How Locals Need to Prepare for the Future of V2V/V2I Connected Vehicles

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Technical Report Documentation Page

1. Report No. MN/RC 2019-35	2.	3. Recipients Accession No.	
4. Title and Subtitle How Locals Need to Prepare for the Future of V2V/V2I Connected Vehicles		5. Report Date August 2019	
		6.	
7. Author(s) Gordon Parikh, Melissa Duhn, John Hourdos		8. Performing Organization Report No.	
9. Performing Organization Name and Address Minnesota Traffic Observatory Department of Civil, Environmental, and Geo- Engineering University of Minnesota 500 Pillsbury Dr SE Minneapolis, MN 55455		10. Project/Task/Work Unit No. CTS Project 2018025	
		11. Contract (C) or Grant (G) No. (c) 1003325 (wo) 22	
12. Sponsoring Organization Name and Address Local Road Research Board Minnesota Department of Transportation Office of Research & Innovation 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes http:// mndot.gov/research/reports/2019/201935.pdf			

16. Abstract (Limit: 250 words)

Connected and Automated Vehicles (CAVs) are expected to affect the foundations of transportation operations and roadway maintenance as they become more prevalent on the roadways. This report is an effort to address this complex subject for the various owners, agencies and stakeholders involved in traffic operations. It discusses the connected vehicle ecosystem and its background, potential CAV applications, types of communication and hardware required for CAV systems, and recommendations to local road owners. The report also includes a survey sent to local road owners to assess the current readiness of the transportation system for CAVs. Although it is too early to give specific recommendations, general guidance is provided for road owners to begin preparing for the future of CAVs.

| 17. Document Analysis/Descriptors
Connected vehicles, Intelligent vehicles, Vehicle to vehicle communications, Dedicated short range communications, Vehicle to infrastructure communications, City planning (Epdumc), Mobile communication systems | | 18. Availability Statement
No restrictions. Document available from:
National Technical Information Services,
Alexandria, Virginia 22312 | |
| 19. Security Class (this report)
Unclassified | 20. Security Class (this page)
Unclassified | 21. No. of Pages
135 | 22. Price |

HOW LOCALS NEED TO PREPARE FOR THE FUTURE OF V2V/V2I CONNECTED VEHICLES

FINAL REPORT

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August 2019

ACKNOWLEDGMENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ATC – Advanced Transportation Controller

AV – Automated Vehicle

BSM – Basic Safety Message (SAE J2735)

CA – Certificate Authority

CAV – Connected and Automated Vehicle

CV – Connected Vehicle

C-V2X – Cellular based Vehicle to Anything communication (part of 5G communication protocol)

DSL – Digital Subscriber Line (Internet service connection medium)

DOT – Department of Transportation

DSRC – Dedicated Short-Range Communication (IEEE 802.11p and IEEE 1609)

FHWA – Federal Highway Administration

GPS – Global Positioning System. The USA version of Global Navigation Satellite System (GNSS)

I2V – Infrastructure-to-Vehicle (communication)

IEEE – Institute of Electrical and Electronics Engineers

IoT – Internet of Things

IP – Internet Protocol

ITS – Intelligent Transportation Systems

JPO – Joint Programs Office (as in FHWA ITS JPO)

MnCORS – Minnesota Continuously-Operating Reference Station

MnDOT – Minnesota Department of Transportation

NEMA – National Electrical Manufacturers Association

NHTSA – National Highway Traffic Safety Administration

NTCIP – National Transportation Communications for Intelligent Transportation Systems Protocol

OBU – On-Board Unit

PKI – Public Key Infrastructure

PoE – Power over Ethernet

PSM – Pedestrian Safety Message

RSE – Road-Side Equipment

RSU – Road-Side Unit

RTCM – Radio Technical Commission for Maritime Services Message (SAE J2735)

SAE – Society of Automotive Engineers

SCMS – Security Credential Management System

SDK – Software Development Kit

SPaT – Signal Phasing and Timing (SAE J2735)

SRM – Signal Request Message (SAE J2735)

SSM – Signal Status Message (SAE J2735)

TIM – Traveler Information Message (SAE J2735)

TMC – Traffic Management Center

TSR—Traffic Sign Recognition

USDOT – United States Department of Transportation

V2I – Vehicle-to-Infrastructure (communication)

V2V – Vehicle-to-Vehicle (communication)

V2X—Vehicle-to-Everything (e.g. Infrastructure, Vehicle, etc.) (communication)

EXECUTIVE SUMMARY

Connected and automated vehicles (CAVs) are expected to affect the foundations of transportation operations and roadway maintenance as they become more prevalent on roadways. This report is designed for road operators, agencies and stakeholders so they can become familiar with the background of CAVs and learn more about their potential.

CAVs are made up of two categories: connected vehicles (CVs) and automated vehicles (AVs). CVs communicate with nearby vehicles and infrastructure, while AVs operate using internal sensors in isolation from other vehicles. Within AVs, there are five different levels of automation defined by the Society of Automotive Engineers. These levels range from 0 "No Automation" to 5 "Full Automation." Vehicles with both connectivity and some measure of automation are considered CAVs. This distinction among CVs, AVs, and CAVs, along with their individual capabilities, applications and requirements, is important to make as the transportation industry moves forward with roadway operation decisions. Figure 1 shows the levels of automation.

SAE J3016™ LEVELS OF DRIVING AUTOMATION

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	You **are** driving whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			You **are not** driving when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			**These are automated driving features**		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering OR brake/ acceleration support to the driver	These features provide steering AND brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering OR • adaptive cruise control	• lane centering AND • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/ steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

Society of Automotive Engineers (SAE) automation levels

This report discusses potential CAV applications, categorized by the level of automation required. Types of CAV applications are shown below in Table 1. Most of the applications examined in the report belong

to level 0, or "No Automation," in which warnings and information are provided to assist drivers but no control is removed from the driver. These applications will be the first implemented as market penetration for CVs is expected to be faster than AVs or CAVs.

Types of CAV applications

Category	Description	Examples
In-Vehicle	Applications that involve interactions between different components within the vehicle.	Diagnostics, predictive maintenance, and safety applications.
Drivers and Passengers	Applications that involve interactions with a user within the vehicle.	Entertainment, navigation, personal device integration, and remote control.
Third-party Services	Applications that facilitate transactions with third parties using the vehicle.	In-car payment services, roadside assistance, insurance, and more.
Infrastructure and Other Vehicles	Applications that primarily operate through interactions with other vehicles and connected infrastructure.	Crash response, adaptive traffic lights, and emergency vehicle warnings.

After applications are explored, the report shifts to an examination of CV systems and hardware and the types of communication required to support them. Two concerns of user groups are driver privacy and system security, so standards and practices for these are described as well. Costs, both monetary and in terms of effort, are broken down per application.

Current road infrastructure and controls are examined along with survey results from local road operators on their interest in different types of CAV technologies. This survey was given to ensure the findings of this project were relevant to Minnesota road operators.

It is too early to give specific recommendations for CAV applications, but general recommendations for CAV readiness close out this report. These recommendations include maintaining road markings and clear road signage, modernizing roadway design information and controllers, developing communication infrastructure where possible, and following guidance from the U.S. Department of Transportation as well as local DOT agencies.

To accompany this report, a deliverable matrix was created, which lists the CAV applications most local groups are interested in. The matrix breaks down infrastructure, sensor, and communication needs to

support the application, as well as "costs" associated with the application. These "costs" are both monetary (equipment purchasing) and abstract (cost of effort to install, operate and maintain the application). This matrix was designed to be a truncated version of the applications section of the report that local road owners can easily access and understand.

In addition, this project produced a 100-plus page literature review extensively documenting prior research into CAVs. The literature review incorporates technologies, applications, and readiness options, as well as the current pilot sites in Florida, Wyoming and New York. This literature review stands on its own as a document that any interested stakeholder can read for background knowledge on CAV efforts.

CHAPTER 1: INTRODUCTION

Connected vehicles (CVs), vehicles that communicate wirelessly with one another, and automated vehicles (AVs), where the driver is replaced partially or completely by a computer—collectively referred to as connected and automated vehicles (CAVs)—have the potential to fundamentally change transportation operations and road maintenance. Therefore, agencies that own and operate roads throughout the country have good reason to be aware of these trends and want to ensure that the infrastructure they operate will be compatible with future developments. In addition, as their constituents continue to adopt vehicles with automation technologies, road operators will increasingly be mandated to maintain the infrastructure needed to allow these vehicles to operate correctly. Due to the time scales over which maintenance of road infrastructure occurs, road operators must begin taking action today to ensure that they are prepared for the future.

While there are currently no standards in the *Manual on Uniform Traffic Control Devices* (MUTCD) that govern CV technology, unlike the traditional infrastructure that currently exists in the field, there are still things operators can do to minimize the cost of deploying CV infrastructure when they are ready to do so. Because of the dependence of many CV-application-related hardware components on information from the infrastructure, notably traffic signal controllers, purchasing equipment that complies with the latest standards is the best way to ensure that it will be interoperable with equipment deployed in the future, such as dedicated short-range communication (DSRC) road-side Units (RSUs) that are used to communicate with vehicles. Standards like the National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP), the Advanced Transportation Controller (ATC), and the handful of standards governing controller cabinets currently provide a framework through which hardware manufacturers and software vendors can ensure compatibility with other technologies now and into the future. Being aware of these standards, and whether or not a device complies with them, will give road operators the ability to keep their infrastructure prepared even as technology evolves.

The rate of development of CAV technology, along with the wide variety of public and private stakeholders that will be affected by it, means that it is hard to say exactly what road operators will have to do in the long term. However, at this point, road operators can begin to take action by informing themselves about ongoing developments, deciding what they would like to get out of this nascent technology, and soliciting input from their constituents to ensure that the citizens they serve are involved in the process. To help with this process, this report, and the larger research project, collects information from a wide variety of sources and distills it to the aspects that are most relevant now to local road operators. While the amount of information can seem daunting, by focusing on the specific applications that can be implemented, the hardware required to do so, and the options afforded by the current hardware in the field, this information can be used by road operators to take an organized approach to planning and decision-making.

CHAPTER 2: REPORT OVERVIEW

Connected Vehicles are a complex subject, with many different owners, agencies and stakeholders involved, all with their own needs and interests. To guide the reader, a brief overview of the report and additional deliverables is provided here.

The report gives background on the Connected Vehicle Ecosystem, and introduces the concept and potential for a Connected Automated Vehicle (CAV) system without requiring the reader to have an extensive background knowledge of CAVs. Some background is given to familiarize the reader with the difference between Connected Vehicles (CVs), Automated Vehicles (AVs), and CAVs, as that is a major source of confusion with the new technology.

After levels of automation are discussed, the report moves into potential CAV applications. It categorizes them based on the level of automation. The majority of applications discussed in the report focus on "level 0" technologies; i.e., no automated control, but warnings and information to assist drivers. These technologies will be the first implemented in the CAV ecosystem, as market penetration for CVs will no doubt be faster than AVs or CAVs. In addition, an effort was made to separate hype from feasible applications. Section 3.2 is a thorough look these feasible current and future CV applications, and what will be required of local road owners to implement them.

Chapter 4 describes CV systems and hardware, and the types of communication that will be required to implement CAV systems. Driver privacy and system security are also discussed, as they are a concern for user groups. Roadside Units (RSUs) and types of wireless communication that will allow for V2V/V2I/V2X applications are also laid out. Each application discussed in Chapter 3 has a corresponding section in Chapter 4 dealing with hardware and communication needed to realize the application.

Chapter 5 returns the results of a survey to local road operators on their interest in types of CAV technologies. It also discusses current readiness of infrastructure and controls.

Chapter 6 is a brief collection of recommendations for local road owners. While each CAV application has different levels of equipment and communication requirements, there are commonalities for general readiness which are presented.

To accompany the final report, a deliverable matrix was created which lists out the CAV applications most local groups were interested in. The matrix breaks down infrastructure, sensor, and communication needs to support the application, as well as "costs" associated with the application. These "costs" are both monetary (equipment purchasing) and abstracted (cost of effort to install, operate and maintain the application). This matrix was designed to be a truncated version of Chapter 2 of the report that local road owners could easily access and understand.

 In addition, this project produced a 100+ page literature review extensively documenting prior research into CAVs. The literature review incorporates technologies, applications, and readiness options, as well as the current pilot sites in Florida, Wyoming and New York. This literature review stands on its own as a document that any interested stakeholder may read for background knowledge of CAV efforts.

CHAPTER 3: CONNECTED VEHICLE ECOSYSTEM OVERVIEW

While connected vehicle technology is often discussed as if it were a unified system, in reality it is better to consider connected vehicles as an ecosystem of different entities and concepts that interact to provide advanced functions. To help address some of the confusion that may result from this, the researchers offer the following high-level overview of connected vehicle concepts with some key clarifications.

At the highest level, CV technology simply means that vehicles have the ability to communicate wirelessly with other vehicles and with infrastructure, exchanging much more detailed information than is capable with current technology. This communication is facilitated through the addition of a radio system with a certain operating frequency and communication protocol, though the specific radio technology used is not particularly important. This radio system is connected to existing systems, such as a vehicle's controller bus or a signal controller's local network, which must exchange data with the radio using a standard protocol so that information may be broadcast to other actors in the system. This kind of technology does not imply any automation of vehicle control. The details of what radio technology are used, what information they exchange as well as how they do so, and how these radios integrate with existing systems is discussed in the coming chapters.

The technology used for communication forms a platform on which more advanced technologies can be built. These technologies are referred to as *applications*, as in *Connected Vehicle Applications*. These applications take advantage of the ability to quickly transmit information wirelessly to enable additional warnings for drivers, enhanced cooperation between vehicles, improved efficiency of the transportation network, or access to better data for road operators to manage the infrastructure. Many specific applications have already been envisioned, some of which have been thoroughly defined conceptually or even implemented in pilot studies. The functions of many of these applications are described later in Chapter 2, and the specific information and hardware requirements for a subset of these applications are discussed in Chapter 3.

A somewhat related, though distinctly different, concept that is often discussed along with connected vehicles is Automated or Autonomous Vehicles (AVs). These are vehicles that have the capability to automate some or all of the driving task, taking control of the vehicle away from the driver. AVs do not imply any connectivity; instead, all information is obtained through sensors mounted on the vehicle. While these concepts are often discussed as if they are the same thing, they are not and do not necessarily have any interaction, though if combined they would act synergistically. Though AVs have generally received much greater media attention in recent years, many of the expected benefits proclaimed by the people developing AV technologies, such as platooning of vehicles, are in actuality CV technologies.

This project is not intended to address fully autonomous vehicles, and only discusses automated vehicles in the context CV applications and in regards to infrastructure requirements for the correct operation of AV technologies. From the perspective of road operators, AVs are generally not something they can influence beyond the policy level, and so are mostly outside the scope of this report.

To that end, the remainder of this chapter delves deeper into the core concepts and functionality of connected vehicles. Following the discussion of some background information that is meant to help readers understand the language used to describe CVs and how they are expected to operate from a high-level perspective, a number of specific applications are described to outline some of the anticipated capabilities of CVs and the resulting benefits of these technologies.

3.1 BACKGROUND ON CONNECTED VEHICLE TECHNOLOGIES AND CONCEPTS

To help readers follow the remainder of this report, the following background information on the core technologies and concepts of connected vehicles (CVs) is provided.

3.1.1 Connected Vehicles, V2V, V2I, and V2X

Recently, connected vehicles have been considered one of the technologies that make up the Internet of Things (IoT), a term used to describe the set of physical objects embedded with sensors or actuators and connected to a network. Automakers are embedding intelligence and sensing capabilities into vehicles using several different technologies, such as low-cost sensors, low-power, high-capacity processors, cloud computing, and wired and wireless connectivity. As a result, vehicles have more data, connectivity, and interactivity.

Before the emergence of the IoT concept, "CV" generally referred to both connecting vehicles and infrastructure, and to connection among all ground vehicle players: cars, freight trucks, and buses – and potentially motorcycles, bicycles, and pedestrians. CV includes vehicle-to-vehicle communication (V2V), vehicle-to-infrastructure communication (V2I), and "V2X", broadly representing communication between vehicles, infrastructure, and other road users (such as pedestrians and cyclists).

V2X involves deployment of sensing and connectivity in infrastructure and potentially interfaces with advanced traffic applications utilizing Intelligent Transportation Systems (ITS). This capability creates machine awareness of the trajectories of equipped vehicles in the immediate vicinity, that applies to vehicles as well as specific features of the infrastructure, such as intersections and curves. Such machine awareness may be used to identify safety risks, but also to condense or smooth traffic flow. These applications of the technology require warnings or notifications for drivers in order for the driver to make the required vehicle corrections.

3.1.2 Relationship Between Connected Vehicles and Automated Vehicles

CVs and AVs have generally pursued parallel technological and policy paths, and their relationship is evolving, although there continues to be no formal relationship at the national level. The major national stakeholders, including USDOT and state agencies, have been active in both CV and AV and have encouraged a supportive relationship between the technologies. It is commonly believed that CV is an enabler of AV, and that incorporating CV with AV is critical to realizing societal benefits such as reduced congestion, improved mobility, and reduced fuel consumption. However, there are some companies that are pursuing AV without a strong CV component.

There is no doubt that AVs have dominated both the popular press and the trade media; this coverage has perhaps overshadowed the high value of CV and the significant investment by both the public and private sectors over more than a decade. Nevertheless, CV remains highly-aligned with state DOT goals and is complementary to the rollout of AVs [1].
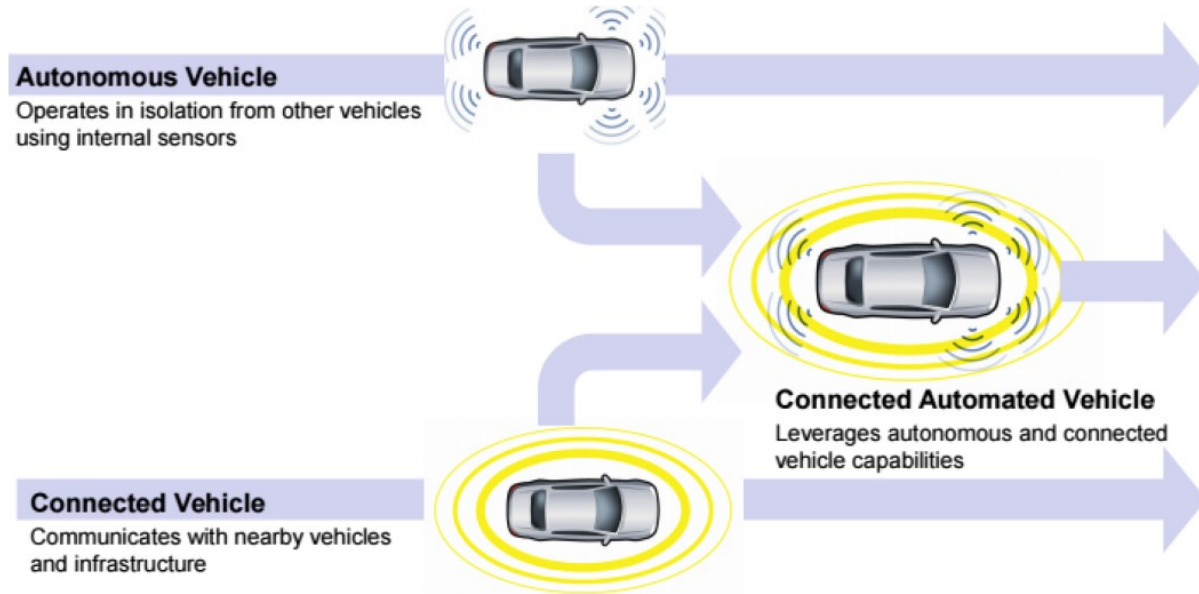
Figure 3.1 USDOT Vision of Connected/Automated Vehicles.

3.1.3 Levels of Automation

An important concept for understanding automated vehicles is the idea of "Levels of Automation," described in Figure 3.2 and Table 3.1. The levels are meant to clarify the set of functions that may be provided by an automated vehicle and provide a unified language for describing the stages in the development of AV technology. Developed by the Society of Automotive Engineers (SAE) and put forth as policy by the National Highway Traffic Safety Administration (NHTSA) in 2013 through the release of a document entitled "Preliminary Statement of Policy Concerning Automated Vehicles" [2], the Levels of Automation consist of five vehicle automation technology levels. Levels 0 through 2 encompass technology that is commercially available today; Levels 3 and 4 are currently being tested.

Figure 3.2 Society of Automotive Engineers (SAE) Automation Levels.

Level 0, or no automation, means that the driver is completely responsible for the primary vehicle controls: braking, steering, throttle, and motive power, as is the case with most vehicles on the road today. *Level 1*, or function-specific automation, indicates that one or more specific control functions are automated. Examples include electronic stability control (ESC) and pre-charged brakes (where the vehicle automatically assists with braking to enable the driver to regain control after skidding or to stop faster than possible by acting alone). Other examples include adaptive cruise control (ACC) and lane-keeping assistance (LKA). *Level 1* technologies will involve the automated control of either longitudinal (acceleration or braking) or lateral (steering) movement of the vehicle, but not both. *Level 2*, or combined-function automation, implies automation of at least two primary control functions designed to work together to relieve the driver's control of those functions. Examples include a combination of ACC and LKA. *Level 3*, or limited self-driving automation, indicates that vehicles at this level enable the driver to cede full control of all safety-critical functions under certain traffic and environmental conditions. This technology allows the driver to rely heavily on the vehicle to monitor for changes in those conditions, which may require the driver to interfere from time to time. The driver is still expected to be available for occasional control, but after a warning and some comfortable transition time (3 to 5 seconds). *Level 4*, or high automation, indicates that the vehicle is designed to perform all driving functions for the entire trip, however the driver may be required to take control under certain conditions. *Level 5*, or full automation,

involves a vehicle that is capable of performing all driving functions under all conditions. This design anticipates that the driver will provide the destination or navigation input, but the driver is not expected to be available for vehicle control at any time during the trip.

3.2 CONNECTED VEHICLE APPLICATIONS

An important aspect of the Connected Vehicle ecosystem, as it is currently envisioned, is the concept of "Connected Vehicle Applications." Similar to a software application, a Connected Vehicle application is a system that is designed to perform a set of coordinated functions to benefit one or more users. In the case of CVs, the users are drivers and other road users, along with the road authority and any other person or entity that has a stake in the vehicular transportation system. Again similar to a software application, a CV application is a general concept of which there are many specific examples, each providing a unique function that is meant to improve the safety, efficiency, or environmental impact of transportation by taking advantage of the ability for vehicles and other road users to communicate in real time in ways that have not been possible before.

Broadly speaking, CV applications are what provides the end benefit of a CV ecosystem. Just as a computer is essentially useless without software, a connected vehicle and connected infrastructure will not provide any meaningful benefit unless these entities are able to actually interpret and use the information transmitted between them. CV applications represent a means for doing this, describing the information requirements and flow between entities in the system, the decisions that are made and by whom, and how these decisions translate into actions. Currently there are a number of CV applications that have been conceived, many of which have been conceptually laid out to a high degree or even demonstrated in pilot implementations, and some of which still remain to be defined beyond a basic idea. These applications are capable of providing much of the anticipated benefit of a CV ecosystem. However, one can imagine that there are applications that have not even been conceived that will become important in the future.

The following section provides an overview of a number of CV applications presented in the sequence of the NHTSA Levels of Automation described in Section 3.1.3 . The majority of the CV applications fall into the Level 0 category since they involve the generation of warnings to the driver rather than exerting any kind of control over the vehicle. There are two main groups of applications. The first group includes applications that do not have any infrastructure requirements, depending only a vehicle's sensors or information from other vehicles' Basic Safety Message (BSM) data (discussed in Section 4.1.1.4). The second group includes those that are dependent to some degree on information from infrastructure, such as Signal Phasing and Timing (SPaT) data (discussed in Section 4.1.1). A number of applications that benefit the road authority or traffic management effort as a whole, rather than just individual vehicles and driver behavior, are presented separately.

Understanding these applications is key to understanding how connected vehicles will affect the future of transportation, as well as what it means to implement or support a CV application from the perspective of a road authority.

3.2.1 Application Categories

Connected vehicle applications come in four primary categories based on how they connect with the vehicle, the user, a service, or other vehicle and infrastructure systems (Table 3.1). Some of these applications fit into multiple categories, but each is primarily associated with one. For example, navigation applications can use in-vehicle connectivity linking a transponder to the vehicle's on-board display, but this functionality is secondary to its interaction with the end user. Therefore, we classify navigation applications in the "Drivers and Passengers" category.

Table 3.1 Typology of Connected Vehicle Applications based on type of interaction.

Category	Description	Examples
In-Vehicle	Applications that involve interactions between different components within the vehicle.	Diagnostics, predictive maintenance, and safety applications.
Drivers and Passengers	Applications that involve interactions with a user within the vehicle.	Entertainment, navigation, personal device integration, and remote control.
Third-party Services	Applications that facilitate transactions with third parties using the vehicle.	In-car payment services, roadside assistance, insurance, and more.
Infrastructure and Other Vehicles	Applications that primarily operate through interactions with other vehicles and connected infrastructure.	Crash response, adaptive traffic lights, and emergency vehicle warnings.

US-wide Survey Results of Driver Interest in Automation Technologies

Technology	Not Interested	Slightly Interested	Very Interested
Electronic stability control	29%	42%	29%
Lane centering	38%	39%	23%
Left-turn assistance	47%	35%	18%
Cross traffic sensor	32%	39%	29%
Adaptive headlights	35%	40%	26%
Pedestrian detection	31%	37%	31%
Adaptive cruise control	32%	37%	31%
Blind-spot monitoring	17%	32%	51%
Traffic sign recognition	53%	30%	17%
Emergency auto braking	23%	31%	46%
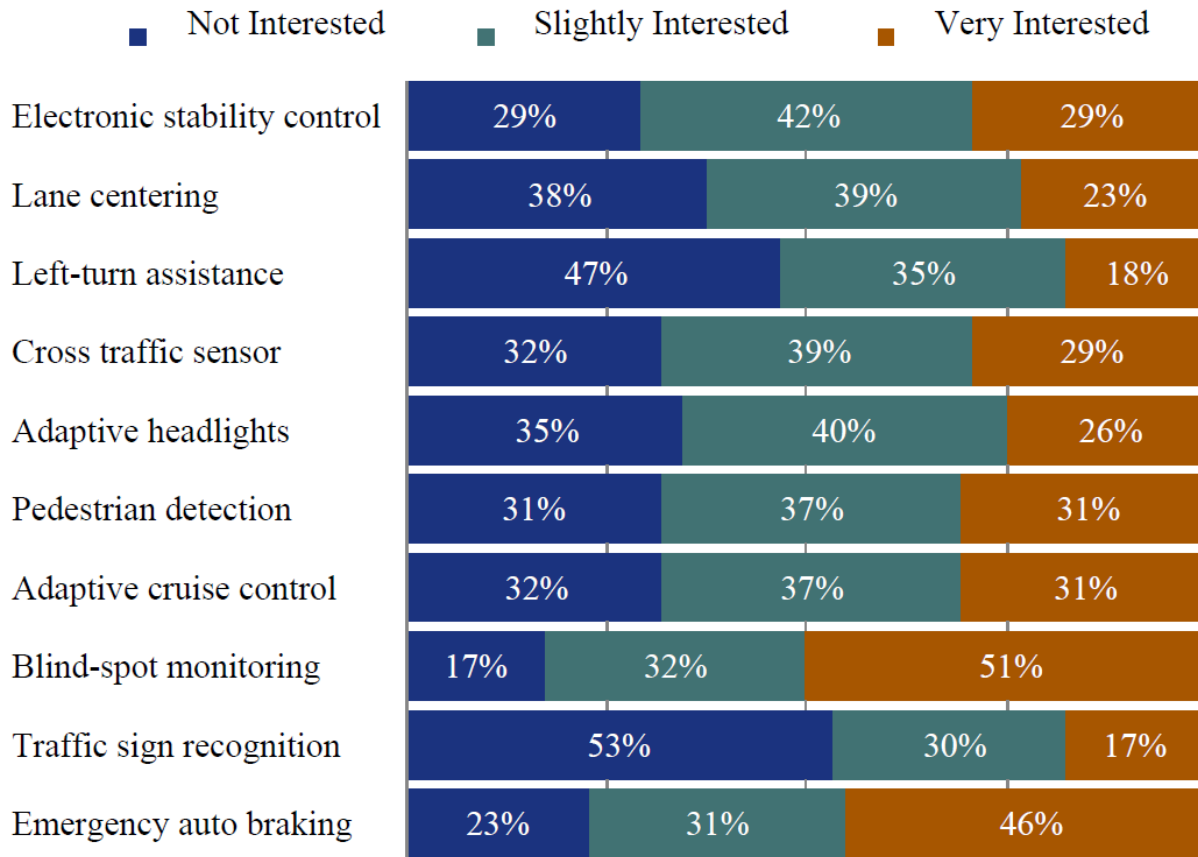
Figure 3.3 Interest in automation technologies (Texas Survey [3])

3.2.2 Level 0 Technologies Group 1

Applications in this group are Level 0 Automation Technologies, providing no automated control of the vehicle but additional warnings and other information to help the driver. The Level 0 Group 1 technologies are distinguished from the Level 0 Group 2 technologies (Section 3.2.3) in that they do not require any involvement from infrastructure, depending only on the vehicle's sensors or communication with other vehicles.

