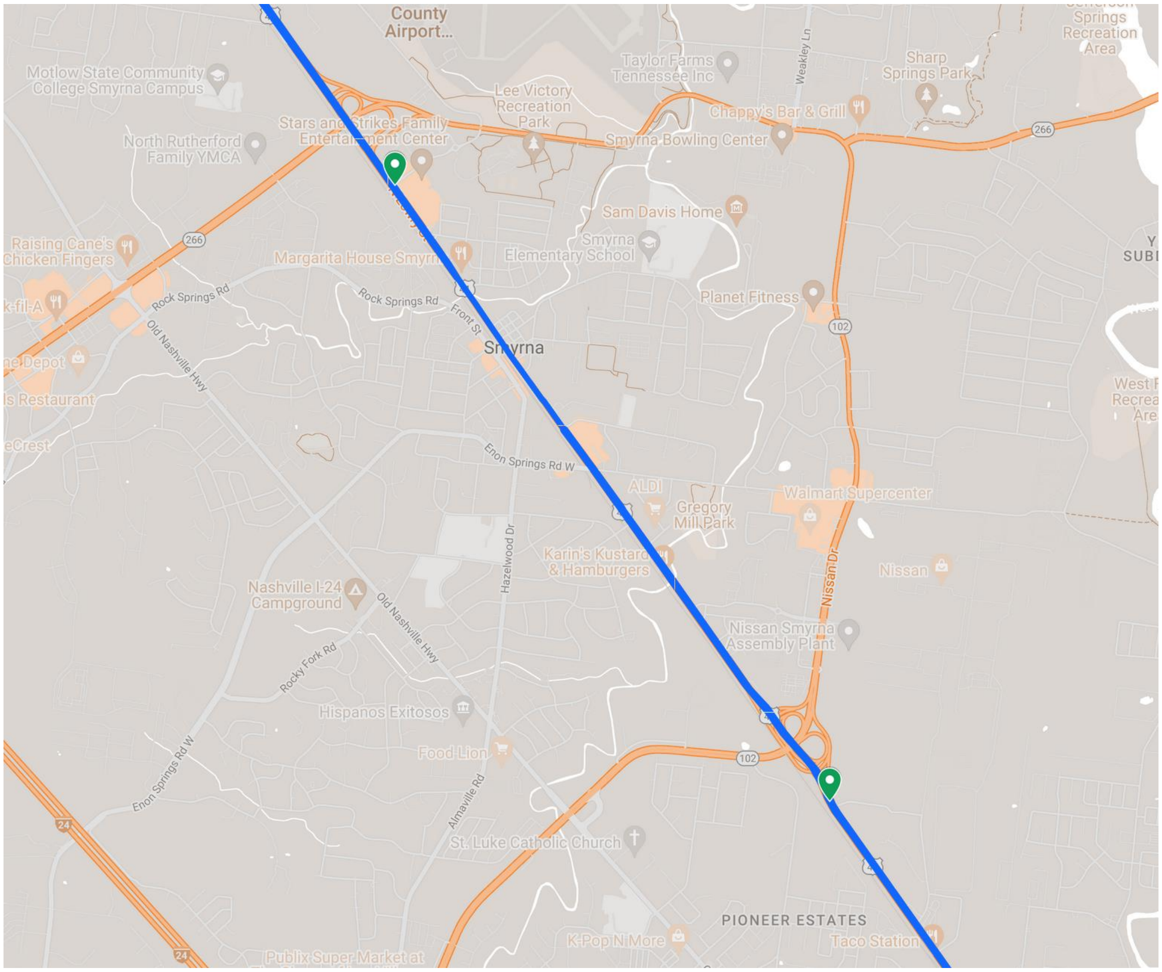


Figure 2 - C-V2X RSUs on US-41 in Smyrna

Noteworthy Observations

Aside from the small number of detected units, issues and other observations of note for the C-V2X RSUs included lane alignment, inconsistent security, inconsistent MAP / SPaT combinations, and the presence of at least one testing TIM.

Lane Alignment

It was observed in field capture playback that the Commsignia OBU used in testing failed to identify or could only partially identify its occupied lane at 6 intersections based on a combination of its own GPS and the MAP contents.

Of particular note were two intersections with missing lane information:

- 088 (Medical Center Pkwy @ Maplegrove Dr) appeared to be missing a lane on its eastern leg and did not have correct movements defined in the MAP for lane 11; the MAP should permit straight through movement for this lane but only permitted right turns.
- 085 (Medical Center Pkwy @ Honey Locust Ln) appeared to have been modernized since the MAP was created, as there is a new northern bidirectional approach to the intersection that does not have lane definitions in the MAP.

Security

Of the 12 sites with functioning C-V2X RSUs, 7 of them (58%) were broadcasting insecure messages. Interestingly, sites 085 (Medical Center Pkwy @ Honey Locust Ln), 088 (Medical Center Pkwy @ Maplegrove Dr), and 089 (Medical Center Pkwy @ Arnhart) were broadcasting secure MAP but unsecured SPaT, or vice versa, suggesting a misconfiguration of the RSUs' message parameters.

It should be noted that by design, RSUs with security enabled for a given set of messages should cease broadcasting those messages when its certificates expire and it is unable to acquire new ones. This may be one cause for the very small percentage of RSUs detected in the field testing; if the majority of other RSUs are enabled with security but cannot get new certificates, it would explain why so many of them appear silent.

MAP / SPaT Consistency

All detected C-V2X intersection RSUs broadcasted MAP but 4 of them did not seem to be broadcasting SPaT at all. There were also two intersections that appeared at least at one point to be broadcasting SPaT with a J2735 intersectionID of 0:

- 088 (Medical Center Pkwy @ Maplegrove Dr) was only ever seen to broadcast SPaT with an intersectionID of 0.

