Texas A&M Transportation Institute

Connected Vehicle Infrastructure: Deployment and Funding Overview

Final report

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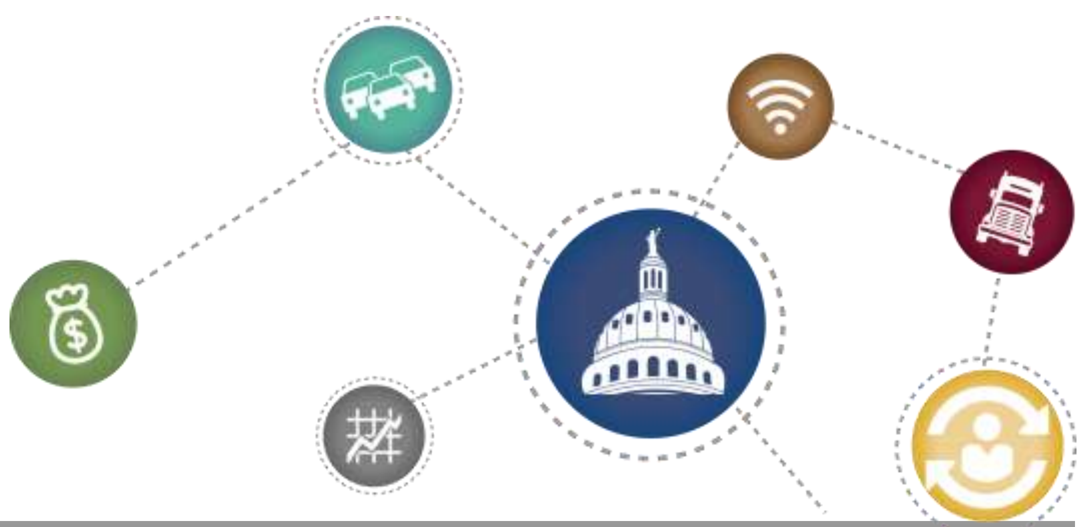

TRANSPORTATION Policy Research CENTER

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Connected Vehicle Infrastructure (CVI), a component of the broader category of Intelligent Transportation Systems (ITS), focuses on communications and connectivity between vehicles and infrastructure. This report provides an overview of CVI technology, reviews existing and proposed legislation relevant to CVI implementation, identifies existing funding mechanisms, reviews CVI pilot programs, and presents potential implementation barriers.

- CVI technology uses Vehicle to Infrastructure (V2I) technology and Infrastructure to Vehicle (I2V) technology to allow units in vehicles, or on-board units (OBU), to communicate with units built into transportation infrastructure and vice-versa. Other types of connected vehicle technology allow vehicles to communicate with other vehicles, data networks, or pedestrians, all using the same OBU that is needed for V2I communication.
- CVI related legislation, funding, and deployments have primarily come from the federal level. Many states have passed automated or connected vehicle legislation, but none directly address CVI.
- Given the variety of uses of this technology, funding can be acquired through several federal-aid programs. Federal-aid programs which include ITS funding typically provide 80 to 90 percent of eligible project costs if certain criteria are met.
- While the benefits that can be derived from these technologies can be substantial, the high initial costs of deployment can be a barrier. As such, the need for funding opportunities for state and local governments is crucial.
- The emerging nature of CV technology has resulted in the creation of numerous test sites and pilot programs across the country. Some are federally funded, but most are affiliations of state and local governments and private interests.
- The National Highway Traffic Safety Administration (NHTSA) has proposed a requirement that dedicated short range communication (DSRC) devices be installed in new passenger vehicles by 2023, which would allow most personal vehicles to take advantage of CVI technology and create the fleet market penetration that would strengthen the value proposition for public investment.
- Many barriers to CVI technology implementation exist. Absent a federal mandate, it seems unlikely that DSRC-based CVI will be prevalent in the future. There is also uncertainty over continued allocation of the 5.9GHz band for DSRC uses, as the Federal Communications Commission is considering the possibility of sharing this spectrum with Wi-Fi devices. There are also questions about whether 5G cellular network technology could render DSRC technology obsolete.

Table of Contents

List of Tables

Executive Summary

This report reviews existing and proposed legislation relevant to connected vehicle infrastructure (CVI) implementation, identifies existing funding mechanisms for CVI implementation, reviews CVI pilot programs and case studies, and provides an overview of CVI technology.

CVI technology is one component of the broader category of Intelligent Transportation Systems (ITS). Specifically, CVI technology focuses on communications and connectivity between vehicles and infrastructure. This technology allows units in vehicles to communicate with units built into transportation infrastructure, and offers potential safety, mobility, and environmental benefits. Pilot programs have been established through the U.S. Intelligent Transportation Systems Joint Program Office (ITS JPO) and serve as demonstrations to the potential applications of the technology to realize these benefits. There are also established connected vehicle test beds located across the country which allow for members of the program, both public and private entities, to test CV technologies and share their findings.

Generally, this report found that CVI related legislation, funding, and deployments have primarily come from the federal level. Many states have passed automated or connected vehicle legislation, but none directly addressing CVI. A major unknown is the National Highway Traffic Safety Administration (NHTSA) proposal to require dedicated short range communication (DSRC) devices in passenger vehicles. If this requirement is passed it would allow most personal vehicles to take advantage of CVI technology and create the fleet market penetration that would strengthen the value proposition for public investment.

Like CVI legislation, many of the CVI technology pilot deployments are federally funded programs, while new and existing federal funding programs provide the bulk of available funding for CVI projects. Such programs include the Congestion Mitigation and Air Quality Improvement (CMAQ) Program and the Highway Safety Improvement Program (HSIP). ITS applications as part of larger projects can become eligible to receive additional federal funding. Federal-aid programs which include ITS funding typically provide 80 to 90 percent of eligible project costs if certain criteria are met. As there are typically limited funds available at the state or local level, these federal programs are the primary source of funding. There are also opportunities for private investment, but the availability of these are not guaranteed or consistent.

Finally, there are many barriers to implementation of CVI technology. The unknown outcome of the NHTSA DSRC proposal creates uncertainty, as does the ongoing Federal Communications Commission (FCC) discussion of allowing non-DSRC devices to share the radio spectrum needed for DSRC. Without the NHTSA mandating installation of DSRC devices in new vehicles, it seems unlikely that DSRC-based CVI will be prevalent in the future. This may be a moot point however, as the future introduction of 5G mobile networks may be able to provide equal or greater benefits than DSRC at a lower cost to state and local governments.