3.2.2.1 Forward Collision Warning

NHTSA defines a *Forward Collision Warning* (FCW) system as "one intended to passively assist the driver in avoiding or mitigating a rear-end collision via presentation of audible, visual, and/or haptic alerts, or any combination thereof." An FCW system has forward-looking vehicle detection capability, using sensing technologies such as cameras, radar, and Lidar. Sensor data are processed and analyzed, and alerts are provided if a collision with another vehicle is imminent [4, 5, 6].

3.2.2.2 Blind Spot Monitoring

There are two different types of *blind spot monitoring* (BSM): active and passive. An active BSM generally uses radar or a camera to detect when another vehicle gets close to the BSM equipped vehicle. If any such vehicles are detected, the BSM-equipped vehicle will notify its driver. The type of notification can depend on how likely it is that two vehicles will collide; as the likelihood of collision increases, so does the magnitude of the warning that the driver receives. The other type of BSM is the passive, which involves only additional mirrors. Car manufacturers offer the choice to have a special small convex mirror added in the corner of the regular rearview mirror, which can provide additional visual access to the blind spot [7, 4, 5, 6].

3.2.2.3 Lane Departure Warning

Lane Departure Warning (LDW) is similar to BSM. The system detects the approaching vehicles' speed and distance from neighboring lanes and warns the driver of potential danger if the driver wants to change lanes. A lane departure warning system can also warn the driver if it detects that the car is leaving its current lane. It is anticipated that in the future, the system will incorporate features such as monitoring the driver's eye activities to determine drowsiness [8].

3.2.2.4 Traffic Sign Recognition

Traffic Sign Recognition (TSR) is a technology capable of identifying and displaying upcoming traffic signs that may be missed by drivers. A typical system functions using a camera to detect oncoming traffic signs, a recognition system that identifies the meaning of the signs recorded by the camera through image processing, and a display pane. The road sign information can be displayed either on the vehicle's instrument panel cluster or on the driver's navigation system screen. TSR systems' reliability, especially at high speeds, depends on the camera's image resolution. In a natural environment, TSR may encounter three main challenges, namely poor lighting and visibility, the presence of other objects, and variation of traffic and road signs.

The first TSR systems were developed by Mobileye (a technology company that develops vision-based advanced driver assistance systems) in 2007 and have been available since 2008 on the BMW 7 Series as a dual vision and satellite navigation system. Honda also released its advanced driver assistive system called "Honda SENSING" in late 2014 [9]. According to Mobileye, TSR systems have been developed with high detection accuracy and may have additional information from digital maps and navigation systems [10]. TSR systems can also function in conjunction with other Mobileye technologies, including lane-centering technology, intelligent headlight control, and other systems that use visual sensors.

3.2.2.5 Left-Turn Assist

Left-Turn Assist (LTA) systems use a camera and GPS to warn drivers against attempting a left turn into an intersection where the conditions are unsafe. The LTA is designed to work at very low speeds, less than

10 km/hour (roughly 6 mph). LTA was first mass publicized by BMW in 2011 and further research is currently being conducted on utilizing V2V communication [4, 5, 6].

3.2.2.6 Emergency Electronic Brake Lights

Emergency Electronic Break Lights (EEBL) is an application where the driver is alerted to hard braking in the traffic stream ahead. This provides the driver with additional time to look for, and assess situations developing ahead [4, 5, 6].

3.2.2.7 Do Not Pass Warning

Do Not Pass Warning (DNPW) is an application where alerts are given to drivers to help avoid a head-on crash resulting from passing maneuvers [4, 5, 6].

3.2.2.8 Vehicle Turning Right in Front of Bus Warning

Vehicle Turning Right in Front of Bus Warning is an application that warns transit bus operators of the presence of vehicles attempting to go around the bus to make a right turn as the bus departs from a bus stop [11, 12, 13].

3.2.3 Level 0 Technologies Group 2

The applications in this group are also Level 0 Automation Technologies, but require information from connected infrastructure (V2I/I2V communication) in order to work properly.

3.2.3.1 Cooperative Intersection Collision Avoidance System

Cooperative Intersection Collision Avoidance System (CICAS) is a V2I strategy that is designed to reduce the frequency of collisions that occur at both signalized and stop-controlled intersections. Intersections that are equipped with CICAS technology warn vehicles via DSRC signal communications of an impending collision. There are several CICAS technologies that research centers are currently looking into. Because of the frequency of crashes that occur at roadway intersections, implementing CICAS can potentially reduce the amount of fatalities, injuries, and property damage occurring each year on roadways.

These CICAS technologies have largely focused on improving safety of vehicle passengers at controlled intersections, but other applications include preventing fatalities and injuries caused by vehicles contacting pedestrians. The primary three CICAS technologies that address intersection safety are *Red Light Violation Warning, Stop Sign Gap Assist*, and *Stop Sign Violation Warning*.

3.2.3.1.1 Red Light Violation Warning

A *Red Light Violation Warning* (RLVW) system's primary purpose is to alert CVs or AVs that a current trajectory will result in running a red light, thus allowing the CV's driver or the AV itself to take preventive action. The vehicle that receives this data can pass this information to other AVs equipped with V2V tech

so that those vehicles can make the proper adjustments as well. Figure 3.4 shows the visual configuration of RLVW at a typical intersection. The CAVs would receive the warning from the installed RSE, which, in the case of an RLVW application, would broadcast the traffic signal phase and timing information. The AV uses the information from that device to determine whether it will violate the red light [14]. The CAV can then adjust its speed to ensure that it will not run the light. This information will also be broadcast to other vehicles using V2V technology so they may prepare to take evasive action should the vehicle violate the red light.
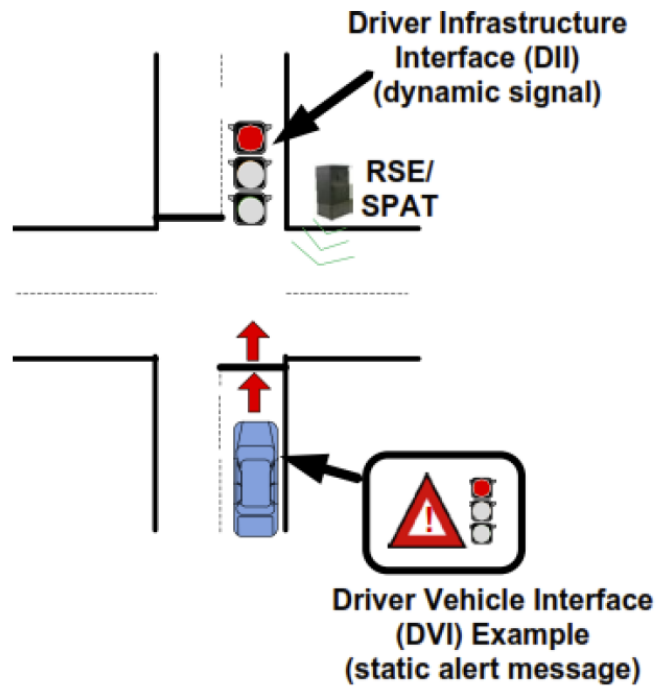
Figure 3.4 Red Light Violation Warning Configuration [14].

3.2.3.1.2 Stop Sign Gap Assist

A V2I strategy that helps improve safety at stop-controlled intersections is *Stop Sign Gap Assist* (SSGA). The goal of SSGA is to help vehicles determine if there is a satisfactory time gap for the vehicle to make a left turn, thru-movement, or right turn at an intersection. An RSE emits information about cross-traffic to approaching vehicles, and the AV can determine whether it needs to stop or if it can enter the intersection safely using this information. A simple SSGA installation is shown in Figure 3.5 [15, 16, 17]. SSGA addresses two pre-crash scenarios: Left Turn Across Path/Opposite Direction (LTAP/OD) at Non-Signalized Junctions and Straight Crossing Paths at Non-Signalized Junctions.
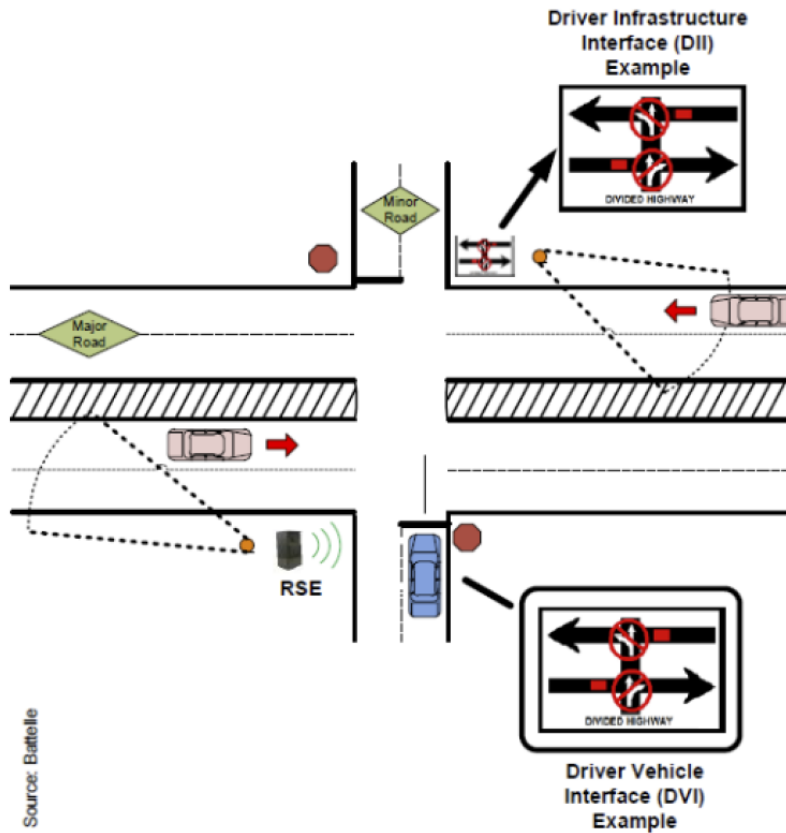
Figure 3.5 Stop Sign Gap Assist Configuration

3.2.3.1.3 Stop Sign Violation Warning

The RLVW equivalent for stop-controlled intersections is *Stop Sign Violation Warning* (SSVW). This safety application helps CAVs approaching the intersection avoid crashes that result from running a stop sign. This strategy is set up similarly to the configuration depicted in Figure 3.4 for RLVW (with the exclusion of the traffic signal). AVs approaching the intersection would receive notification of the stop sign from the roadside device and determine whether it is at risk of running the stop sign, which will allow the AV to make the proper speed change. This information would also be communicated to approaching vehicles downstream using V2V technology. [15, 17, 18]

3.2.3.2 Curve Speed Warning

Curve Speed Warning (CSW) is an application where alerts are provided to the driver who is approaching a curve at a speed that may be too high for safe travel through that curve [15, 16, 19].

3.2.3.3 Oversize Vehicle Warning

Oversize Vehicle Warning (OSW) is an application that alerts drivers if their vehicle cannot clear a bridge or tunnel [15, 17, 18].

3.2.3.4 Reduced Speed/Work Zone Warning

Reduced Speed/Work Zone Warning (RSWZ) is an application that utilizes roadside equipment to broadcast alerts to drivers warning them to reduce speed, change lanes, or come to a stop within work zones [15, 17, 18, 20].

3.2.3.5 Pedestrian in Signalized Crosswalk Warning (Transit)

Pedestrian in Signalized Crosswalk Warning (Transit) is a transit-specific application that warns bus operators when pedestrians, within the crosswalk of a signalized intersection, are in the intended path of the bus [15, 18, 10, 21, 22, 23].

3.2.3.6 Railroad Crossing Warning

Railroad Crossing Warning (RCW) is an application that alerts drivers who are approaching an at-grade railroad crossing if they are on a trajectory to collide with a crossing or approaching train [15, 17].

3.2.3.7 Restricted Lane Warning

Restricted Lane Warning (RLW) is an application that provides drivers with travel lane restriction information (e.g., high occupancy vehicles, transit only, or public safety vehicles only) [15, 17, 18].

3.2.3.8 Smart Roadside—Smart Truck

Smart Roadside – Smart Truck is an application that provides information such as hours of service constraints, location and supply of parking, travel conditions, and loading/unloading scheduling to allow commercial drivers to make advanced route planning decisions [18, 24, 25, 26, 27, 28, 29, 30, 31].

3.2.3.9 Spot Weather Impact Warning

Spot Weather Impact Warning (SWIW) is an application that warns drivers of local hazardous weather conditions by relaying weather data from a management center and other sources to roadside equipment, which then re-broadcasts the data to nearby vehicles [15, 18, 19, 17, 20].

3.2.3.10 Warnings about Hazards in a Work Zone

Warnings about Hazards in a Work Zone is an application that provides warnings to maintenance personnel within a work zone about potential hazards (e.g., a vehicle traveling at a high speed or entering the work zone) [15, 17, 18].

3.2.3.11 Warnings about Upcoming Work Zone

Warnings about Upcoming Work Zone is an application that provides approaching vehicles with information about work zone activities, such as travel lane obstructions, lane closures, lane shifts, speed reductions, or vehicles entering/exiting the work zone [15, 17, 18].

3.2.3.12 Eco-Approach and Departure at Signalized Intersections

Eco-Approach and Departure at Signalized Intersections is a V2I application where intersection traffic signals broadcast the current state of signal phasing (red, yellow, or green) and time remaining in that phase (SPaT). These data are used by connected vehicles to support eco-friendly speed trajectories as vehicles approach and depart from a signalized intersection.

Figure 3.6 Audi Traffic Signal Information Display

An implementation of this application has already been developed by emulating communication of the information included in SPaT and MAP messages by a private provider over a cellular connection. Figure 3.6 shows the view of the system included in selected vehicles by Audi [32]. Other vehicle manufacturers have also implemented similar solutions. Traffic Signal information can vary from historical to real-time depending the availability of this information by the Signal owner agency. Companies like Connected Signals, Traffic Technology Services [33] (which has partnered with Siemens to provide this service as a feature in Siemens controllers), Inrix, and Live Traffic Data have developed solutions that include hardware to be placed in the cabinet or Traffic Management Center (TMC) snooping on the communication between the controller and the center or even the signal heads.

3.2.4 Level 0 Technologies for System Level Benefit

3.2.4.1 Transit/Freight Signal Priority or Eco-Transit/Freight Signal Priority

In the case of *Transit/Freight Signal Priority*, this proposed application allows agencies to manage bus service by adding the capability to grant buses priority based on a number of factors. The proposed application provides the ability for transit vehicles to communicate passenger count data, service type, scheduled and actual arrival time, and heading information to roadside equipment via an on-board device. For freight, a similar goal can be achieved near freight facilities based on current and projected freight movements. The goal is to reduce delays and increase travel time reliability for freight traffic, while enhancing safety at key intersections.

Eco-Transit/Freight Signal Priority is an application version that allows transit or freight vehicles approaching a signalized intersection to request signal priority, works as above but priority decisions are optimized for the environment by considering vehicle type, etc.

3.2.4.2 Intelligent Traffic Signal System

Using high-fidelity data collected from vehicles through V2V and V2I wireless communications as well as pedestrian and non-motorized travelers, the *Intelligent Traffic Signal System* (ISIG) application seeks to control signals and maximize flows in real time. The ISIG application also plays the role of an overarching system optimization application, accommodating transit or freight signal priority, preemption, and pedestrian movements to maximize overall network performance.

3.2.4.3 Smart Roadside—Wireless Inspection

Smart Roadside—Wireless Inspection is an application that uses roadside sensors to provide identification, hours of service, and sensor data directly from trucks to carriers and government agencies [18, 24, 25, 26, 27, 28, 29, 30, 31].

3.2.4.4 Connected Eco-Driving

Connected Eco-Driving is an application that uses V2I and V2V data to provide customized real-time driving advice to drivers, including recommended driving speeds and optimal acceleration/deceleration profiles, so that drivers can adjust their driving behavior to save fuel and reduce emissions.

3.2.4.5 Work Zone Traveler Information

Work Zone Traveler Information is an application that monitors and aggregates work zone traffic data.

3.2.4.6 Intelligent Network Flow Optimization (INFLO)

Advancing applications for *Intelligent Network Flow Optimization* (INFLO) can offer important system-wide benefits to traffic flow and safety. The INFLO [34] bundle consists of applications related to queue warning, speed harmonization, and cooperative, adaptive cruise control. Current practices for queue detection and warning and speed harmonization are fundamentally limited by their exclusive reliance upon infrastructure- based detection and warning. This imposes a number of limitations on the system, affecting its ability to:

- Locate and distribute queue warnings sufficiently along a facility and ensure that generated warnings are received by drivers
- Obtain sufficient traffic and road weather data to be able to produce accurate warnings
- Operate for sufficient periods in the day to provide warnings whenever queues occur
- Target appropriate speed recommendations to specific portions of the facility and ensure that generated speed recommendations are received by drivers

- Obtain sufficient traffic and road weather data to be able to produce accurate speed recommendations
- Operate for sufficient periods in the day to provide speed guidance whenever the need may arise.

In addition, cooperative adaptive cruise control is reliant upon yet-to-be-deployed connected vehicle technologies.

A connected vehicle system that is both vehicle- and infrastructure-based has the potential to provide a broader and more dynamic set of data and data exchange that will support the INFLO applications in a manner that will addresses today's limitations.

The three applications that comprise INFLO include *Queue Warning*, *Dynamic Speed Harmonization*, and *Cooperative Adaptive Cruise Control*. These applications are each discussed separately in the following sections.

3.2.4.6.1 Queue Warning

The objective of *Queue Warning* (Q-WARN) is to provide a vehicle operator with sufficient warning of an impending queue backup in order to brake safely, change lanes, or modify the route such that secondary collisions can be minimized or even eliminated. It is distinct from collision warning, which pertains to events or conditions that require immediate or emergency actions. Queue warnings are provided in order to reduce the likelihood of the formation of such emergency events.

A queue backup can occur due to a number of conditions, including:

- Daily recurring congestion caused by bottlenecks
- Work zones, which typically cause bottlenecks
- Incidents, which, depending on traffic flow, lead to bottlenecks
- Weather conditions, including icing, low visibility, sun angles, and high wind
- Exit ramp spillovers onto freeways due to surface street traffic conditions

In all cases, queuing is a result of significant downstream speed reductions or stopped traffic and can occur with freeways, arterials, and rural roads. Queuing conditions present significant safety concerns; in particular, the increased potential for rear-end collisions. They also present disruptions to traffic throughput by introducing shockwaves into the upstream traffic flow. A queue warning system will be successful at minimizing secondary collisions and the resulting traffic flow shockwaves by being able to: rapidly detect the location, duration, and length of a queue propagation; formulate an appropriate response plan for approaching vehicles; and disseminate such information to the approaching vehicles readily and in an actionable manner.

The *INFLO Q-WARN* application concept aims to minimize the occurrence and impact of traffic queues by using connected vehicle technologies, including V2I and V2V communications, to enable vehicles within the queue event to automatically broadcast their queued status information (e.g., rapid deceleration, disabled status, lane location) to nearby upstream vehicles and to infrastructure-based central entities

(such as the TMC). The conceptual Q-WARN application performs two essential tasks: queue determination (detection and/or prediction) and queue information dissemination. In order to perform these tasks, Q-WARN solutions can be vehicle-based or infrastructure-based or utilize a combination of each.

It is important to note that the Q-WARN application concept is not intended to operate as a crash avoidance system (e.g., like the FCW safety application). In contrast to such systems, Q-WARN will engage well in advance of any potential crash situation, providing messages and information to the driver in order to minimize the likelihood of his needing to take crash avoidance or mitigation actions later. As such, Q-WARN-related driver communication will always give priority to crash avoidance/mitigation safety applications when such applications determine that a safety-related warning is necessary.

3.2.4.6.2 Dynamic Speed Harmonization

The objective of *Dynamic Speed Harmonization* (SPD-HARM) is to dynamically adjust and coordinate maximum appropriate vehicle speeds in response to downstream congestion, incidents, and weather or road conditions in order to maximize traffic throughput and reduce crashes. A dynamic SPD-HARM system will be successful at managing upstream traffic flow by being able to: reliably detect the location, type, and intensity of downstream congestion (or other relevant) conditions; formulate an appropriate response plan (i.e., vehicle speed and/or lane recommendations) for approaching vehicles; and disseminate such information to upstream vehicles readily and in a manner which achieves an effective rate of compliance. Improved safety results, in terms of reduced crash rates and less severe crashes, have shown to be the most significant and consistent achievements across deployments that exist today at some level. In addition, SPD-HARM techniques promote reduced vehicle speeds and speed variance, especially in unsafe driving conditions; support modest improvements in throughput; and have a moderately positive impact on travel time reliability. There are three key factors that contribute to the operation of an effective speed harmonization system. The first factor is the availability of information on the prevailing condition on the field. The second factor is the existence of a reliable strategy for the speed limit selection. The last factor is the flow of information from the field to decision making center and vice versa.

Research and experimental evidence has consistently demonstrated that by reducing speed variability among vehicles, especially in near-onset flow breakdown conditions, traffic throughput is improved, flow breakdown formation is delayed or even eliminated, and collisions and severity of collisions are reduced. The INFLO SPD-HARM application concept aims to realize these benefits by utilizing connected vehicle V2V and V2I communication to detect the precipitating roadway or congestion conditions that might necessitate speed harmonization, to generate the appropriate response plans and speed recommendation strategies for upstream traffic, and to broadcast such recommendations to the affected vehicles.

3.2.4.6.3 Cooperative Adaptive Cruise Control

The objective of *Cooperative Adaptive Cruise Control* (CACC) is to dynamically and automatically coordinate cruise control speeds among platooning vehicles in order to significantly increase traffic throughput. By tightly coordinating in-platoon vehicle movements, headways among vehicles can be significantly reduced, resulting in a smoothing of traffic flow and an improvement in traffic flow stability. Additionally, by reducing drag, shorter headways can result in improved fuel economy providing the environmental benefits of lowered energy consumption and reduced greenhouse gas emissions.

The CACC operational concept represents an evolutionary advancement of conventional cruise control (CCC) systems and adaptive cruise control (ACC) systems by utilizing V2V and V2I communication to automatically synchronize the movements of many vehicles within a platoon. As with SPD-HARM and Q-WARN, CACC- related driver communication will always give priority to crash avoidance/mitigation safety applications when such applications determine that a safety-related warning is necessary.

3.2.4.6.4 Interaction of INFLO Applications

Because the INFLO applications are so closely linked, the effectiveness of each can be improved by taking advantage of the benefits to traffic flow and safety that the others provide. In fact, research-to-date has shown that the most successful implementations have been those that combine multiple different freeway management control applications. For example, SPD-HARM benefits Q-WARN by slowing and managing upstream traffic, thus reducing the risk of secondary collisions. CACC benefits SPD-HARM by providing a mechanism for harmonizing traffic flow and reducing or mitigating acceleration variability. Q-WARN benefits CACC by providing the platoon sufficient notification of an impending queue to effectively manage a response.

Importantly, SPD-HARM and Q-WARN are technologies that can be implemented in the near-term. Their benefits are optimized when implemented as infrastructure-based applications that reside at a central entity such as a Traffic Management Center (TMC) as the TMC system has broader visibility into the traffic state, allowing operators to implement a more proactive approach for predicting queues and congestion.

In addition to the benefits of deploying the three bundled INFLO mobility applications in concert, the applications would also benefit from integrating with other applications, including safety systems like *electronic stability control* (ESC) systems, night vision systems, curve speed warning systems, lane departure warning systems, alcohol monitoring systems, brake assist systems, steering assist systems, FCW systems, and pre-crash sensing systems. Coordination with ramp metering systems would also help provide the INFLO applications a better connection with the overall transportation network. Finally, integrating the INFLO applications with Advanced Traveler Information Systems (ATIS) would provide road users enhanced information about the state of the transportation system, pre-trip planning, route-making, and incident avoidance.

3.2.4.7 Probe-based Pavement Maintenance

Probe-based Pavement Maintenance is an application that allows vehicle to automatically report potholes or other pavement anomalies to the road authority.

3.2.4.8 Probe-enabled Traffic Monitoring

Probe-enabled Traffic Monitoring an application that utilizes communication technology to transmit real time traffic data between vehicles and infrastructure.

3.2.4.9 Vehicle Classification-based Traffic Studies

Vehicle Classification-based Traffic Studies is an application that would allow sorting of vehicle behavior data by vehicle type for performing traffic studies.

3.2.4.10 CV-enabled Turning Movement & Intersection Analysis

CV-enabled Turning Movement & Intersection Analysis is an application that uses paths self-reported by vehicles to track turning ratios, delay, and other intersection metrics.

3.2.4.11 CV-enabled Origin-Destination Studies

CV-enabled Origin-Destination Studies is an application that uses connected vehicle technology to monitor the beginning and end points of a vehicle's journey and extrapolate the route in between.

3.2.5 Level 1 Technologies

The following applications are Level 1 Automation technologies, providing automated control of the vehicle either longitudinally (acceleration/braking) or laterally (steering), but not both simultaneously.

3.2.5.1 Adaptive Cruise Control

Adaptive Cruise Control (ACC) systems allow vehicles to maintain a constant speed under operation, just as a conventional cruise control system would. However, when approaching a slower moving vehicle, drivers with a conventional cruise control system must respond by braking and slowing down to adjust their speed to the vehicle ahead. In contrast, an ACC system is able to address this concern by detecting the speed of the leading vehicle and adjusting its own speed accordingly. In ACC, the system maintains a comfortable and safe distance between itself and the leading vehicle. Once the space ahead is clear again, the ACC will accelerate the vehicle back to the desired cruising speed. Currently, most ACC systems use radar or laser (less popular) headway sensors and a digital signal processor to determine the distance and speed of the vehicle ahead [35]. Sensor information is transmitted to a central controller, which reads the desired settings of the driver. The central controller also controls the engine and/or braking system to respond appropriately.

ACC systems were first introduced into the consumer market in the early 2000s [36]. Early systems deployed both lasers and radars on vehicles, but radars are more popular because they function better in inclement weather. Nevertheless, an ACC's abilities are still limited by heavy rain and snow and will shut off under severe weather conditions. While many automobile manufacturers still do not include ACC systems as a standard feature, the technology is offered in many luxury models. ACC systems currently range in price from $500 to $2,500 [37]. ACC systems are expected to further integrate with crash detection systems and other V2V communication technology.

3.2.5.2 Cooperative Adaptive Cruise Control

CACC, also discussed in Section 3.2.4.6.3 , works by having leading vehicles send messages via V2V communication to following vehicles that give a recommended speed and (in some cases) lane assignment. After the following vehicle receives the message, the driver will usually not need to take any action because the vehicle will respond appropriately on its own. With CACC, drivers still need to supervise the vehicles closely. As such, CACC is a driver assistance function, and drivers are still fully responsible for the driving.

There are two main objectives of CACC technology, as discussed below. There is no industry-wide consensus on which of the two benefits is more important. The first objective is improving driver comfort. By allowing a CACC vehicle to adjust speeds (and possibly, though rarely, lanes) without the need for driver interference, a driver will feel much more comfortable. This will allow drivers to focus on keeping the vehicle safe [38]. Another objective of CACC is to greatly increase highway throughput by allowing closer headway between vehicles that are both CACC-equipped. This is possible because the brake reaction time (BRT) of a CACC vehicle following another CACC vehicle is only 0.1 seconds. This is almost five times less than the fastest human BRT, which is 0.47 seconds. In addition, throughput will increase, given that any change ahead due to braking, hazards, etc., can be immediately relayed to following vehicles, preventing abrupt slowdowns or stops [39].

