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MPO Guide for Implementing DSRC Technology in PennDOT District 8-0

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TCRPC Tri-County Regional Planning Commission

Memorandum

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To:	Steve Deck, AICP Executive Director, Tri-County Regional Planning Commission
From:	Jeffrey Bergsten, P.E. Michael Baker International
Subject:	District-Wide DSRC Coordination Plan **MPO Guide for Implementing DSRC Technology in PennDOT District 8-0**

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Document Overview

This document is intended to assist PennDOT District 8's Planning Partners and MPOs/RPOs across Pennsylvania with their development and implementation of Dedicated Short-Range Communication (DSRC) technology into the planning process. DSRC technology provides the opportunity to create a safer, more efficient, roadway network. This document is comprised of three sections which are as follows:

1. **Define the Technology –** This section summarizes what is meant by Connected and Automated Vehicles (CAV) including the differences between these terms and various roles of communication technology for Connected Vehicles (CVs). Some of the pros and cons of the leading technology candidates, such as DSRC, Cellular Vehicle to Any Device (C-V2X) and 5G, are explained within the document.
2. **DSRC V2I Deployment Impacts and Priorities –** This section summarizes possible CV applications using DSRC, the likely/expected penetration timeline, and a GIS-based criteria map to assist in the selection of corridors which are best suited for DSRC technology. There are several communications technologies that could advance vehicle-to-infrastructure (V2I) applications, such as DSRC, C-V2X, and Cellular 5G. However, this plan is focused on DSRC as it has been widely tested and deployed in the U.S.
3. **Cost & Design Considerations –** This section provides general, preliminary, cost and design considerations along with scenario schedule recommendations to assist with understanding when facilities should undergo design and construction. Additional topics such as compatible equipment identification, and ownership and maintenance responsibilities, are also addressed.

Common Terms and Acronyms

ADAS	Advanced Drive-Assisted Systems
ATC	Advanced Traffic Controller
AV	Automated Vehicle
BSM	Basic Safety Message
CAV	Connected and Automated Vehicle
Cellular 5G	Cellular 5th Generation
CMAQ	Congestion Mitigation and Air Quality Improvement Program
CV	Connected Vehicle
C-V2X	Cellular Vehicle-to-Everything
DSRC	Dedicated Short-Range Communications
FCC	Federal Communications Commission
FMVSS	Federal Motor Vehicle Safety Standard
GIS	Geographic Information System
IPv6	Internet Protocol Version 6
I-SIG	Intelligent Traffic Signal System
ITS	Intelligent Transportation System
ITS-JPO	USDOT's Intelligent Transportation System Joint Program Office
LRTP	Long-Range Transportation Plan
MMITSS	Multi-Modal Intelligent Traffic Signal System
MPO	Metropolitan Planning Organization
NTCIP	National Transportation Communications for Intelligent Transportation Systems Protocol
OBU	On-board Unit
PCIT	Pennsylvania Crash Information Tool
PoE	Power-over-Ethernet
RPO	Rural Planning Organization
RSU	Roadside Unit
SAE	Society of Automotive Engineers
SPaT	Signal Phasing and Timing
STIP	PennDOT State Transportation Improvement Program
TIM	Traveler Information Message
TIP	Transportation Improvement Program
TSAMS	Traffic Signal Asset Management System
TSMO	Transportation Systems Management & Operations
TYP	Twelve Year Program
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
WAVE	Wireless Access in Vehicular Environment protocol

Table of Contents

Document Overview i
Common Terms and Acronyms ii
Section 1. Defining the Technology 1
1.1. Technology Background 1
Automated Vehicles 1
Connected Vehicles 2
Connected and Automated Vehicles (CAV) 5
1.2. Role of Communication Technologies for Connected Vehicles – DSRC & 5G 5
DSRC 5
Fifth Generation (5G) Cellular Communications 7
Section 2. V2I Deployment Impacts & Priorities 9
2.1. Priority Applications 9
Safety 9
Mobility 10
Environment 11
Agency Data 11
2.2. Projected Penetration Rate Scenarios & Anticipated Impacts 12
General Timeline 12
Scenarios 13
Planning for Connected Vehicles 15
2.3. Corridor Prioritization 16
Initial Criteria 16
Urban Corridor Criteria 16
Rural Corridor Criteria 17
Feasibility of Implementation 17
2.4. Long Range Plan Integration 18
Priority Corridor Identification 18
Stakeholder Engagement 18
Plan Integration 19

Future of DSRC Coordination Plans 19
Section 3. Cost & Design Considerations 20
3.1. Project Selection 20
Selecting the Right Project 20
Project Lifecycle Timing 20
Project Types 21
Project Funding 21
3.2. Design Considerations 22
Compatible Infrastructure 22
Unit Placement 22
3.3. Cost Overview 24
Element Cost Breakdown for the Deployment of One DSRC Unit 25
Deployment Cost Scalability 26
Additional Cost Considerations 26
3.4. Ownership and Maintenance Responsibilities 27
Appendix A – Current Pilot Programs 29
Appendix B – Example 2019 TIP Projects in PennDOT District 8 30
References 31
Section 1. Defining the Technology 31
Section 2. V2I Deployment Impacts and Priorities 32
Section 3. Cost & Design Considerations 33

Section 1. Defining the Technology

1.1. Technology Background

Emerging transportation technologies are promising to significantly improve the safety and accessibility of our nation's transportation network. Technologies such as those enabling Connected and Automated Vehicles propose to reduce crashes, improve transportation efficiency, and increase transportation access to those with mobility challenges. While connected and automated vehicles promise to be the future of transportation technology, both of these solutions rely on different types of technology and could require different types of interaction with the transportation infrastructure and support environment. These technology types could work independently, or ultimately in cooperation, with each other.