Connected Vehicle Infrastructure Overview

CVI technology is one aspect of the broader category of ITS, with a specific focus on communications and connectivity. The Federal Highway Administration defines ITS as "electronics, communications, or information processing, used singly or in combination to improve the efficiency or safety of a surface transportation system" (*1*). ITS includes myriad technologies including CVI technology, collision avoidance systems, traffic enforcement cameras, variable speed lanes, dynamic traffic signals, as well as the back-end data systems supporting these technologies.

ITS offers potential benefits in safety, mobility, and environmental impacts. Safety applications have the potential to reduce crashes by informing drivers of roadway hazards or other dangerous situations that they are unable to see. Mobility applications could provide drivers and transportation managers with data from thousands of vehicles in the system. This has the potential to reduce traffic by helping drivers to plan more efficient routes and by allowing transportation managers to optimize system performance through timing of signals or other means. Additionally, more efficient system performance could provide environmental benefits, related to fuel savings (*2*). While connected vehicle technology is just one part of broader ITS, it could potentially offer many of these same benefits.

CVI technology works using Vehicle to Infrastructure (V2I) technology and Infrastructure to Vehicle (I2V) technology. This technology allows units in vehicles, or on-board units (OBU) to communicate with units built into transportation infrastructure and vice-versa, and will be the primary type of technology covered in this report. Other types of connected vehicle technology include Vehicle to Vehicle (V2V), Vehicle to Network (V2N), and Vehicle to Pedestrian (V2P). These other types of CV technology allow vehicles to communicate with other vehicles, data networks, or pedestrians, all using the same OBU that is needed for V2I communication. Altogether, these technologies are sometimes referred to as Vehicle to Anything/Everything (V2X). An overview of these technologies is provided in the Appendix.

Legislation

The USDOT has strongly encouraged the use of ITS to improve safety and system efficiency of public roads in recent years. Given the possibly significant safety, mobility, and environmental benefits derived from the use of ITS technology, the USDOT supports state, local, and private initiatives to develop these technologies. Voluntary deployments of ITS are allowed as long as they meet the requirements of Part 940 of Title 23 within the Code of Federal Regulations (23 CFR 940) and other applicable regulations (*3*).

The following identifies existing legislation at the federal and state levels that impact connected vehicle (CV) technology and CVI deployment.

Federal

The establishment of V2I deployments is covered under 23 CFR 771.117(c)(21) as a Categorical Exclusion (CE) due to their function of improving the efficiency or safety of a surface transportation system, supporting the CV security system, and enhancing passenger convenience (*3*).

The establishment of CV technologies is encouraged by DOT, but there are no requirements on the types of communication technology that must be used. As discussed earlier in this report, part of the wireless spectrum has been dedicated to the delivering of safety messages over DSRC. As was also previously covered, the proposed NHTSA rule mandating that DSRC devices be installed in new vehicles has not yet been finalized. If this rule is approved in 2019, all new vehicles would be required to have DSRC devices by 2023 (*35*).

The NHTSA has proposed Federal Motor Vehicle Safety Standard (FMVSS) 150, Vehicle-to-Vehicle (V2V) Communication System, which would require vehicles weighing equal to or less than 10,000 pounds to be equipped with V2V technology. The rule proposes that DSRC and technologies interoperable with DSRC be the mandated technology. The primary focus of this proposed rule would be to create an environment that would allow for the rapid communication of the basic safety message to and from other vehicles. There is considerable interest on both sides of this issue. As will be discussed later in this report, the passage or failure of this proposed rule will have an impact on the use of DSRC as the prominent CV technology and how states and local governments will focus CV testing in the future.

State

At the state level, ITS legislation in recent years has focused on Autonomous Vehicle (AV) rules and regulations, but has included CV components. As of 2017, there have been 33 states that introduced AV/CV legislation, with 20 states and Washington, D.C., passing legislation (*4*). Much of the legislation passed has focused on AV technology. Four states[1] have introduced six

[1] States include Illinois, Maryland, Missouri, and Tennessee

pieces of legislation directly impacting CVI. Of the six bills, three have failed and three were pending at the time of this report.

Texas passed two bills regarding AV/CV technology in 2017.[2] While HB 1791 85(R) allowed for the use of connected braking systems, neither piece of legislation included rules or regulations specifically focused on CVI.

[2] SB 2205 85(R) & HB 1791 85(R)

Funding

Funding for ITS programs remains a challenge for transportation agencies at all levels of governments. While the benefits that can be derived from these technologies can be substantial, the high initial costs of deployment can be a barrier. As such, the need for funding opportunities for state and local governments is crucial.

This section aims to identify common funding sources for CVI development.

Local Investments

As seen in the pilot programs and various deployments, there exists the opportunity for local and private-sector investments into CV technology. In addition to a private-sector investor pledge of an additional $10 million to the winner of the Smart City Challenge competition, there was also a cumulative $500 million in funding generated by competing cities to supplement federal commitments. Columbus, OH, the winner of the competition, leveraged an additional $90 million in investments during the competition. Since winning, local investments in their program has grown to $500 million from private sector organizations in the form or public-private partnerships (*5*).

It is unclear whether large investments into CV technology made by the private sector are commonplace. As there are numerous governmental and non-governmental test beds across the country, many of which receive no federal funding, there are opportunities for development of public-private partnerships. As such, the most reliable sources of funding come from federal-aid programs.

Federal-Aid Funding Programs

The Fixing America's Surface Transportation (FAST) Act includes several programs which provide federal funding for CV infrastructure. Projects pertaining to equipment, installation, preventative maintenance, and operational costs are eligible for federal-aid programs which allow for ITS investments.

Given the variety of uses of this technology, funding can be acquired through several federal-aid programs. Federal-aid programs which include ITS funding typically provide 80 to 90 percent of eligible project costs if certain criteria are met.

The following are programs authorized in the FAST Act that provide funding specifically for CV infrastructure, or other ITS deployments that could include CV infrastructure.

Intelligent Transportation System (ITS) Program

The ITS Program provides for the research, development, and operational testing of ITS. The purpose of ITS is to achieve mobility, environmental, and safety goals, while increasing efficiencies of transit and commercial vehicle operations. As such, a wide variety of technologies can be used to meet these goals, including CVI.

The FAST Act has authorized $500 million for this program. See Table 1. This program requires a 20 percent local match unless stated otherwise.

Table 1. ITS Program Authorization.

Fiscal year	2016	2017	2018	2019	2020
Authorization	$100 M	$100 M	$100 M	$100 M	$100 M

Advanced Transportation and Congestion Management Technologies Deployment Program

The Advanced Transportation and Congestion Management Technologies Deployment Program has created competitive grants for the development and testing of technologies aimed at improving safety, efficiency, system performance, and infrastructure return on investment. Grant recipients may develop technologies which include the following: [3]

- Advanced traveler information systems.
- Advanced transportation management technologies.
- Infrastructure maintenance, monitoring, and condition assessment.
- Advanced public transportation systems.
- Transportation system performance data collection, analysis, and dissemination systems.
- Advanced safety systems, including vehicle-to-vehicle and vehicle-to-infrastructure communications.
- Technologies associated with autonomous vehicles, and other collision avoidance technologies, including systems using cellular technology.
- Integration of intelligent transportation systems with the Smart Grid and other energy distribution and charging systems.
- Electronic pricing and payment systems.
- Advanced mobility and access technologies, such as dynamic ridesharing and information systems to support human services for elderly and disabled individuals.