There are some limitations with CACC. Reduced time gaps between two vehicles can only occur when both vehicles have CACC technology. Therefore, the impact of CACC relies heavily on market penetration. One study found that CACC technology needs to have at least 40% market penetration to have any considerable impact [39].

3.2.5.3 Automatic Emergency Braking

Also known as forward collision avoidance, *Automatic Emergency Braking (AEB)* has the potential to significantly decrease collisions by automatically braking a vehicle when an imminent collision is foreseen. AEB systems are made up of sensors that observe and categorize objects within range, control systems to process the data produced by the sensors, and an automatic braking actuation system to physically stop or slow the vehicle. To assess the impacts of AEB, Doecke et al. analyzed and recorded data that included vehicle trajectories, speeds, braking location, and impact locations from 103 real-world crashes [40]. This study showed that AEB technologies are capable of reducing the impact speed of unavoidable crashes, as well as preventing some crashes altogether. They also estimated that the baseline system was able to

prevent 54% of all unobscured pedestrian crashes, 63% of all rear end crashes, and 22% of all straight crashes on fixed objects. These results strongly indicate that by application of a baseline AEB system, the number of crashes involving visible pedestrians, rear end collisions, and objects struck head on would decrease significantly. Results also showed that a reduced impact speed for unavoidable accidents would be accomplished for many other collisions.

A major complication with the current AEB design is its inability to differentiate between an actual impending collision and a false alarm. However, this issue may possibly be resolved as more advanced AEB technologies continue to emerge.

An exclusion added to SAE Standard J3016 now lists AEB as an exclusion from Level 1, instead calling it Level 0. Their reasoning is as follows:

> "Active safety systems, such as electronic stability control and automated emergency braking, and certain types of driver assistance systems, such as lane keeping assistance, are excluded from the scope of this driving automation taxonomy because they do not perform part or all of the DDT on a sustained basis and, rather, merely provide momentary intervention during potentially hazardous situations. Due to the momentary nature of the actions of active safety systems, their intervention does not change or eliminate the role of the driver in performing part or all of the DDT, and thus are not considered to be driving automation [60]."

3.2.5.4 Lane-Keeping

Lane-Centering and *Lane-Keeping* technologies are used to keep automobiles from drifting out of a lane on high-speed roads. The system is designed to function as a safety tool rather than a fully hands-free driving mechanism. With lane-centering, the adapted system uses electronically controlled steering to maintain a center position in the lane. The technology uses a camera mounted on a vehicle's windshield to watch the lane markers on the road; the camera is able to recognize both yellow and white lines. If the camera detects that the driver is beginning to drift out of a lane without the use of a turn signal, the device will alert the diver with a warning sound, and then activate the electronic power steering control to steer the vehicle back into the center of the lane [41]. Electronic steering is a safety device that may be overridden by the driver.

There are several limitations to current lane-centering technology. The cameras use visible light and require clear lane markings in order to function. Inclement weather and reduced visibility in low-light conditions are also major concerns. In addition, many systems have a minimum speed requirement.

Note that the exclusion clause to SAE Standard J3016 referenced in 3.2.5.3 applies to Lane-Centering as well as AEB.

3.2.6 Level 2 Technologies

Compared to the Level 0 and Level 1 systems, Level 2 and Level 3 systems place greater control and decision making on the vehicle's automated components. This section describes major Level 2

technologies, which provides combined automated functions (e.g. simultaneous acceleration and steering) but still require the driver to be engaged with driving and monitoring the environment at all times.

3.2.6.1 Traffic Jam Assist

Traffic Jam Assist (TJA) functions on limited access highways at slow speeds [42]. This system provides full control of driving in congested conditions. Under these two conditions, primary lateral and longitudinal controls are ceded by the driver. The driver will have direct supervision of the vehicle during this process, will receive continuous system feedback, and is still responsible for the overall operation of the vehicle. The Mercedes S-Class features a representative TJA system. The driver is expected to be engaged in driving with TJA, with hands on the steering wheel. If the system detects that the driver is not touching the steering wheel, a warning will be issued and the TJA function will be disabled after a few seconds. The European HAVEit project (Highly Automated Vehicles for Intelligent Transport) —designed to "develop technical systems and solutions that improve automotive safety and efficiency" [43] — demonstrated this concept on heavy trucks.

3.2.6.2 High Speed Automation

High Speed Automation (HSA) is being tested by several car manufacturers. General Motors has described a "super cruise" system, with one option providing full speed range ACC in conjunction with lane-keeping. Cameras and radars are used for sensing, and the system can automatically steer, accelerate, and brake in highway driving. Drivers may leave hands off the steering wheel until the driver wants to change lanes or when the system can no longer handle deteriorating road conditions, or when an unexpected issue occurs. Other car manufacturers developing similar products include Honda (Europe), Infiniti, Audi, and BMW. Infiniti's system automatically reduces the discrepancies between the intended and actual path, and claims to reduce driver fatigue by reducing fine-grained steering adjustments. BMW's system not only provides lateral and longitudinal control, but also responds to merging traffic from the right and can perform a lane change when safe. Google's driverless cars can operate up to 75 mph on highways in this mode. Google's car combines ACC and lane-keeping, but does not change lanes automatically.

3.2.6.3 Automated Assistance in Roadwork and Congestion

One system demonstrated in Europe's HAVEit project was *Automated Assistance in Roadwork and Congestion*. This system aims to enable automated driving through a work zone, so as to support the driver in overload situations like driving in narrow lanes [43]. It considers the possibility that lane lines are not accurate, and it uses other objects, such as trucks, beacons, and guide walls, for guidance.

3.2.7 Level 3 Technologies

In Level 3, direct supervision by drivers is not needed in conventional situations. When the driver is required to resume control, these technologies allow sufficient transition time. This section outlines some specific Level 3 technologies.

3.2.7.1 On-Highway Platooning

In an *On-Highway Platoon*, vehicles can have a shorter headway between each other. This technology allows a human to drive the lead vehicle, followed closely by fully AVs in platoon formation. A prototype of this technology was developed in Europe's SARTRE project (Safe Road Trains for the Environment) using Volvo cars and trucks. PATH has demonstrated this technology in California as well.

3.2.8 Safety Benefits from Connected Vehicles

The applications presented above are envisioned to help prevent the occurrence of many common crashes by allowing the vehicle to react to dangerous situations before a human would be capable of doing so. To help outline this, Table 3.2 presents a mapping of various pre-crash scenarios to the application(s) that are expected to prevent the associated crashes.

Table 3.2 Mapping pre-crash scenarios to CAV technologies based on 2013 GES

No.	Pre-Crash Scenario	Mapping Safety Applications
1	Vehicle failure	CLW
2	Control loss with prior vehicle action	
3	Control loss without prior vehicle action	
4	Running red light	CICAS
5	Running stop sign	
6	Road edge departure with prior vehicle maneuver	RDCW & LKA
7	Road edge departure without prior vehicle maneuver	
8	Road edge departure while backing up	
9	Animal crash with prior vehicle maneuver	AEB & ESC
10	Animal crash without prior vehicle maneuver	
11	Pedestrian crash with prior vehicle maneuver	V2P
12	Pedestrian crash without prior vehicle maneuver	
13	Pedalcyclist crash with prior vehicle maneuver	V2Ped
14	Pedalcyclist crash without prior vehicle maneuver	
15	Backing up into another vehicle	BCI
16	Vehicle(s) turning – same direction	BSW & LCW
17	Vehicle(s) changing lanes – same direction	
18	Vehicle(s) drifting – same direction	
19	Vehicle(s) parking – same direction	SPVS
20	Vehicle(s) making a maneuver – opposite direction	DNPW
21	Vehicle(s) not making a maneuver – opposite direction	
22	Following vehicle making a maneuver	FCW & CACC
23	Lead vehicle accelerating	
24	Lead vehicle moving at lower constant speed	
25	Lead vehicle decelerating	
26	Lead vehicle stopped	
27	LTAP/OD at signalized junctions	CICAS
28	Vehicle turning right at signalized junctions	
29	LTAP/OD at non-signalized junctions	
30	Straight crossing paths at non-signalized junctions	
31	Vehicle(s) turning at non-signalized junctions	
32	Evasive action with prior vehicle maneuver	AEB & ESC
33	Evasive action without prior vehicle maneuver	
34	Non-collision incident	None
35	Object crash with prior vehicle maneuver	AEB & ESC
36	Object crash without prior vehicle maneuver	
37	Other	Combined Impacts of Safety Applications

CHAPTER 4: CONNECTED VEHICLE SYSTEMS AND HARDWARE

From a hardware perspective, there are several important components that are essential to a properly functioning V2X connected vehicle ecosystem. In every case, any CV ecosystem requires the equipment for communication to connect the different actors in the system together. In the current state of the industry, the technology of choice for this is Dedicated Short-Range Communication (DSRC), along with the associated standards for securing and exchanging information on these networks. While there are other communication technologies that have demonstrated potential for use in V2X applications, some of which are operational and some of which are still under development, from the perspective of local road operators DSRC is the most ready technology for deployment in this area (see Section 4.1.2 for more information). Though future developments in the industry may change this, this report will focus on what is necessary to integrate DSRC technology alongside existing infrastructure to achieve CV-readiness based on the hardware currently available on the market.

In addition to communication, a CV ecosystem may require other components depending on the application(s) that are to be supported. This may include traffic signal controllers for applications that involve signalized intersections, application-specific sensors for collecting information that is not already in a digital format, and general processing and/or storage capabilities to process and store data for a variety of purposes. Finally, a DSRC ecosystem also requires backhaul communication to connect Road-Side Equipment (RSE) to the Internet to secure and validate the information transmitted through the system. To help explain where each piece of the system comes into play, this report will first describe in detail the basic requirements of any CV system from an infrastructure perspective, then delve into the additional requirements that are needed to implement various V2I/I2V applications.

It is important to note that a large number of connected vehicle applications are vehicle-to-vehicle applications, and thus do not actually require any external infrastructure. This includes applications like Forward Collision Warning, Automatic Emergency Braking, and Adaptive Cruise Control, among others. While V2V applications are an important part of the connected vehicle ecosystem, with the potential to provide wide-reaching safety benefits in the near future, from the perspective of road operators there is little they need or can do to affect how these applications work, as they only require V2V equipped vehicles. Because of this, this report focuses on the V2I and I2V applications that require actions from road operators to deploy and maintain the infrastructure to make these applications feasible, though an overview of other CAV-related concepts can be found in the Chapter 2.

4.1 CV INFORMATION EXCHANGE

The following sections are largely based on the recently drafted *MnDOT Connected Corridor System Concept of Operations* [44]. The information exchanged between the various entities in the traffic system, i.e. vehicles, infrastructure, operators, traffic information providers, etc., has been codified into several sets of messages for which there are now established industry standards. Specifically, the Society of Automotive Engineers (SAE) is the recognized authority for establishing standards for communication to and from vehicle systems. The National Transportation Communications for ITS Protocol (NTCIP)

establishes standards for communication to and from infrastructure-based ITS devices. A summary of these data standards is provided in Table 4.1.

Table 4.1 ITS standards relating to connected vehicles.

Standard Number and Title	
SAE J2735	Dedicated Short Range Communications (DSRC) Message Set Dictionary
SAE J2945/1	On-Board System Requirements for V2V Safety Communications
SAE J2540/2	International Traveler Information Systems Phrase Lists
NTCIP 1202	National Transportation Communications for ITS Protocol - Object Definitions for Actuated Traffic Signal Controller (ASC) Units
NTCIP 1203	National Transportation Communications for ITS Protocol - Object Definitions for Dynamic Message Signs

4.1.1 Connected Vehicle Message Set (SAE J2735)

This section presents the message set intended to be used by connected vehicles to support the applications discussed in Section 3.2 . While these messages are generally associated with the Dedicated Short-Range Communication (DSRC) protocol that is used as the physical communication layer for transmitting these messages, they are a separate standard that can and would likely be adopted even if another communication protocol, such as 5G Cellular, were to become dominant in the connected vehicle industry.

4.1.1.1 Signal Phase and Timing (SAE J2735 SPaT Message)

The *Signal Phase and Timing* (SPaT) message is used to convey the current status of one or more signalized intersections. Along with the *MapData* (MAP) message (which describes a full geometric layout of an intersection), the receiver of this message can determine the state of the signal phasing and when the next expected phase will occur. The SPaT message uses the same intersection ID that the MAP message uses. For each intersection, the message can provide information for up to 254 signal groups, which relate to signal phases.

The SPaT message contains the current signal state of each approach to an intersection. Additionally, it may optionally include timing details such as the start time of the phase, the min/max end times of the phase, and the best estimate of the end time of the phase. Movements are mapped to specific approaches and connections of ingress to egress lanes are specified. The current signal preemption and priority status values (when present or active) are also sent.

4.1.1.2 Intersection Geometry (SAE J2735 MAP Message)

The MAP message conveys many types of geographic road information. Its primary use is to convey one or more intersection lane geometries within a single message. A given single MAP message may convey descriptions of one or more geographic areas or intersections. The contents of this message involve defining the details of indexing systems that are used in SPaT messages to relate additional information (such as the current signal state) to specific geographic locations on the roadway.

4.1.1.3 Position Correction (SAE J2735 RTCM Corrections Message)

The *Radio Technical Commission for Maritime Services* (RTCM) Corrections message provides differential corrections for GPS and other radio navigation signals. In Minnesota this is handled by the *Minnesota Continuously Operating Reference Station* (MnCORS). The Continuously Operating Reference Station Network is a cooperative effort between MnDOT, other state agencies and institutions, counties, cities and private enterprises with the goal of providing Global Navigation Satellite System (GNSS) corrections state-wide.

4.1.1.4 Location and Motion (SAE J2735 BSM Part I)

The *Basic Safety Message* (BSM) is used in a variety of CV applications to exchange safety data regarding vehicle state. From a vehicle, this message is broadcasted frequently to surrounding vehicles with data content as required by safety and other applications. Part I of the BSM is typically used to support safety-of-life applications through wireless communications. Data contained in this messages includes location (latitude/longitude), elevation, positioning accuracy, transmission state, speed, heading, steering wheel angle, acceleration (lateral, longitudinal, vertical, yaw), brake system status, and the vehicle size. Such data is generally obtained from a GNSS and/or a vehicle data bus. These messages are nominally broadcast from a vehicle at a rate of 10 times per second, when congestion algorithms do not specify a reduced rate (specified in SAE J2945/1). Part 2 of the BSM contains more application specific data that is not transmitted at 10 times per second, but rather as required by application.

4.1.1.5 Traveler Information Message (SAE J2735 TIM)

The *Traveler Information Message* is used to send various types of information (advisory and road sign types) to equipped devices. It makes heavy use of the International Traveler Information Systems (ITIS) encoding system (SAE J2540/2) to send well known phrases, but allows limited text for local place names. The expressed messages are active at a precise start and duration period, and contain an affected local area which can be expressed using either a radius system or a defined region.

4.1.1.6 Signal Priority Request (SAE J2735 SRM)

The *Signal Request Message* is used to request signal priority or preemption. Each request defines a path through the intersection which is desired in terms of lanes and approaches to be used. Each request can also contain the time of arrival and the expected duration of the service.

4.1.1.7 Signal Status Message (SAE J2735 SSM)

The *Signal Status Message* communicates the current status of the signal and the collection of pending or active preemption or priority requests acknowledged by the controller. It also sends information about preemption or priority requests which were denied. The data contained in this message provides a "ranking" among all requestors, as well as to see the currently active requests. Once priority has been executed, the active priority active event is also reflected in the contents of the SPaT message.

4.1.2 Wireless Communication Alternatives

Although for a long time the only method for wirelessly transferring the aforementioned messages was Dedicated Short-Range Communication (DSRC), currently the federal government and other agencies have started to accept other options and acknowledge that there may not be a single technology that will cover all the needs of the CV ecosystem. Table 4.2 lists the currently considered alternatives and hypothesizes regarding future roles for each. The following sections present some important details regarding current state of some of these technologies.

Table 4.2 Overview of wireless communication technologies that may be used by connected vehicles.

V2X Technology	Current Maturity	Likely Evolution
DSRC (Dedicated Short-Range Communications)	5.9 GHz DSRC has been extensively tested in the USDOT's vehicle infrastructure integration (VII) Proof of Concept, Safety Pilot, and other related research projects. However, standards governing this technology remain somewhat in flux. Applicable standards are IEEE 802.11p, IEEE 1609, SAE J2735, and SAE. The low-latency and protected (licensed) spectrum of this technology makes it ideal for safety-critical applications.	The DSRC standards are expected to stabilize over the coming years, and DSRC hardware is expected to have progressed through certification programs. Based on the NHTSA direction, the V2V portions of SAE J2735 and SAE J2945 will be more mature than their V2I counterparts, but the lower-level IEEE standards should be stable. The potential sharing of the DSRC spectrum with unlicensed devices could have an impact on the reliability of CV applications.
Cellular	Cellular technology is mature and the current providers are experienced in the introduction of new generations of technology (e.g., 3G, 4G, 5G, and LTE).	Coming advances in cellular technology will allow it to be used in some of the safety-related applications. The primary challenge with using cellular for CV communications is the network access and data ownership models of private telecom companies.
Satellite	Satellite communication is mature and providers have a broad customer base. Satellite communications can be used to provide service where RSEs (for DSRC) and cellular are not available. The communications is lower-bandwidth and higher-latency than DSRC, and also there are challenges in providing "regional" information.	Satellite service providers are making progress in the CV area. These providers will continue to enhance their capability to provide traveler information to their customer base while collecting data from vehicles.
Wi-Fi	Wi-Fi is a mature, ubiquitous technology, and is cost-effective with high-bandwidth capabilities. Today, Wi-Fi can be used as both a probe and end connection technology. Security considerations are well understood with continually maturing solutions. However, a-priori knowledge of a Wi-Fi network for information dissemination is a challenge. Additionally, Wi-Fi utilizes a "handshake" process to establish communication, which is detrimental in a CV environment.	Wi-Fi access will continue to proliferate and operate in a crowded 2.4GHz /5GHz operating environment. Applications may emerge that use Wi-Fi to implement various V2X interactions (especially connectivity to backhaul systems in areas where traffic may be stopped—e.g., intersection). These apps may minimize a-priori concerns by pre-authorizing network names within the application environment.
Bluetooth and Low-Energy Bluetooth	Bluetooth is another mature, pervasive, and cost-effective technology used for both probe and reception. Bluetooth technology has implemented a number of service-level and device-level security measures, which require authorization and authentication before accepting data, making it a robust platform for communications. Bluetooth standards compliance is exceptionally high.	Future uncertainties over range as manufacturers embrace lower-power radio implementations. Discovery options for Bluetooth may differ for smartphones vs. in-vehicle navigation devices. Bluetooth will continue to operate in the crowded 2.4GHz spectrum.

4.1.2.1 Dedicated Short-Range Communication (DSRC)

The most researched, developed, tested, and understood communication regime is *dedicated short-range communication* (DSRC). In the CV Ecosystem, these are available as *On-Board Units* (OBUs) and *Road-Side Units* (RSUs). Work by FHWA has developed the connections between RSUs and traffic controllers, and ITS/controller companies have developed SPAT products. R&D has been carried out to develop "pseudo BSMs" that broadcast BSMs on behalf of unequipped vehicles present in an intersection. The concept of OBUs and RSUs is at the moment described only in the context of DSRC although there is no reason why the other technologies cannot follow the same paradigm [45].

DSRC is a two-way short-to-medium range wireless communications capability that permits very high data transmission critical in communications-based active safety applications. Such applications require near-instant transmission of data (from one vehicle to another or from the roadside to a vehicle) to alert a driver when immediate action is required to prevent a crash or a potential unsafe maneuver. DSRC can be used to transmit several message types (standardized in SAE J2735 and SAE J2945/1) which enable applications the improve traveler safety and mobility. Another major benefit to DSRC is that it allows devices to communicate directly with each other (as opposed to relying on a network backbone) while ensuring message authenticity and preserving user anonymity.

In 2016, the National Highway Traffic Safety Administration (NHTSA) proposed a rule to "mandate V2V communication" via DSRC on light-duty vehicles, which would also enable V2I communications via DSRC. While this proposed rule has not been mandated, there have been several efforts moving forward using DSRC on light-duty vehicles.

There are currently few places where DSRC communications are used in a live transportation environment, though the number is growing. DSRC is the specified communications technology to be used in CV Pilots projects sponsored by USDOT in New York City (New York), Tampa (Florida), and along Interstate 80 in Wyoming. These projects deploy CV technology in vehicles and on the roadside to support safety and mobility for system users. DSRC is also planned for deployment in Columbus (Ohio), as part of the USDOT Smart Cities Program.

The DSRC spectrum is currently protected for use in ITS systems, though there is uncertainty regarding the future protected status of the DSRC spectrum. Furthermore, there is no timeline for a mandate for vehicles to be DSRC-compatible. DSRC is governed by IEEE 802.11p, IEEE 1609.2, IEEE 1609.3, and IEEE 1609.4 standards. Use of DSRC is necessary to address the SPaT use case (and to support the objectives of the SPaT Challenge, described in Section 4.1), and therefore most use cases to be supported by the system are anticipated to utilize DSRC to avoid deploying duplicate infrastructure or systems, and to illustrate early use cases for DSRC technology.

4.1.2.2 Cellular

There are several different potential types of cellular communications that should be considered when discussing CVs. These include 4G LTE, 5G and C-V2X, discussed below.

4.1.2.2.1 4G LTE

4G LTE is currently one of the most popular methods of transmitting traveler information to travelers. Through in-vehicle systems or smart phones, travelers can receive roadway travel times, information on roadway closures, or real-time transit data. One of the major benefits of 4G LTE is its coverage area, particularly on highly-traveled corridors. However, because communication between devices on a 4G network are routed through fixed-location transceivers, communications latency may become an issue, which can preclude a system network relying on 4G LTE from supporting safety of life applications. Using 4G LTE to transmit messages to vehicles in a specific location would require a backend process for determining which vehicles receive a specific message. Furthermore, since the 4G LTE network is managed through wireless telecommunications providers, a subscription to a mobile data plan is required for individuals to utilize 4G LTE, which may be a barrier of entry for some roadway users.

4.1.2.2.2 5G and C-V2X

Cellular-V2X is an emerging communications technology that allows data to be transmitted from vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-pedestrians (mobile devices), vehicle-to-cloud, and vehicle-to-network (to connect to systems that are accessible via the Internet) [46]. C-V2X utilizes two interfaces: one which allows it to communicate with the network (Uu interface), and one which allows it to directly communicate to other devices independent of the cellular network (PC5 interface). Direct communication between devices utilizes the DSRC spectrum to allow for low-latency communications that supports safety-of-life applications. Communicating with the network requires a SIM card (and associated data plan, similar to 4G), while device-to-device communications does not. C-V2X has a forward compatible evolution path to 5G (the next generation of wireless communications). The major drawback to C-V2X is that it is currently under development.

In 2016, the standard development organization 3rd Generation Partnership Project created initial C-V2X standards, and the technology is already undergoing tests in San Diego, California [47, 48]. Importantly, the safety-related V2V communications (either DSRC or C-V2X) require a relatively small amount of bandwidth, but specialized connections to maintain low-latency at highway speeds, for example.

4.1.2.3 Future Uncertainty

Though 5G and C-V2X are rapidly being developed and deployed by wireless network operators, it is still nonetheless too early to speculate when either will be available for use by connected vehicles. DSRC, by contrast, is ready to be deployed now. In addition to this, the SAE J2735 messages used for connected vehicles to communicate with each other are not attached to any specific wireless communication technology. The CV applications discussed in Section 3.2 also do not depend on any specific communication technologies and would have the same information requirements. Communication hardware would still interface with infrastructure hardware like traffic signal controllers using the same standards such as NTCIP 1202.

For these reasons, local agencies do not need to be especially concerned about the uncertainty in the area of communication technology. Given the potential safety benefits from connected vehicles, agencies can begin deploying connected vehicle hardware as soon as they are ready to do so, as many agencies are currently doing. Agencies that are not in a position to do so, for instance due to lack of funding, can still

prepare for this future by ensuring their equipment is kept up to date while these issues are worked out. Further guidance and recommendations for how agencies can do this will be provided in the coming chapters.

4.1.3 Privacy

The connected vehicle ecosystem is designed with several layers of security and privacy protection to ensure that drivers can rely on messages sent from other vehicles, and that NHTSA and vehicle manufacturers can identify defective V2V equipment without collecting or using any personal information about specific vehicles or drivers. The following directives have been established by the USDOT in regards to privacy:

- The V2X system will not collect or store any personally identifiable information about individuals or vehicles.
- The safety messages exchanged by vehicles cannot be used by law enforcement or private entities to identify a speeding or erratic driver.
- The V2X system will not permit tracking through space or time of specific owners, drivers, or passengers.
- Third parties attempting to use the V2V system to track a vehicle would find it extremely difficult to do so, particularly in light of simpler and cheaper means available for that purpose.
- The V2X system will not collect financial information, personal communications, or personally identifiable information about individuals or vehicles. It will enroll V2V-enabled vehicles automatically, without collecting any information identifying specific vehicles or owners.
- The V2X system will not provide a "pipe" into the vehicle for extracting data. It will enable the National Highway Traffic Safety Administration (NHTSA) and motor vehicle manufacturers to find lots or production runs of potentially defective V2V equipment without use of VIN numbers or other information that could identify specific drivers or vehicles

4.1.4 Security

As detailed in NHTSA's V2V research report [49], NHTSA and industry research partners developed a security system design based on the mature and successfully applied public key infrastructure (PKI). PKI is widely used in our daily lives. Its functionality most familiar to consumers is probably banking and credit card transactions. However, the system envisioned for V2V is unique in that involves machine-to-machine PKI which improves some of the vulnerabilities associated with other PKI systems. The V2V system consists of three primary components:

1. Certificates are needed for messages to be trusted. A Security Credentials Management System (SCMS) is the entity that issues, distributes, and revokes security credentials for devices operating in the system;
2. Devices need to have valid certificates in order to communicate. V2V devices that broadcast and receive DSRC messages, communicate with the SCMS for digital security credentials that provide message authentication; and

3. Occasionally, devices will need to securely receive new certificates via a communications network, which facilitates two-way encrypted communications between an SCMS and a device (and, potentially, roadside infrastructure).

An important finding to date is that the security function is most effectively implemented by a central authority, with regional and local authorities providing systems in a supporting role. This allows for greater consistency of security and reduces the complexity of implementing connected vehicle systems.

4.2 BASIC CONNECTED VEHICLE SYSTEM REQUIREMENTS

This section provides an overview of the basic connected vehicle system requirements that are shared by all applications with an infrastructure component. This includes a radio for wireless communication with vehicles, as well as backhaul communication to connect infrastructure to the Internet and the Security Credential Management System (SCMS) that ensures that communications are secure and trustworthy. In addition to these requirements, this section will also discuss the two main architectural options for deploying connected vehicle infrastructure, which is important to understand when planning for equipment procurement and deployment.

The most critical component for any CV system is a radio, providing the physical means for vehicles to communicate with each other and with infrastructure. The remainder of this report will assume that the technology of choice will be DSRC, as it is currently ready to deploy. However, the role of the DSRC radio could just as easily be replaced by a future operational technology like 5G cellular.

From an infrastructure perspective, meeting the communication requirement means placing DSRC Road-Side Units (RSUs) in locations where infrastructure must communicate with vehicles. This equipment also requires a backhaul communication line to connect it to the Internet, along with access to the Security Credential Management System (SCMS) to ensure communications are secure and trusted.

4.2.1 DSRC Road Side Units

There are several manufacturers of DSRC roadside equipment, the most experienced of which are Savari Networks, Cohda Wireless (closely affiliated with Siemens), and Lear Corporation (recently acquired Arada Systems and close affiliation to SiriusXM). Though more recently there have been some new entrants into the market, such as Wave Mobile, the products manufactured by the more established companies have had the greatest amount of field testing by agencies at the forefront of CV pilot deployments. DSRC devices are generally interoperable with a wide variety of other equipment, taking advantage of a number of technical standards that specify protocols for communication between devices, though these issues are still being worked out. Some of these manufacturers have also created partnerships with manufacturers of traffic signal controllers, such as Savari and Econolite, Wave Mobile and Intelight [50], or Cohda and Siemens. Siemens is the only Traffic Control equipment manufacturer who makes its own RSUs.