- 037 (SR 1 Lowry St @ Nolan Dr) exhibited strange behavior. Multiple passes were made through this intersection over the course of testing, but with different results almost every time. Sometimes, SPaT would have the correct intersectionID matching the MAP (40982), but other times, the only detected SPaT had an intersectionID of 0. Additionally:
  - When the SPaT had an ID of 0, it was unsecured.
  - When the SPaT had an ID of 40982, it was secured with a certificate.
  - A reasonable explanation could be that intersection 037 is broadcasting the correct SPaT and some other intersection nearby is broadcasting it with an ID of 0. However, there was never a point where both SPaT IDs were visible to the OBU at the same time.
  - Another cause could be the controller being mistakenly configured for two different SPaT streams, and the RSU is attempting to broadcast both sets but can only send one at a time.

TIM Messages

Judging by intersection proximity when the messages were received, it appeared that at least 2 RSUs were broadcasting the same test TIM message. Specifically, the TIM was noticed near intersection 089 (Medical Center Pkwy @ Arnhart) and 037 (SR 1 Lowry St @ Nolan Dr). The content of each was the same:

- ITIS code values **771**, **8196**
  - Translates to **closed ahead**, **right lane**
- roadSignID and region anchor GPS coordinates of **38.8961329, -77.0219150**
  - These fields define the precise location of a virtual (or real) road sign as represented by the TIM, and the reference point for a defined region in which that sign is valid.
  - These coordinates map to the intersection of E St NW @ 7th St NW in Washington, DC.
- region circle centerpoint GPS coordinates of **34.4212099, -83.3213100**
  - This field defines the center of a polygon (a circle in this case) that defines the valid region for the TIM. (This is defined differently from the anchor.)
  - These coordinates map to a rural location in Carnesville, GA, about 88 miles northeast of Atlanta.
- No security certificate signatures were applied.

This TIM was likely created for testing purposes and mistakenly left on the RSUs to broadcast perpetually. The figures below show the locations of the GPS coordinates identified in the TIMs.

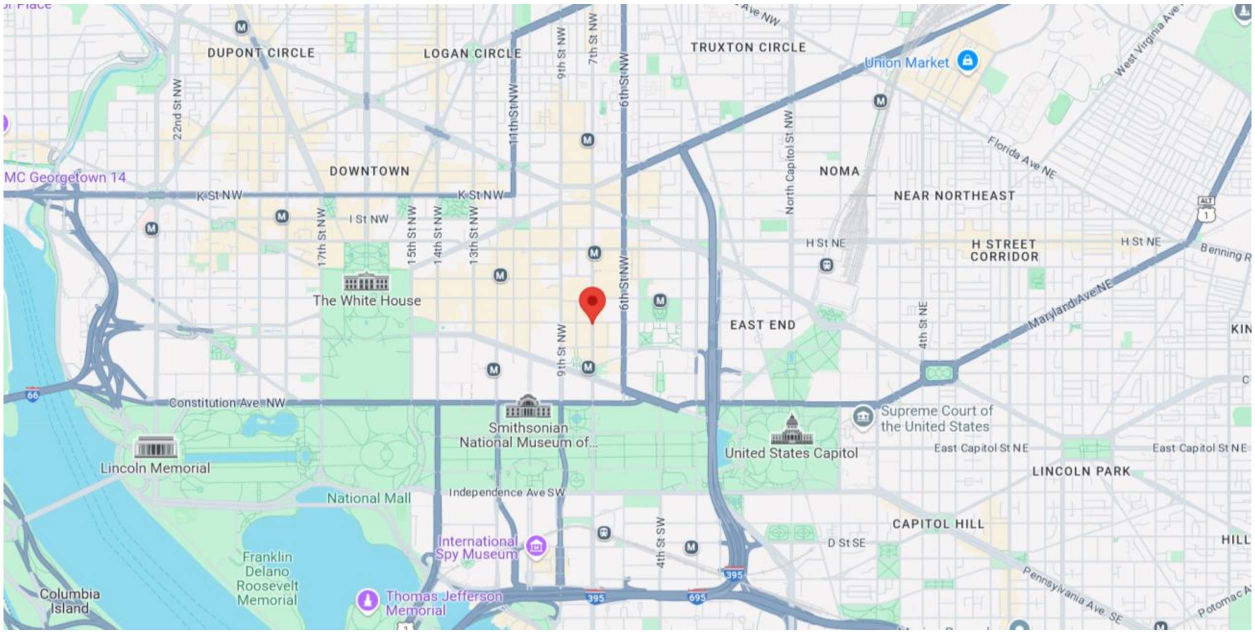


Figure 3 - Coordinates of TIM roadSignID and region anchor points. Washington, DC