Automated Vehicles

Automated vehicles (AVs) by definition supplement or replace, part or all of the dynamic driving task of a human vehicle operator. Within the 5 levels of automation adopted by the Society of Automotive Engineers (SAE) and the U.S. Department of Transportation (USDOT), the "highly automated vehicles" exhibit level of automation 3 or higher. These levels (from 0 to 5) are described in Figure 1. The advanced automated driving systems for these future vehicles are designed and built by vehicle manufacturers, frequently partnering with technology companies.

Currently, the highest level of automation available for a consumer passenger vehicle is Level 2, most commonly seen in vehicles manufactured by Tesla, and the SuperCruise function in some General Motors products. Other automobile manufacturers will also soon be bringing Level 2 vehicles to market. Most currently available vehicles with automation Level 2 do not require any specific input or information from the infrastructure or transportation system operators. However, as an example, SuperCruise works only where General Motors has previously mapped the area. The vehicle itself has data about the road network, and this data could become stale and inaccurate. Low-speed transit vehicles that can operate at an automation Level 4 are available, but currently are restricted by federal regulations to operate at no higher than 25 mph on public roadways. These systems also have limited ability to operate in a dynamic, uncontrolled traffic environment.

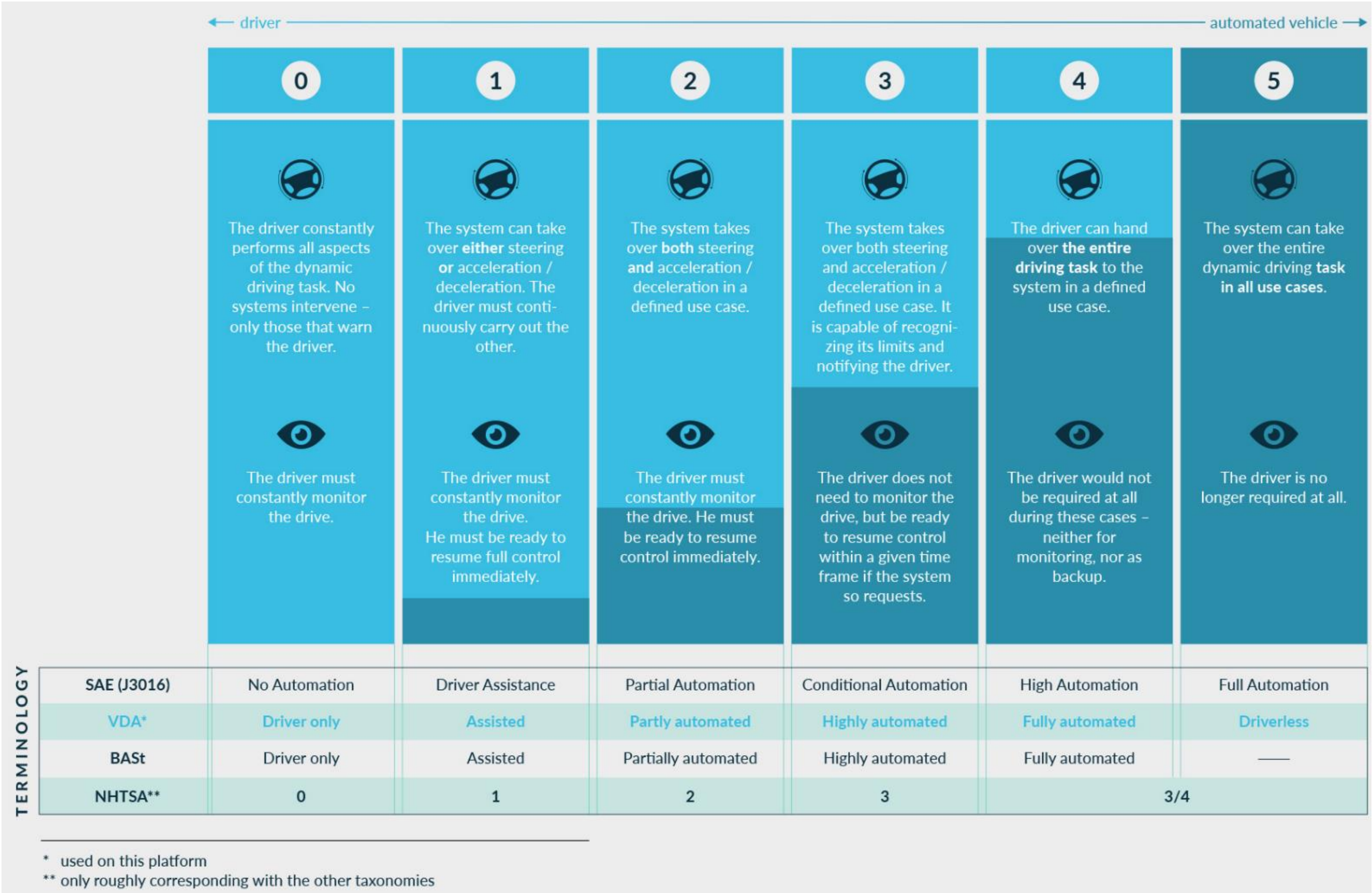


Figure 1 – Displays the various levels of Autonomy. Level 0 represents traditional driving and level 5 represents complete vehicular autonomy.