RSU specifications are outlined in the *Dedicated Short Range Communications Roadside Unit Specifications* document produced by the FHWA ITS Joint Program Office (JPO), the most recent version of which (4.1) was published in April 2017. This specification requires certain features, such as powering

of devices via Power-over-Ethernet (PoE); support for Internet Protocol (IP) networking capabilities; the presence of an integrated GPS receiver for positioning and timing; packaging in a NEMA 4X (water and dust-proof) enclosure; internal processing and non-volatile storage; and support for the IEEE 1609, SAE J2735, and SAE J2945 standards governing service advertisements and message formats. The specification also requires software to perform basic message transmission and processing functions, and devices are often also provided along with a Software Development Kit (SDK) for users to develop more advanced applications for the RSU [51]. Many devices currently for sale support this specification, and in the near future all devices should, though some older devices may only support the 4.0 specification.

Before deploying equipment, each agency operating DSRC RSUs must have a license for operating this equipment in their geographic location, and must register each RSU deployed, both processes handled by the FCC. DSRC On-Board Units (OBUs), the in-vehicle counterpart to RSUs, do not have to be registered. There are also a number of considerations that must be made when deploying equipment. For one, the RSUs must be mounted to something outside such as a signal mast, arm, or luminaire. The devices must also be powered, meaning that electrical power must be available at the location from infrastructure. Power, delivered to the device from the cabinet via PoE, shares the same cable as the Ethernet required for communication. Because of this, deploying an RSU typically requires selecting a mounting point, pulling an outdoor-grade Ethernet cable from this location to a cabinet with AC power and an Ethernet network, and ensuring the wiring is waterproof, similar to wiring signal heads and other weatherized electronics.

In addition to these requirements, DSRC installations must also be connected to an agency's network or directly to the Internet to allow the Security Credential Management System to function. These requirements will be elaborated in the coming sections.

4.2.2 Backhaul Communication

As a requirement for the Security and Credential Management System that DSRC relies on, roadside equipment must be connected to the Internet to facilitate communication between the device and the Certificate Authority (CA) that issues signing certificates. This is required in order to sign messages transmitted by the RSU so that they can be trusted by vehicles. This connection may also be used to allow the RSU to occasionally distribute new keys and certificates to vehicles, though alternate means may be used as described in Section 4.2.3 . While the SCMS requires some amount of communication to ensure certificates are up to date, the periods over which these certificates change are not short enough to require a low-latency, high-bandwidth connection, meaning that communication technologies such as DSL or cellular should meet the requirements.

It is important to note that the backhaul communication network used for the SCMS must not only be IP, but IP version 6 (IPv6) specifically. For one, this is required by the RSU 4.1 specification, however due to the potentially large number of devices a CV ecosystem would entail, IPv6 will ultimately be required in order to have all of these devices connected to a network. This means that agencies must ensure that their networks support IPv6, something that has been largely put off by many public and private organizations, but has become increasingly relevant as IPv4 addresses have been exhausted.

Specific applications may also require that roadside equipment be connected to the Internet to provide additional information beyond what is available on the local network and from vehicles. In this case, the bandwidth and latency requirements of this connection vary depending on the application, ranging from the limited requirements for SCMS support, to a high-bandwidth, low-latency connection required for supporting time-critical applications. Much of this also relates to the overall architecture chosen by an organization for implementation of these applications (described in Section 4.2.4).

4.2.3 Security Credential Management System (SCMS)

The Security Credential Management System employed by DSRC uses a Public Key Infrastructure (PKI) to ensure messages from vehicles and infrastructure can be trusted, and that new certificates can be obtained on a regular basis to maintain up-to-date information about any untrustworthy entities in the system. This system is managed by a central organization overseen by the federal government. The connection to this system for vehicles can be implemented in one of two ways: a DSRC-only approach, which uses DSRC RSUs to distribute keys and certificates obtained from the CA via a backhaul communication line; or a hybrid approach, which uses a combination of cellular, Wi-Fi, and satellite communication to distribute keys and certificates to vehicles. A notable variant of the hybrid approach, in use by the Wyoming DOT CV Pilot, uses SiriusXM satellite communication to push new certificates to the vehicles, with DSRC RSUs only in spot problem locations. While this is a very high-latency approach, because of the infrequency with which certificates must be updated it works well in cases where a very large geographic area with low road volumes must be covered.

These are all valid approaches, and the novelty of CV system implementations means that many of the potential issues with either system are still being worked out. From the perspective of local road operators, however, it is important to note that the SCMS communication mechanism that is implemented must be compatible with the vehicles to be served. Because of adjacent and overlapping road jurisdictions, agencies must coordinate and cooperate to ensure that the infrastructure they deploy is capable of serving the same vehicles as the infrastructure deployed by nearby agencies. This means that agencies will likely have limited choices in what SCMS implementation they use, restricted largely by the choices of larger agencies that have led the way in deploying CV infrastructure.

4.2.4 Local or Hub Architecture

The last overarching consideration of a CV system implementation involves the choice of an overall architecture for how information will flow throughout the network and where key activities will physically take place. In this regard, aside from the connection to the SCMS, an agency must choose whether it is to use a "local" (or "distributed") architecture, where information processing occurs on the roadside, or a "hub" (or "centralized") architecture, where most processing occurs at a centralized location such as the agency's Traffic Management Center (TMC). This choice is largely a matter of preference, as each approach comes with tradeoffs. However due to the wide reaching implications of this decision, it is best to make it early.

In the local architecture, because processing happens at the roadside, operators must ensure that their roadside equipment has sufficient computing power and storage to support whatever application is being implemented. This means that there is often more equipment to maintain at the roadside, which may pose challenges. The advantage, however, is that, depending on the application, the system is more fault-tolerant, being capable of withstanding brief disruptions in communication with the outside world (though at some point certificates must be updated). In addition to this, the backhaul communication used to connect the RSE to the Internet does not have particularly stringent bandwidth or latency requirements, as it is only needed to occasionally update certificates and other information that is not as time-critical. Because of these considerations, this architecture may be more suited to implementations covering larger geographic areas, where reliable communication cannot always be guaranteed.

By contrast, the hub architecture, where processing happens mostly at the TMC, requires reliable, high-bandwidth, low-latency communication to all equipped roadside stations. In order to ensure that time-critical applications can be supported, there must be a near-zero latency connection to the TMC. In addition to this, any momentary disruption may completely disable the system. This means that to use this architecture, an agency must have a reliable, fast, and redundant network for their roadside installations, namely a fiber optic network. In return, however, processing and storage needs can be centralized in a location where they can be more easily maintained, such as a data center environment, which may be attractive to some agencies. In comparison to the local architecture, the hub architecture may be more suited to implementations in dense urban areas, where reliable, hard-wired communication networks may already be in place.

Though these two architectures are described as alternatives, in reality they form two ends of a spectrum that represents many potential implementations. Agencies may choose to use a combination approach, having some activities occur at the roadside and others at the TMC. This could be done to balance the hardware that must be deployed at the roadside, to improve the fault-tolerance of a system, or to allow the staged deployment and/or development of applications as the means of an agency allows.

4.3 REQUIREMENTS FOR APPLICATIONS INVOLVING SIGNALIZED INTERSECTIONS

As will be discussed in the next section, there are several connected vehicle applications that involve signalized intersections. In each of these applications, vehicles must be provided with Signal Phasing and Timing (SPaT) information from the signal controller, along with geometric information describing the intersection layout, to understand where the signal controller is in the cycle and make decisions based on that information. This information is transmitted using the SAE J2735 SPaT and MAP messages (see Section 4.1.1 for more information about these messages), respectively. In recent years, the USDOT has issued the SPaT Challenge, a challenge to state and local transportation infrastructure owners and operators to deploy an operational installation of DSRC infrastructure with SPaT broadcasts in at least one corridor or network consisting of approximately 20 signalized intersections. So far, 25 states have committed to the challenge and have deployed DSRC infrastructure at 216 signals and planned deployments for 2,036 intersections.

This initiative, along with the three CV Pilot initiatives, has both pushed agencies to make support of connected vehicles a priority, and has encouraged manufacturers to work on improving their support of features enabling connected vehicle infrastructure. As of now, several of the major controller manufacturers are currently selling hardware capable of natively generating either J2735 SPaT messages directly or SPaT information that can be converted into J2735 SPaT messages for broadcast by a DSRC radio. Generally speaking, whether or not a particular controller is capable of doing this can be determined by looking at product specifications for a specific SPaT generation feature, or compliance with key standards such as Advanced Transportation Controller (ATC) and/or National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP) 1202.

In the case of MAP information, because this is based on geometric information, it must be generated manually and stored for broadcast on either the signal controller, DSRC radio, or an intermediate processor. This information only needs to be updated when changes to the layout of an intersection are made, such as during active work or after reconstruction. Because this message is an accompanying requirement to SPaT broadcast, a tool for developing the J2735 MAP message using aerial imagery has been developed by the USDOT and is available to anyone.

4.3.1 Current Traffic Signal Controllers and Standards

The area of traffic signal controllers is one of the places where the currently available equipment is as ready for a CV ecosystem as possible, given the current state of things. As the general field of Intelligent Transportation Systems (ITS) have evolved, two notable standards, ATC and NTCIP 1202, governing controller operation, necessary features, and interoperability with different devices have helped pave the way for the more recent developments specific to CVs. Controllers that support both of these standards are effectively guaranteed to be compatible with CV infrastructure with minimal additional hardware and effort.

4.3.1.1 NTCIP 1202

Originally developed in 1996 as NEMA TS 3.5, the National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP) 1202 standard governing traffic signals dictates a number of required features for traffic signal controllers, along with a communication protocol that must be accessible over one of the supported physical communication technologies (defined in the base NTCIP standards). Version 2 of this standard was published in 2005 and the most recent Version 3 is currently awaiting final publication [52].

Controllers that support even older versions of this standard will have the capability of outputting information about the active signal phasing and timing information and the current status of the signal. This is provided over either a serial port (in older controllers) or an Ethernet network. For controllers that support NTCIP 1202, it is possible to use the NTCIP data to generate J2735 SPaT messages using software. Some DSRC RSU manufacturers provide this software along with their hardware; for those that do not, the open-source V2I Hub software package, developed by the FHWA ITS JPO, has a SPaT plugin that is

capable of doing this. This software can be run on a variety of Linux-based platforms, including low-power ARM-processor-based computers that are commonly used as field-hardened computers.

4.3.1.2 ATC (Advanced Transportation Controller)

The Advanced Transportation Controller standard, originally published in 2006, is meant to expand on the previous standards governing traffic signal controllers, such as NEMA TS2 and Model 2070, to create a controller that is more flexible for the needs of today's rapidly advancing transportation network. This standard is quite broad and covers more than just traffic signal control. The most notable thing about the ATC standard that separates it from previous ones is the requirement of a Linux operating system running on a field-hardened computer with minimum processing, memory, storage, and interface requirements. Because of this, controllers that support this standard are very flexible, providing users the ability to run applications developed by the manufacturer or third parties with this platform.

In addition to this, the ATC standard is more or less cabinet agnostic allowing manufacturers to develop models that are compatible with existing NEMA TS2 and Model 2070 cabinets. Because it also requires an IEEE 802.3 Ethernet port, it is also compatible with newer hardware (specifically DSRC RSUs), meaning that these controllers can help bridge the gap between newer and older hardware [53]. It is also compatible with the recent ITS Cabinet standard (discussed in Section 4.3.1.3), which is meant to serve a purpose similar to the ATC standard for cabinets.

4.3.1.3 ITS Cabinet

The last standard that is relevant to traffic signal controllers is the ITS Cabinet standard, published in 2006. Though not required by the ATC standard, it is related to it and intended to be the cabinet counterpart of the ATC standard. This standard collects the best elements of the NEMA and Model 170-family traffic signal cabinets while adding further requirements allowing the cabinets to support a variety of ITS applications beyond signal control such as traffic surveillance, ramp metering, toll collection, lane control, and many others. The standard is based on a 19-inch rack-mount design like the 170-family providing flexibility in the amount and type of equipment that can be installed. Because of the flexibility afforded by these cabinets, they are the ideal choice when installing new cabinets. However, as mentioned in regards to the ATC standard, ITS cabinets are not a requirement for using ATC compliant controllers [54].

4.4 CV APPLICATION-SPECIFIC REQUIREMENTS AND COSTS

When looking to implement any particular application, there are a number of requirements that must be considered. Many of these are shared by all or some of the potential applications, such as those discussed in Sections 4.2 and 4.3 , while others are application-specific. Some of these, such as broadcasting SAE J2735 SPaT, MAP, and BSM messages, are relatively well-defined by existing standards and pilot implementations. SAE J2735 RTCM messages containing GPS position correction information are also well-defined and can optionally be applied to applications relying on GPS data for positioning and speed information to improve the accuracy of this data; however, it requires infrastructure for this like the Minnesota Continuously-Operating Reference Station (MnCORS) Network. In contrast to this, use of the

SAE J2735 Traveler Information Message (TIM) for sending application-specific alerts, is not well-defined at this point and still needs to be developed in much detail beyond basic conjecture. In all cases though, there are steps that can be taken by local road operators to ensure that any equipment they purchase in the near future should at least be compatible with a CV ecosystem, even if additional equipment or software that is not yet available may need to be acquired in the future.

Because of the focus of this project on local road operators, the discussion in this section will focus on applications that have an infrastructure component, requiring the road authority to take some action required for the application to work correctly. Other applications that do not have an infrastructure component are beyond the scope of this report. V2I (or V2X) applications are split into groups based on common application requirements to help readers understand how their infrastructure relates to the applications that can be supported. The discussion will focus on the specific information and hardware requirements for the applications, in addition to providing a brief look at how easy or inexpensive it would be to implement each application. It is important to note that, unless stated otherwise, there is no off-the-shelf infrastructure-based software available to implement any of these applications. In these cases, fully implementing the application would either require the software to run in the vehicle, or would require the development of custom software. This is an active area of development, however, and either commercial or open-source software may be available in the future. In some cases, open-source software is currently available via the Open Source Application Development Portal (OSADP) managed by the Federal Highway Administration (FHWA), however using this code would still require effort by the agency deploying it to integrate it with their systems, and would likely require maintenance and additional development as the software is refined through field deployments.

Much of the information about the application requirements was based on the Connected Vehicle Reference Implementation Architecture developed by the USDOT's ITS JPO [55] Background information about each application can be found in Section 3.2 . An overview of the availability of software with information about open-source projects for each application is provided in Section 4.5 . Additional details on the minimum deployment size and monetary cost of implementation of each application are provided in Section 4.6 .

4.4.1 Level 0 Applications with No Communication Requirements

The applications in this group are (primarily) Level 0 automation technologies, as defined by SAE (Figure 3.2) where the vehicle's sensors provide assistance to the driver but all driving tasks are performed by the driver. They do not require any communication infrastructure, but do require that road operators keep their existing infrastructure well-maintained and aligned with defined quality standards like sign reflectivity, lane marking continuity, MUTCD standards for signs and lane markings, etc.

4.4.1.1 Lane Departure Warning and Lane Keeping

Described in Sections 3.2.2.3 and 3.2.5.4 , *Lane Departure Warning*, and by extension its Level 1 counterpart *Lane-Keeping*, are notable with regards to road operators in that they require highly visible pavement lane markings to function properly. These technologies are typically based on camera systems

that are sensitive to variations in the visibility of pavement markings. Whereas humans are generally able to deduce the location of faded lane markings without much trouble, computer systems can have trouble correctly identifying faded lane markings and may either fail to find a suitable line, or misidentify other pavement markings or stains as a lane marking. In these cases, the system would not operate correctly and either turn itself off, or require the driver to disable it.

Beyond this requirement, there is nothing else that road operators need to consider for these applications to work. All other hardware and software necessary for them to work is contained in the vehicle and does not require any data communication with infrastructure or other vehicles. The cost for an agency to adequately support this application can be estimated by using existing figures for maintenance of pavement markings and extrapolating the cost of maintaining higher-quality markings

4.4.1.2 Traffic Sign Recognition (TSR)

Similar to *Lane Departure Warning* and *Lane Keeping*, *Traffic Sign Recognition (TSR)*, described in Section 3.2.2.4 , requires a commitment from road operators to maintain visible, recognizable traffic signs. This means that a jurisdiction's signs must meet retroreflectivity standards and be in otherwise good condition to allow the camera systems on equipped vehicles to correctly recognize the sign and act accordingly. In addition to this, there is the potential that future changes to the technology used by vehicles to recognize traffic signs may require actions by road operators, such as replacing signs with QR-code-equipped signs that are more easily recognizable by automated systems. Any such change would need to be approved and incorporated into the MUTCD before becoming mandatory. However, in the event this happens road operators would be responsible for ensuring a jurisdiction's traffic signs meet any new standards.

Similar to *Lane Departure Warning* and *Lane Keeping*, proper maintenance of traffic signs is the only requirement for Traffic Sign Recognition to function properly as all other hardware and software required is contained in the vehicle and no V2V or V2I communication occurs. However, there are other CV applications that share the same requirement of well-maintained traffic signs in addition to DSRC roadside equipment and potentially other roadside sensors. The cost for an agency to support this application can be estimated by extrapolating the costs of current sign maintenance activities.

4.4.2 Level 0 Technologies Group 1

The applications in this group are Level 0 technologies providing additional information to the driver without automation. They are distinguished from the next group (Level 0 Group 2) in that they do not have significant requirements from infrastructure to provide highly-detailed, dynamic information. The applications in this category can be implemented as static warning message systems.

4.4.2.1 Stop Sign Gap Assist

Described in Section 3.2.3.1.2 , *Stop Sign Gap Assist* shares the requirement with TSR of recognizable traffic signs, as the sign must be recognized in order to trigger the application behavior. In addition to this, this application also requires roadside equipment to measure gaps in the conflicting traffic stream and

communicate this information in real-time to drivers attempting to enter or cross that stream. Communication is achieved by a DSRC RSU requiring a connection to the SCMS to ensure the security and trustworthiness of messages. Gap measurements can be collected either by using SAE J2735 Basic Safety Message (BSM) positioning data from vehicles or by using roadside sensors such as radar to measure gaps from a fixed location. This information must also be processed by roadside equipment to determine if a gap can be safely accepted based on the geometry of an intersection so the information can be broadcast to vehicle OBUs via a SAE J2735 TIM (Traveler Information Message) to inform the driver or AV.

This application is one of several that is relatively inexpensive to implement and can be deployed to as few as one stop-controlled intersection. All hardware for implementing this application is currently available for purchase, and it is possible to use roadside sensors or dynamic message signs to increase the benefit of the application while the market penetration of CVs is low. Though there is currently no off-the-shelf software available to implement this application, such software could be developed relatively easily and may be available in the future.

4.4.2.2 Stop Sign Violation Warning

Stop Sign Violation Warning, described in Section 3.2.3.1.3 , also requires that TSR can function properly, as well as DSRC roadside equipment with a connection to the SCMS to communicate with drivers. In this application, roadside equipment uses vehicle location and speed data, obtained via roadside sensors or vehicle BSM data, along with geometric information to determine if a vehicle is at risk of running a stop sign, transmitting this information to the vehicle via a J2735 TIM to provide it with the opportunity to adjust its behavior accordingly. This information can also be augmented with road surface or other weather-related information, such as from pavement sensors (temperature, moisture, ice), to determine if a vehicle can stop safely in the current conditions. A warning of the impending violation is also transmitted to other vehicles in the vicinity to notify them of the risk so they may take evasive action. Roadside processing capabilities are also required to incorporate all of this information into the warning. This application is also relatively inexpensive to implement and can be deployed on a small scale with hardware that is currently available, though there is no off-the-shelf software available.

4.4.2.3 Railroad Crossing Warning

The *Railroad Crossing Warning* application, described in Section 3.2.3.6 , warns vehicles that are approaching an at-grade railroad crossing if they are on a trajectory to collide with a crossing or approaching train. This application requires the presence of equipment to detect the status of a train that is approaching or blocking a railroad at-grade crossing, roadside processing capabilities to evaluate the current traffic status information, and a DSRC RSU with connection to the SCMS to communicate this via a J2735 TIM to drivers. As with *Stop Sign Violation Warning*, weather-related pavement condition data can be included in the application as well to augment the required stopping distance to avoid a collision with the train. This application is relatively inexpensive to implement and can be deployed on a small scale with hardware that is currently available. Software for implementing this application is available via the open-source V2I Hub and the separate RCVW plugin.

4.4.2.4 Curve Speed Warning

The *Curve Speed Warning* application, described in Section 3.2.3.2 , uses DSRC RSUs with a connection to the SCMS to notify vehicles approaching a curve with reduced speed requirements. This requires that the infrastructure broadcasts the curve radius, along with pavement condition information obtained from sensors, to vehicles via a TIM so they may reduce their speed and safely traverse the curve. An alternate implementation, currently available as a plugin for the USDOT's V2I Hub, uses the curve radius and pavement conditions along with roadside processing to break the curve up into a number of zones with a recommended speed range, then broadcast this information to vehicles via a TIM so vehicles may adjust their speed. This application is relatively inexpensive to implement and can be deployed on a small scale with hardware that is currently available. Software for implementing this application is available via the open-source V2I Hub and the integrated CSW plugin.

4.4.2.5 Reduced Speed/Work Zone Warning

The *Reduced Speed/Work Zone Warning* application, described in Section 3.2.3.4 , requires DSRC RSUs with a connection to the SCMS to communicate information to vehicles via TIMs, as well as information about a work zone (or other reduced speed zone) to notify vehicles that need to reduce speed, change lanes, or stop in a work zone. Implementing this application in an isolated location using a simple, pre-set message would be relatively inexpensive and could be done on a small scale with hardware that is currently available, however a more advanced system would require a live work zone information source that is not yet available.

4.4.2.6 Warnings about Upcoming Work Zone

The *Warnings about Upcoming Work Zone* application, described in Section 3.2.3.11 , requires DSRC RSUs with a connection to the SCMS to notify vehicles of upcoming work zone activities via TIMs. This application requires accurate information about lane obstructions, lane closures, lane shifts, and speed reductions in the work zone. Vehicles can also be warned about work vehicles entering/exiting the work zone if they are equipped and roadside processing is available to use BSMs from these vehicles to generate advisory messages. This application also requires sufficient DSRC RSU coverage to provide adequate advanced warnings to drivers before they enter the work zone, due to limitations in the coverage area of DSRC. Implementing this application in an isolated location using a simple, pre-set message would be relatively inexpensive and could be done on a small scale with hardware that is currently available, however a more advanced system would require a live work zone information source that is not yet available.

4.4.2.7 Stationary/Slow Moving Vehicle Warning

The *Stationary/Slow Moving Vehicle Warning* application notifies vehicles if there is a vehicle stopped or moving slowly in the road for instance due to a crash, breakdown, or maintenance activities. This application does not require any infrastructure hardware.

4.4.3 Level 0 Technologies Group 2

The applications in Level 0 Group 2 are also Level 0 technologies. However, they have a significant infrastructure component that requires hardware to broadcast dynamic information about the infrastructure. This includes things like broadcasting SAE J2735 SPaT and MAP messages for signalized intersections, RTCM position correction messages for improving GPS position accuracy, and Traveler Information Messages (TIMs) for providing specific information to vehicles.

4.4.3.1 Red Light Violation Warning

The *Red Light Violation Warning* application, described in Section 3.2.3.1.1 , is similar in concept to *Stop Sign Violation Warning*, but requires information about the current timing phase at the intersection along with vehicle speed information via the J2735 SPaT message. It also requires BSM data to determine vehicle location and speed information. This information, which can be augmented with weather information from pavement sensors or other sources, is used to determine if a vehicle risks running a red light so it and other vehicles can be warned via a J2735 TIM. Alternatively, the software for detecting violations could also run in the vehicle. This application can be implemented at a single intersection and still provide a benefit compared to other signalized intersection applications that require many intersections. This application can be supported relatively easily by equipping an intersection to broadcast SPaT and MAP information if the warning logic is running in the vehicle, though infrastructure-based software for doing so is not yet available. Software to facilitate broadcasting of SPaT and MAP messages is available commercially from manufacturers of signal controllers or DSRC RSUs as well as from open-source projects such as V2I Hub.

4.4.3.2 Pedestrian in Signalized Crosswalk Warning (Transit)

The *Pedestrian in Signalized Crosswalk Warning (Transit)* application, described in Section 3.2.3.5 , is intended to warn transit bus operators of a pedestrian crossing in front of the vehicle in a signalized crosswalk. This application requires that the intersection be equipped with a pedestrian detection system either in the form of dedicated sensors or by listening for SAE J2945/9 Pedestrian Safety Messages (PSMs) emitted from pedestrians equipped with such devices along with processing to use this to determine crossing status. The intersection must also broadcast SPaT information so that the status of the walk signal can be known. The pedestrian crossing status is broadcast via a TIM to alert vehicles so transit vehicles may avoid infringing on the pedestrian's right of way. This application is relatively inexpensive to implement and can be deployed on a small scale with hardware that is currently available, though software is not yet available.

4.4.3.3 Eco-Approach and Departure at Signalized Intersections

The *Eco-Approach and Departure at Signalized Intersections* application, described in Section 3.2.3.12 , requires that intersections broadcast J2735 SPaT and MAP messages to allow vehicles to estimate the most fuel-efficient approach and departure acceleration patterns depending on the status of the signalized intersection. In addition to the DSRC RSUs required to communicate this information, vehicles

must also have the processing ability to evaluate the SPaT and MAP information and take appropriate action. This application requires several intersections within a corridor to be equipped with this application as the benefit provided by an individually equipped intersection is small compared to a larger number of intersections, however the per-intersection cost of implementing this application is fairly low. Software to facilitate broadcasting of SPaT and MAP messages is available commercially from manufacturers of signal controllers or DSRC RSUs as well as from open-source projects such as V2I Hub.

4.4.3.4 Queue Warning

The *Queue Warning* application, described in Section 3.2.4.6.1 , uses DSRC RSUs to collect BSMs from vehicles and roadside or center-based processing to track the location of a queue on the road. The location of the queue can then be broadcast via a TIM so vehicles can slow down safely in advance of the queue. This application requires sufficient coverage of RSUs to track the queue over time either in spot locations with recurring problems or in larger segments of a corridor. This is a fairly expensive application to implement because of the significant hardware requirements. Open-source software for this application is currently available via the INFLO-PRO project.

4.4.3.5 Dynamic Speed Harmonization

The *Dynamic Speed Harmonization* application, described in Section 3.2.4.6.2 , uses DSRC RSUs to collect BSMs from vehicles over a large geographic area to track traffic conditions. This information is then processed on the roadside or in the traffic management center to determine the optimal speed of vehicles along the corridor maximizing throughput. To broadcast variable speed advisories to vehicles, the corridor is broken into a number of zones with recommended speeds that intelligence in the vehicles can utilize to determine the appropriate speed for the vehicle's current location. This speed can then be communicated to the driver or used directly by a capable automated vehicle. Like *Queue Warning*, this application is fairly expensive to implement. Open-source software for this application is also available via the INFLO-PRO project.

4.4.3.6 Spot Weather Impact Warning

The *Spot Weather Impact Warning* application, described in Section 3.2.3.9 , uses data from pavement sensors, other local weather sensors, and/or a management center to notify vehicles of hazardous weather conditions in a specific location with DSRC RSUs via a TIM. Information can also be collected via BSM Part II data that may contain weather and pavement-condition information from properly equipped vehicles. This application requires placement of RSUs with adequate coverage to be capable of informing vehicles with sufficient advanced notice allowing them to take the appropriate action in response to the hazard. Implementing this application in a single problem location would be relatively inexpensive, though software for generating the warning is not yet available.

4.4.4 Applications for Benefit of Road Authority

The *Benefit of Road Authority* applications provide information to the road authority to help inform maintenance activities or traffic operations, with only secondary benefits to road users. They require DSRC RSUs and a connection to the SCMS to collect information from vehicles, along with additional application-specific requirements.

4.4.4.1 Probe-Based Pavement Maintenance

The *Probe-Based Pavement Maintenance* application, described in Section 3.2.4.7 , requires DSRC RSUs to collect information from vehicles about deteriorating pavement conditions. This application requires vehicles to have sensor(s) such as an accelerometer and software to detect potholes and other issues with pavement conditions. Vehicles could then transmit this information to infrastructure via Part II of a BSM. There must also be sufficient data storage on the roadside or in the management center to record this information, along with a system to notify road operators of needed maintenance. Due to a lack of information describing how this application would be implemented, the cost of deploying this application at any scale is unknown.