The FAST Act authorized $300 million for this program, as shown in Table 2. Grant recipients are required to provide a local match of at least 50 percent of the project costs. Grant recipients are allowed to use up to 5 percent of awarded funds for performance management planning and reporting.

[3] [23.U.S.C. 503(c)(4)(E)]

Table 2. Advanced Transportation and Congestion Management Technologies Deployment Program Authorization.

Fiscal year	2016	2017	2018	2019	2020
Authorization	\$60 M	\$60 M	\$60 M	\$60 M	\$60 M

Transportation Infrastructure Finance and Innovation Act (TIFIA)

The TIFIA Program provides credit assistance for eligible highway, transit, intercity passenger rail, some types of freight rail, intermodal freight transfer facilities, and some modifications inside of a port terminal. Credit assistance comes in the form of direct loans, loan guarantees, and standby lines of credit. Since this program provides credit assistance rather than direct funding, there is a wide-berth on the types of eligible projects. Therefore, CVI projects would qualify depending on the specific goal of the ITS.

Projects that qualify for TIFIA credit assistance are typically larger transportation investments. Costs must equal or exceed \$50 million, or at least one-third of the most recent fiscal year's total state apportionment. For ITS projects, the threshold is much lower at \$15 million. Table 3 shows the year-to-year authorization amount.

Table 3. TIFIA Authorization.

Fiscal year	2016	2017	2018	2019	2020
Authorization	\$275 M	\$275 M	\$285 M	\$300 M	\$300 M

Congestion Mitigation and Air Quality Improvement (CMAQ) Program

The CMAQ Program is funding dedicated to aid local agencies in alleviating environmental issues to meet the requirements of the Clean Air Act. These funds are available to non-attainment and maintenance (former non-attainment) areas to reduce congestion and emissions. Non-attainment areas are planning areas which have emissions that exceed the national ambient air quality standards.

Funds may be used to develop transportation plans and projects that contribute to the attainment or maintenance of the national ambient air quality standards. The installation of vehicle-to-infrastructure communications equipment are eligible under this program.[4]

Table 4 shows the authorized amount for this program by fiscal year. Local match follows the federal standard under 23 U.S.C. 120.

[4] [23 U.S.C. 149(b)(9)]

Table 4. CMAQ Program Authorization.

Fiscal year	2016	2017	2018	2019	2020
Authorization	$2.309 B	$2.360 B	$2.405 B	$2.449 B	$2.499 B

Highway Safety Improvement Program (HSIP)

The HSIP aims to significantly reduce traffic fatalities and serious injuries on all public roads. To do this, the FAST Act has broad definitions on what projects are eligible under the program. Under MAP-21, the program allowed for the development of both infrastructure and non-infrastructure related projects that address a safety issue, as long as those projects are in accordance with the State's strategic highway safety plan (SHSP).

Under the FAST Act, the types of projects were limited to those listed in the statute, the majority of which are infrastructure-safety related. The following are specifically identified in the bill:

- Installation of vehicle-to-infrastructure communication equipment.
- Pedestrian hybrid beacons.
- Roadway improvements that provide separation between pedestrians and motor vehicles, including medians and pedestrian crossing islands.
- Other physical infrastructure projects not specifically enumerated in the list of eligible projects.

Table 5 identifies the authorized amount for the program by fiscal year. Local match follows the federal standard under 23 U.S.C. 120.

Table 5. HSIP Authorization.

Fiscal year	2016	2017	2018	2019	2020
Authorization	$2.226 B	$2.275 B	$2.318 B	$2.360 B	$2.407 B

National Highway Performance Program (NHPP)

The focus of the NHPP is to directly support the National Highway System (NHS) through providing maintenance and support, the construction of new NHS facilities, and to ensure that established performance targets are being achieved or seeing progress toward achievment.

Project eligibility under the NHPP remains the same as under MAP-21. The FAST Act established four additional categories for funding. The following category directly relates to CV infrastructure:

- Installation of vehicle-to-infrastructure communication equipment [23 U.S.C. 119(d)(2)(L)];.

Table 6 identifies the authorized amount for the program by fiscal year. Local match follows the federal standard under 23 U.S.C. 120.

Table 6. NHPP Authorization.

Fiscal year	2016	2017	2018	2019	2020
Authorization	$22.332 B	$22.828 B	$22.262 B	$23.741 B	$24.236 B

Other Federal Funding Programs

Not all programs specifically list the development of CVI as an eligible activity. Some indicate that the use of ITS and other innovative technology are eligible for funding. These projects must meet the goals of the program to be eligible. The following are federal funding programs that list or indicate that some type of ITS project would be eligible:

- National Highway Freight Program.
- Railway-Highway Crossing Program.

Connected Vehicle Pooled Fund Study

In addition to these federal funding programs, states have also explored the option of a "pooled fund." Virginia, with its Connected Vehicle Pooled Fund Study (PFS), developed a proposal that suggests a partnership of transportation agencies to develop a program that will facilitate the development, field demonstration, and deployment of connected vehicle infrastructure applications (*6*). The purpose of this program is to aid transportation agencies in the justification of large-scale CVI deployments.

The PFS currently has fifteen core members, including: Virginia, California, Florida, Michigan, Minnesota, New Jersey, New York, Ohio, Pennsylvania, Texas, Utah, Washington, Wisconsin, Maricopa County, and FHWA. These members participated in research to provide education for transportation agencies, worked with USDOT on the DMA program with partial funding, and developed and tested connected vehicle applications.

Per the program's Partnership and Operating Policies, core members were asked to contribute $50,000 per year from their State Planning and Research (SP&R) allocation. If this is not feasible, core members are asked to donate their "fair share." A "fair share" will be determined as a percentage of a state's annual SP&R allocation (*6*).

While this program is not designed to be a direct funding source for a state's connected vehicle projects, it does represent a potential solution for funding shortfalls among states. This program allows for the means to generate funding and further research in CVI applications.

Deployments

The emerging nature of CV technology has resulted in the creation of numerous test sites and pilot programs across the country. Many of these locations are not funded by USDOT, but rather designed to promote information sharing and collaboration. There are programs that are federally funded, but most sites are affiliations of state and local governments and private interests.