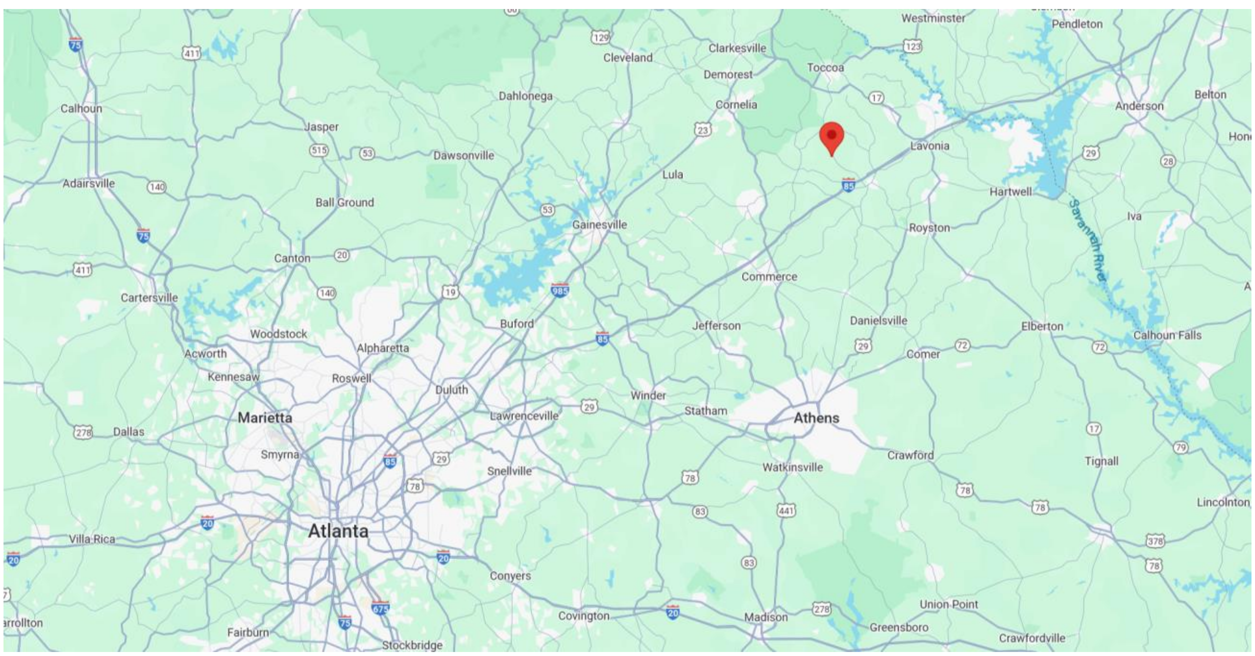


Figure 4 - Coordinates of TIM region circle centerpoint. Carnesville, GA.

Detailed Results: DSRC

DSRC RSUs were not concentrated in any one particular area like the C-V2X units, but slightly more than half were detected in the Murfreesboro area.

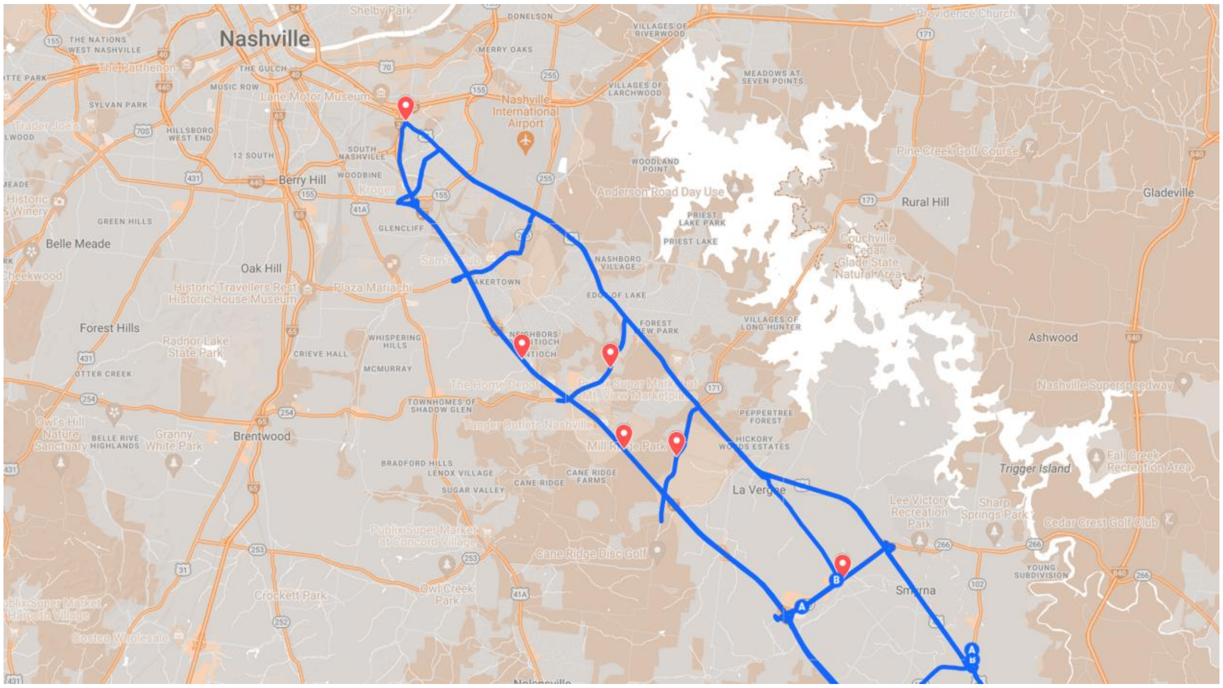


Figure 5 - Group of RSUs detected near Nashville.