4.4.4.2 Probe-Enabled Traffic Monitoring

The *Probe-Enabled Traffic Monitoring* application, described in Section 3.2.4.8 , requires DSRC RSUs and roadside processing to use BSMs to collect vehicle position and speed information and translate it into traffic measurements such as flow, density, and travel time. Depending on the traffic measurement, this application requires relatively high penetration of traffic monitoring probe equipped vehicles to provide accurate traffic information. This information can be collected by the road authority to monitor traffic conditions and plan future developments of the roadway network. Traffic information can also be broadcast to other vehicles via a TIM. This application would require a large deployment to provide a noticeable benefit, requiring significant field hardware over a large area and high-bandwidth connections to the TMC. Software for collecting traffic data from BSMs is not currently available.

4.4.4.3 CV-Enabled Traffic Studies

The *CV-Enabled Traffic Studies* application includes both the *CV-Enabled Turning Movement and Intersection Analysis* application described in Section 3.2.4.10 and the *CV-Enabled Origin-Destination Studies* application described in Section 3.2.4.11 . The first of these applications use DSRC RSUs to collect travel information from vehicles via BSMs and collect turning movement counts at an intersection to help perform traffic signal optimizations. The second application, while theoretically possible given that vehicles broadcast their position information via BSMs, is not actually allowed by the currently-envisioned CV architecture due to privacy concerns. Because of frequently changing vehicle IDs broadcast with BSMs and rules against tracking vehicles, it is not possible to do true origin-destination studies without explicit consent from drivers and software in the vehicles. This application could be implemented at a single intersection or with a portable station relatively easily, though the software for collecting traffic data from BSMs is not currently available.

4.4.4.4 Intelligent Traffic Signal System

The *Intelligent Traffic Signal System* application, described in Section 3.2.4.2 , uses vehicle position and speed data, as well as data from pedestrians and other vulnerable road users, to control signals to maximize flow in real time. This application requires intersections be equipped with DSRC RSUs with a connection to the Traffic Management Center to obtain current demand information via BSMs and PSMs. Signal communications will also include priority requests from transit, freight, and emergency vehicles via the SAE J2735 Signal Request Message (SRM) and responses to these requests via the SAE J2735 Signal Status Message (SSM). In addition to these communication requirements, the intersections must also be equipped with a controller capable of using this information to optimize the intersection control in real time, something that does not exist yet. Some of the software required to implement this system is available via the Multi-Modal Intelligent Traffic Signal System (MMITSS) open-source project, however. For this application to work, all vehicles and other road users, as well as all intersections in the area, would need to be properly equipped. Centralized hardware would also likely be required to coordinate the actions of multiple intersections to optimize the corridor or network level. This is one of the most expensive CV applications to implement.

4.4.5 Autonomous Vehicles

In addition to the previously noted standards and requirements, it should be noted that fully autonomous vehicles may need all of the above applications in order to function properly. Alternatively, well organized roads and traffic control that autonomous vehicle systems are capable of interpreting may also allow them to function properly. The degree to which this is true will depend on the state of autonomous vehicle technology as it is developed.

4.5 AVAILABILITY OF SOFTWARE FOR CV APPLICATIONS

While the hardware and information requirements for most CV applications are fairly well defined, there is a wide range in the availability of actual software implementations of these applications. For some applications, such as those requiring only SPaT and MAP broadcast from signalized intersections like *Eco-Approach and Departure at Signalized Intersections*, some signal controllers or DSRC RSUs are capable of natively performing this function, with support only likely to improve with time. There are also open-source applications capable of performing this function for controllers that do not natively support it but have NTCIP capabilities. In these cases though, the majority of the requirements are pushed onto the vehicles, which must have the necessary hardware and software to support the applications.

In other cases where there are specific information requirements that must be provided by the infrastructure the availability of software varies. In the case of *Curve Speed Warning*, for instance, an open-source implementation of this application is available in the V2I Hub project. By comparison, however, there is no software implementation of *Upcoming Work Zone Warning* that is currently available. In some cases there are partial software implementations, for instance in the case of *Intelligent Traffic Signal System*, where much of the system has been implemented but the interface

with the controller is not defined because there are no controllers capable of supporting this application. There are also cases where there are complete software implementations, but given the complexity of these applications they are still very much in development and will require considerable work to be made functional, for instance the *Queue Warning* and *Dynamic Speed Harmonization* applications that are supported by the open-source INFLO-PRO project.

In any case, this is an active area of development that will change considerably over the coming years. Hardware manufacturers and Advanced Traffic Management System (ATMS) developers have increasingly capitalized on the interest in this area by providing support for CV applications in their commercial systems, something that is likely only to increase as more agencies demand this support. Meanwhile, the USDOT and individual agencies themselves have been working to develop their own implementations of some applications, many of which have been made available as open-source applications. A notable example here is the V2I Hub project, which provides a unified framework for supporting many CV applications and a growing library of software plugins to support individual applications. This and other open-source applications can be found on the FHWA's Open Source Application Development Portal (OSADP).

Table 4.3 provides an overview of the current state of software availability for the applications with a significant infrastructure component. In cases where there is at least one open-source project that provides some or all of the required functionality, the relevant project(s) is/are listed in the corresponding column. All open-source projects are available on OSADP.

Table 4.3 Availability of software for CV applications with an infrastructure component.

Application	Software Available?	Open-Source Project Name(s) (if any)	Notes
Stop Sign Gap Assist	No	-	
Stop Sign Violation Warning	No	-	
Railroad Crossing Warning	Yes	RCVW (V2I Hub Plugin)	V2I Hub Plugin
Curve Speed Warning	Yes	V2I Hub CSW Plugin	In V2I Hub
Reduced Speed/Work Zone Warning	No	-	A static-message warning could be implemented fairly easily. For larger-scale projects, dynamic messaging may need to be implemented.
Upcoming Work Zone Warning	No	-	
Red Light Violation Warning (local)	Yes	V2I Hub SPaT/MAP plugin, SPaT 1.2	Both open-source and commercial SPaT/MAP broadcast software available.
Red Light Violation Warning (hub)	Yes	V2I Hub SPaT/MAP plugin, SPaT 1.2	Both open-source and commercial SPaT/MAP broadcast software available.

Pedestrian in Signalized Crosswalk Warning (local)	Partial	D2X Hub	D2X Hub provides PSM broadcast, but no software for processing this or other pedestrian detection information
Eco-Approach and Departure at Signalized Intersections (local)	Yes	V2I Hub SPaT/MAP plugin, SPaT 1.2	Both open-source and commercial SPaT/MAP broadcast software available.
Eco-Approach and Departure at Signalized Intersections (hub)	Yes	V2I Hub SPaT/MAP plugin, SPaT 1.2	Both open-source and commercial SPaT/MAP broadcast software available.
Queue Warning	Yes	INFLO-PRO	
Dynamic Speed Harmonization	Yes	INFLO-PRO, CaA-Speed-Harmonization	
Spot Weather Impact Warning	Partial	RW-PM, PIKALERT, IMRCP	Several software packages for collecting/aggregating road weather condition information from a variety of sources.
Probe-Based Pavement Maintenance	No		
Probe-Enabled Traffic Monitoring (hub)	No		
CV-Enabled Traffic Studies	No		
Intelligent Traffic Signal System (hub)	Partial	MMITSS	MMITSS-AZ has modules for Savari MobiWave and StreetWave RSUs designed for Intelligent Signal Control. Has also been ported to Siemens RSUs in MMITSS THEA. Method for interfacing with signal controllers is unclear and not implemented.

4.6 COST OF IMPLEMENTING OR SUPPORTING CV APPLICATIONS

With the large range of CV applications, there is considerable variability in the cost of implementing each application. While the hardware components required to implement any applications may not change much, the amount of effort required for each application can vary due to the required scale of deployment, the additional expertise required to configure and maintain the equipment, and the current state of an agency's infrastructure. To help illustrate these variations, this section presents a breakdown of V2I applications and the relative difficulty of implementing them. To go along with this, a look at the different options for upgrading or retrofitting existing infrastructure to achieve support of many of these applications is provided in Section 0.

While the infrastructure hardware required to support many CV applications is largely the same, because of the details of the applications there is a wide range of costs associated with implementing or supporting a particular application. This not only includes financial cost, but also time requirements, personnel needs, and a minimum scale of the deployment to realize a benefit. For one, the additional complexity of the hardware being deployed and maintained, which now involves a larger networking component and other IT implications, means that many personnel who are used to working with traditional signal control hardware may not be familiar with these new concepts, requiring training or even the addition of new personnel. Also in many cases, while an application can technically be implemented at a single intersection or location, the benefit may be miniscule until a certain number of intersections or locations are equipped. Therefore, while there are some minimum costs that are associated with working towards even a minimum level of CV-readiness, agencies must carefully consider the costs of individual applications they wish to implement when planning their future activities.

Table 4.6 presents a breakdown of the applications discussed in Section 4.4 with details about the minimum deployment size to realize a benefit and the cost of implementing each application. For each CV application, there are two cost estimates provided: one on a relative scale from 1 to 5 (in number stars), and another in dollars. For each estimate there are four categories: equipment costs, which is purely the cost of purchasing hardware; installation/deployment costs, which is the effort required to install the hardware in the field or TMC; software and integration costs, which is the cost required to either purchase commercial software or develop custom software, as well as the cost to integrate that software with existing systems; and operations and maintenance costs that are required to keep the system running over time. For the relative costs, installation/deployment costs are assumed to be approximately 50% time (cost for labor) and 50% complexity (requiring more training for personnel). Operations and maintenance costs are assumed to be approximately 20% time (cost for labor) and 80% complexity (training for personnel).

Determining monetary cost estimates for each of the applications discussed in this section involved several steps. To start, researchers obtained information about cost ranges for the critical equipment required for each application based on the experiences of pilot implementations, information from hardware vendors, and records collected by the United States Department of Transportation Intelligent Transportation Systems Joint Program Office (USDOT ITS JPO) for their Cost Database. Using this information, estimates about the minimum deployment sizes were created based on the nature of the applications and their intended benefit. These were then used to estimate an equipment cost figure for each application based on the average cost of equipment for the minimum deployment size. In most cases, installation costs were assumed to be equivalent to the cost of equipment. Annual operations and maintenance costs were estimated from the operations and maintenance costs of the equipment and software. In most cases, the communication required for each application, which is necessary for the DSRC hardware to connect to the SCMS for message validity, was assumed to be provided via a cellular modem with an average-cost data plan. In cases where a high-bandwidth, low-latency connection was deemed necessary, this is mentioned in the notes along with the per-mile cost range for installing fiber optic communications.

Table 4.4 shows the ranges for the major hardware components that were considered when estimating the cost of implementation for specific applications. While researchers did their best to provide the most accurate cost information possible, the actual costs may vary depending on the specific equipment purchased and the needs of the particular agency. Table 4.5 shows similar ranges for the costs of software and integration with other agency systems. Similar to the cost ranges for equipment, these costs represent researchers' best estimates based on costs for software components that do exist and general systems integration costs. The actual cost of the software required for implementing CV applications and integrating them with existing systems may vary considerably, especially considering the limited work in this area as discussed in Section 4.4 . The cost estimates for individual applications, presented in Table 4.6, have been rounded to demonstrate the uncertainty in these estimates. Table 3.7 represents a relative cost of equipment purchases, and relative costs of effort of initial effort to install and /or deploy the application as well as ongoing maintenance and management of the system. Those costs are represented on a scale of 1 to 5 relative to each other, representing the uncertainty of total finalized costs of the application at this point in time.

For example, compare the Red Light Violation warning (local) to the Red Light Violation warning (hub). The local cost of equipment will be less (depending on how many installation sites there are) as each intersection only requires local connectivity rather than a connection to a Regional Traffic Management Center through infrastructure such as fiber optic.   Initial installation effort is roughly the same, as skilled laborers will need to place the infrastructure at all deployment sites (theoretically, the hub Red Light Violation could be placed at only one intersection, perhaps as a test site). However, ongoing costs of maintenance and management are much higher for the local application; each site will need to be visited regularly to ensure it is working properly. If a site experiences issues, multiple sites may need to be visited to ensure the rogue controller is found. Compare this to the hub approach, where the entire system can easily be monitored at the RTMC. If an intersection has an issue, it will be easily identified from the RMTC and experts can be sent out to fix it.

Table 4.4 Estimated equipment cost ranges used for estimating cost of implementation for CV applications. Some costs have been modified slightly from the noted source based on researchers' experience and other information.

Component	Source	Cost Range	Operations and Maintenance Cost (Annual)
DSRC RSU	UDOT Presentation (SPaT Challenge)	$1,200 - $3,300	$250
Field Computer	Public Pricing Information	$500 - $1,200	$85
New Controller Unit	ITS JPO RS-C, Signal Controller [56]	$6,000 - $11,000	$850
Cellular Modem	Public Pricing Information	$500 - $1,000	$600
Traffic Sensor (Microwave)	ITS JPO RS-D, Remote Traffic Microwave Sensor [56]	$7,000 - $10,000	$280
Pedestrian Sensor (Microwave)	ITS JPO RS-D, Pedestrian Detection Microwave [56]	$400 - $800	$60
Rail Crossing Train Detector (Controller and Detection Circuit)	ITS JPO R-RC, RS022 + RS023 [56]	$15,000 - $19,000	$560
Environmental Sensing Station (Weather Station)	ITS JPO RS-D, Environmental Sensing Station (Adjusted) [56]	$10,000 - $35,000	$2,250

Table 4.5 Estimated software and integration cost ranges used for estimating cost of implementation for CV applications. Some costs have been modified slightly from the noted source based on researchers' experience and other information.

Item	Source	Cost Range	Operations and Maintenance Cost (Annual)
Software for Probe Information Collection	ITS JPO TM, TM034 [56]	$18,000 - $23,000	$2,000
Integration for Probe Information Collection	ITS JPO TM, TM035 [56]	$138,000 - $169,000	$15,000
Software for Rail Crossing Monitor	ITS JPO TM, TM037 [56]	$18,000 - $23,000	$2,000
Integration for Rail Crossing Monitor	ITS JPO TM, TM038 [56]	$92,000 - $113,000	$10,000
Real-time, Traffic Adaptive Signal Control System	ITS JPO TM, Real-time, Traffic Adaptive Signal Control System [56]	$116,000 - $145,000	$19,000
Software, Integration for Signal Control	ITS JPO TM, TM006 [56]	$107,000 - $153,000	$13,000
Road Weather Information System (RWIS)	ITS JPO TM, Road Weather Information System (RWIS) [56]	$7,000 - $7,000	$1,000
Software, Integration for Freeway Control	ITS JPO TM, TM007 [56]	$175,000 - $214,000	$20,000
Systems Integration (General)	ITS JPO ISP, IS017 [56]	$91,000 - $111,000	$10,000

Table 4.6 Estimated costs per application, rounded.

Application	Minimum Deployment Size	Equipment	Installation / Deployment	Software and Integration	Operations and Maintenance	Notes
Lane Departure Warning/Lane Keeping						Requires uninterrupted, clearly-visible lane markings.
Traffic Sign Recognition						Requires clearly visible, unoccluded traffic signs with good retroreflectivity.
Stop Sign Gap Assist	1 intersection	$15,000	$10,000	$100,000	$12,500	Assumes traffic sensors (e.g. radar) are used to measure gap sizes (requires sensor selection and calibration). Assumes no weather information is included. Weather station cost would add $10,000-$35,000 to both equipment and installation costs.
Stop Sign Violation Warning	1 intersection	$15,000	$10,000	$100,000	$12,500	Assumes traffic sensors (e.g. radar) are used to measure vehicle speeds (requires sensor selection and calibration). Assumes no weather information is included. Weather station cost would add $10,000-$35,000 to both equipment and installation costs.
Railroad Crossing Warning	1 intersection	$5,000	$5,000	$120,000	$13,500	Assumes rail crossing controller and train detection circuit already installed. A new rail crossing controller would cost approximately $5,000 - $6,000 and a new detector circuit approximately $10,000 - $13,000.
Curve Speed Warning	1 location	$5,000	$5,000	$100,000	$11,500	Assumes no weather information is included. Weather station cost would add $10,000-$30,000 to both equipment and installation costs.
Reduced Speed/Work Zone Warning	1 location	$5,000	$5,000	$100,000	$11,500	Assuming a fixed warning regarding the change in speed limit and/or change in number of lanes, nothing else.
Upcoming Work Zone Warning	1 location	$5,000	$5,000	$100,000	$11,500	Assuming a static warning about an upcoming work zone.

Red Light Violation Warning (local)	1 intersection	$5,000 - $15,000	$5,000 - $15,000	$100,000	$11,500	Only requires SPaT and MAP broadcast. Requires integrating DSRC with CU (and possibly a new CU) and creating MAP message. Additional cost for upgrading controller unit reflected in price range for equipment and installation/deployment.
Red Light Violation Warning (hub)	10 intersections	$50,000 - $150,000	$50,000 - $150,000	$130,000	$16,500	Requires SPaT and MAP broadcast and communication with TMC. Hub architecture model for SPaT generation requires high-bandwidth, low-latency communication like fiber optic. If fiber optic lines are not currently available, installation will range from $21,000 - $55,000 per mile. Additional cost for upgrading controller unit reflected in price range for equipment and installation/deployment.
Pedestrian in Signalized Crosswalk Warning (local)	1 intersection	$10,000	$10,000	$100,000	$11,500	Requires pedestrian detection. Assumes dedicated pedestrian sensors will be used.
Eco-Approach and Departure at Signalized Intersections (local)	5 intersections	$25,000 - $75,000	$25,000 - $75,000	$100,000	$17,500	Only requires SPaT and MAP broadcast. Requires integrating DSRC with CU (and possibly a new CU) and creating MAP message. Additional cost for upgrading controller unit reflected in price range for equipment and installation/deployment.
Eco-Approach and Departure at Signalized Intersections (hub)	3 arterials (15 intersections)	$75,000 - $225,000	$75,000 - $225,000	$130,000	$23,000	Requires SPaT and MAP broadcast (integrating DSRC with CU and possible CU upgrades) and communication with TMC. Hub architecture model for SPaT generation requires high-bandwidth, low-latency communication like fiber optic. If fiber optic lines are not currently available, installation will range from $21,000 - $55,000 per mile. Additional cost for upgrading controller unit reflected in price range for equipment and installation/deployment.

Queue Warning	1 bottleneck	$100,000	$100,000	$200,000	$43,000	Requires high-density of equipment from bottleneck to maximum observed queue length plus 1 mile advanced warning. Assumes additional traffic sensors (e.g. radar) will be used to augment traffic data when DSRC market penetration is low.
Dynamic Speed Harmonization	1 bottleneck	$100,000	$100,000	$200,000	$43,000	Requires high-density of equipment from bottleneck to maximum observed queue length plus 1 mile advanced warning. Assumes additional traffic sensors (e.g. radar) will be used to augment traffic data when DSRC market penetration is low.
Spot Weather Impact Warning	1 location	$30,000	$20,000	$7,000	$3,500	Assuming installation of weather station at high-risk location to collect information about hazardous conditions.
Probe-Based Pavement Maintenance	Unknown	Unknown	Unknown	Unknown	Unknown	Requires intelligence in vehicle that has not yet been defined.
Probe-Enabled Traffic Monitoring (hub)	30 intersections	$125,000	$50,000	$170,000	$37,000	Requires communication with TMC. Hub architecture model for SPaT generation requires high-bandwidth, low-latency communication like fiber optic. If fiber optic lines are not currently available, installation will range from $21,000 - $55,000 per mile.
CV-Enabled Traffic Studies	1 intersection	$20,000	$5,000	$170,000	$20,000	Assuming a portable data collection station that can be moved from intersection to intersection. Additional equipment cost reflects need to provide power and security for portable system.
Intelligent Traffic Signal System (hub)	30 intersections	$200,000 - $400,000	$200,000 - $400,000	$260,000	$82,000	Requires SPaT and MAP broadcast and communication with TMC. Hub architecture model for SPaT generation requires high-bandwidth, low-latency communication like fiber optic. If fiber optic lines are not currently available, installation will range from $21,000 - $55,000 per mile. Signal controllers for implementing this are currently not available and would almost certainly require hardware upgrades.

Table 4.7 represents a relative cost of equipment purchases, and relative costs of effort of initial effort to install and /or deploy the application as well as ongoing maintenance and management of the system. Those costs are represented on a scale of 1 to 5 relative to each other, representing the uncertainty of total finalized costs of the application at this point in time.

For example, compare the Red Light Violation warning (local) to the Red Light Violation warning (hub). The local cost of equipment will be less (depending on how many installation sites there are) as each intersection only requires local connectivity rather than a connection to a Regional Traffic Management Center through infrastructure such as fiber optic.   Initial installation effort is roughly the same, as skilled laborers will need to place the infrastructure at all deployment sites (theoretically, the hub Red Light Violation could be placed at only one intersection, perhaps as a test site). However, ongoing costs of maintenance and management are much higher for the local application; each site will need to be visited regularly to ensure it is working properly. If a site experiences issues, multiple sites may need to be visited to ensure the rogue controller is found. Compare this to the hub approach, where the entire system can easily be monitored at the RTMC. If an intersection has an issue, it will be easily identified from the RMTC and experts can be sent out to fix it.

Table 4.7 Relative cost of equipment, relative estimates of initial installation effort and ongoing effort to maintain and manage the application. On a scale of 1 to 5. $ represents monetary cost, ◆ represents effort.

Application	Minimum Deployment Size	Equipment	Installation / Deployment	Software and Integration	Operations and Maintenance	Notes
Lane Departure Warning/Lane Keeping						All sensors are onboard the vehicle; costs and effort only apply to roadway upkeep.
Traffic Sign Recognition						All sensors are onboard the vehicle; costs and effort only apply to roadway upkeep.
Stop Sign Gap Assist	1 intersection	$$$	◆◆	◆◆	◆◆	Requires deployment of roadside equipment, and software to collect information about cross-traffic and emit it to approaching vehicles
Stop Sign Violation Warning	1 intersection	$	◆◆	◆◆	◆◆	Requires deployment of roadside equipment, and software to either alert the driver or the automated vehicle if they are about to violate the stop sign
Railroad Crossing Warning	1 intersection	$	◆	◆◆	◆	Assumes use of existing rail control. Control would need to be updated to emit warnings to oncoming vehicles about the status of the tracks.
Curve Speed Warning	1 location	$$$	◆	◆◆	◆	Assumes static message (ie, bottleneck area identified, and clear signage placed)
Reduced Speed/Work Zone Warning	1 location	$$$	◆	◆◆	◆	Assumes static message (ie, work zone identified, and clear signage placed). Dynamic messaging would increase costs.
Upcoming Work Zone Warning	1 location	$	◆	◆◆	◆	Assumes static message (ie, work zone identified, and clear signage placed). Dynamic messaging would increase costs.

Red Light Violation Warning (local)	1 intersection	$$	◆	◆◆	◆	Can be implemented on a smaller scale than the hub application; requires more effort to maintain due to needing to visit each individual site.
Red Light Violation Warning (hub)	10 intersections	$$	◆	◆◆	◆	Requires a larger implementation than local, but requires less effort to maintain as the system can be monitored from the RTMC.
Pedestrian in Signalized Crosswalk Warning (local)	1 intersection	$$	◆◆◆	◆◆	◆◆◆	Requires alert when pedestrian enters crosswalk (ie, on pedestrian's cellular phone) and dissemination of that alert to transit operators.
Eco-Approach and Departure at Signalized Intersections (local)	5 intersections	$$$	◆◆◆	◆◆◆	◆	Requires equipping a local network of intersections, and algorithms to examine vehicle speeds and trajectories to optimize traffic flow through the network
Eco-Approach and Departure at Signalized Intersections (hub)	3 arterials (15 intersections)	$$	◆◆	◆◆	◆	Similar to local, but on a larger scale of deployment; all information will be routed to the RTMC and back to CAVs traversing the arterials.
Queue Warning	1 bottleneck	$$$	◆◆	◆◆	◆	Requires roadside equipment, algorithms to detect queues, and methods to disseminate that information to drivers (V2V or infrastructure-based warning systems).
Dynamic Speed Harmonization	1 bottleneck	$$$	◆◆◆	◆◆◆	◆◆	Requires roadside equipment, and algorithms to detect congestion, incidents, weather, etc. and warn drivers in a way that achieves compliance. (AVs would automatically follow system recommendations.)

Spot Weather Impact Warning	1 location	$$$$	♦♦♦♦	♦♦♦♦	♦♦♦	Requires weather sensor and RSE to alert drivers of potentially problematic weather conditions.
Probe-Based Pavement Maintenance	Unknown	$$$$ $$$	♦♦♦♦ ♦♦	♦♦♦♦ ♦	♦♦♦ ♦♦	Requires intelligence in vehicle that has not yet been defined.
Probe-Enabled Traffic Monitoring (hub)	30 intersections	Unknown	Unknown	Unknown	Unknown	Requires RSE deployment and connection to RTMC; large scale of deployment.
CV-Enabled Traffic Studies	1 intersection	$$$$	♦♦♦	♦♦♦♦	♦♦♦	Currently a wide range of hypothetical studies, including vehicle classification-based, turning movement and intersection analysis, and origin-destination studies.
Intelligent Traffic Signal System (hub)	30 intersections	$$$	♦♦	♦♦♦♦	♦♦♦	Requires high-fidelity data collection; includes pedestrian and non-motorized travelers; will require development of system wide optimization algorithms and software.

4.7 CONTROLLER UPGRADE AND RETROFIT OPTIONS

While there are many different CV applications, each with a different data needs and flows, ultimately the applications share many of the same hardware needs, especially from an infrastructure perspective. Arguably, the most significant of these is the equipment needed to generate and broadcast J2735 SPaT and MAP data, which requires a compatible signal controller, networking hardware, processing power, and a DSRC radio. Several applications require this functionality to work at all, while other applications may only require some of these components.

As was seen in Chapter 3, signal control hardware is typically turned over quite slowly. The importance of this hardware and need for reliability, combined with the cost of the equipment, personnel costs for maintenance, and the large number of signals managed by some agencies, this hardware is often not replaced for decades at a time. Therefore, an important part of preparing for connected vehicles lies in determining the various options an agency has for equipping their signals to operate in a CV environment.

Given the information on the common controllers in Minnesota, the discussion can now focus on the degree of interoperability afforded by each model, particularly in regards to the standard(s) to which the controllers comply. Essentially, the issue comes down to whether a controller has the capability to transmit SPaT information to another device in a format that device can read using a compatible physical interface. In the event a controller is not capable of this, it is important to establish the options for upgrading that controller without replacing other equipment, such as the cabinet and wiring, which would add a significant cost to the process.

Figure 4.1 through Figure 4.7 contain a number of schematics summarizing the general options available to Minnesota road operators for upgrading their hardware to achieve CV readiness. Because the majority of signals in Minnesota follow the NEMA family of standards, most of these cases relate to the options for dealing with TS1 and TS2 cabinets, with the last case relevant to the few Model 170 controllers remaining in the state.

All of these figures have some things in common, primarily due to the common hardware required for an intersection to support CV applications. These include the DSRC RSU for communicating with vehicles from the roadside; a local Ethernet network for connecting the RSU, signal controller, and other devices in the cabinet; and some form of network connection to the Internet to communicate with the SCMS. The decision as to what kind of communication line is suitable depends on the resources (and existing communication infrastructure) of the agency, the architecture used (local/distributed vs. center/hub), and the applications to be supported. These issues, which are discussed in more detail in Section 4.2.4 , guide whether an agency can use existing low-bandwidth connections, quickly install a high-latency cellular modem, or if they must install a fiber optic line to the cabinet. Depending on the CV application(s) to be implemented, agencies may also need to place application-specific sensors, such as pavement sensors for detecting poor pavement conditions due to weather, or pedestrian sensors.