There are no deployment sites listed in this report that focus exclusively on CVI technologies. All deployments have a wide-range of CV technology applications. However, CVI plays an integral role in these deployments. Therefore, it is necessary to highlight these programs and how federal, state, and local authorities are involved in these projects.

Due to the structure of these programs, private sector interests in these technologies, and lack of public information available on testing facilities, this list is not exhaustive. Locations presented in this report represent the programs which had publicly available information at the time of publication.

Pilot Deployment Program

The CV Pilot Deployment Program is an effort by USDOT, sponsored by the ITS-JPO, to test cutting-edge multiple CV technologies at three locations across the country: New York City, Tampa, and Wyoming. Agencies responsible for CV activities in each respective location are the New York City Department of Transportation (NYCDOT), Wyoming Department of Transportation (WYDOT), and the Tampa Hillsborough Expressway Authority (THEA).

The program began in 2015 and consists of three phases:

- Phase 1: Concept Development – 12 Months.
- Phase 2: Design/Build/Test – 20 Months.
- Phase 3: Operate & Maintain – 19 Months.

For Phase 1, no money was awarded to the designated agencies. Each agency was tasked with developing a structured concept for CV application deployment, as well as performance monitoring and management strategies in their regions.

In 2016, USDOT awarded three cooperative agreements worth more than $45 million for Phase 2 of the program. The pilot sites, over the course of 20 months, were tasked to design, construct, and begin testing CV applications. Table 7 highlights estimated funding amounts for each deployment location.

Table 7. Notice of Funding Opportunity.

CV Pilot Site	Phase 2 Federal Funding (Est).	Phase 2 Site Cost Share (Est).	Phase 3 Federal Funding (Est).	Phase 3 Site Cost Share (Est).	Total
Tampa/THEA	$13,340,283	$3,335,071	$1,921,133	$480,283	**$19,076,770**
New York City DOT	$13,694,163	$3,423,541	$3,304,150	$826,038	**$21,247,892**
Wyoming DOT	$3,200,565	$800,141	$1,238,928	$309,732	**$5,549,366**
Total	**$30,235,011**	**$7,558,753**	**$6,464,211**	**$1,616,053**	**$45,874,028**

Source: Amendment 1 to Notice of Funding Opportunity Number DTFH6116RA00007 Connected Vehicle (CV) Pilot Deployment Program – Phases 2 and 3

The following subsections provide an overview of key objectives and technological needs of each pilot program site during Phase 1 of the program. These subsections are intended to highlight goals of CV applications and the technological needs of each agency to determine how to achieve these goals. These summaries do not include details of deployment or lessons learned from Phase 1.

Wyoming

The focus of the Wyoming CV Pilot is to address weather-related safety and efficiency along Interstate 80 (I-80) in the southern part of the state. This is a highly-trafficked freight corridor which moves over 32 million tons per year (*7*). Strong winds and other severe weather conditions during winter months have led to higher crash rates and road closures costing millions of dollars (*8*). WYDOT believes this can be avoided through safety warnings and routing information delivered via CV technology.

The work completed during Phase 1 estimated that five CV safety applications would meet the goals of the pilot. See Table 8.

Table 8. WYDOT Pilot Site Proposed CV Applications.

Category	ICF/WYDOT – CV Application
V2V Safety	Forward Collision Warning (FCW)
V2I/I2V Safety	I2V Situational Awareness*
	Work Zone Warnings (WZW)*
	Spot Weather Impact Warning (SWIW)*
V2I and V2V Safety	Distress Notification (DN)

The CV applications of the pilot require the equipment found in Table 9. This is a mix of V2I, I2V, and V2V devices.

Table 9. WYDOT Pilot Site Proposed Devices.

ICF/WYDOT – Devices	Estimated Number
Roadside Unit (RSU)	75
WYDOT Fleet Subsystem On-Board Unit (OBU)	100
Integrated Commercial Truck Subsystem OBU	150
Retrofit Vehicle Subsystem OBU	25
Basic Vehicle Subsystem OBU	125
Total Equipped Vehicles	400

New York City

The focus of CV technology for the NYC Pilot Program is to reduce pedestrian fatalities in accordance with the long-term plan of the city. CV technology will be deployed along three corridors/areas. The first is a high-accident area within Manhattan containing 204 intersections. The second is FDR Drive on the east side of Manhattan with over-height restrictions that cost nearly $2 million in delays in 2014 (*9*). The third is Flatbrush Ave. in Brooklyn, which has a high-accident rate at the 35 intersections in the pilot area.

To address the issues of these three corridors, the NYCDOT determined during Phase 1 that the CV applications shown in Table 10 are necessary.

Table 10. NYCDOT Pilot Site Proposed Applications.

NYCDOT – Needs	Application
Discourage Spot Speeding	*Modified* Eco-Speed Harmonization
Reduce Accidents at High Intersection Locations	Red Light Violation Warning
Improve Pedestrian Safety on Heavily Traveled Bus Routes	Pedestrian in Signalized Cross Walk Warning
	Vehicle Turning Right in Front of Bus Warning
Improve Safety of Visually Impaired Pedestrians	Mobile Accessible Pedestrian Signal System (PED-SIG)
Improve Truck Safety	Curve Speed Warning
Address Bridge Low Clearance Issues	Freight-Specific Dynamic Travel Tool
Enforce Truck Route Restrictions	
Improve Work Zone Safety	Reduced Speed/ Work Zone Warning
Balance Mobility	Intelligent Traffic Signal System (i-SIG) In-Vehicle Information Potential
Reduce Crashes, Injuries, and Delays	Forward Collision Warning (FCW)
	Emergency Electronic Brake Light (EEBL)
	Blind Spot Warning (BSW)
	Land Change Warning/Assist (LCA)
	Intersection Movement Assist (IMA)
	Stationary Vehicle Ahead (SVA)

The CV applications of the pilot require the equipment found in Table 11. This is a mix of V2I, I2V, and V2V devices.

Table 11. NYCDOT Proposed Devices.

NYCDOT – Devices	Estimated Number
Roadside Unit (RSU) at Manhattan and Brooklyn Intersections and FDR Drive	353
Taxi Equipped with Aftermarket Safety Device (ASD)*	5,850
MTA Fleet Equipped with ASD*	1,250
UPS Truck Equipped with ASD*	400
NYCDOT Fleet Equipped with ASD*	250
DSNY Fleet Equipped with ASD*	250
Vulnerable Road User (Pedestrians/Bicyclists) Device	100
PED Detection System	10 + 1 spare
Total Equipped Vehicles	8,000

**600 spare ASDs to be purchased.*

Tampa

The Tampa Hillsborough Expressway Authority (THEA) Connected Vehicle Pilot Program focuses on utilizing CV technology to alleviate many safety and mobility concerns around Tampa's central business district (CBD). According to the THEA Pilot Program webpage, the program aims to equip both public transit and personal vehicles with connected vehicle technology to allow V2V and V2I communications.