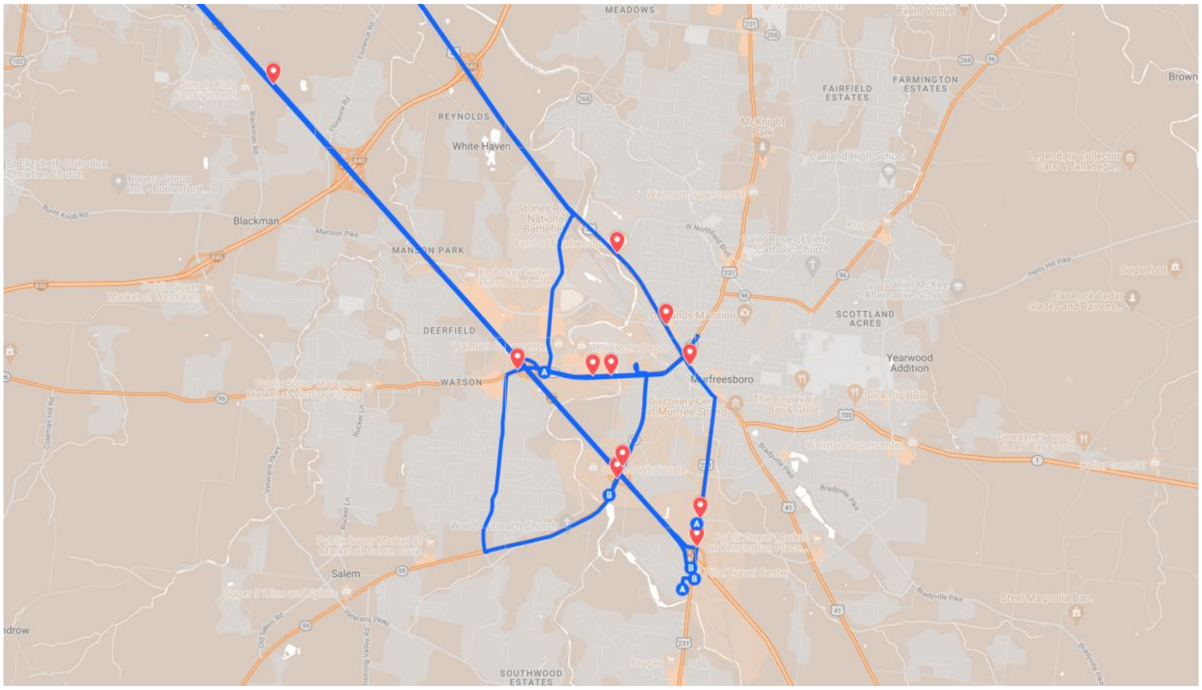


Figure 6 - Group of RSUs detected near Murfreesboro.

Noteworthy Observations

Aside from the small number of detected units, issues and other observations of note for the DSRC RSUs included an almost complete absence of secure messages and some MAP / SPaT inconsistencies. No TIM messages were detected over DSRC.

Note: Because previously performed DSRC captures could not be visualized in a playback mode like the C-V2X captures, drive paths were approximated by sampling self-reported BSM GPS coordinates and it was not possible to assess factors like lane alignments in the MAP messages.

Security

No messages received over DSRC contained security certificate signatures with the ***sole exception*** of 099 (SR 266 Sam Ridley Pkwy @ Old Nashville Hwy).

It should be noted that by design, RSUs with security enabled for a given set of messages should cease broadcasting those messages when its certificates expire and it is unable to acquire new ones. This may be one cause for the very small percentage of RSUs detected in the field testing; if the majority of other RSUs are enabled with security but cannot get new certificates, it would explain why so many of them appear silent.

MAP / SPaT Consistency

The following locations appeared to be broadcasting SPaT messages without an accompanying MAP message defining the intersection and its lanes:

- 029 (SR 1 Murfreesboro Rd @ Medical Center Pkwy)
- 001 (SR 1 Murfreesboro Rd @ I-24 WB off ramp)
- 105 (Old Hickory Blvd @ Cane Ridge High School)
- 110 (Bell Road @ Zelida Avenue)
- 099 (SR 266 Sam Ridley Pkwy @ Old Nashville Hwy)

Normally, RSUs detected during testing were identified as being located at specific intersections by plotting the GPS coordinates of the MAP message's reference point. For the intersections without MAP listed above, intersection locations were approximated by plotting the GPS coordinates of BSM messages sent by the OBU at the same time the SPaT was received and cross-referencing the nearest intersection in TDOT's site list.

There was also one intersection, 080 (SR96 Old Fort Pkwy @ Stones River Mall Blvd), that broadcasted MAP without any accompanying SPaT. The three detected I-24 installations (122, 125, and 138) also broadcasted MAP without SPaT, but this is expected for freeway sites. However, only 1 or 2 messages were received from sites 122 and 125, indicating a possible antenna / transmitter or interval configuration problem.

Recommendations

Based on the results of field testing and after-analysis, the project team recommends several follow-up actions to troubleshoot the identified issues and optimize identified inconsistencies:

Troubleshooting & Correction

- Enabling local transmission PCAP logging on RSUs and / or use of native RSU diagnostic utilities to confirm what the RSU self-reports to be broadcasting;
- Investigation of physical antenna connections on the RSUs;
- Investigation of the SCMS health status for each RSU and whether they have recently received new certificates from the system;
- Investigation of signal controllers not producing SPaT or producing SPaT with intersectionID of 0;
- Verification of the MAP messages, including possibly expired DeliveryStop value;
- Use of network utilities like tcpdump or Wireshark to confirm (on the RSU directly or using a temporary stand-in computer with the same IP) whether the RSU is receiving SPaT messages from the controller on the correct UDP port;
- Confirm the integration between RSUs and local signal controllers for priority / preemption functionality;
- Confirm DSRC RSUs are configured to broadcast all messages on channel 180;
- Confirm C-V2X RSUs are configured to broadcast all messages on channel 183;

Optimization & Modernization

- Re-factoring MAP message and SPaT message intersectionID designations to match the site enumeration convention used by TDOT (e.g., setting the intersectionID for MAP / SPaT to “89” for site 089), which will aid in future field diagnoses and troubleshooting;
- Updating MAP message lane definitions to reflect new intersection geometries and / or define more accurate lanes. Use of LiDAR imagery to generate MAP messages has proven to be a highly accurate and reliable way to produce MAPs over hand-wheeling or use of online satellite imagery tools;
- Updating MAP message PSIDs to 0x204097 instead of 0x8002 to reflect new PSID convention standards distinguishing MAP from SPaT;
- Include the PSID for SRM (0x204096) in WAVE Service Advertisements for OBUs that expect to receive it;
- With the recent release of the FCC’s Second Report and Order on use of the 5.9GHz band, which includes notice of a 2-year sunset period for DSRC

installations following publication of the rules, it is also recommended that agencies (including TDOT) begin planning for modernization of their existing DSRC infrastructure to use C-V2X exclusively. To assist with that effort, several federal grant programs (ATTAIN, RAISE, etc.) exist that agencies can use specifically for modernization of existing DSRC infrastructure.