In addition to this, each controller variant that is referenced must have two key features: a method for communicating with other devices, either an Ethernet port or a serial port; and NTCIP-compliance, which

enforces a standardized communication protocol for encoding signal programming and status information. Both of these features are mandated by the NEMA TS2 (which requires an RS-232 serial port) [57], and ATC standards (which requires an Ethernet port) though in many modern TS2 controllers manufacturers have gone above the requirements and included an Ethernet port. As in most of these scenarios, controllers that have an Ethernet port are the easiest to work with, since they can be connected directly to a network. By contrast, the scenarios presented in Figures Figure 4.2 and Figure 4.4, in which the controller has only a serial port, the controller can still be used by installing a serial-to-Ethernet server, which makes the serial port of the modem available to network devices.
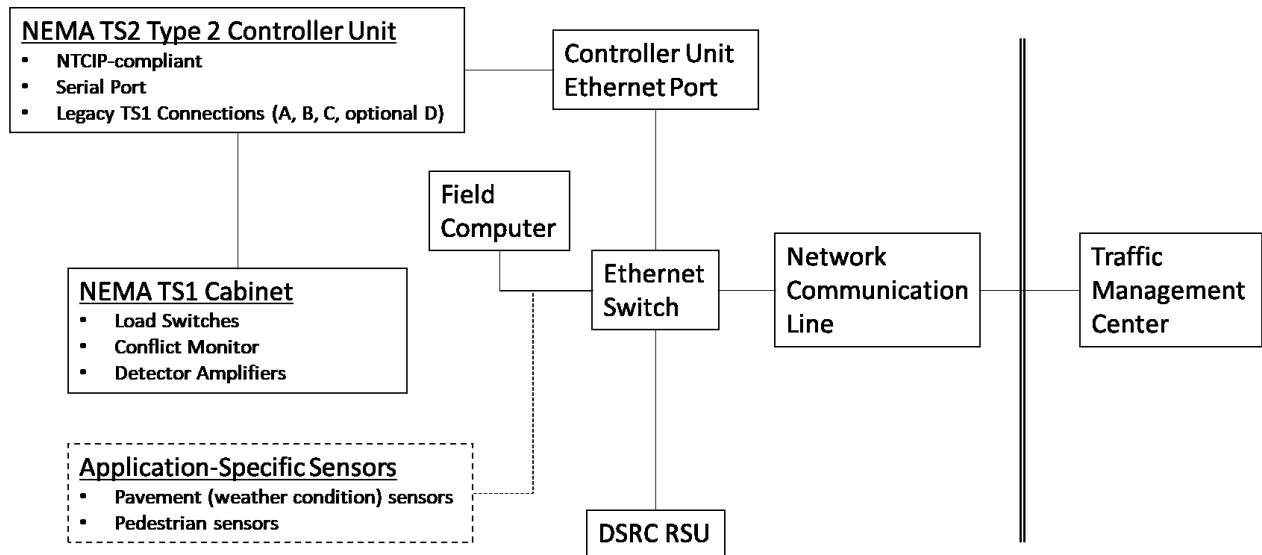
Figure 4.1 Schematic of a retrofit scenario involving a NEMA TS1 Cabinet and a TS2 Type 2 Controller Unit with an Ethernet port, achieving CV readiness through addition of networking hardware, a field computer, and a DSRC RSU.
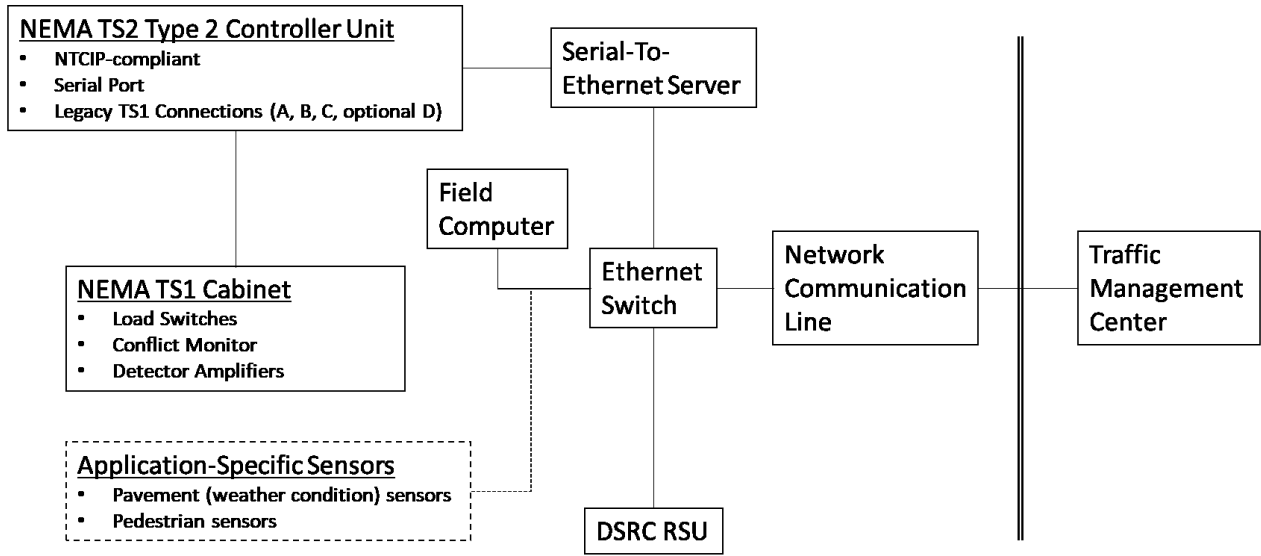
Figure 4.2 Schematic of a retrofit scenario involving a NEMA TS1 Cabinet and a TS2 Type 2 Controller Unit with a serial port, achieving CV readiness through addition of a serial-to-Ethernet server, networking hardware, a field computer, and a DSRC RSU.
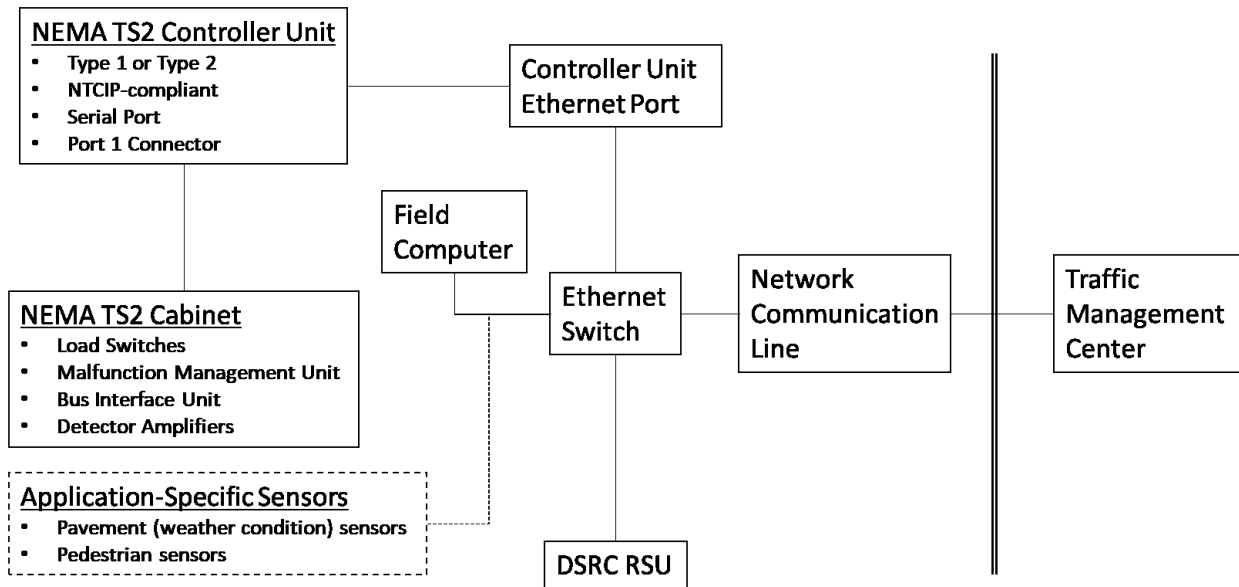
Figure 4.3 Schematic of a retrofit scenario involving a NEMA TS2 Cabinet and a TS2 (Type 1 or 2) Controller Unit with an Ethernet port, achieving CV readiness through addition of networking hardware, a field computer, and a DSRC RSU.
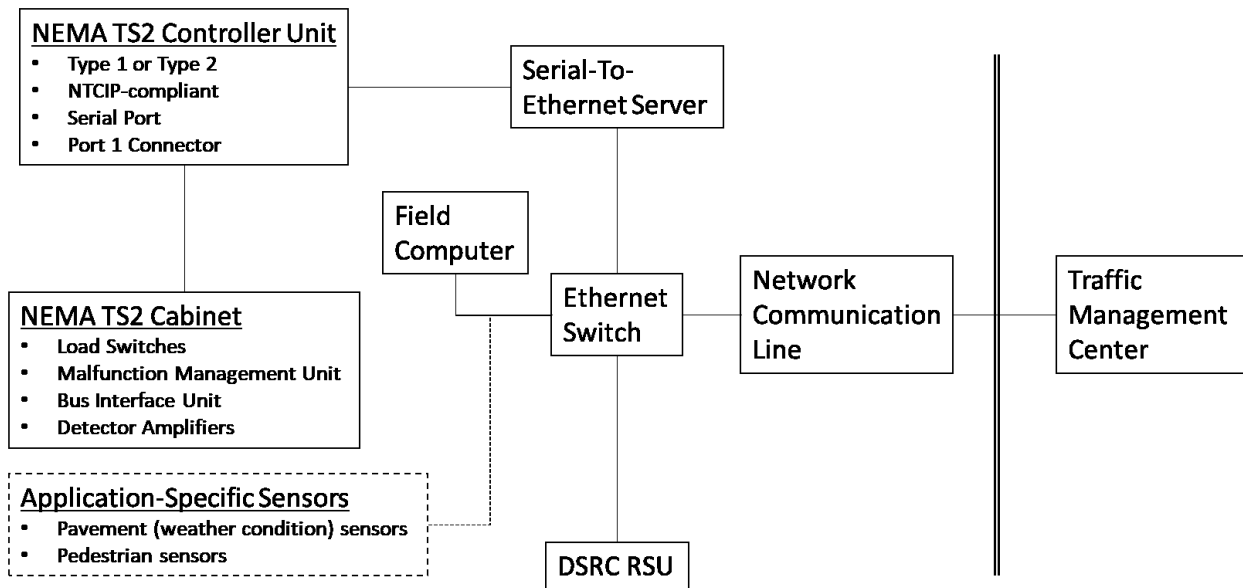
Figure 4.4 Schematic of a retrofit scenario involving a NEMA TS2 Cabinet and a TS2 (Type 1 or 2) Controller Unit with a serial port, achieving CV readiness through addition of a serial-to-Ethernet server, networking hardware, a field computer, and a DSRC RSU.
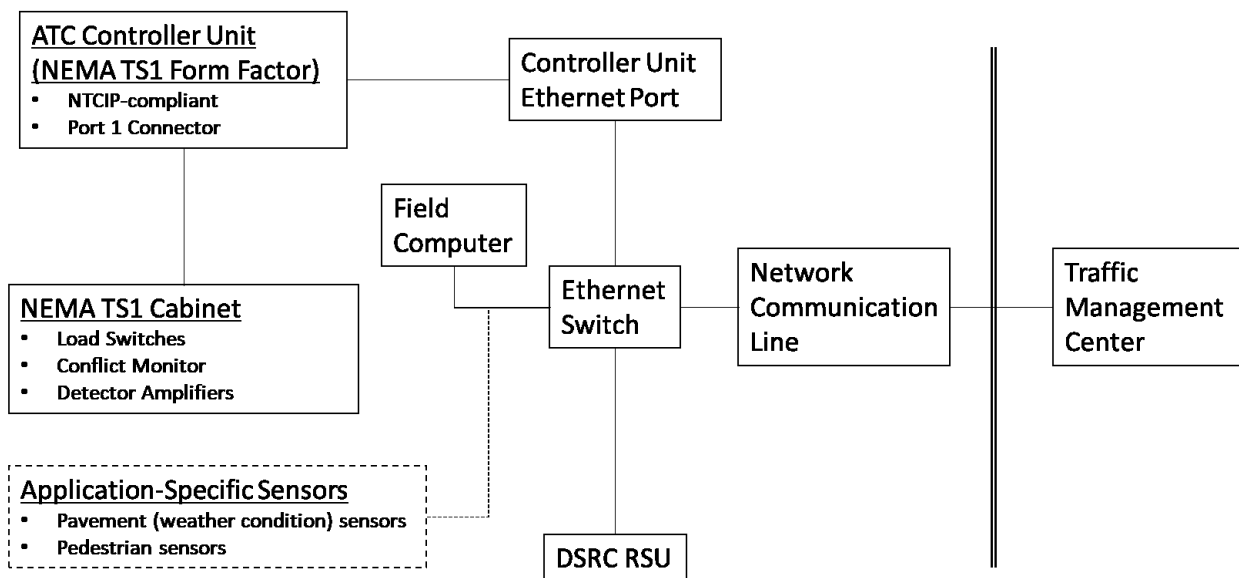
Figure 4.5 Schematic of an upgrade (or potentially retrofit) scenario involving a NEMA TS1 Cabinet and a TS1-form factor ATC Controller Unit. The ATC simplifies provides base functionality that simplifies attaining CV readiness, in some cases producing J2735 SPaT messages natively, requiring the addition of networking hardware, a field computer (if additional processing power is needed for applications), and a DSRC RSU.
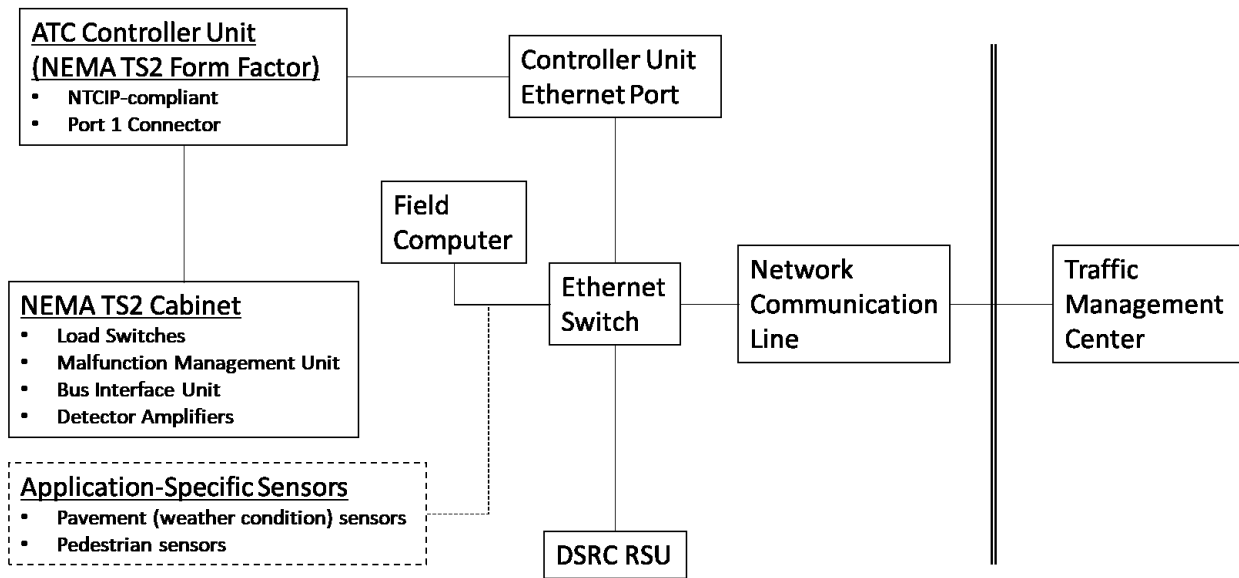
Figure 4.6 Schematic of an upgrade (or potentially retrofit) scenario involving a NEMA TS2 Cabinet and a TS2-form factor ATC Controller Unit. The ATC simplifies provides base functionality that simplifies attaining CV readiness, in some cases producing J2735 SPaT messages natively, requiring the addition of networking hardware, a field computer (if additional processing power is needed for applications), and a DSRC RSU.
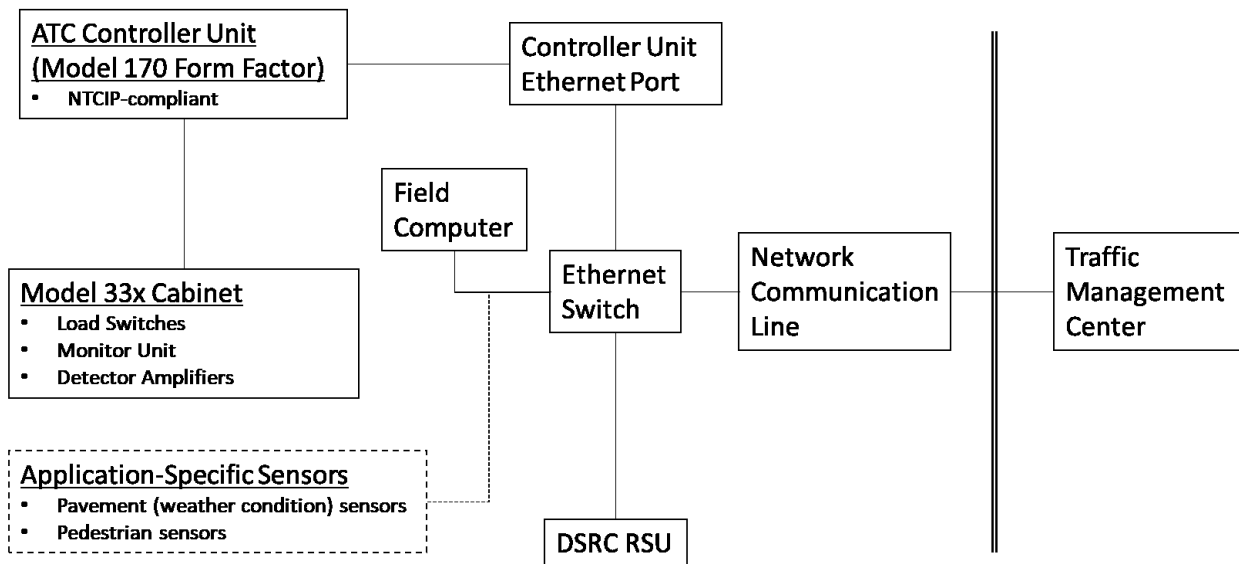
Figure 4.7 Schematic of an upgrade scenario involving a Model 33x Cabinet (such as for a Model 170, Model 2070, or TEES controller) and a Model 170-form factor ATC Controller Unit. The ATC simplifies provides base functionality that simplifies attaining CV readiness, in some cases producing J2735 SPaT messages natively, requiring the addition of networking hardware, a field computer (if additional processing power is needed for applications), and a DSRC RSU.

The last thing to note about the ATC scenarios specifically is that the ATC standard requires that controllers have a field-hardened processor capable of running arbitrary software installed by the user (agency). This may eliminate the need for a separate physical field computer. However, depending on the deployment the integrated processor may not be sufficiently powerful to run software for certain applications. If agencies simply wish to generate and broadcast J2735 SPaT and MAP messages, the integrated processor may be sufficient (and may be accompanied with software for producing these messages), with any application-specific software running in the vehicles. If the agency wishes to run more complex applications, they may determine through testing whether or not the integrated processor is powerful enough to meet the needs of the application.

CHAPTER 5: CURRENT READINESS OF LOCAL STAKEHOLDERS FOR CONNECTED VEHICLE FUTURE

When it comes to the issue of connected and automated vehicles, the primary area of concern for local road operators relates to the traffic control infrastructure they manage. The most notable of these are traffic signal controllers and cabinets. However, some static traffic control devices such as traffic signs and pavement markings are also important to CAVs, as described in Chapter 2. With the focus of this project on the needs of these stakeholders, researchers made a point to gather information about their needs, priorities, and practices as they relate to CAVs. This information was used to help direct efforts ensuring that the findings of the project were as useful to Minnesota road operators as possible and minimizing any irrelevant information. To obtain this information, researchers employed two methods. First, a survey was distributed to road operators asking about their practices for maintaining traffic control hardware, as well as their interest in connected vehicles in general and in regards to specific applications. In addition to this, researchers also worked with MnDOT's Signal Operations group to obtain a catalog of information describing the signal hardware maintained by the majority of agencies that operate signals. Together, these information sources allowed researchers to develop an assessment of the readiness of these agencies and for the future of connected vehicles.

5.1 SURVEY OF LOCAL ROAD OPERATORS

Because of the information obtained from MnDOT describing signal hardware around the state, the survey that was distributed was developed to compliment this data. This meant focusing primarily on identifying equipment turnover and maintenance practices, any non-standard or customized hardware currently in the field, and the respondents' interest in connected vehicle applications. A summary of the most relevant findings is presented in the following sections; the full survey text can be found in Appendix A, while full response information can be found in Appendix B.

5.1.1 Equipment Turnover and Maintenance

To understand how local agencies deal with the maintenance of their infrastructure, the survey included questions asking how frequently they replace equipment and how they decide to do so. On the issue of traffic signal controllers, the vast majority of respondents stated that they only replace controllers when the need arises. For those that did provide a timeframe, the most common answer was every 16-20 years. The most common reason for replacement was due to old, obsolete, or damaged controllers, though a small percentage of respondents stated replacing controllers after construction or changes in the intersection.

Signal cabinets are primarily replaced when necessary, albeit somewhat less frequently than controllers, with the most common answer from those who provided a timeframe being every 25-30 years. Reasons for replacing cabinets were similarly primarily due to damage or poor condition, though a significant number also recorded replacing cabinets after construction or changes in the intersection. A small share of respondents also stated that space restrictions in the cabinet were a driver for replacement.

Regarding traffic signs, most respondents indicated that they replaced signs every 10-15 years, with the next most common answer being every 15-20 years. This matches the typical life expectancy of traffic signs, which is anywhere from 12 to 30 years, depending on the type of sheeting material used [40]. Most respondents indicated that they performed inspections to evaluate which signs are in need of replacement, though regularly-scheduled replacements and reports from the public were also used to make these decisions. The quality of pavement markings was mostly maintained by regularly-scheduled applications, as winter weather conditions significantly shorten the life expectancy of pavement markings in Minnesota. Pavement marking inspections were also a significant factor. Though the question was not included in the survey, the MnDOT Traffic Engineering Manual indicates that the lifespan of surface-applied pavement markings on arterials is typically 1 year for Latex paint and 3-5 years for Epoxy. Recessed pavement markings, which one respondent recorded using, typically last slightly longer, with a life expectancy of 5-7 years [59].

Respondents were also asked how they keep records regarding the maintenance of infrastructure. By a small margin, the most popular answer to that question was the use of an asset management software or service. This is encouraging, as an asset management system provides the best means for ensuring a centralized record of the condition of infrastructure that may be critical for the operation of CAVs with minimal manual effort. However, in many cases agencies still use spreadsheets, paper records, or PDF files to track maintenance activities. Due to the manual effort required to keep these types of records up-to-date for all the relevant parties, it is recommended to change to a less labor intensive, centralized record keeping system as CAV technology evolves and proliferates.

5.1.2 Non-Standard Hardware and Communication Capabilities

As traffic signal technology has evolved, one of the most important developments has been the increase in the use of technical standards to ensure functionality and interoperability of traffic control systems. While newly-acquired equipment is generally standard-compliant, due both to the demand from operators purchasing the equipment and from manufacturers committing to the standards that have been developed the extended turnover rates of this equipment means that there is still a considerable amount of old hardware in the field. This affects the ability of operators to support many CV applications, as non-standard or custom hardware can be difficult to integrate with the newer hardware that is required for these applications. In addition to this, while many agencies have made efforts to add communication capabilities to their signals, many still have not. This is also important, as a robust communications network is a basic requirement of all V2I/I2V CV applications. This information from survey responses is presented in Table 5.1.

On the issue of non-standard cabinets, most agencies have few of these remaining in service, making up about 4% of cabinets of known status. Use of custom wiring, which is a common method for implementing phase overlaps when controllers lack functionality or for working around a hardware phase limit in an older cabinet is somewhat more common, but is still only known to be used in about 9% of cabinets. Given the number of "Unknown" responses, there is some error associated with this estimate.

Table 5.1 Information about traffic signals collected from survey of local road operators, sorted by descending number of signals. Responses are reported more or less as stated by the respondent, with a few inconsistent/unreliable responses removed entirely. Survey totals were calculated by calculating the number of signals in each category using the total number of signals and percentages, then dividing the number of known values by the corresponding number of signals (excluding unknowns).

Agency Signal Count	% Non-standard Cabinets	% Custom Wiring	% With Communication
250	0	5	95
200	5	25	60
180	0	0	40
125	10	10	95
100	0	0	75
55	Unknown	Unknown	Unknown
30	15	10	0
17	Unknown	Unknown	0
16	Unknown	Unknown	Unknown
16	15	0	70
15	0	Unknown	Unknown
10	Unknown	Unknown	Unknown
8	0	50	75
7	0	Very Little	0
4	100	Unknown	0
3	0	0	0
2	0	0	0
1	0	0	0
1	0	0	0
1	0	0	100
1	0	0	0
1	1	0	0
Survey Total	**4%**	**9%**	**68%**

Regarding communication, the survey data shows that a majority of signals are connected to an agency's network in one form or another. Agencies that manage more signals tend to have more networked signals, as it considerably helps streamline their operations, though some of the smaller agencies are also fairly well covered. As with the question of non-standard cabinets and custom wiring though, there are some errors in these numbers.

5.1.3 Interest in Connected Vehicle Applications

In addition to finding out information about the signals managed by each agency, the respondents' interest in connected vehicles, both generally and with regards to specific applications, was also queried.

In general, most respondents were "somewhat interested" in connected vehicles, with "very interested" and "neither interested nor disinterested" the next most popular responses. Few respondents indicated that they were "not very" or "not at all interested." When asked why they were interested in connected vehicles, the most popular answers were "improving road user safety" and "improving mobility," with a significant share also stating interest in things such as improving fuel economy, reducing environmental impacts, better communicating information to drivers, improving incident/emergency management, and improved data collection for operations and maintenance, the last of which is particularly suited to road owners.

When asked about specific CV applications, the most popular applications were in the "Safety" group, with Work Zone Warning, Curve Speed Warning, and Pedestrian in Signalized Crosswalk warning the most popular choices. Applications in the "Road Weather" category, such as Weather-Responsive Traffic Management were also popular. Mobility Applications, such as Integrated Corridor Management and Queue Warning and Speed Harmonization, while generally less applicable to local road operators than to State DOTs that manage freeways, were also popular. Environmental Applications, especially Eco-Traffic Signal Priority and Eco-Traffic Signal Timing, which are directly related to local road operators and the signals they manage, were also quite popular. The number of votes and interest score (which combines interest ratings from 1 to 5) for each application are presented in Table 5.2.

Table 5.2 Number of votes and interest score for each application mentioned in the survey. Respondents were asked to choose up to two applications from each categories (each counting as a "vote"), then rate each of their chosen applications on a scale from 1 to 5. The interest score is calculated as a weighted average of the score, with a rating of 1 weighted by 1/5, a rating of 2 weighted by 2/5, and so on.

Application	Number of Votes	Interest Score
Environmental Applications		
Eco-Approach and Departure at Signalized Intersections	5	3
Eco-Freight Signal Priority	1	0.6
Eco-Transit Signal Priority	7	3.6
Eco-Traffic Signal Timing	9	5.4
Mobility Applications		
Connection Protection	4	3
Dynamic Ridesharing	1	0.4
Integrated Corridor Management	11	8.2
Queue Warning and Speed Harmonization	10	4.8
Response, Emergency Staging and Communications, Uniform Management and Evacuation (R.E.S.C.U.M.E.)	8	5
Road Weather Applications		
Road Weather Connected Vehicle Applications	13	10
Information and Routing Support for Emergency Responders	2	1.8
Enhanced Maintenance Decision Support System (MDSS)	7	5.2
Information for Freight Carriers	1	0.6

Information for Maintenance and Fleet Management Systems	5	3.4
Motorist Advisories and Warnings	8	6.2
Weather-Responsive Traffic Management	8	6.4
Safety Applications		
Do Not Pass Warning	2	1.4
Emergency Electric Brake Light Warning	2	1.4
Intersection Movement Assist	3	2.4
Lane Change Warning/Blind Spot Warning	5	3.6
Forward Collision Warning	5	4
Truck Forward Collision Warning	1	0.8
Left Turn Across Path	3	2.4
Vehicle Turning Right in Front of Bus	0	0
Red Light Violation Warning	4	4
Stop Sign Gap Assistance	5	4
Work Zone Warning	13	10.6
Curve Speed Warning	9	7.2
Pedestrian in Signalized Crosswalk	7	6.6
Connected Vehicle for Safety Rail	0	0
Transit Bus Stop Pedestrian Warning	0	0

5.2 TRAFFIC SIGNAL CONTROLLERS AND CABINETS CURRENTLY IN THE FIELD

Traffic signal controllers and cabinets play a critical role in a CAV ecosystem by providing Signal Phasing and Timing (SPaT) information, a basic requirement of many CV applications, to vehicles. Ensuring that the roads operated by an agency are ready for CAVs means ensuring that the traffic control hardware in use is compliant with the relevant standards that govern how this hardware interacts with the emerging V2I/I2V communication infrastructure.