The three major challenges of the THEA Pilot Program are to address safety, mobility, and vehicle emissions though CV technology. The agency specifically targeted morning backups (congestion), wrong-way entry, pedestrian safety, transit signal priority, streetcar conflicts, and traffic flow optimizations as key objectives.

Table 12 highlights the proposed CV applications for the program.

Table 12. Tampa (THEA) Pilot Site Proposed CV Applications.

Category	Tampa (THEA) – CV Application
V2I Safety	End of Ramp Deceleration Warning (ERDW)
	Pedestrian in Signalized Crosswalk Warning (PED-X)
	Wrong Way Entry (WWE)
V2V Safety	Emergency Electronic Brake Lights (EEBL)
	Forward Collision Warning (FCW)
	Intersection Movement Assist (IMA)
	Vehicle Turning Right in Front of a Transit Vehicle (VTRFTV)
Mobility	Mobile Accessible Pedestrian Signal System (PED-SIG)
	Intelligent Traffic Signal System (I-SIG)
	Transit Signal Priority (TSP)
Agency Data	Probe-enabled Data Monitoring (PeDM)

The CV applications of the pilot require the equipment found in Table 13. This is a mix of V2I, I2V, and V2V devices.

Table 13. Tampa (THEA) Pilot Site Proposed CV Devices.

Tampa (THEA) – Devices	Estimated Number
Roadside Unit (RSU) at Intersection	40
Vehicle Equipped with On-Board Unit (OBU)	1,600
Pedestrian Equipped with App in Smartphone	500
HART Transit Bus Equipped with OBU	10
TECO Line Street Car Equipped with OBU	10
Total Equipped Vehicles	1,620

Per the THEA Pilot Program, the CV communication equipment will be installed on vehicles by mid-2018 and be able to communicate with infrastructure.

Connected Vehicle Test Bed

The USDOT Connected Vehicle Test Bed is a federally funded resource located in Novi, Michigan. The goal of the test bed is to test connected-vehicle applications in a real-world setting. The test bed consists of 50 roadside equipment (RSE) units along major corridors in Novi. This infrastructure communicates with vehicles via 5.9 GHz DSRC.

Noted benefits of this using the test bed are the following (*10*):

- CVI and equipment to perform tests at no cost to the user.
- Pre-existing agreements with local agencies eliminating the need for complex testing arrangements with roadway operators.

- Highly skilled staff who can help users test a variety of complex scenarios.

There are also resources available to users wishing to participate in testing at the test bed. The ITS JPO notes the following are available (*10*):

- 22 intersections broadcasting SPaT and GID information.
- 3 new portable RSE units that allow for private testing or for testing in atypical locations, such as a parking lot.
- Data Center running 24-7 and on 99 percent uptime.
- Test vehicles and drivers, upon request.
- On-site experts with years of experience in ITS and CV systems.

While the Connected Vehicle Test Bed in Novi is a USDOT sponsored resource, there are additional test beds in the surrounding southeast Michigan area. While the USDOT sponsors the Connected Vehicle Test Bed, MDOT operates eight additional testing locations in the region. These additional locations are a part of the Affiliated Interoperable Test Beds Program.

Affiliated Interoperable Test Beds

The purpose of the Affiliated Interoperable Test Beds Program is to offer sites across the nation where public and private agencies can test connected vehicle technology for real-world V2V and V2I applications. The test beds focus on the communication of safety and operation data between infrastructure and vehicles. These test beds are affiliated through the USDOT ITS JPO Connected Vehicle Program and are made up of partners and collaborators. Partners of the program are agencies that have an established, affiliated test bed site. Partners for the program include (*11*):

- U.S. Department of Transportation.
- California Department of Transportation.
- Florida Department of Transportation.
- Michigan Department of Transportation.
- New York State Department of Transportation.
- Road Commission for Oakland County.
- Vehicle Infrastructure Integration Consortium.

The Office of the Assistant Secretary for Research and Technology (OST-R) has signed 87 memorandums of agreement with various public, private, and academic entities to act as affiliates in the program, including TTI in their agreement with TxDOT (*12*). These entities are directly involved with the partner test beds, and agreed to test technologies and share information between members. These affiliations are non-binding, precompetitive agreements to encourage and facilitate information sharing among agencies, as well as create consistency in design and standards of CVI components.

While no federal funding has been allocated to the participants of this program, the noted benefits include the ability for members to openly share information and contribute to the development of CV technology. TTI, as a member of the Affiliated Test Bed, is able to use the official Affiliated Test Bed mark on CV research documents and promotional material (*13*). However, there is not currently an affiliated test bed that has been established in the state.

An exhaustive list of all established test bed locations at the time of this report is not publicly available. From the USDOT ITS-JPO online resources and available information, the following cities are locations of CV test beds (*14*):

- Phoenix, AZ.
- Palo Alto, CA.
- Orlando, FL.
- Novi, MI.
- Minneapolis, MN.
- Manhattan, NY.
- Oak Ridge, TN.
- McLean, VA.

Each location has unique testing capabilities and foci of CV technologies. An example of this is seen at the MDOT-operated affiliated test beds in southeast Michigan. The Southeast Michigan Test Bed was created in 2007 to serve as a proof-of-concept testing facility for both the USDOT and private auto manufacturers. The test bed seeks to understand the possibilities and limitations of DSRC operating at the 5.9 GHz bandwidth. The operations, and types of testing being done at these locations, can be found in Palo Alto.

Founded in 2005, the Palo Alto test bed was the first DSRC test site in the country. The creation of the site was the result of a partnership between Caltrans, the San Francisco Bay Area's Metropolitan Transportation Commission (MTC), and the University of California-Berkley's Partners for Advanced Transportation Technology (PATH) program. While PATH manages the operations, it is supported by Caltrans, MTC, and USDOT's ITS-JPO. The test bed is located along a two-mile stretch of El Camino road in Palo Alto, which is equipped with 5.9 GHz DSRC devices placed across 11 intersections. The primary function of these systems is to broadcast signal phase and timing (SPaT) and MAP messages over DSRC.

Texas Automated Vehicle Proving Ground Partnership

The Texas Automated Vehicle Proving Ground Partnership is an agreement between TxDOT, TTI, The University of Texas at Austin's Center for Transportation Research (CTR), and 32 municipal and regional partners (*15*). The following are locations with major Texas cities involved in the Proving Ground (*16*):

- Austin Area — Austin-Bergstrom International Airport and Riverside Drive corridor.
- Houston Area — Texas Medical Center, Houston METRO HOV lanes, and Port of Houston.
- Dallas/Fort Worth/Arlington Area — UTA campus, Arlington streets, I-30 corridor and Managed Lanes.
- San Antonio Area — Fredericksburg Road/Medical Drive corridor and bus rapid transit system.
- El Paso Area — Tornillo/Guadalupe Port of Entry.