Auto manufacturers are working on deploying passenger vehicles with Level 4 automation capabilities within the next 5 years, that can reportedly be deployed in a very controlled, geo-fenced, and centrally operated system.

Connected Vehicles

Connected Vehicle technologies, in which vehicles can exchange real-time information with other vehicles and/or transportation infrastructure systems, are designed to support a human driver in performing the dynamic driving task. With a Connected Vehicle, the human driver is still responsible for all aspects of the dynamic driving task but may be supplemented by existing advanced driver-assistance systems (ADAS) such as cruise control, parking assistance, blind spot detection, automated emergency braking and lane departure warnings. Connected Vehicle technology does not take control over the vehicle systems; it provides real-time information to assist the driver in avoiding imminent safety hazards or could provide real-time information back to transportation infrastructure owners and operators. For example, transportation entities could be provided with traffic data to facilitate where improvements need to be prioritized.

In addition, Connected Vehicles are expected to decrease traffic law violations and can be tied into emergency services for faster deployment. Roadway crews can also be notified of roadway safety hazards at specific locations because of higher resolution monitoring and sensor data collection made possible with Roadside Unit (RSU) installation.

Automated data collection from implementing Connected Vehicle technology on infrastructure can be useful to assess the effectiveness of the roadway by documenting vehicle speed, acceleration, delay, queue, travel time and traffic density. Origin – destination studies can also provide more insight on what kinds of drivers are on the road, and when and where they are driving.

Connected Vehicle systems and applications generally fall under the following types of operation:

Vehicle-to-Vehicle (V2V) – Vehicles exchange data with each other regarding their respective status, speed, direction, and other characteristics, allowing them to generate warnings to avoid collisions. V2V applications require a vehicle to be equipped with compatible On-Board Units (OBUs), which broadcast, receive, and process the data from other similarly equipped vehicles. Some benefits of V2V connectivity are provided in Figure 2.

Vehicle-to-Infrastructure (V2I) – Vehicles exchange data with roadside infrastructure, such as traffic signals, allowing for a variety of safety and mobility applications, such as (but not limited to) generating warnings within vehicles of a pending red light, or generating speed warnings to vehicles prior to traveling around a curve. In a V2I network, communications occur between a vehicle equipped with an OBU, and infrastructure equipped with one or more RSUs. The RSU's broadcast data to a vehicle equipped with an OBU, which in turn receives and processes the data, generating any pertinent warning, alert, or information for the driver. RSU's may also be configured to receive broadcasts from vehicle OBU's, allowing the exchange of real-time and near real-time data with a larger communications network, allowing for dynamic analysis of the performance of the transportation network. Some additional benefits of V2I connectivity are provided in Figure 2.

Vehicle-to-"Everything" (V2X) – A more encompassing term for connected vehicle applications, where vehicles exchange data with other vehicles, the infrastructure, pedestrians, or a network environment.

The key to any connected vehicle system are the applications that the exchanged data allows. USDOT, in conjunction with public sector transportation agencies and vehicle manufacturers, has identified dozens of potential connected vehicle applications that can be deployed.

Additional CV benefits related to Agency Data, the Environment, Road Weather, Mobility, and Smart Roadside are also provided in Figure 2. Information regarding specific examples in Figure 2 can be found at the USDOT's Intelligent Transportation System Joint Program Office (ITS-JPO) Website.

V2I Safety

- Red Light Violation Warning
- Curve Speed Warning
- Stop Sign Gap Assist
- Spot Weather Impact Warning
- Reduced Speed/Work Zone Warning
- Pedestrian in Signalized Crosswalk Warning (Transit)

V2V Safety

- Emergency Electronic Brake Lights (EEBL)
- Forward Collision Warning (FCW)
- Intersection Movement Assist (IMA)
- Left Turn Assist (LTA)
- Blind Spot/Lane Change Warning (BSW/LCW)
- Do Not Pass Warning (DNPW)
- Vehicle Turning Right in Front of Bus Warning (Transit)

Agency Data

- Probe-based Pavement Maintenance
- Probe-enabled Traffic Monitoring
- Vehicle Classification-based Traffic Studies
- CV-enabled Turning Movement & Intersection Analysis
- CV-enabled Origin-Destination Studies
- Work Zone Traveler Information