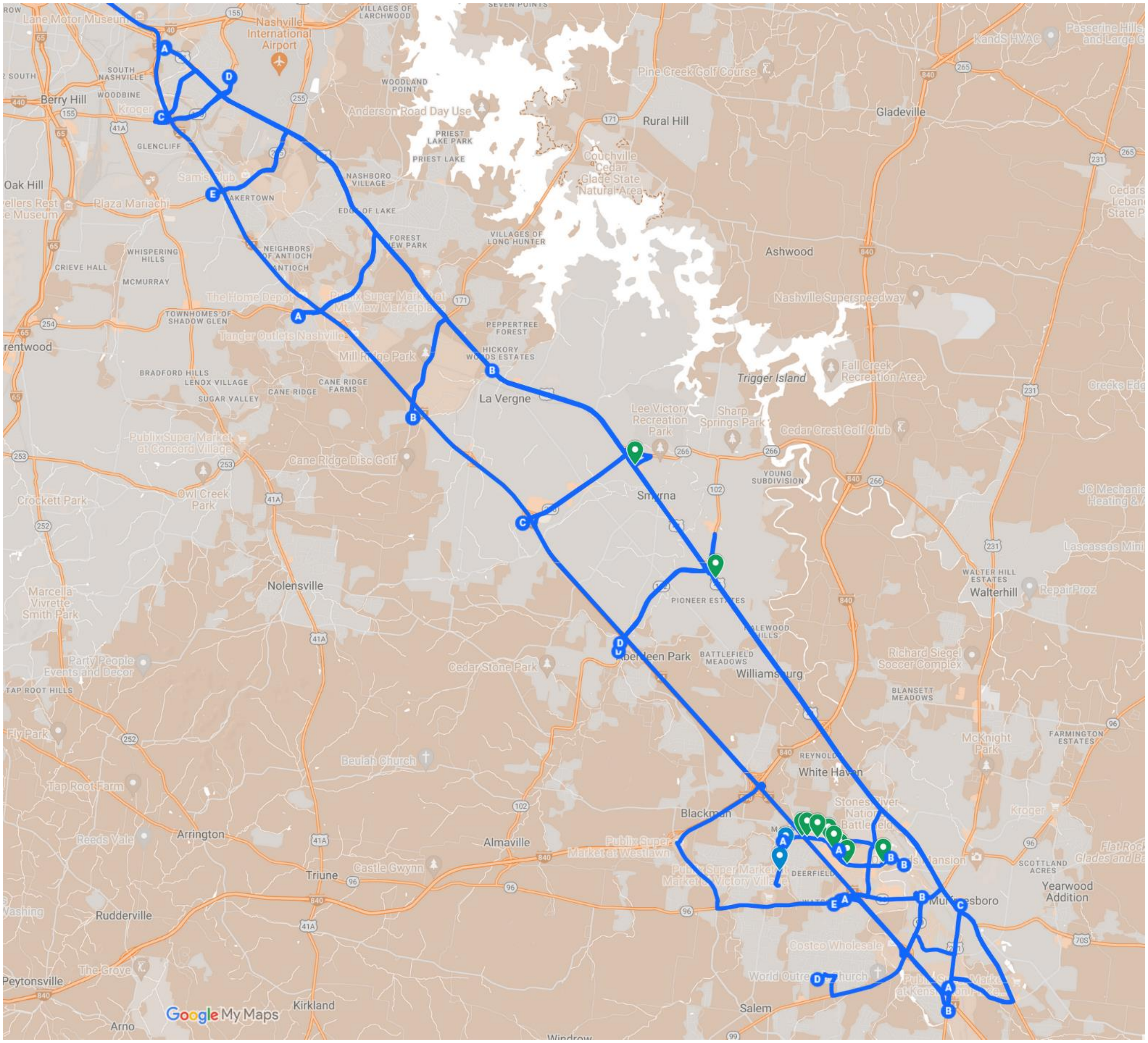
Conclusion

In conclusion, the project team testing could only validate messages received from a small percentage (19%) of the total RSUs TDOT requested be assessed. Of these, roughly 60% were using C-V2X and 40% were using DSRC. This is obviously much lower than either TDOT or the project team expected.