The purpose of the Proving Grounds program, similar to the CV Test Beds Program, is to create an environment for the testing of new AV/CV technologies and encourage the sharing of information between participants in the program. While there are no federal funds dedicated to members of the proving grounds, USDOT states that the proving grounds will foster innovations to safely transform mobility, roadway capacity, and accessibility for disadvantaged populations (*17*). This can be interpreted to mean that the proving grounds are similar in nature to the Affiliated Test Bed Program. USDOT also notes that the creation of these proving grounds is the "logical next step in the Department's effort to advance the safe deployment of automated technology."

The partnership is one of 10 AV proving grounds in the country. The Proving Ground designees chosen from over 60 applicants are as follows (*18*):

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

- Central Florida Automated Vehicle Partners.
- North Carolina Turnpike Authority.

Per USDOT press releases, the focus of the Proving Grounds is AV technology. However, news releases about the Proving Ground indicate that there will be a mix of AV and CV technologies being tested at the various locations across the state.

Smart City Challenge

Launched in late 2015, the USDOT's Smart City Challenge called for cities across America to develop plans for city-wide ITS integration for CV technology, specifically DRSC technology. The competition was designed to challenge cities to find solutions to their most pressing transportation problems through the use of innovative technology. The purpose of the challenge was to encourage competition, collaboration, and experimentation among participating cities. As incentive for participation, USDOT awarded $100,000 to each finalist to develop outreach material, and up to $50 million to the winning city for full development of their submitted plans. Of the $50 million, $40 million came directly from USDOT grants. The additional $10 million came from Vulcan, Inc., a partnering private sector firm.

The program received 78 submittals from cities across the country. Two Texas cities, Austin and Lubbock, were among the applicants for the program. From the 78 applicants, seven finalists were selected. Austin was one of the selected finalists, whose plan focused on traffic, sprawl, safety, and vehicle emissions. The winner of the challenge was Columbus, Ohio, who submitted a plan focused on integrating technologies, including connected infrastructure, to improve residents' quality of life and foster economic growth in the community.

The success of the Smart City Challenge influenced USDOT's decision to allocate an additional $65 million in funding opportunities to support advanced technology transportation projects (*19*). The grants are being awarded through two programs: FHWA's Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) and the FTA's Mobility on Demand (MOD) sandbox program.

Dynamic Mobility Applications (DMA) Program

The Dynamic Mobility Applications (DMA) Program is a completed effort by the ITS JPO's Mobility program, which was designed to support the emergence of CV environments. The objective of the program was to evaluate prototype CV applications that were "bundled" into individual projects. The DMA project bundles are shown in Table 14.

Each project focused on the applications in unique realms of transportation. For example, the Multimodal Intelligent Traffic Flow System (MMITSS) project evaluated the following CV and CVI applications to improve signal operations and allow for the transfer of safety messages through DSRC technology (*20*):

- Intelligent Traffic Signal System (ISIG).
- Transit Signal Priority (TSP).
- Mobile Accessible Pedestrian Signal System (PED-SIG).
- Emergency Vehicle Preemption (PREEMPT).
- Freight Signal Priority (FSP).

The results of each project are intended to be shared amongst transportation stakeholders through webinars and workshops that were held in 2011 and early 2012 respectively.

Table 14. DMA Bundles and Locations.

Application Bundle	Full Name	Location(s)
EnableATIS	Enable Advanced Traveler Information Systems	SmasrTrAC (University of Minnesota)
		CloudCar (Massachusetts Institute of Technology (MIT))
FRATIS	Freight Advanced Traveler Information Systems	Los Angeles, CA
		Dallas, TX
		South Florida
IDTO	Integrated Dynamic Transit Operations	Columbus, OH
		Orlando, FL
INFLO	Intelligent Network Flow Optimization	Seattle, WA
MMITSS	Multimodal Intelligent Traffic Signal System	Anthem, AZ
		Northern California
R.E.S.C.U.M.E.	Response, Emergency Staging and Communications, Uniform Management, and Evacuation	National Capitol Region

Source: (ITS JPO 2015)

The program was set to end in late 2016 or early 2017 when all funded projects had been completed. At the time of this report, it has not been made clear whether the projects for this program have been completed. However, it is the intention of this program to be merged into the CV Pilot Deployment Program to aid in the development of real-world CV and CVI demonstrations.

Deployment Costs

Costs associated with deploying CVI remain varied by the location, size, and scope of each deployment. With limited case studies of existing real-world deployments, determining costs of these technologies can vary significantly. As such, researchers examined existing literature and resources on reported costs of CVI deployments.

The best resource for determining CVI costs is the *ITS Cost Database*. Established by the USDOT ITS JPO, the *ITS Costs Database* filters costs by application, state, and country where available. The most prominent record of CV costs included in the database is a 2013 USDOT study, which partnered with Transport Canada, AASHTO, and other nationwide stakeholders, to conduct a footprint analysis of CVI. This report determined an average CVI deployment cost based on data used for the development of NCHRP 13-101, which sought to conduct a benefit/cost analysis on CV deployments (*21*). At the time this report was written, NCHRP 03-101 had not been completed. However, the data collected for that study were used in the published USDOT study referenced in this document.

At the time of the footprint analysis, only a small number of deployments of CVI had occurred. Deployment sites in Michigan, Virginia, Arizona, and the Turner-Fairbank Highway Research Center (TFHRC) were included. This means the sample size for cost analyses was limited. As such, these numbers provide only a preliminary estimate on the total costs of CVI deployments.

Two key costs examined for this report are the direct costs of deploying CVI, and backhaul costs with connecting the devices for communication. Direct costs include the cost of hardware, installation, and design and planning. The direct costs from the existing deployments are shown in Table 15.

Table 15. Average Total Direct Costs per DSRC Site (2013).

Deployment Site	Michigan	Arizona	Virginia	TFHRC	Average
CV DSRC Hardware	$ 9,850	$ 420	$ 8,400	$ 6,100	$ 7,450
Installation Labor	$ 4,000	$ 3,000	$ 3,800	$ 3,400	$ 3,550
Design and Planning	$ 7,300	$ 5,900	$ 6,900	$ 6,400	$ 6,600
Total Direct CV Costs	**$ 21,150**	**$ 13,100**	**$ 19,100**	**$ 15,900**	**$ 17,600**

Source: (21)

Backhaul is the connection between the CVI and the servers or traffic management centers (TMCs). The study also found these average costs through an examination of the same deployment locations. Backhaul costs from the existing deployments are shown in Table 16.