Environment

- Eco-Approach and Departure at Signalized Intersections
- Eco-Traffic Signal Timing
- Eco-Traffic Signal Priority
- Connected Eco-Driving
- Wireless Inductive/Resonance Charging
- Eco-Lanes Management
- Eco-Speed Harmonization
- Eco-Cooperative Adaptive Cruise Control
- Eco-Traveler Information
- Eco-Ramp Metering
- Low Emissions Zone Management
- AFV Charging / Fueling Information
- Eco-Smart Parking
- Dynamic Eco-Routing (light vehicle, transit, freight)
- Eco-ICM Decision Support System

Road Weather

- Motorist Advisories and Warnings (MAW)
- Enhanced MDSS
- Vehicle Data Translator (VDT)
- Weather Response Traffic Information (WxTINFO)

Mobility

- Advanced Traveler Information System
- Intelligent Traffic Signal System (I-SIG)
- Signal Priority (transit, freight)
- Mobile Accessible Pedestrian Signal System (PED-SIG)
- Emergency Vehicle Preemption (PREEMPT)
- Dynamic Speed Harmonization (SPD-HARM)
- Queue Warning (Q-WARN)
- Cooperative Adaptive Cruise Control (CACC)
- Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)
- Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)
- Emergency Communications and Evacuation (EVAC)
- Connection Protection (T-CONNECT)
- Dynamic Transit Operations (T-DISP)
- Dynamic Ridesharing (D-RIDE)
- Freight-Specific Dynamic Travel Planning and Performance
- Drayage Optimization

Smart Roadside

- Wireless Inspection
- Smart Truck Parking

Figure 2 – Lists many of the capabilities of Connected Vehicle technology. **Source: USDOT**

Currently, only a few models of vehicles come equipped with connected vehicle capabilities. However, announcements by major automobile manufacturers such as General Motors and Toyota promise an increase in the number of new vehicles that will be equipped with these technologies. In addition, there are "after-market" devices that can be added to existing vehicles that enable the use of connected vehicle communications and applications.

There are currently functional vehicle-to-infrastructure (V2I) deployments in at least 19 states. In Pennsylvania, Harrisburg has 8 operational RSUs, Pittsburgh has 46 operational RSUs and an additional 45 planned for deployment, and Philadelphia is planning to equip 160 RSUs by 2020. Most of these are limited pilot-type deployments to demonstrate the feasibility of the technology and applications, although there are a few deployments that are intended to be longer-term and expandable.

Early connected vehicle deployments have been spearheaded by US DOT's Intelligent Transportation System Joint Program Office (ITS-JPO), which has distributed grants for developing and implementing the technology as well as provided documentation and technical resources to agencies executing ITS projects. The Federal Highway Administration (FHWA) has also developed guides in ITS architecture implementation from a system engineering standpoint to plan, design, construct, test and operate CV systems. In addition, a national connected vehicle Signal Phasing and Timing (SPaT) deployment challenge is challenging state and local public sector transportation infrastructure owners and operators to deploy DSRC infrastructure with SPaT broadcasts in at least one corridor or network in each of the 50 states by January 2020. Progress and resources can be found at www.transportationops.org/spatchallenge.

Connected and Automated Vehicles (CAV)

In the coming years, a vehicle may be connected; or, it may be automated. In reality, the most benefit will be achieved when these two solutions are deployed concurrently, resulting in Connected and Automated Vehicles. While the future of CAVs are both promising and exciting, there are currently over 350 million registered vehicles on the nation's roadways. Thus, for the foreseeable future one can expect a "mixed fleet," including: a mix of non-automated vehicles, vehicles with varying levels of automation, and connected vehicles.

1.2. Role of Communication Technologies for Connected Vehicles – DSRC & 5G

Connected vehicles operating in a V2I and / or a V2V environment require secure, high-speed, low-latency (low delay) communications. Many connected vehicle applications are safety-related and require a reliable communications system. Currently, there are two types of communication technologies that are being promoted for connected vehicle systems: DSRC, and 5G. While some of the hardware configurations may be different between these technologies, the intent of the systems is the same; using a defined wireless spectrum to quickly and securely transmit critical safety and mobility information.

DSRC

Dedicated Short-Range Communications (DSRC) is a wireless communication technology, much like the Wi-Fi communications that many are familiar with, that allows vehicles to communicate with other vehicles and the surrounding infrastructure via short range signals. The short range signals avoid/minimize signal overlap and allow the vehicle to have a 360-degree communication with similarly-equipped infrastructure and vehicle systems.

The term "Dedicated" refers to the fact that the Federal Communications Commission (FCC) has set aside a communications bandwidth specifically for transportation safety purposes. DSRC uses channels that transfer information through a combination of OBUs and RSUs facilitating V2X communications through the licensed 5.9 GHz band (5.850-5.925 GHz band). This bandwidth was allocated to ITS operations by the FCC for uses in "traffic light control, traffic monitoring, travelers' alerts, automatic toll collection, traffic congestion detection, emergency vehicle signal preemption of traffic lights, and electronic inspection of moving trucks through data transmissions with roadside inspection facilities" (FCC, 1999).