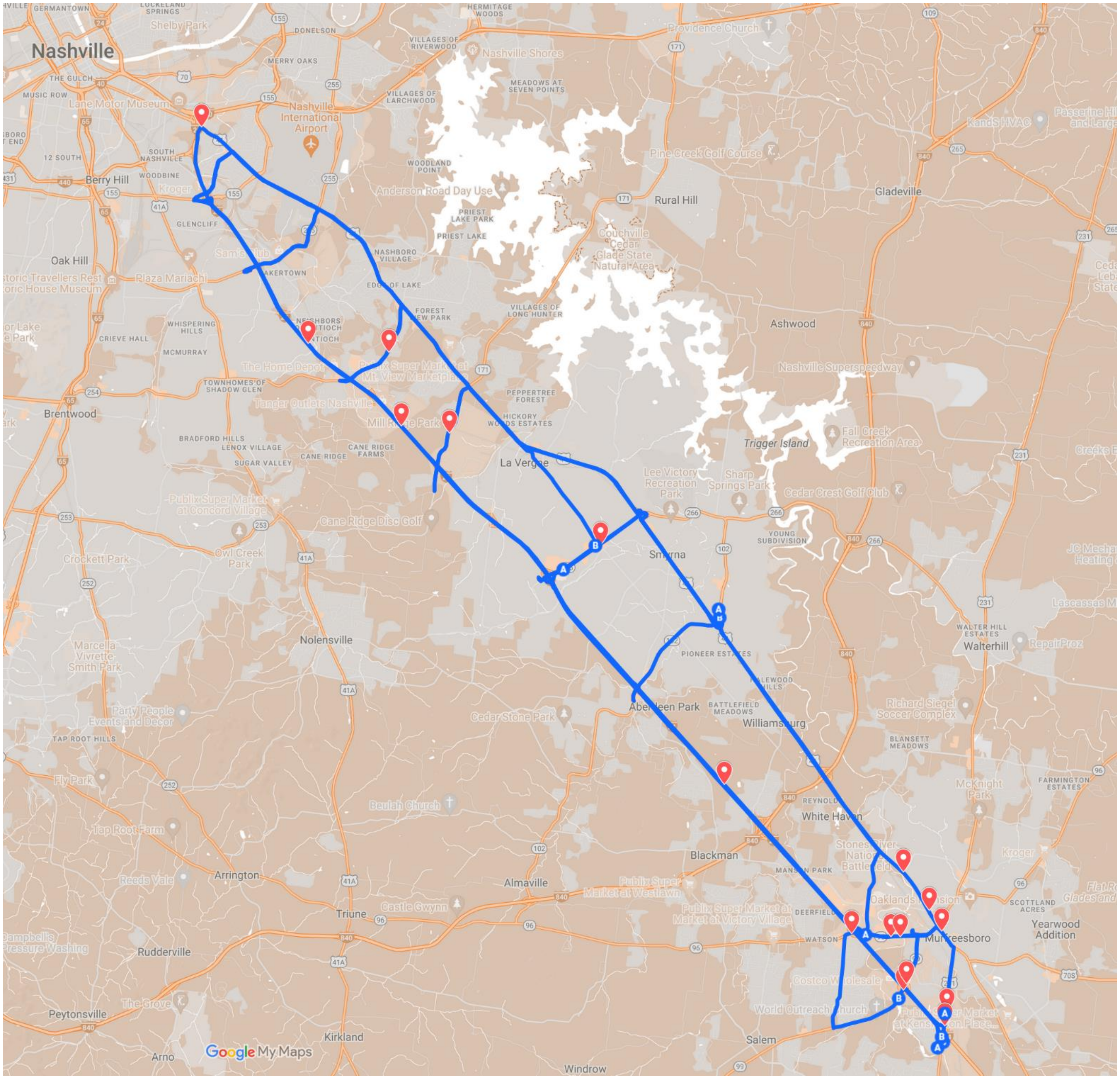
As a result, the team recommends TDOT perform a full investigation into the health and operation of their RSUs from a network infrastructure standpoint, including assessment of their traffic signal controllers. For this purpose, several troubleshooting steps are listed in the previous section. DSRC RSUs that are found to be no longer functional are recommended for replacement with C-V2X over attempted RMA or repair.

Beyond device functionality, this team also recommends assessment of the MAP messages themselves for accurate lane definitions and permitted movements. Documents recently and soon to be published by the Connected Transportation Interoperability Committee (CTIC – CTI 4501 and SAE J2945/B) will aid greatly in defining the requirements for MAP, SPaT, and signal priority / preemption at intersections.

Appendix A: Map of C-V2X Capture Routes and RSUs with Accompanying KMZ


Nashville International Airport
Berry Hill
Oak Hill
Rural Hill
Gladeville
Ashwood
Priest Lake
Nashville Superspeedway
Trigger Island
La Vergne
Smyrna
Nolensville
Walterhill
Aberdeen Park
Williamsburg
White Haven
Blackman
Murfreesboro
Arrington
Almaville
Triune
Rudderville
Peytonsville
Kirkland
Salem
Arno
Yearwood Addition
Google My Maps

Appendix B: Map of DSRC Capture Routes and RSUs with Accompanying KMZ


Nashville
Berry Hill
Oak Hill
Brentwood
Nashville International Airport
Rural Hill
Gladeville
Ashwood
Nashville Superspeedway
Trigger Island
La Vergne
Nolensville
Aberdeen Park
Williamsburg
Walterhill
White Haven
Blackman
Almaville
Arrington
Triune
Rudderville
Peytonsville
Kirkland
Arno
Salem
Windrow
Yearwood Addition
Google My Maps

Appendix C: Matrix of TDOT Sites, Detected Messages, and Notes

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Appendix C: V2X Application Deployment Locations