Table 16. Costs Associated with Backhaul Installation (2013).

Deployment Site	Michigan	Arizona	Virginia	TFHRC	Average
Reported Backhaul Costs*	$ 31,100	$ 1,700	$ 18,900	$ 18,900	$ 13,400
Planning	$ 4,700	$ 300	$ 2,800	$ 2,800	$ 2,000
Design	$ 6,200	$ 300	$ 3,800	$ 3,800	$ 2,700
Construction Inspection	$ 4,700	$ 300	$ 2,800	$ 2,800	$ 2,100
System Integration & License	$ 1,500	$ 1,500	$ 1,500	$ 1,500	$ 1,500
Traffic Control	$ -	$ -	$ -	$ -	$ -
Total Backhaul Costs	**$ 48,200**	**$ 4,100**	**$ 29,800**	**$ 29,800**	**$ 21,700**

** Costs reported by deployed sites are underlined.*
Source: (21)

The costs listed in Table 15 and Table 16 come from real-world deployments of CVI. However, as with most technologies, the costs of those technologies in 2013 are most likely higher than costs today. As new studies identifying CVI deployment costs are conducted, the database will be updated to reflect current costs.

Barriers to CVI Implementation

There are currently some potential barriers to the implementation of DSRC based CVI technology, including uncertainty over the mandate of DSRC in new vehicles, uncertainty over the continued allocation of the 5.9GHz band for DSRC uses, and the possibility that 5G could soon render DSRC technology obsolete.

DSRC Mandate

As previously covered, the NHTSA is currently in the rule making process for a rule that would mandate that all new vehicles come equipped with DSRC OBU. Assuming this rule is approved in 2019, a three-year phase in period would begin in 2021, meaning all new vehicles would come equipped with DSRC by 2023 (*35*).

Although this proposed rule would likely be an important step for deployment of DSRC-based V2I, it has created a wide range of reactions from stakeholders. Many automakers support this proposed rule, such as the Association of Global Automakers[5], as these companies have already invested substantially in DSRC and see the mandate as the "best way to ensure nationwide deployment." Other manufacturers such as Tesla and BMW are less supportive. Tesla commented that they would prefer policy guidance and industry cooperation over a mandate, while BMW commented that they would prefer a technology-neutral approach to V2V, as they believe many of the shortcomings of DSRC can be addressed with future 5G networks (*22*). While failure to pass this rule may not negatively impact future V2I in general, as future 5G networks may very well be a better technology, it would certainly be a substantial setback for DSRC-based V2I. Without this mandate far fewer vehicles would come equipped with OBU, although it is likely that some manufacturers would offer vehicles with OBU regardless, as Cadillac has already begun to do.

5.9 GHz Band Allocation

The 5.9GHz spectrum band is the range of radio frequencies on which DSRC operates. This band has been reserved specifically for ITS uses since 1999 (*26*). Recently the FCC has begun to consider the possibility of sharing this spectrum band with Wi-Fi devices. In June, 2016, the FCC began taking comments in order to evaluate the possibility of opening up this spectrum band for Wi-Fi. As part of the comment process, the FCC has asked for studies which test interference with DSRC units (*23*).

Qualcomm, Broadcom, and The Internet & Television Association state that the 5.9GHz band is the "single best near-term opportunity to make unlicensed spectrum available for broadband services." They state that DSRC deployment has not yet begun and that it is possible for the spectrum to be shared without interference (*24*). Conversely, Toyota's comments state that

[5] This association represents Aston Martin, Ferrari, Honda, Hyundai, Isuzu, Kia, Maserati, McLaren, Nissan, Subaru, Suzuki, and Toyota.

billions of dollars have been spent, across many sectors of the economy, bringing DSRC technology to market. They state that these systems have been designed under the FCC's existing DSRC rules, and therefore, any sharing adopted by the FCC "must unequivocally protect DSRC operations from harmful interference" (*25*). The FCC has not yet reached a decision on this matter. If this spectrum was opened up for Wi-Fi use, it will likely have some negative impact on the implementation of DSRC technology, although it is unclear to what extent.

Future 5G Networks

The final potential barrier to DSRC-based CVI is the possibility that 5G mobile networks will make existing DSRC technology obsolete. As previously covered, the standards for 5G are expected to be released in late 2018, with the first deployments a few years after that (*28*). This timeframe alone presents a challenge to DSRC-based CVI. 5G networks will be widespread after deployment in much the same way that LTE networks are today. A car equipped with 5G technology is envisioned to be able to both connect to a 5G cellular tower network and also have device to device (D2D) connectivity without having to go through the cellular network. 5G is therefore believed to potentially provide the same safety and other benefits offered by D2D DSRC connectivity. This presents a problem as DSRC technology currently requires substantial public funding to fully implement a sufficient number of roadside units (RSU). Furthermore, as this report has shown, there are currently some opportunities for federal funding, however state and local funding mechanisms are limited. While DSRC-based CVI offers many benefits, this slow rollout due to limited funding may allow 5G to be fully deployed before DSRC can take root.

Appendix: CVI Technologies

Communication Technology

Currently, the primary method for all CV communication, including V2I is 5.9GHz Dedicated Short Range Communication (DSRC). DSRC is a short range, one or two-way radio communication device. V2I uses involving DSRC would require that the driver's vehicle is equipped with a DSRC in-vehicle unit. This would then allow DSRC devices integrated into transportation infrastructure to communicate with the vehicle, and vice versa.

DSRC devices are reliant on having allocated radio frequency spectrum. In 1999 the FCC allocated radio frequency spectrum in the 5.9GHz band for DSRC uses, specifically for ITS purposes (*26*). This allocation is essential for DSRC to function, as it reserves this band specifically for ITS uses. Without this allocation, DSRC devices would be subject to potential radio interference from other devices, which could negatively impact any ITS uses.

While DSRC is the primary communication technology that has been used thus far, and is the primary technology covered in this report, 5th Generation Mobile Networks (5G) provide a potential future method of V2I communication. 5G will be the successor to current 4G mobile networks, and is being designed with CV uses in mind. It will provide increased data throughput, lower latency, and increased reliability over existing 4G networks. This would work much the same way as 4G currently works on mobile devices, with the vehicle sending and receiving information from a cell tower, or nearby 5G unit. This would allow for uses that existing DSRC technology does not, as it would allow a vehicle to stay continuously connected to infrastructure networks (*27*). In addition to cellular connections, 5G is expected to also provide the same device-to-device connectivity as DSRC without having to communicate through the cellular network. This direct radio functionality could therefore provide the very low latency and localized basic safety messaging capability provided by DSRC as an essential component to CV/AV operations.