In terms of hardware or physical installation, RSUs operate with point-to-point connections to deliver deployment location-specific messages. For example, an intersection may need an RSU that is programmed with a signalized intersection's road geometry to advise an optimal driving speed for approaching vehicles 150 feet before getting to the queue. However, a bridge historically known to have ice patches in the winter, may have an RSU to communicate a weather warning when appropriate climate changes occur. RSUs will likely be mounted overhead to achieve a better line-of-sight for the radio communications. They will also require a transmission method, typically Power-over-Ethernet (PoE), which pairs data transmission and power. PoE pairs data and power, but only for short distances (100m max). For areas requiring additional coverage a PoE injector can be used as a repeater to transmit the signal over longer distances.

Standards referenced by USDOT include IEEE 802.11p and the 1609 Wireless Access in Vehicular Environment (WAVE) protocol. ITS hardware and infrastructure have been developed for these systems, but the technology will continue to further mature as additional deployments occur. This technology will consist of “open air” broadcasting, meaning anyone (including public transportation agencies) with compatible equipment can freely access any broadcast data. However, no personally identifiable information is involved with DSRC systems “open air” broadcasting. Any fixed site that is broadcasting over the 5.9 GHz band is required to be licensed by the FCC.

Additional standards have been developed by the SAE for V2X communications involving Basic Safety Messages (BSMs) generated by OBUs, and Traveler Information Messages (TIMs) and SPaTs which are generated by RSUs. Collection of traffic messages and statistics from DSRCs can be tied into a backhaul network (a center for data reception, collection and distribution) for remote management and data processing.

DSRC Pros

DSRC is a guaranteed technology that has been proven for more than 12 years, with significant guidance and resources available to deploy it nationwide. DSRC-based connected vehicle systems have already been implemented with preliminary regulatory measures, mainly regarding cybersecurity and standards for ITS and other V2I infrastructure installation. Transportation agencies across the country, working jointly with vehicle manufacturers and technology companies, have deployed and support DSRC-based systems.

One of the greatest advantages of DSRC is its ability to operate without network connectivity. DSRC communications can still be implemented in rural areas with little to no backhaul (fiber optic or cellular) coverage in V2V and V2I applications. This allows for many, especially safety-based, V2I applications to be operated locally in rural areas.

DSRC Cons

DSRC-based V2I systems require the deployment of RSUs within roadway right-of-way. Long-term updates and maintenance would fall to the transportation infrastructure owners and operators. Currently, there is limited technical experience when it comes to configuration and maintenance of RSUs, which may hinder municipal deployment of the technology, especially at the local government level.

Agencies may be discouraged from supporting DSRC deployment under the assumption that rapid development of technology, standards, software, and methods may render their initial investments obsolete. However, this can be offset by supporting efforts to make much of the initial hardware investments in DSRC systems compatible with future emerging technologies that may exist in the V2X world.

While the financial burden of DSRC systems is expected to fall largely to the public sector, ubiquitous deployment of roadside infrastructure is not required to achieve major benefits. Localized deployment of infrastructure can achieve safety and mobility goals; additionally, V2V applications do not require supporting roadside infrastructure.

DSRC Implementation Requirements

Standards for a DSRC-based deployment, while still ongoing some development, have matured significantly as deployments have progressed. Some of the following standards are available for DSRC deployments:

- SAE J2735 and SAE J2945 standardize the transmission of data in a DSRC environment.
- National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) establishes compatibility requirements with roadside communication infrastructure.
- IEEE 802.11p and IEEE 1609 standardize the technical requirements of DSRC communications.
- The USDOT has developed a specification for DSRC RSUs (Version 4.1).
- The FCC has provided guidelines for licensing devices within the 5.9 GHz communications bandwidth for DSRC and ITS applications.

The National Highway Traffic Safety Administration (NHTSA) has issued a notice of proposed rulemaking, proposing Federal Motor Vehicle Safety Standard (FMVSS) No. 150 Vehicle-to-Vehicle Communication Systems, which require all light vehicles to have V2V communications using OBUs with DSRC capabilities. The proposed rulemaking and comments from interested parties is currently in front of the United States Office of Administrative Services (OAS) for future action.

Fifth Generation (5G) Cellular Communications

Cellular technology is working to advance to 5G connectivity for higher bandwidth, accessibility and network density. 5G is a radio access technology that will be implemented by retrofitting existing platforms such as 2G, 3G, 4G, and Wi-Fi. Because 5G it is not yet suitable as the single cellular platform to support the different needs of today's users, it will need to coexist with existing platforms until fully implemented. By the installation of many small cell towers, a shorter range is obtained which allows for a higher bandwidth and faster speeds. Due to the installation requirements, 5G services will be rolled out to densely populated areas initially and will take many years to expand to rural, or less dense, areas.

It would be possible to leverage the standards developed by a 5G cellular network to develop 5G-based V2X technologies. With a 5G-based V2X system, operations would be very similar to a DSRC-based system, in that dedicated equipment would be required to generate and receive data between vehicles and the infrastructure. 5G V2X systems would use the same 5.9 GHz band for communications between vehicles and infrastructure as DSRC systems; the differences lie in the equipment and backhaul communication configurations. While 5G V2X systems have not yet been developed or piloted, it is expected that most of the DSRC-based applications would also be used in a 5G V2X environment.