5.2.1 Traffic Signal Controllers and Cabinets

At first sight, the issue of CAV compatibility with traffic signal controllers may seem daunting. With many different manufacturers selling signal controllers and cabinets that comply with multiple standards and have varying levels of backwards-compatibility, several manufacturers of DSRC hardware, and hardware and software vendors offering "plug-and-play" solutions for obtaining real-time information from any traffic signal controllers distinguishing fact from sales pitches can be difficult. Ultimately the issue can be reduced down to a few key standards, discussed in Section 4.3.1 , that clearly define the required hardware and software interoperability, as well as options for retrofitting older hardware with newer, backwards-compatible models. Regardless of the manufacturer, compliance with these standards will be clearly defined and that can be used to assess the options for working with or replacing a particular piece of hardware. This section gives an overview of the common controllers in Minnesota, based on

information obtained from MnDOT signal operations staff on the hardware in place at the majority of signalized intersections around the state (last updated in April 2016), for context. This leads into the discussion of CAV-readiness in Chapter 4, which focuses on the standards that these controllers do or do not comply with and any features that might otherwise affect interoperability with other systems.

5.2.1.1 Common Controllers and Cabinets in Minnesota

A notable piece of information accompanying the signal catalog information obtained from MnDOT is the manufacturer and model of controllers at each of the signalized intersections. A summary of this information is provided in Table 5.3. Though in some cases this information is limited, as the level of detail provided by each agency varies, it is still helpful in providing a picture of the hardware currently in the field and the general readiness of these systems for future developments in CAV technology. Regarding controller manufacturers, by far the most common controllers in Minnesota are manufactured by Econolite. The notable exception to this is the City of Minneapolis, which primarily uses Siemens controllers in addition to some Peek controllers. There are also a handful of Eagle Traffic Control Systems controllers (now owned by Siemens). Finally, there are a handful of older 170 controllers where a manufacturer is not specified.

While knowing the manufacturer of a controller can be helpful for context, regarding CAV compatibility the more important issue is the model of the controller, which provides information on any standards the controller complies with and any important features that make it more or less interoperable with other systems. In some cases it is not clear what specific model is being used, but nonetheless there are some key takeaways. First, the majority of the controllers currently installed are either ASC/3 or ASC/2 Econolite models, which are fairly recent models. Most of these are the 2100 series, indicating that they are NEMA TS2 Type 2 controllers. However, that means that they may be installed in NEMA TS2 cabinets, or older NEMA TS1 cabinets, for which Type 2 TS2 controllers provide backwards compatibility. In some cases the specific model of ASC/3 controller is not specified, so it is possible that they may be the Cobalt model, which is ATC-compliant. While ASC/2 models generally do not have an Ethernet port for network connectivity, they do have a serial port and are NTCIP 1202-compliant, meaning that they are still capable of interfacing directly with other hardware. ASC/3 controllers, by contrast, do have an Ethernet port in addition to maintaining NTCIP compliance. In addition to these controllers, there are a number of ASC/2 and ASC/3 1000-series models. These are NEMA TS2 Type 1 controllers, meaning that they must be installed in a NEMA TS2 cabinet, which is a much more recent standard. Though these controllers are relatively new and can likely work with other systems, there are a few dozen cases of much older Econolite ASC-8000 models, which are NEMA TS1 controllers. It is difficult to find detailed information about these controllers given their age, but the available materials suggest that they do have a serial telemetry port that could be used to output real-time controller information. Despite this, however, the controllers predate the NTCIP 1202 standard, making interoperability with newer devices difficult or impossible.

The signal controller catalog information that researchers have available does not specify the models of Siemens or Peek controllers that are installed. Regarding the approximately two dozen Eagle controllers in the field, a few of these are M52 models, which are NEMA TS2-compliant, though the remainder are EPAC-3000 controllers, which are NEMA TS1 controllers and thus present the same issues as the Econolite

ASC-8000. The last group of controllers, which are based on the 170 standard, are also quite dated, though the considerations regarding these controllers are different as this standard comes with a different form factor and different design considerations.

In addition to these controllers, MnDOT has also recently begun working with controllers manufactured by Intelight, the same vendor that provides their ATMS system MaxView. All of these controllers are ATC-compliant controllers, and though other agencies do not yet seem to be using them, it is likely that some will follow MnDOT in experimenting with these controllers.

Table 5.3 Information describing traffic signal controller manufacturers, models, and standards around Minnesota, broken down to totals for State-, County-, and City- level jurisdictions. These data were partially cleaned by researchers to create consistent categories, assuming the oldest technology where it was not clearly specified to provide a worst-case picture of agency CV-readiness.

City / County	ASC/2S-2100 (NEMA TS2 Type 2)	ASC/2S-1000 (NEMA TS2 Type 1)	ASC/2M-1000 (NEMA TS2 Type 1)	ASC/3-2100 (NEMA TS2 Type 2)	ASC/3-1000 (NEMA TS2 Type 1)
MnDOT	51.6%	0.0%	0.0%	45.5%	0.1%
County Totals	57.6%	7.3%	0.1%	29.1%	2.8%
City Totals	5.4%	0.0%	0.2%	6.6%	0.0%
Statewide Totals	36.1%	2.7%	0.1%	24.6%	1.1%
(continued)	ASC-8000 (NEMA TS1)	DELTA 3 (Standard Unknown)	EAGLE EPAC-300 (NEMA TS1)	EAGLE M52 (NEMA TS2 Type 2)	170
MnDOT	0.4%	0.1%	1.0%	0.0%	0.0%
County Totals	2.7%	0.0%	0.1%	0.0%	0.0%
City Totals	1.1%	0.0%	1.3%	0.3%	5.2%
Statewide Totals	1.5%	0.0%	0.8%	0.1%	2.0%
(continued)	PEEK	Siemens	Under Construction	Unknown	Total # Signals
MnDOT	0.0%	0.0%	0.0%	1.2%	671
County Totals	0.0%	0.0%	0.0%	0.2%	983
City Totals	1.9%	76.3%	0.1%	1.7%	1029
Statewide Totals	0.7%	29.3%	0.0%	1.0%	2683

5.2.1.2 Communication Capabilities of Controllers in Minnesota

In addition to information about the controller manufacturers and models around the state, the signal catalog provided by MnDOT also provides information describing any communication present at the cabinet. This is similar to the information requested in the survey, but goes into a greater level of detail in describing the actual communication technology used (e.g. fiber optic lines, DSL/phone lines, cellular modems, etc.). While the specific technology used is not especially important for this report, the bandwidth and latency afforded by the technology does have an impact on the options for an agency

when implementing various applications. Again, there are limitations to this information due to variations in the specificity provided and terminology used by each agency, however it is still a good gauge of the degree of CV-readiness around the state regarding communication.

Table 5.4 presents a summary of this information showing frequency of high- or low- bandwidth communication lines, and general presence or lack of communication, again broken down to totals for State-, County- and City- level jurisdictions. Some assumptions were made when processing these data to account for lack of specificity provided by the signal operators, declaring any ambiguous answers to be the lowest-bandwidth, highest-latency technology of the potential options. As for how the different technologies fall into high-bandwidth/low-latency vs. low-bandwidth/high-latency, the only technology considered high-bandwidth/low-latency was a fiber optic connection, which provides the best performance over long distances compared to the alternatives. Other technologies may be capable of providing sufficient bandwidth or latency depending on the application, however without more detailed information the only assuredly safe communication technology is fiber optic.

Table 5.4 Information describing the communication availability for traffic signals around the state, broken down into high-bandwidth or low-latency technologies (fiber optic) and low-bandwidth or high-latency technologies (DSL, cellular, etc.). These data were partially cleaned by researchers to create consistent categoeis, assuming the lowest-bandwidth, highest-latency technology where it was not clearly specified to provide a worst-case picture of agency CV-readiness and implementation options.

City / County	Total # Signals	% High-Bandwidth or Low-Latency	% Low-Bandwidth or High-Latency	% With Any Comm.	% No or Unknown Comm.
MnDOT	671	33.7%	59.0%	92.7%	7.3%
County Totals	983	15.4%	25.2%	40.6%	59.4%
City Totals	1024	7.5%	81.3%	88.8%	11.2%
Statewide Totals	2678	17.0%	55.1%	72.1%	27.9%

It is also important to note that, in absence of more detailed information, some of these signals may need additional communication hardware to meet the requirements of a CV ecosystem. Namely in the case where the communication is a phone line that requires a point-to-point connection, and where there is no modem present (i.e. operators still dial the controllers one at a time), these controllers would not support the specifications required for the basic CV infrastructures. In these cases, the number of which is not clear (if any remain), agencies would need to install modems that support the Point-to-Point Protocol (or similar) to bring these signals onto their network. This is necessary because CV hardware assumes Internet Protocol communications to be present to provide the flexibility and scalability required by these systems.

CHAPTER 6: RECOMMENDATIONS

Though at this point in time, it is impossible to predict the true costs or benefits that will come from CAVs, local road operators can generally prepare for their deployment in the following ways.

6.1 MAINTAIN ROAD MARKINGS

Both clarity and reflectivity of road markings will determine the success of lane-marking based applications such as lane keeping and lane departure warning. At early stages of CAV development and deployment, the sensors that CAVs use to perceive other vehicles, the roadway surface, and other roadway objects must be able to detect and discern pavement lane markings.

Two major barriers to accurate lane marking detection are paint wear and inclement weather, such as severe rain or snow, which reduce retroreflectance. Especially with the potential for extreme winter weather in Minnesota, this will need to be taken into account for roadway maintenance schedules and materials used in road markings.

As CAV technologies mature, advances in sensor technology content-based navigation (i.e., using light poles as navigational markers) are expected to be developed. Until then, local road operators should follow any MUTCD updated guidelines on retroreflectivity as the FHWA adopts them.

6.2 MAINTAIN CLEAR ROAD SIGNS

Like road markings, clarity and reflectivity are critical to road sign based applications such as stop sign gap assist. Sensors and cameras on CAVs must be able to detect signs clearly and quickly enough to react. If signage is poor, more expensive and advanced sensors will be required to detect non-compliant signage or make the correct decision without it.

As CAVs are being developed, local road owners may want to rehabilitate signs, and update them to have better retroreflectance. As technology advances, signs themselves may either have new RSE attached to them, or need to be replaced with RSE-integrated infrastructure. Road owners are encouraged to keep up with these advancements and determine what solution works best for their roadways.

6.3 MODERNIZE ROADWAY DESIGN INFORMATION

The increase in CAVs will most likely lead to changing requirements and consistent updates in the Roadway Design Manual. Certain requirements that may change include those for sight distance, curve radii, cross-sectional slopes, and other geometric elements of design. Ideally, road owners will make updates in concurrence with any changes to the AASHTO Roadway Design Manual; even if AASHTO does not make significant changes, road owners should still consider updating their own documentation to ensure that road users can benefit from CAVs, and to ensure the safety of these road users.

Additionally, accurate, high-resolution digital maps will be required for certain applications, and helpful for others. These maps will need to detail exactly where the roadways are and what their features are. They will also need to be kept up to date, as CAV applications depend on current, precise information. Smaller jurisdictions with no digital maps will need to create them; even larger jurisdictions with existing digital maps will need to ensure that they are in an upgradeable and uploadable form. Currently, GIS and CAD are two upgradable, uploadable, and ubiquitous formats for these maps.

Road design information should also move to fully digital form, preferably GIS but at a minimum CAD. MnDOT has set an industry example by collaborating with EZRI for ArcGIS server links to GIS road design information. Even with multiple departments involved in road design, they are able to create and upload compatible files via the GIS department.

6.4 MODERNIZE CONTROLLERS

Current controllers are already universally standardized with ASC wiring and NEMA language, but as CAVs enter the market, controllers will become a "wild west" of technology. A simple, industry standard controller with ASC-2 and NEMA will be able to upgrade to ASC-3 as it becomes available, but doesn't have the potential for more than that. More complex controllers are already on the market, including an additional on-board computer with ports for connections, as well as extra space for expanding computing power and connection ports. These controllers have room to grow with the unpredictable demands of the developing CAV marketplace. Also, without a computer and connections, after-market equipment cannot be connected to industry standard controllers without custom solutions.

Companies are moving toward generic computing platforms; this disruption is fueled by uncertainty regarding CAV technology needs. With a computer on board, controller companies can develop software to meet the needs of CAV applications; this is much cheaper and easier than upgrading hardware or releasing new boxes every time a controller upgrade is required by new technology. With connection ports, after-market equipment can be easily added to a cabinet.

As possible, local road owners should consider investing in a controller with a computer and ports to aid the transition into CAV technologies. A controller with room for growth is ideal, as it is hard to predict what software and after-market hardware will be developed for CAVs.

6.5 DEVELOP COMMUNICATION INFRASTRUCTURE IF POSSIBLE

In places without communication infrastructure, road owners should consider installing information networks capable of handling the amount of data a connected roadway will produce (e.g. extend fiber networks, etc). Particularly for hub-based applications, high speed communication will be important for real-time applications with the potential to be affected or rendered useless by lag.

Connectivity is critical for new deployments of hardware; isolated, disconnected islands of technology will soon become deficient as the "Internet of Things" is created. Not all RSUs will require costly, high speed connections; the level of communication an RSU needs will vary depending on applications it is

used for. A simple 3G smartphone may be all that is necessary for a local communication, whereas high speed fiber optic will be required for hub applications.

6.6 FOLLOW GUIDANCE FROM USDOT, LOCAL DOT

It will be important for road owners to look to transportation agencies at the federal, state and local level for guidance while preparing for CAVs. In addition, staying up to date on current CAV research and pilot sites such as those in Florida, Wyoming and New York will be critical to bridge the gap between simulated connected roadways and real-world ones. Road owners should also follow any legislative and policy developments at the state and federal levels.

CHAPTER 7: CONCLUSION

This report serves as a comprehensive guide to feasible CAV technologies and applications at present. Local road owners, agencies, or anyone with an interest in CAVs can read it to better understand the current state of readiness and what steps will need to be taken to ensure roadways are ready for CAV deployment.

Though each stakeholder and agency will have different interests, general recommendations for CAV readiness are provided in CHAPTER 6: . Specific application efforts are also available in CHAPTER 4: for those seeking more detailed requirements and recommendation.

Stakeholders may also reference the deliverable matrix developed to accompany this document for a quick overview of CAV applications and needs. CHAPTER 4: has descriptions of all applications included on the matrix, and the other categories are defined in Table 7.1.

The matrix is included here as Table 7.2.

In addition, the comprehensive literature review created as a task for this report incorporates technologies, applications, and readiness options, as well as the current pilot sites in Florida, Wyoming and New York. This literature review stands on its own as a document that any interested stakeholder may read for background knowledge of CAV efforts.

For the benefits of this project to be truly realized, new policies will need to be determined and supported. For example, ways to implement the findings of this research may involve enacting legislation to stimulate CAV testing, implementing new contractual mechanisms with private service providers, investing in CAV infrastructure, or subsidizing CAVs by implementing land-use policies and parking requirements, or granting CAVs priority access to dedicated lanes. Even then, the recommendations provided in this report offer considerations for state and local agencies given the best information available at this time. Technology direction may change, consumers may not adopt certain products, and any number of global economic or environmental drivers could alter the policy course. Even within such uncertainty, it is incumbent on state and local agencies to use available policy and planning strategies to nudge private-sector choices regarding CAVs toward outcomes that would benefit society, thus aligning public- and private-sector interests in the technologies. Ultimately, transportation planning and policy making for CAVs will be informed through a cycle of learning and leveraging of early adopter agencies that support testing, evaluation, research, and continuous knowledge creation.

Table 7.1 Deliverable definitions.

Category	Definition
Operational Context	Infrastructure-based (i.e., visual cues, signs), V2I, V2V, or V2X
Road Side Unit required?	Whether or not the application requires a road-side unit to function; it may be communicating only with vehicles or with the Regional Traffic Management Center
Sensors	The type of sensors required for the application, e.g., vehicle-based sensors (cameras), crosswalk pedestrian sensors, train detection circuits
Communication	Local or global; also indicates whether Signal Phasing and Timing (SPaT) and MAP messages are required for the application
Infrastructure Architecture Needs	Any infrastructure needs specific to the application
Weather	Whether weather information is required for the application — "N/A" means the application is unaffected by weather conditions, "optional" means it could be included to upgrade application functionality, and "required' is required.
Infrastructure-based software available?	Whether or not infrastructure-based software for the application is available at the time of publication.
Estimate of cost of equipment** $ to $$$$$	Represents the material cost of equipment (sensors, infrastructure, etc.) required for the application. This cost varies dependent on existing infrastructure and equipment. Our estimate is based on the most prevalent, current infrastructure in Minnesota.
Estimate of initial effort*** ◆ to ◆◆◆◆◆	Represents the abstract cost of effort representing the skilled labor and training required to deploy equipment or set up internal system infrastructure required for the application. For example, this would be the comparable cost of hiring a contractor to implement a system.
Estimate of integration effort**** ◆ to ◆◆◆◆◆	Represents the abstract cost required to install software, train staff or employ experts, and calibrate and maintain the system.
Estimate of ongoing cost***** ◆ to ◆◆◆◆◆	Represents the abstract cost of effort involved in the maintenance of equipment and systems, management of the system, as well as maintaining current staff in addition to employing specialists familiar with the system to run it, calibrate it, and keep it calibrated.
Minimum Deployment Size	The minimum deployment size to realize benefits of the application
System Level Benefit?	Does this application promote system wide benefits?

Table 7.2 Matrix of CAV Applications

Application	Operational Context*	Road Side Unit required?	Sensors	Communication	Infrastructure Architecture Needs	Weather	Infrastructure-based software available?	Estimate of cost of equipment** $ to $$$$	Estimate of initial effort*** ◆ to ◆◆◆◆◆	Estimate of integration effort**** ◆ to ◆◆◆◆◆	Estimate of ongoing cost***** ◆ to ◆◆◆◆◆	Minimum Deployment Size	System Level Benefit?
Lane Departure Warning/Lane Keeping	Infrastructure-based	No	Vehicle-Based	N/A	Uninterrupted and clearly visible lane markings	Optional	N/A						No
Traffic Sign Recognition	Infrastructure-based	No	Vehicle-Based	N/A	Clearly visible and reflective signage	Optional	N/A						No
Stop Sign Gap Assist	V2I	Yes	Sensors on the main road	Local	Signage	N/A	No	$$$	◆◆	◆◆	◆◆	1 intersection	No
Stop Sign Violation Warning	V2I	Yes	None	Local	Signage	N/A	No	$	◆◆	◆◆	◆◆	1 intersection	No
Railroad Crossing Warning	V2I	Yes	Train detection circuit	Local	Rail crossing controller	N/A	Yes	$	◆	◆◆	◆	1 intersection	No
Curve Speed Warning (I-B)	I-B	No	Sensors on the main road	Local	Signage	Optional	Yes	$$$	◆	◆◆	◆	1 location	No
Curve Speed Warning (V2I)	V2I	Yes	Sensors on the main road	Local	Signage	Optional	Yes	$$$	◆	◆◆	◆	1 location	No
Curve Speed Warning (CAV)	V2I	Yes	None	Local	None	Optional	No	$	◆	◆◆	◆	1 location	No
Reduced Speed/Work Zone Warning	V2I	Yes	None	Local	Static warnings (i.e., speed limit, change in lanes)	N/A	Yes	$$	◆	◆◆	◆	1 location	No
Upcoming Work Zone Warning	V2I	Yes	None	Local	Static warning of upcoming work zones	N/A	No	$$	◆	◆◆	◆	1 location	No
Red Light Violation (local)	V2V	Yes	None	Local; SPaT and MAP integrated with DSRC	none	N/A	Yes	$$	◆◆◆	◆◆	◆◆◆	1 intersection	No
Red Light Violation (hub)	V2V	Yes	None	Global; SPaT and MAP integrated with DSRC	Connection to Traffic Control Center	N/A	Yes	$$$	◆◆◆	◆◆◆	◆	10 intersections	No
Pedestrian in Signalized Crosswalk Warning (local)	V2I	Yes	Vehicle-based; crosswalk pedestrian sensor	Local	Intersections equipped with pedestrian detectors	N/A	Partial	$$	◆◆	◆◆	◆	1 intersection	No
Eco-Approach and Departure at Signalized Intersections (local)	V2I	Yes	None	Local; SPaT and MAP integrated with DSRC	Connected signals	N/A	Yes	$$$	◆◆	◆◆	◆	5 intersections	No
Eco-Approach and Departure at Signalized Intersections (hub)	V2I	Yes	None	Global; SPaT and MAP, communication with TMC	Connection to Traffic Control Center	N/A	Yes	$$$	◆◆◆	◆◆◆	◆◆	3 arterials (15 intersections)	No
Queue Warning	V2V, V2I	Yes	None	Local or global	Identification of bottleneck area	Optional	Yes	$$$$	◆◆◆◆	◆◆◆◆	◆◆◆	1 bottleneck	Yes
Dynamic Speed Harmonization	V2V, V2I	Yes	None	Global	Identification of bottleneck area	Optional	Yes	$$$$	◆◆◆◆	◆◆◆◆	◆◆◆	1 bottleneck	Yes
Spot Weather Impact Warning	V2I	Yes	Weather sensor	Local	Weather station	Required	Partial	$$$	◆◆	◆	◆◆	1 location	No
Probe-Based Pavement Maintenance	V2I	Unknown	Unknown	Unknown	Unknown	N/A	Pilots	Unknown	Unknown	Unknown	Unknown	Unknown	Yes
Probe-Enabled Traffic Monitoring (hub)	V2I	Yes	None	Global; capture and processing of BSM	Connection to Traffic Control Center	Optional	No	$$$$	◆◆◆	◆◆◆◆◆	◆◆◆	Urban network	Yes
CV-Enabled Traffic Studies	V2I	Yes	None	Local	Portable data collection station	Optional	No	$$$	◆◆	◆◆◆◆	◆◆◆	1 intersection	Yes
Intelligent Traffic Signal System (hub)	V2V, V2I	Yes	Unknown	Global; SPaT and MAP, communication with TMC	Fiber optic or equivalent; upgraded signal controllers (currently unavailable)	Optional	Yes	$$$$$	◆◆◆◆◆	◆◆◆◆◆	◆◆◆◆◆	30 intersections	Yes

*Infrastructure-based (i.e., visual cues, signs), V2I, V2V, or V2X

** This column represents the material cost of equipment (sensors, infrastructure, etc.) required for the application. This cost varies dependent on existing infrastructure and equipment. Our estimate is based on the most prevalent, current infrastructure in Minnesota.

*** This column represents the abstract cost of effort representing the skilled labor and training required to deploy equipment or set up internal system infrastructure required for the application. For example, this would be the comparable cost of hiring a contractor to implement a system.

**** This column represents the abstract cost required to install software, train staff or employ experts, and calibrate and maintain the system.

***** This column represents the abstract cost of effort involved in the maintenance of equipment and systems and management of the system, as well as maintaining current staff in addition to employing specialists familiar with the system to run it, calibrate it, and keep it calibrated.

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APPENDIX A
SURVEY FOR LOCAL ROAD OPERATORS

Demographic Information

As part of a research project sponsored by the Local Road Research Board (LRRB), the University of Minnesota is working to inform local agencies as to how they can best prepare for the upcoming future of Vehicle to Vehicle (V2I) and Vehicle to Infrastructure (V2I) capable vehicles, often referred to as Connected Vehicles (CVs). While there are many potential benefits that may come as CV adoption increases, the varied infrastructure investments required to support the wide variety of CV applications mean that local engineers must balance the time and money spent with the benefit obtained. This project is intended to help local stakeholders better navigate the CV realm and understand both how they can benefit from technological advancements and what effort will be required to realize that.

To inform this effort, researchers are surveying local stakeholders to determine their needs and priorities as they relate to CVs. Input from you about your policies and plans regarding procurement of equipment, such as traffic signal hardware, and maintenance of other infrastructure, such as road signs and striping, will help researchers better understand how they can focus their efforts to provide the greatest benefit to you and the taxpayers.

This survey should take less than 15 minutes to complete. If you have any questions regarding this survey or this research, please contact the University of Minnesota at mtolab@umn.edu. Your participation is greatly appreciated.

Please select the job title that best describes your position.

○ Public Works Director/City Engineer
○ County Engineer
○ Traffic Engineer (city employee)
○ Consultant Engineer
○ Traffic Operations
○ Other (please specify) [   ]

How many years have you been in this role?

[   ]

Interest in Connected Vehicles

How interested are you in connected vehicles in ways related to your job?

○ Very interested

○ Somewhat interested

○ Neither interested nor disinterested

○ Not very interested

○ Not at all interested

Why are you interested in connected vehicles? Select all that apply.

☐ Improving road user safety

☐ Improving mobility

☐ Improving fuel economy/reducing environmental impact of transportation

☐ Better communication of information to drivers

☐ Improving incident/emergency management

☐ Data collection for maintenance purposes (e.g. pavement maintenance)

☐ Better traffic data collection

☐ Other (please specify) [   ]

Traffic Signals

Approximately how often do you typically replace traffic signal controllers?

○ Less than 10 years

○ Every 11-15 years

○ Every 16-20 years

○ Every 20-25 years

○ Every 25-30 years

○ More than 30 years

○ Only when the need arises

What is the most common reason you replace traffic signal controllers?

○ Damaged

○ No longer needed/obsolete

○ Relocated due to construction

○ Condition of controller

○ Change in intersection

○ Other (please specify) [   ]

How often do you typically replace traffic signal controller cabinets?

○ Less than 10 years

○ Every 11-15 years

○ Every 16-20 years

○ Every 20-25 years

○ Every 25-30 years

○ More than 30 years

○ Only when the need arises

What is the most common reason you replace traffic signal controller cabinets?

○ Damaged

○ Relocated due to construction

○ Condition of cabinet

○ Change in intersection

○ Not enough space

○ Other (please specify) [   ]

How many signals are under your jurisdiction?

[   ]

What approximate percentage of your controller cabinets are non-standard?

[   ]

What approximate percentage of the time do you use custom wiring in standard cabinets (e.g. to implement turn overlaps)?

[   ]

What approximate percentage of your cabinets have communication lines (hardwire or cellular)?

[   ]

Signs and Lane Markings

How often do you typically have to replace road signs (e.g. stop signs)?

⭕ Less than 10 years
⭕ Every 10-15 years
⭕ Every 15-20 years
⭕ More than 20 years
⭕ Only when the need arises

How do you monitor/maintain the quality of road signs (e.g. stop signs)? Select all that apply.

☐ Inspections
☐ Reports from public
☐ Regularly-scheduled replacements

☐ Other means (please specify) [   ]

How do you monitor/maintain the quality of lane markings? Select all that apply.

☐ Inspections
☐ Reports from public
☐ Regularly-scheduled painting
☐ Other means (please specify) [   ]

How do you store information regarding the maintenance of your agency's infrastructure (e.g. installation date, last inspection/maintenance, etc.)? Select all that apply.

☐ Asset Management Software/Service
☐ GIS
☐ Spreadsheets
☐ PDF files of digital documents
☐ PDF files of scanned documents
☐ Paper records
☐ Other (please specify) [   ]

Other Comments

Do you have any other comments regarding how you manage your agency's infrastructure?

[   ]

Connected Vehicle Applications Interest

For each of the categories below, please select 1-2 connected vehicle applications that you are most interested in. For more information about the applications, please visit https://www.its.dot.gov/infographs/index.htm.

General

- ☐ Predicting the Future of Transportation
- ☐ Training for the Future

Data Capture

- ☐ Data Capture and Management

Environment

- ☐ Eco-Approach and Departure at Signalized Intersections
- ☐ Eco-Freight Signal Priority
- ☐ Eco-Traffic Signal Priority
- ☐ Eco-Traffic Signal Timing

Mobility

- ☐ Connection Protection
- ☐ Dynamic Ridesharing
- ☐ Integrated Corridor Management
- ☐ Queue Warning and Speed Harmonization
- ☐ Response, Emergency Staging and Communications, Uniform Management and Evacuation (R.E.S.C.U.M.E.)