While 5G offers promising results in the future, it is still being developed. 5G standards will not be finalized until late 2018, with the first deployments sometime after that (*28*). While this technology could potentially supplant DSRC as the primary CV communication technology, this eventuality is too far distant to adequately cover. Instead this report focuses on DSRC, as it is a mature technology, with documented uses and existing funding mechanisms including anticipated OEM OBUs.

Infrastructure

The infrastructure required for DSRC-based V2I includes in vehicle on-board units (OBU), roadside units (RSU), traffic management centers, and backhaul support systems. OBU are DSRC devices installed in vehicles. These communicate with roadside units that are tied into transportation infrastructure and broadcast the basic safety message (BSM). This data is managed by traffic management centers, while the backhaul systems support the network of information being relayed to vehicles and from vehicles to the network.

Basic Safety Message

The BSM is the core vehicle data being transmitted by the DSRC device. The BSM includes the vehicle's speed, position, heading, acceleration, size, brake status, and other relevant information (*29*). It is low latency high bandwidth (up to 6Mbps), has a range of 300 to 1,000 meters, and is transmitted 10 times per second (*30*, *31*). This means that DSRC devices can quickly transmit essential data without interruption between in-vehicle units and roadside units. The DSRC applications discussed in this appendix are all reliant upon this stream of data.

On Board Units

The OBU is an essential piece of DSRC-based CV technology. It is a DSRC device installed in the driver's vehicle. This device allows the vehicle to communicate with other DSRC devices on the roadway and in other vehicles. This device can either be factory-installed on the vehicle or be added aftermarket by the owner.

In a 2012 study, the Michigan Department of Transportation conducted a survey of CV experts. These experts estimated that by 2017 a factory-installed OBU would raise the cost of a vehicle by $350, while an aftermarket device would cost the user $200 (*32*). Similarly, the NHTSA estimates that an OBU would cost $350 per vehicle in 2020 (*33*). Currently very few vehicles are available for purchase with DSRC and few options exist for aftermarket devices. As of 2017 the Cadillac CTS is one of the only consumer vehicles with DSRC as a standard feature. Because this is built into the base cost of the vehicle, it is difficult to determine the cost of adding it (*34*).

In January 2017, the NHTSA proposed a rule mandating DSRC devices be installed on all new light vehicles. The proposed rule would begin two years after the final rule is adopted. There would then be a three-year phase in period. After this period, DSRC would be required on all new vehicles. The proposed rule estimates a final rule issue in 2019, meaning the phase in period would begin in 2021, with all vehicles subject to the rule by 2023. As of August 2017, no final decision has been reached on this rule (*35*).

Roadside Units

RSU are the second piece of infrastructure necessary for DSRC based V2I deployment. An RSU is a DSRC device placed along a roadway which transmits data to and receives data from OBU in vehicles. These units allow communication between vehicles, traffic control equipment, and back-end data networks. These are the primary pieces of infrastructure required for V2I deployment.

The primary applications of RSU are to increase safety and mobility on roadways. A 2013 FHWA report outlined several potential safety applications of RSU. These potential applications are covered below:

- **Stop Sign Violation Warning:** This application would improve safety at intersections with stop signs. The RSU would alert the driver of the upcoming stop and warn the driver if there is another vehicle approaching the intersection.

- **Railroad Crossing Violation Warning:** This application would improve safety at at-grade railroad crossings. The RSU would alert the driver of an upcoming railroad crossing and warn the driver if there is a train approaching.

- **Weather Information Warning:** This application would improve safety on roadways subject to adverse weather events. This could include rain, snow, ice, flooding, or high winds. The RSU would alert the driver to these conditions and inform the driver of the need to reduce speed or divert to another roadway.

- **Oversize Vehicle Warning:** This application would alert drivers of oversize vehicles of upcoming clearance restrictions on roadways. The RSU would alert the driver of upcoming potential collisions with bridges, tunnels, or other low-height clearances.

- **Reduced Speed Zone Warning:** This application would alert drivers who are approaching a reduced speed zone. The RSU would alert the driver of the reduced speed and any changes in roadway configurations such as lane closures or lane shifts (*36*).

The Intelligent Transportation Systems Joint Program Office (ITS JPO) completed the Dynamic Mobility Applications Program, which found several potential mobility applications for V2I units. This program was discussed in this report, while the applications found are covered below:

- **Intelligent Traffic Signal System:** This system would collect data from vehicles, non-motorized travelers, and pedestrians. This data would be used in conjunction with control signals to optimize transit, freight, and pedestrian movements, increasing overall network performance.

- **Transit Signal Priority:** This application would allow buses to transmit passenger counts, service type, arrival times, and heading to an RSU. This would increase performance by allowing certain buses priority on roadways.

- **Mobile Accessible Pedestrian Signal System:** This application integrates data from RSU and pedestrian mobile devices. This will help visually impaired pedestrians safely navigate crosswalks.

- **Emergency Vehicle Preemption:** This application would build off existing technology, optimizing the movement of multiple emergency vehicles through a traffic network.

- **Freight Signal Priority:** This application would optimize freight traffic near freight facilities, based on freight movement data collected (*37*).

Many of these applications rely on an RSU transmitting a Signal Phase and Timing (SPaT) message as well as MAP/GID data. The SPaT message contains the current signal light phase at the intersection, while MAP/GID data contains a detailed map of the intersection (*38*).

Traffic Management Centers

Traffic management centers (TMC) are another part of the infrastructure necessary for V2I deployment. These centers will collect and process data collected from OBU and RSU. They may be operated by a local or state authority or a private contractor (*29*).

Existing TMCs typically collect volume, speed, and occupancy data, and more recently collect data using toll tag readers, Bluetooth readers, and third-party data. The center then uses this data for freeway management, arterial management, incident management, road weather management, traveler information, and maintenance and construction operations (*39*). A 2013 report for the CTS Pooled Fund Study at the University of Virginia outlined 15 expected changes to TMC in a CV environment. These are primarily related to potential uses covered in the previous section, including the ability to better manage crashes, managing increased data necessary for controlling traffic signal systems, and the ability to disseminate traffic information to drivers (*39*).

Backhaul Systems

Backhaul systems are the final piece of infrastructure needed for V2I deployment. These are the behind-the-scenes data systems which connect roadside units to traffic management centers. This is typically a fiber optic or wireless system (*29*).

The amount of backhaul investment needed will vary depending on the location. Areas where current bandwidth is sufficient will need less than areas with minimal bandwidth. As of 2014 it was estimated that for V2I deployment in the US, completely new backhaul systems will be needed at 40 percent of all traffic signals, and 25 percent of all freeway sites. Meanwhile the backhaul systems will require no upgrades at 10 percent of all traffic signals and 75 percent of freeway sites (*40*).

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