5G Pros

The development of larger-scale 5G cellular communications networks is expected to enable a future 5G-based V2X network. As a result, it is possible that much of the infrastructure costs in a 5G V2X network will be borne by telecommunications companies (although this results in some cons, listed below). 5G V2X technology is also expected to be able to use much of the same infrastructure as a DSRC-based system, ensuring that much of the investment in DSRC systems are not “lost” to new technology. Many DSRC equipment manufacturers are currently developing both RSU and OBU hardware to have both DSRC and 5G V2X capabilities, allowing for the leveraging the benefits of both technologies.

5G Cons

The greatest con of 5G V2X communication is that 5G wireless technology simply does not exist yet. There are some pilot deployments of 5G communications networks that telecommunications companies have deployed in the United States, but full-scale deployment has yet to begin. 5G V2X deployment can only occur where a 5G cellular network exists. As a result, wide-spread deployment of 5G V2X solutions will be limited geographically to where reliable 5G communications capabilities are available. 5G cellular network rollout is expected to take several years, and possibly longer in rural areas. A transitional period will likely occur over the course of many years, emulating the transition from 3G to 4G LTE.

Specific 5G V2X standards and equipment has not yet been developed. It is expected that 5G V2X technology will have to undergo the same robust and compatibility testing and development for use in an automotive environment as DSRC has done. This means it could be another 8 – 10 years before real, practical 5G V2X applications are ready for initial deployment.

The nature of a 5G V2X revolves around “point-to-point” communications, meaning that devices would communicate directly with each other (and the associated 5G cellular network). As a result, exchanged data would not be available “open air,” such as would be the case with a DSRC network. As a result, data generated by equipped vehicles would not be readily available to transportation infrastructure owners and operators. This eliminates a significant attraction of a connected vehicle network: using data to assist with the real-time and near-real time ability of managing a transportation network. So, while a 5G V2X system may reduce public sector infrastructure costs, agencies will have no access to data unless they sign a contract with the private service provider. This allows private companies to have control over the data collected, as it will not be available for everyone’s use.

5G Implementation Requirements

Prior to implementing a 5G-based V2X system, a larger 5G cellular communications network would be required. This will require the installation of many low power small cell towers to be widespread beacons of signal reception and transmission. Although existing 3G and 4G towers will be used as much as possible and 5G towers will be less intrusive than 3G and 4G, new towers will likely require property acquisition or leasing agreements in which to build or expand cell coverage. 5G cellular networks and 5G V2X deployments would be subject to all FCC rules and regulations regarding cellular communications.

5G V2X deployments will require OBUs and RSUs, much like with DSRC deployments. Equipment manufacturers are currently developing hardware with both DSRC and 5G capabilities, so that the same roadside infrastructure can be used for both types of deployments.

Public agencies can help facilitate the deployment of small-cells by working with the industry to install hardware on existing infrastructure.

Section 2. V2I Deployment Impacts & Priorities

2.1. Priority Applications

V2I technology allows for DSRC-equipped vehicles (connected vehicles) to communicate with surrounding DSRC roadway infrastructure. This communication technology has the ability to alert drivers of safety risks, reduce congestion, send environmental hazard alerts, and reduce the consumption of fuel and electricity. Below are some examples of V2I applications that improve safety, mobility, the environment, and agency data/operations to help with an understanding of how this technology can improve the transportation system and user experience.

Safety

Safety is the highest priority of V2I applications. In addition to enhancing vehicular safety, the implementation of V2I safety applications can help to increase the awareness of, and safety for, nearby bicyclists and pedestrians. According to PennDOT's *2017 PA Crash Facts and Statistics*, pedestrian- and bicycle-related crashes represented 4.2% of the total reported crashes in 2017; however, they accounted for 14% of all traffic fatalities. It is anticipated that implementation of related V2I applications may result in a significant reduction in the number of bicycle and pedestrian fatalities.

V2I Safety applications currently being tested and under development include:

Red Light Violation Warning – This application would notify connected vehicles approaching a DSRC-equipped intersection regarding the signal phase and timing, intersection geometry, and position correction information. If the vehicle is predicted to violate the traffic signal (e.g., run a red light), the driver would receive a warning sufficiently in advance of the intersection to avoid a violation and potential crash.

Stop Sign Gap Warning – This application is intended to alert drivers stopped at a stop sign on a side road of unsafe gaps between vehicles traversing on the major road. If there is insufficient sight distance between vehicles, a vehicle OBU may not be able to receive messages from other vehicles traveling in different directions, therefore an RSU would be required to transmit the message of an oncoming vehicle. This application may be configured to either detect oncoming connected vehicles and then relay a message directly to the stopped vehicle, or the application can utilize current traffic data collection equipment (e.g., vehicle detectors) to detect all oncoming vehicles and relay the message to a roadside sign to alert the driver of insufficient gaps or potential collisions.

Pedestrian Warning – This application would notify connected vehicles of the presence of pedestrians in or approaching the roadway at DSRC-equipped locations (locations with pedestrian activity, signalized intersections, trail crossings, etc.) through activation of a pedestrian push button. This application may have the ability to provide day-one benefits to connected vehicles as it does not rely on interaction with other connected vehicles. Future detection methods for this application may include the use of smart phones to broadcast their locations, or systems that detect pedestrians in the crosswalk.