Road Weather

- [ ] Road Weather Connected Vehicle Applications
- [ ] Information and Routing Support for Emergency Responders
- [ ] Enhanced Maintenance Decison Support System (MDSS)
- [ ] Information for Freight Carriers
- [ ] Information for Maintenance and Fleet Management Systems
- [ ] Motorist Advisories and Warnings
- [ ] Weather-Responsive Traffic Management

Safety

- [ ] Do Not Pass Warning
- [ ] Emergency Electric Brake Light Warning
- [ ] Intersection Movement Assist
- [ ] Lane Change Warning/Blind Spot Warning
- [ ] Forward Collision Warning
- [ ] Truck Forward Collision Warning
- [ ] Left Turn Across Path
- [ ] Vehicle Turning Right in Front of Bus
- [ ] Red Light Violation Warning
- [ ] Stop Sign Gap Assistance
- [ ] Work Zone Warning
- [ ] Curve Speed Warning
- [ ] Pedestrian in Signalized Crosswalk
- [ ] Connected Vehicle for Safety Rail
- [ ] Transit Bus Stop Pedestrian Warning

Connected Vehicle Applications Ranking

Please indicate your interest in each the connected vehicle applications that you previously selected on a scale of 1 to 5, with 5 being the most interested. For more

information about the applications, please visit
https://www.its.dot.gov/infographs/index.htm.

General

	1	2	3	4	5
Predicting the Future of Transportation	O	O	O	O	O
Training for the Future	O	O	O	O	O

Data Capture

	1	2	3	4	5
Data Capture and Management	O	O	O	O	O

Environment

	1	2	3	4	5
Eco-Approach and Departure at Signalized Intersections	O	O	O	O	O
Eco-Freight Signal Priority	O	O	O	O	O
Eco-Traffic Signal Priority	O	O	O	O	O
Eco-Traffic Signal Timing	O	O	O	O	O

Mobility

	1	2	3	4	5
Connection Protection	O	O	O	O	O
Dynamic Ridesharing	O	O	O	O	O
Integrated Corridor Management	O	O	O	O	O

	1	2	3	4	5
Queue Warning and Speed Harmonization	O	O	O	O	O
Response, Emergency Staging and Communications, Uniform Management and Evacuation (R.E.S.C.U.M.E.)	O	O	O	O	O

Road Weather

	1	2	3	4	5
Road Weather Connected Vehicle Applications	O	O	O	O	O
Information and Routing Support for Emergency Responders	O	O	O	O	O
Enhanced Maintenance Decison Support System (MDSS)	O	O	O	O	O
Information for Freight Carriers	O	O	O	O	O
Information for Maintenance and Fleet Management Systems	O	O	O	O	O
Motorist Advisories and Warnings	O	O	O	O	O
Weather-Responsive Traffic Management	O	O	O	O	O

Safety

	1	2	3	4	5
Do Not Pass Warning	O	O	O	O	O
Emergency Electric Brake Light Warning	O	O	O	O	O

	1	2	3	4	5
Intersection Movement Assist	O	O	O	O	O
Lane Change Warning/Blind Spot Warning	O	O	O	O	O
Forward Collision Warning	O	O	O	O	O
Truck Forward Collision Warning	O	O	O	O	O
Left Turn Across Path	O	O	O	O	O
Vehicle Turning Right in Front of Bus	O	O	O	O	O
Red Light Violation Warning	O	O	O	O	O
Stop Sign Gap Assistance	O	O	O	O	O
Work Zone Warning	O	O	O	O	O
Curve Speed Warning	O	O	O	O	O
Pedestrian in Signalized Crosswalk	O	O	O	O	O
Connected Vehicle for Safety Rail	O	O	O	O	O
Transit Bus Stop Pedestrian Warning	O	O	O	O	O

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APPENDIX B

RESPONSE DATA FROM LOCAL ROAD OPERATOR SURVEY

Q1 - Please select the job title that best describes your position. - Selected Choice

Legend:
- Other (please spe...)
- Traffic Operations
- Consultant Engineer
- Traffic Engineer ...
- County Engineer
- Public Works Dire...

Pie values: 9, 3, 2, 2, 31, 17

Other (please specify) - Text

state aid

Traffic Engineer (County Employee)

Traffic Engineer - County

Public Works Director/County Engineer

Assistant Co Eng

Assistant City Engineer

County Traffic Engineer

Assistant County Engineer

Traffic Engineer for a county, not a city.

Q2 - How many years have you been in this role?

How many years have you been in this role?
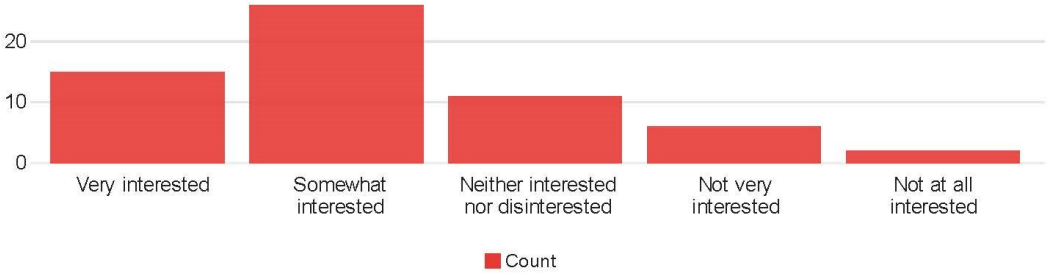
34

Less than 1

10

17

.5

12

14

1

less than 1 year

6

10

5 yrs as County Engineer; 20 yrs as Asst County Engineer

23

17 years

10

10

30

3

1

8

Q3 - How interested are you in connected vehicles in ways related to your job?

Legend: Count

Q4 - Why are you interested in connected vehicles? Select all that apply. - Selected Choice

Other (please specify) - Text

Budget Impacts
i'm not
how it will impact me as a driver
Rural Area, Not Needed at this time

Q9 - How many signals are under your jurisdiction?

How many signals are under your jurisdiction?

365
16
1
17
15
0
250
200
0

x

3

1

1

4

0 - There are no traffic signals on state or county highways

0

1

0

180

125

55

0

8

0
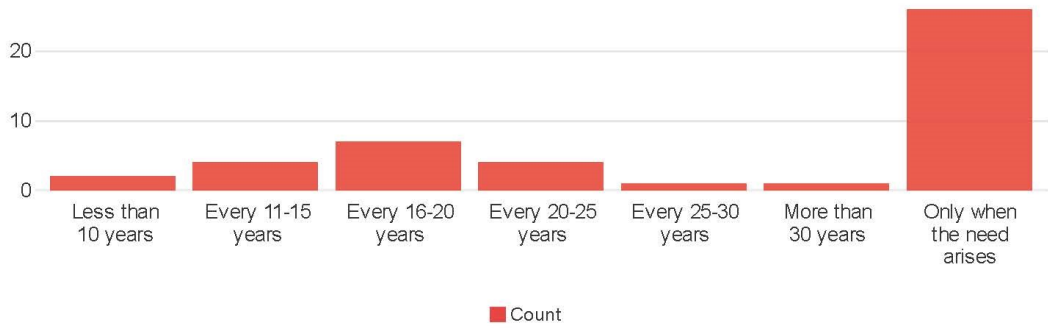
0

7

0

0

16

2

we have 13 in conjunction with Mndot

0

0

1

0

0

10

4

0

0

1

0

Approximately 100.

30

Q5 - Approximately how often do you typically replace traffic signal controllers?

Q6 - What is the most common reason you replace traffic signal controllers? - Selected Choice

Other (please specify) - Text

Do not have any

There are no traffic signals in Faribault County

Don't have any.

obsolete/need greater functionality

no traffic signals in county

I don't have any in the County

Not applicable

poor video graphics

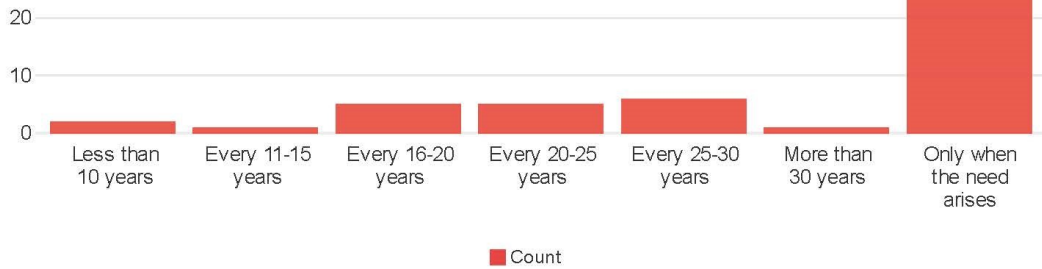We don't have any in Traverse County

NA

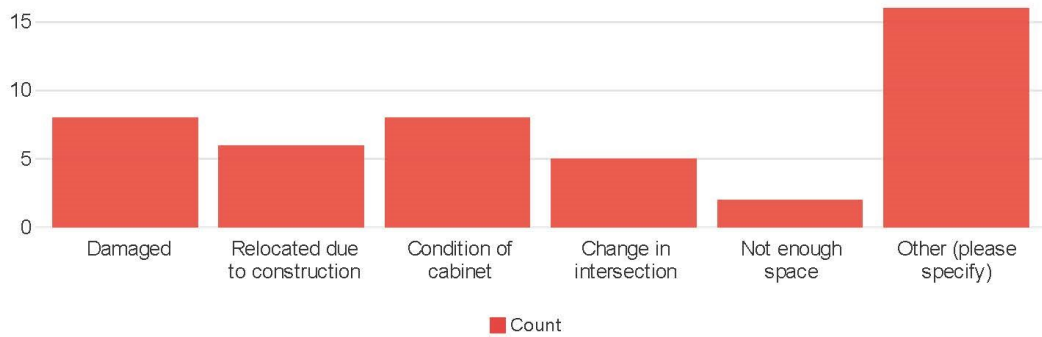Do not have traffic signals to maintain

Damaged Electronics

Do not own any signals

New features needed to run Flashing Yellow Arrow or other new tools not well handled in older controllers.

Q7 - How often do you typically replace traffic signal controller cabinets?

Categories (x-axis): Less than 10 years, Every 11-15 years, Every 16-20 years, Every 20-25 years, Every 25-30 years, More than 30 years, Only when the need arises

Legend: ■ Count

Q8 - What is the most common reason you replace traffic signal controller cabinets? - Selected Choice

Categories (x-axis): Damaged, Relocated due to construction, Condition of cabinet, Change in intersection, Not enough space, Other (please specify)

Legend: ■ Count

Other (please specify) - Text

Do not have any

full signal replacement

There are no traffic signals in Faribault County

Don't have any.

signal replacement

Again I don't have any

Not applicable

Fashions change

NA

No Cabinets

do not maintain traffic signals

Do not own any cabinets

Q10 - What approximate percentage of your controller cabinets are non-standard?

What approximate percentage of your controller cabinets are non-standard?

??

15

1

unknown

0

NA

0

5

0

x

0

0

1

5

100

0

0

0

0

10

unsure

0

0

0

0

0

Nothing we have is "Standard"

Not sure

0

no idea

N/A

NA

?

0

0

NA

100

0

0

0

0

Depends on how you define "non-standard". But I would assume nearly 100% would be considered standard.

15

Q11 - What approximate percentage of the time do you use custom wiring in standard cabinets (e.g. to implement turn overlaps)?

What approximate percentage of the time do you use custom wiring in standard cabinets (e.g. to implement turn overlaps)?

??

0

0

unknown

Not sure

NA

5

25

0

x

0

0

1

3

100

0

0

0

0 - overlaps / others are all done with the controller

10

unsure

0

50

0

0

Very LIttle

0

Blue ones

Not sure

0

no idea

N/A

NA

0

0

100

NA

?

0

0

0

0

All of our FYA cabinets use overlap functions. Only about 5% of our cabinets use turn overlaps. With newer TS2 cabinets, physical custom wiring is often not needed.

10

Q12 - What approximate percentage of your cabinets have communication lines (hardwire or cellular)?

What approximate percentage of your cabinets have communication lines (hardwire or cellular)?

Working on installing this now.

70

0

Not sure

NA

95

60

0

x

0

0

1

4

100

0

100

0

25% today, with upcomming projects we will be at 40%

95

unsure

0

75

0

0

0

0

They are all connected through the mother ship orbiting Orion's belt

Not sure

0

no idea
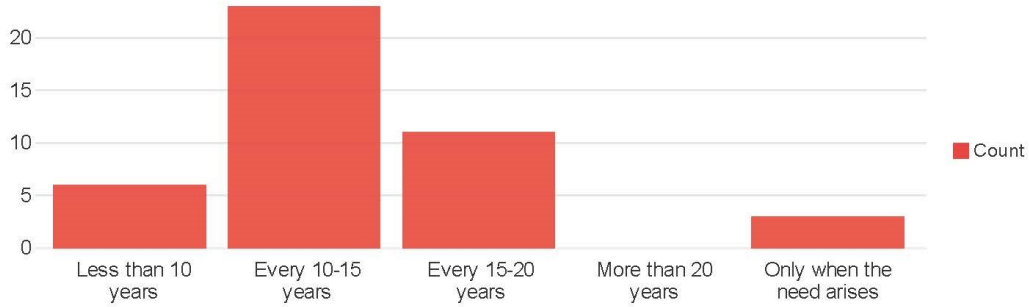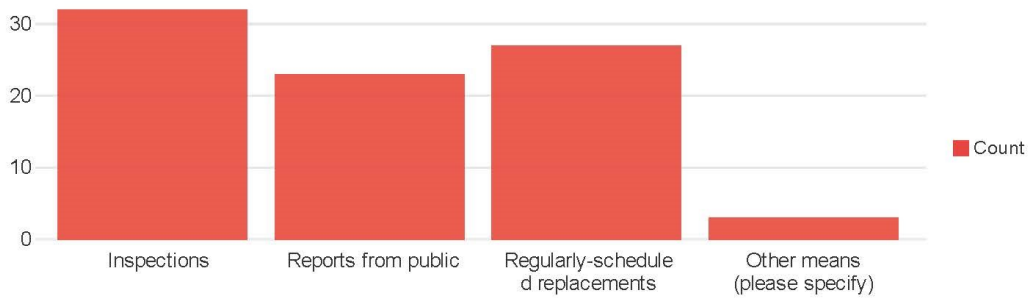
N/A

NA

0

0

0

NA

0

0

0

0

0

75

0

Q13 - How often do you typically have to replace road signs (e.g. stop signs)?

Bar chart with categories on the x-axis and Count on the y-axis (scale 0 to 20):
- Less than 10 years: ~6
- Every 10-15 years: ~23
- Every 15-20 years: ~11
- More than 20 years: 0
- Only when the need arises: ~3

Legend: Count

Q14 - How do you monitor/maintain the quality of road signs (e.g. stop signs)? Select all that apply. - Selected Choice

Bar chart with categories on the x-axis and Count on the y-axis (scale 0 to 30):
- Inspections: ~32
- Reports from public: ~23
- Regularly-scheduled replacements: ~27
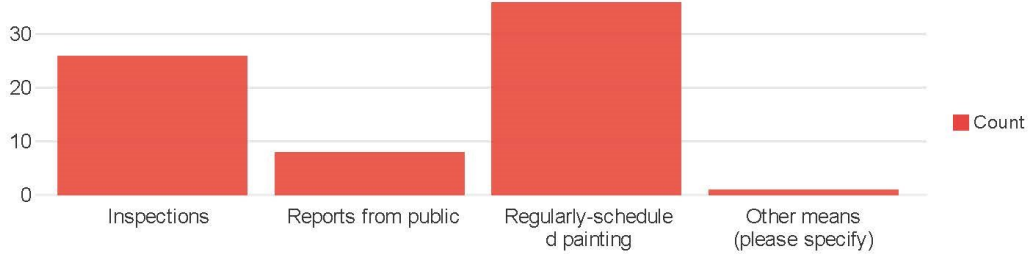- Other means (please specify): ~3

Legend: Count

Other means (please specify) - Text

Coordination with other projects

Staff comments

due to damage

Q15 - How do you monitor/maintain the quality of lane markings? Select all that apply. - Selected Choice

Other means (please specify) - Text

Inlay stripes to last longer

Q16 - How do you store information regarding the maintenance of your agency's infrastructure (e.g. installation date, last inspection/maintenance, etc.)? Select all that apply. - Selected Choice
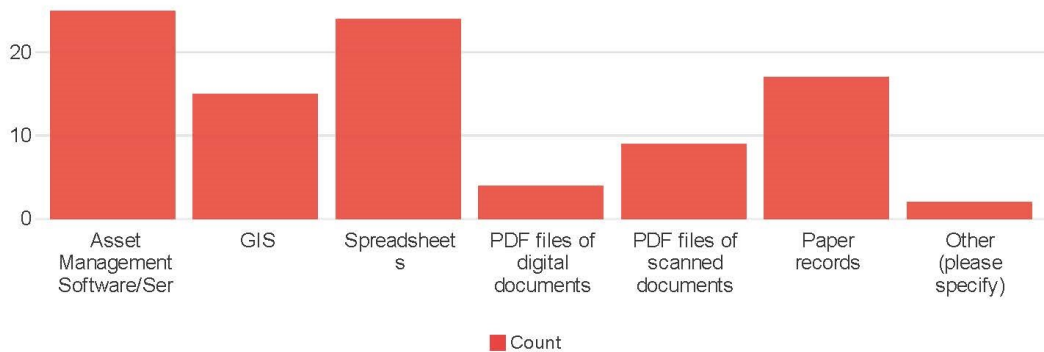
Q16_7_TEXT - Other (please specify) - Text

Other (please specify) - Text

Some data is not available.

Good memory

Q17 - Do you have any other comments regarding how you manage your agency's infrastructure?

Do you have any other comments regarding how you manage your agency's infrastructure?

No.

Not at this time.

I'm interested in how future connected vehicles will navigate counties such as Lake & Cook where there exists many miles of gravel roads with poor (or no) satellite/cell connectivity. Thank you for your work on this study as it will be beneficial for road authorities to have as much advanced notice as possible if our annual/periodic striping and sign maintenance programs need to change to adapt to the traveling public's needs.
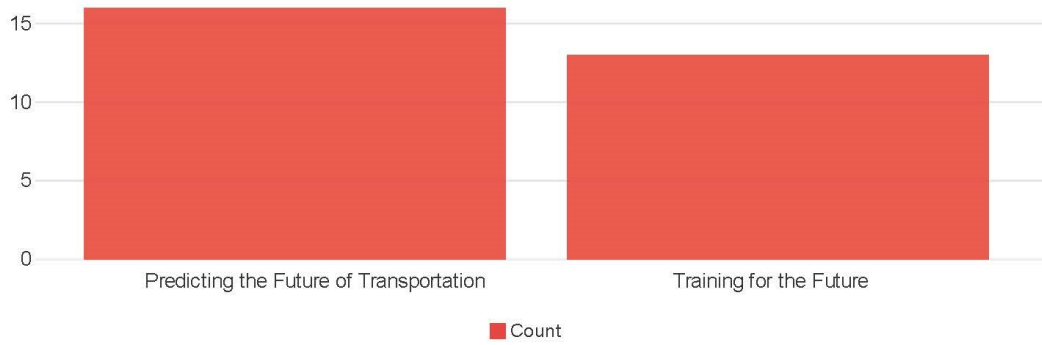
No

Mostly by inspection and performance. Some by scheduled maintenance (signs).

No

Interest in Specific Connected Vehicle Applications by Category

General Applications
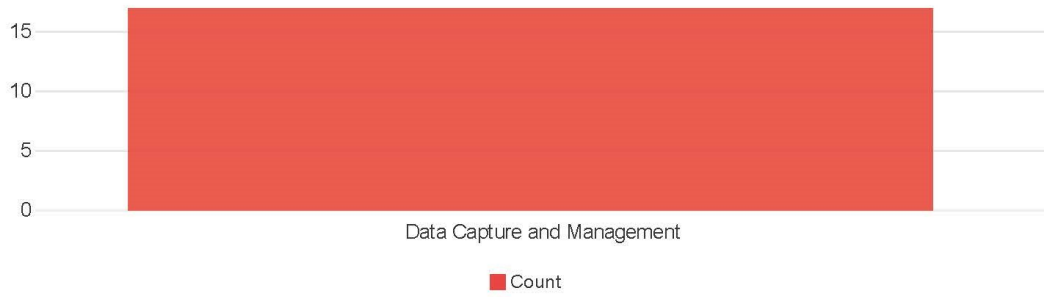
Selections (Maximum 2 per person)
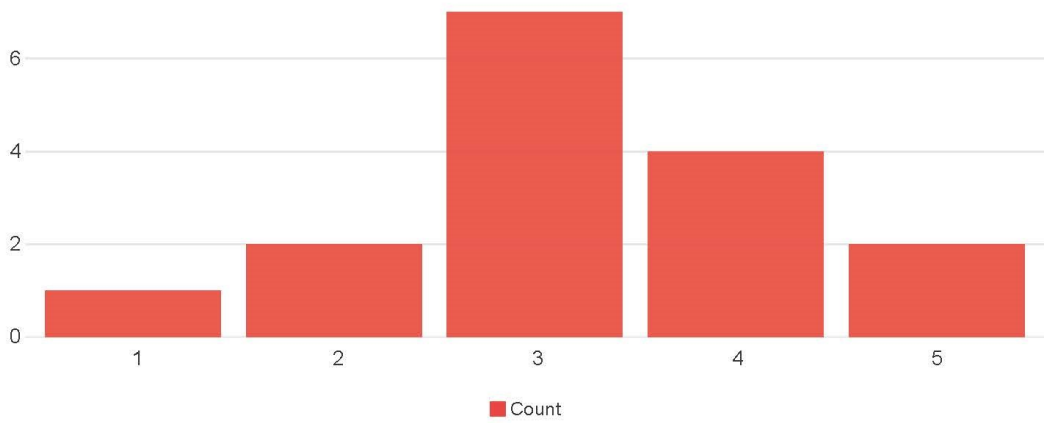

Count

Ratings (5 = Most Interested)

Rating	1	2	3	4	5
Predicting the Future of Transportation	0	0	3	8	3
Training for the Future	3	2	2	4	2

Data Capture Applications

Selections (Maximum 2 per person)

Data Capture and Management

■ Count

Ratings (5 = Most Interested)

■ Count

Environmental Applications

Selections (Maximum 2 per person)

Count
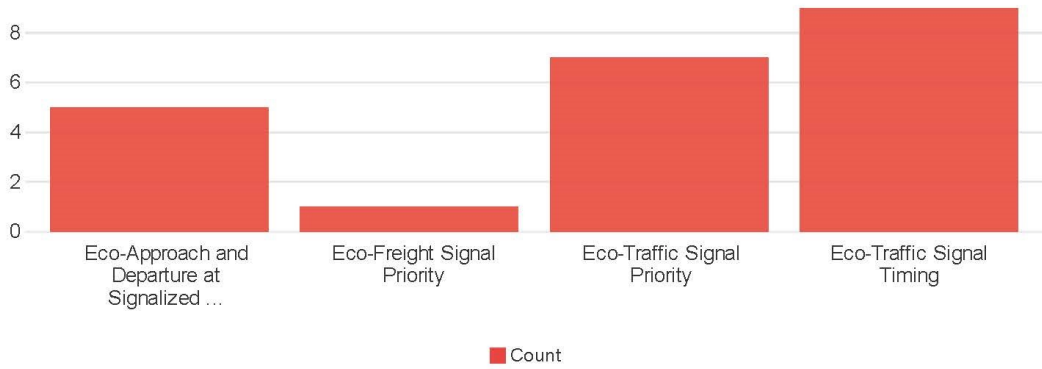
Ratings (5 = Most Interested)

Field	1	2	3	4	5
Eco-Approach and Departure at Signalized Intersections	0	1	3	1	0
Eco-Freight Signal Priority	0	0	1	0	0
Eco-Traffic Signal Priority	1	3	2	0	1
Eco-Traffic Signal Timing	1	2	3	2	1

Mobility Applications

Selections (Maximum 2 per person)

Count
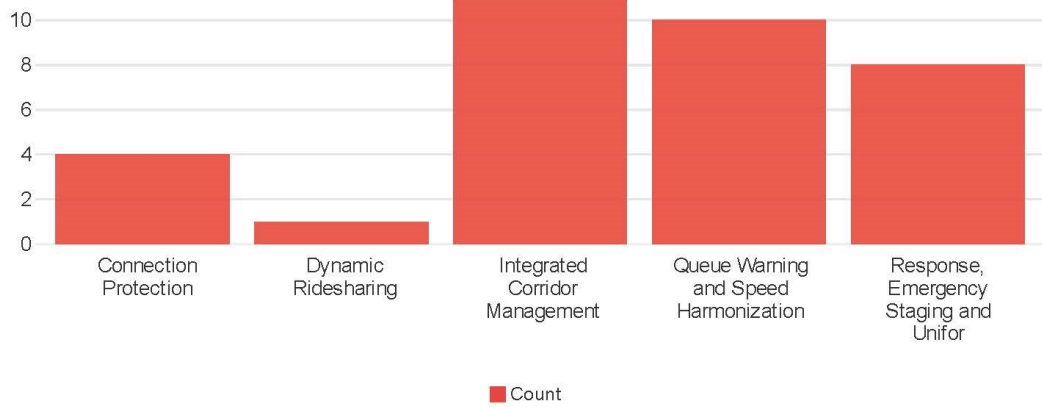
Ratings (5 = Most Interested)

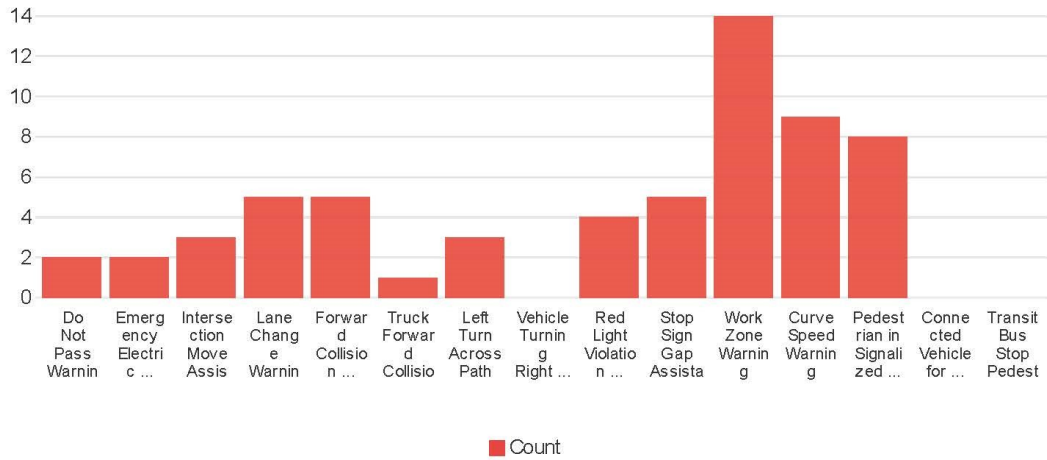| Rating	1	2	3	4	5
Connection Protection	0	0	2	1	1
Dynamic Ridesharing	0	1	0	0	0
Integrated Corridor Management	1	0	3	4	3
Queue Warning and Speed Harmonization	2	3	4	1	0
Response, Emergency Staging and Communications, Uniform Management and Evacuation (R.E.S.C.U.M.E.)	1	0	4	3	0

Road Weather Applications

Selections (Maximum 2 per person)

Count

Ratings (5 = Most Interested)

Rating	1	2	3	4	5
Road Weather Connected Vehicle Applications	0	1	2	8	2
Information and Routing Support for Emergency Responders	0	0	0	1	1
Enhanced Maintenance Decison Support System (MDSS)	0	2	1	1	3
Information for Freight Carriers	0	0	1	0	0
Information for Maintenance and Fleet Management Systems	0	0	3	2	0
Motorist Advisories and Warnings	0	0	1	7	0
Weather-Responsive Traffic Management	0	0	2	4	2

Safety Applications

Selections (Maximum 2 per person)

Count

Ratings (5 = Most Interested)

Rating	1	2	3	4	5
Do Not Pass Warning	0	0	1	1	0
Emergency Electric Brake Light Warning	0	0	1	1	0
Intersection Movement Assist	0	0	1	1	1
Lane Change Warning/Blind Spot Warning	1	0	0	3	1
Forward Collision Warning	0	1	1	0	3
Truck Forward Collision Warning	0	0	0	1	0
Left Turn Across Path	0	0	0	3	0
Vehicle Turning Right in Front of Bus	0	0	0	0	0
Red Light Violation Warning	0	0	0	0	4
Stop Sign Gap Assistance	0	0	1	3	1

Work Zone Warning	0	0	4	4	5
Curve Speed Warning	0	1	2	2	4
Pedestrian in Signalized Crosswalk	0	0	1	0	6
Connected Vehicle for Safety Rail	0	0	0	0	0
Transit Bus Stop Pedestrian Warning	0	0	0	0	0