Appendix C: V2X Application Deployment Locations

Map of Proposed V2X Application Deployment Locations with AADT

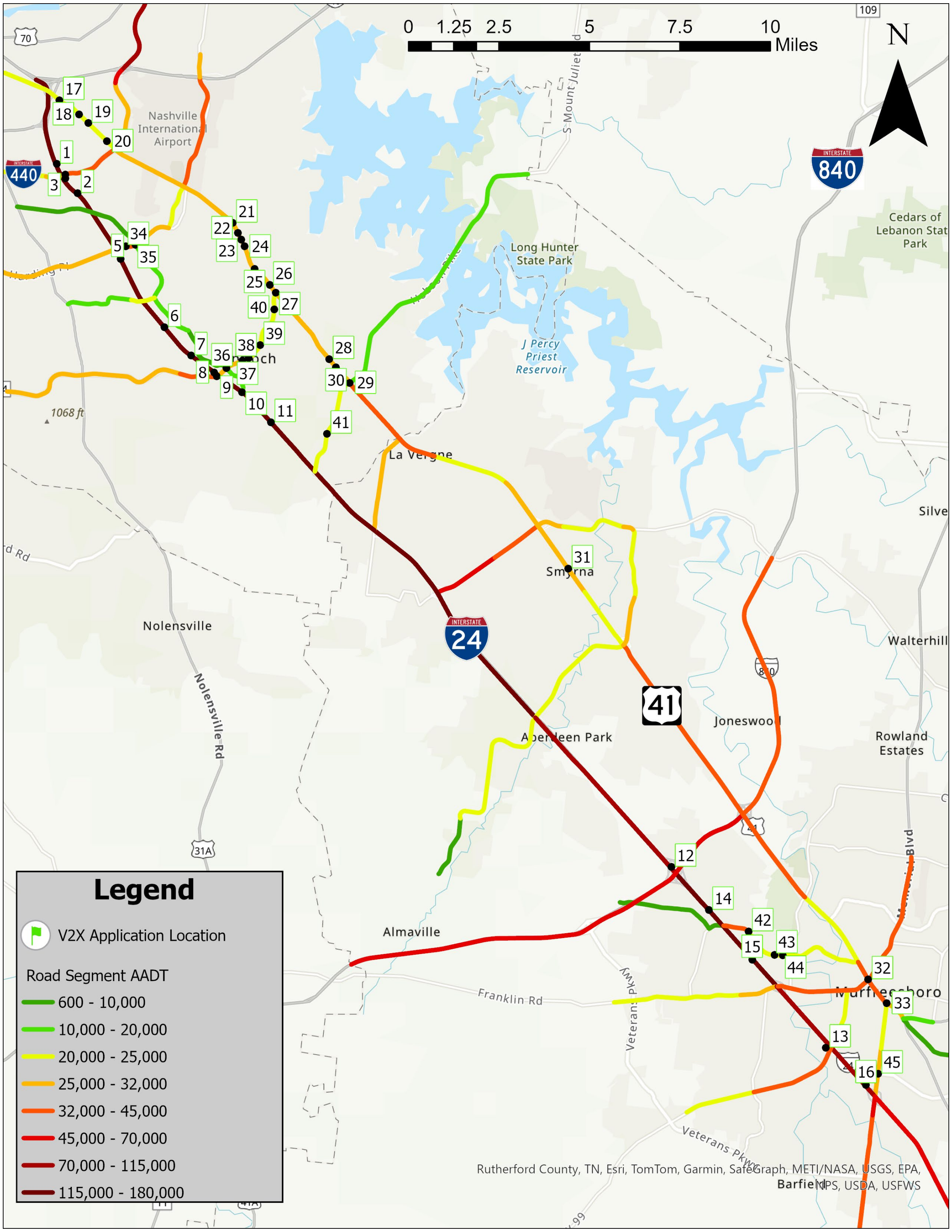

Table of V2X Application Deployment Locations

#	Location	Application
1	Between 440 and Thompson Lane/Briley Parkway	Queue Warning
2	I-24 Westbound, MM 54.2	Queue Warning, Curve Speed Warning
3	I-24 WB off ramp and signal at Briley Pkwy SR 155	Intelligent Traffic Signal System, Red Light Violation Warning
4	NB off-ramp onto SR 155 (High crash location)	Intelligent Traffic Signal System, Red Light Violation Warning
5	I-24 EB on-ramps from Harding, MM 56.0(High crash location)	Queue Warning, Reduce Speed Lane Closure
6	I-24 Both directions, MM 57.8 (High crash location)	Queue Warning
7	I-24 Water Crossing, MM 58.6 (Previous Mill Creek Flooding)	Spot Weather/Flooding
8	I-24 EB Off-ramp to Bell Road, MM 59.2 (Long queues from SB off-ramp)	Queue Warning
9	Intersection of I-24 EB Off-ramps and Bell Road (High congestion intersection)	Intelligent Traffic Signal System
10	Lane reduction on I-24 EB, MM 60.0	Queue Warning, Lane Reduction
11	I-24 Both directions, MM 60.8 (High congestion location)	Queue Warning
12	I-24/I-840 Interchange, MM 74.6	Curve Speed Warning
13	I-24 & New Salem Hwy Interchange, MM 79.8	Curve Speed Warning
14	Lane Reduction on I-24 EB, MM 75.8	Lane Reduction
15	Lane Reduction on I-24 EB, MM 77.2	Lane Reduction

16	Lane Reduction on I-24 EB, MM 81.2	Lane Reduction
17	Murfreesboro Pike at Plus Park Blvd	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
18	Murfreesboro Pike at Millwood Dr	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
19	Murfreesboro Pike at Thompson Ln	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
20	Murfreesboro Pike at Glengarry Dr	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
21	Murfreesboro Pike at Old Murfreesboro Pike/Franklin Limestone Rd	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
22	Murfreesboro Pike at British Wood Dr	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
23	Murfreesboro Pike at Ransom Pl	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
24	Murfreesboro Pike at Una Antioch Pike/Nashboro Blvd	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
25	Murfreesboro Pike at Edge O Lake	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
26	Murfreesboro Pike at Rural Hill Rd	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk

27	Murfreesboro Pike at Bell Rd	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
28	Murfreesboro Pike at Pin Hook Rd	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
29	Murfreesboro Pike at Hobson Pike	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
30	Murfreesboro Pike at Publix Shopping Center	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
31	Lowry St at Washington St	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
32	NW Broad St at Old Fort Pkwy	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
33	SE Broad St at Church St	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
34	Metroplex Dr at Harding Pl	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
35	Antioch Pike at Harding Pl	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
36	Hickory Hollow Pkwy at Bell Rd	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk

37	Bell Rd at Mount View Rd	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
38	Bell Rd at Hickory Hollow Ter	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
39	Bell Rd at Zelida Ave	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
40	Bell Rd at Morris Gentry Blvd	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
41	Old Hickory Blvd at Cane Ridge High School	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
42	Medical Center Pkwy at Gresham Park Dr	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
43	Medical Center Pkwy at Robert Rose Dr	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
44	Medical Center Pkwy at Lothric Way	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk
45	S Church St at W Rutherford Blvd	Mobile Accessible Pedestrian Signal System, Pedestrian in Signalized Crosswalk

Appendix D: ZIP Archive of Field Capture PCAP Files

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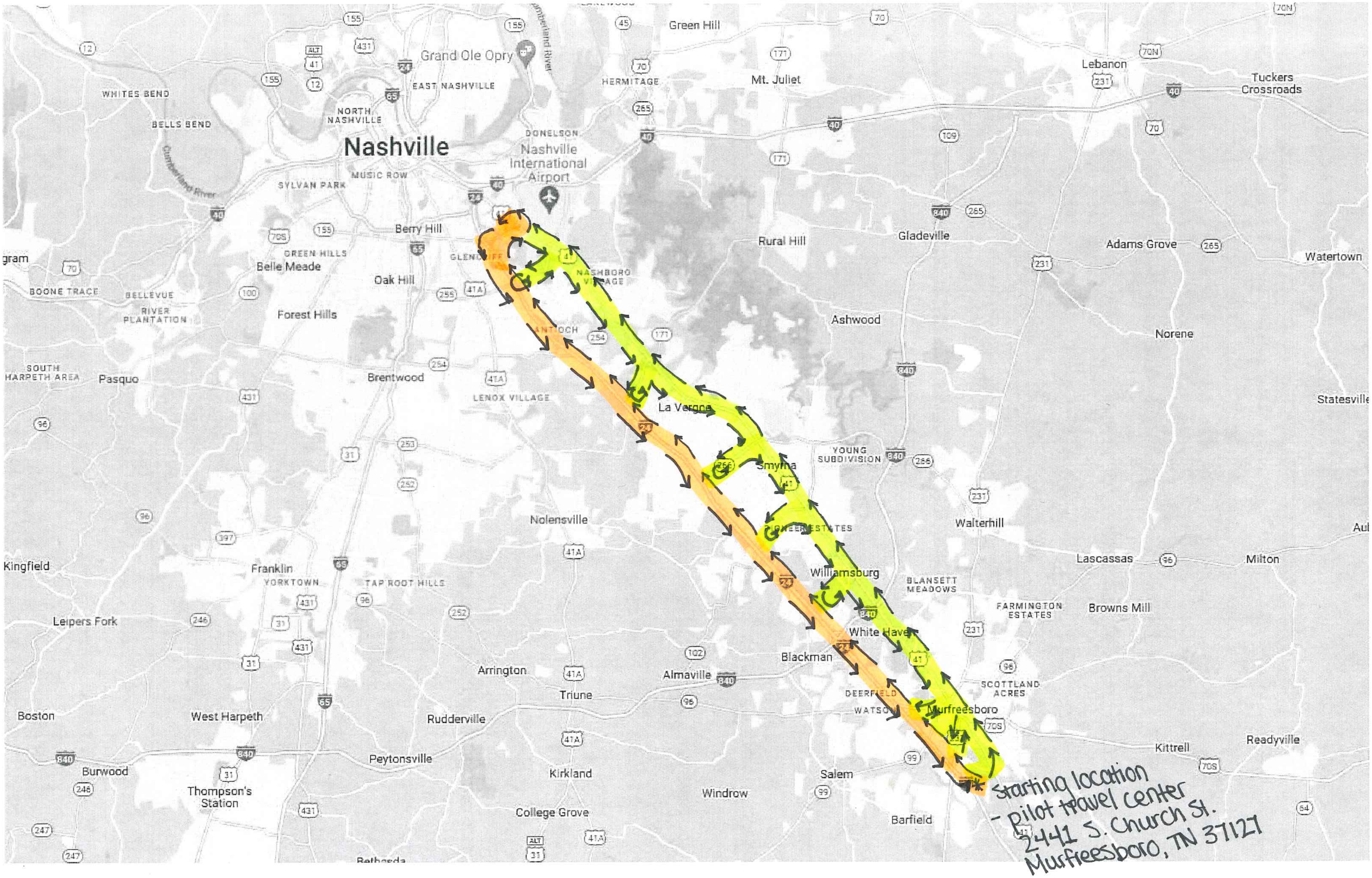
- CV2X Drive [PCAP: 2024_10_22-24tobriley]

[10.22.24] CV2X | iTeris - I24 & Murfreesboro

- CV2x Drive [PCAP: 2024-10-22_first.]

[10.23.24] DSRC | Kapsch

- DSRC | I24, Down & Back
- DSRC | US41, Down, Intersecting Roads, Back



C-V2X | iTeris [10.24.24]

- C-V2X, I24 Down to Briley Pkwy → US41
- C-V2X, US41 Starting near Nashville, going WB all intersecting Roads Both ways

Starting Location
- pilot travel center
2441 S. Church St.
Murfreesboro, TN 37127