Curve Speed Warning – This application would assist drivers in avoiding lane departure crashes by notifying connected vehicles of an upcoming curve and providing an alert or warning to the driver when the vehicle approach speed is too high to safely traverse the curve(s).

Spot Weather Information Warning – This application is designed to warn connected vehicles of inclement weather or adverse roadway conditions by providing an onboard alert or posting a message on a roadside sign. This application is intended to notify drivers of the need to reduce speed or divert from their route for multiple types of weather conditions, such as fog, high winds, surface conditions (snow, ice, rain, flooding), or reduced visibility.

Mobility

The following are Multi-Modal Intelligent Traffic Signal System (MMITSS) applications that may increase mobility through corridors in which they are installed by enabling equipped priority vehicles such as public transit, freight, and EMS to travel through the corridor more efficiently. This is typically accomplished by modifying existing signal operations at equipped intersections.

Transit/Freight Signal Priority – This application would provide designating signal priority for equipped transit and freight vehicles. For example, the traffic signal may be adjusted to switch to the phase that will allow for the transit vehicle to pass through the intersection. This application would typically be utilized on signalized corridors with a high amount of transit and/or freight traffic.

Emergency Vehicle Preemption Priority – This application would facilitate safe and efficient movement of emergency vehicles through intersections by clearing queues, stopping/holding conflicting traffic, and clearing congested traffic. DSRC would allow for 'network-based' pre-emption, where connected vehicles (CVs) communicate within the network to efficiently prioritize emergency vehicles.

Intelligent Traffic Signal (ITS) System – This application would use both vehicle location and movement measurements of connected vehicles to improve traffic signal operations. The higher the proportion of connected vehicles in the traffic stream, the more accurately the Intelligent Traffic Signal System would respond to the traffic demand. This application would typically be utilized on signalized corridors with high amounts of congestion.

Environment

Increasing efficiency of vehicular travel has environmental impacts by reducing fuel and electricity consumption. The following V2I application increases efficiency by reducing headways and delay at signalized intersections.

Eco-Approach and Departure at Signalized Intersections – This application would use signal phasing and timing information combined with the connected vehicle location and speed information to provide suggested speed advice to drivers. Drivers can then adapt their travel speed in order to pass the next signal on green or to decelerate to a stop in an eco-friendly manner. In congested conditions, this is only effective if vehicles ahead of the driver are responding similarly, hence, this application would see greater benefits in a fully penetrated environment.

Agency Data

V2I applications based on data collection from connected vehicles may use this data to create a more efficient and safer roadway network by allowing for alternate solutions to current traffic detection methods, traffic modeling, and maintenance needs.

Probe-based Pavement Maintenance – This application would detect vertical wheel movement and/or body acceleration from connected vehicles to measure road quality. This allows for the detection of potholes (location and size) and surface roughness.

Traffic Monitoring – This application may allow agencies to reduce or phase out current traffic detecting methods such as loop detectors and cameras. To replace current detection at signalized intersections, this application is only viable in a fully penetrated environment. For traffic modeling or monitoring, connected vehicle probe data combined with statistical methods may replace current detectors prior to full deployment.

Probe-enabled Traffic Monitoring – This application would use connected vehicle technology to generally evaluate traffic and travel patterns. This would allow for more accurate traffic model baselining and predictive traffic studies to be done to create more efficient roadways and connections.

2.2. Projected Penetration Rate Scenarios & Anticipated Impacts

General Timeline

While V2I applications have the ability to provide day-one safety benefits to CVs, USDOT has stated that a 30-50% penetration of DSRC equipped vehicles on the roadway can have a significant impact on safety for all vehicles.[1] Currently vehicle manufacturers have been a critical part in the development of CV technology. The following case studies provide insight on potential penetration rate scenarios based on vehicle manufacturer CV deployment rates.

Vehicle Manufacturer Case Study

Over the past 13 years, Toyota has collaborated with other automakers, infrastructure organizations, and the USDOT to further develop DSRC technology and has stated that most of their models will have DSRC capabilities by "mid-2020s."[2] Based on this information, Figure 3 presents a potential DSRC penetration rate for Toyota's vehicles on the roadway in the United States.

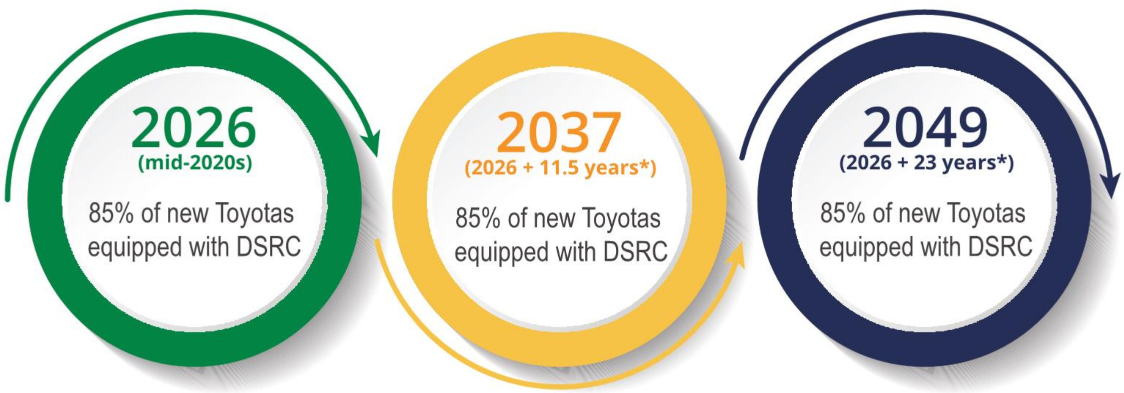


Figure 3 – Toyota DSRC Penetration Scenario
*Median vehicle fleet age estimated to be 11.5 years. Therefore, assume an additional 23 years for turnover of the existing fleet

General Motors will likely have a similar DSRC penetration rate to Toyota's. Currently, General Motors equips a single Cadillac model with DSRC (CTS Sedan). The automaker plans to introduce the technology in a crossover vehicle by 2023 and eventually expand the technology across Cadillac's entire portfolio.[3] General Motors and Toyota alone comprised over 30% of the total vehicles sold in the United States in 2018. In addition, other vehicle manufacturers have similar plans and timelines for implementing DSRC within their vehicles.

[1] Source: https://ecfsapi.fcc.gov/file/60001841106.pdf

[2] Source: https://corporatenews.pressroom.toyota.com/releases/toyota+and+lexus+to+launch+technology+connect+vehicles+infrastruct ure+in+u+s+2021.htm

[3] Source: http://gmauthority.com/blog/2018/06/cadillac-plans-to-bring-v2x-technology-to-new-crossover-by-2023/

Scenarios

The following scenarios have been described regarding mixed fleet and full fleet penetration of DSRC. While related to V2I applications, mixed fleet and full fleet are defined as:

Mixed Fleet – The combination of unequipped and DSRC equipped vehicles on the roadway
Full Fleet – All vehicles on the roadway are DSRC equipped

Urban Corridor

In an urban environment scenario, a highly urbanized, signalized corridor that is prone to congestion and traffic problems is expected. This type of corridor provides ample infrastructure in place for deployment of RSUs for V2I applications. In a typical urban corridor, there are many applications (as described in Section 1) that could be deployed with benefits realized on day-one. This means the driver of a connected vehicle could receive information immediately to help them make better decisions as they travel through the corridor.

Many of the applications are focused on signalized intersection operations because they typically require minimal infrastructure updates to implement. These applications can be deployed to operate in a local mode, without it being necessary to have backhaul communication in place. The age of the existing signal controller is the primary limiting factor prohibiting easy implementation.

Mixed Fleet

In a mixed fleet environment, vehicles that are equipped with OBUs will benefit the most, but safety will be improved for all vehicles on the roadways. The infrastructure RSUs will be providing SPaT information to aid the driver in reducing potentially unsafe driving actions. As described in Section 2.1, the Red Light Violation Warning application is one scenario that provides a driver with a warning if they are projected to run the red light.

The Pedestrian Warning is another application that could be realized by utilizing SPaT information to inform the driver that the pedestrian push button has been activated.

With deployment of OBUs on emergency, transit, or freight vehicles, signal preemption or prioritization could be implemented along the corridor to maximize throughput without requiring other passenger vehicles to be a connected vehicle.

Full Fleet

In a full fleet scenario on the roadway, V2I applications will substantially improve both mobility and safety as they begin to alter traffic operations (eco-approach, for instance) and significantly reduce driver error.

The Intelligent Traffic Signal System (I-SIG) application can utilize vehicle data collected to create predictions of lane-specific platoon flow, platoon size, and other vehicle arrival characteristics. The real-time data availability has the potential to transform how traffic signal systems are designed, implemented and monitored. Developing new systems that use data obtained from V2V and V2I communications to control signals in order to maximize flows in real-time can improve traffic conditions significantly. The I-SIG in a full fleet scenario could play the role of an over-arching system optimization application, that accommodates transit and/or freight signal priority, emergency vehicle preemption, and pedestrian movements to maximize overall arterial network performance.

Rural Corridor

In a rural environment scenario, a typical corridor would be a low-volume, two-lane highway. There would be few signalized intersections, two-way stop sign intersections, and limited Intelligent Transportation System infrastructure. Vehicles may form platoons due to limited traffic, while roadway curvature and weather-related incidents are to be expected. Therefore, the focus for V2I in rural corridors is geared more toward safety rather than mobility. The rural environment causes deployment of RSUs to be more involved due to the lack of existing infrastructure and available power. Communications pose a problem in rural corridors due to winding roads, mountains and valleys. Cellular service is often nonexistent and getting long distance line of sight radio systems is problematic. A clear line of sight for DSRC radios will be crucial for reliable communication. RSU installations should be in appropriate locations in advance of the point where a vehicle must react to the anticipated application.

Applications best suited for a rural scenario are motorist advisories and warnings, such as speed zone warnings or curve speed warnings. These applications may be deployed in a local mode by providing a fixed message to the vehicle without it being necessary to have backhaul communication in place (communication to a center for data reception, collection and distribution for remote management and data processing).

Although for some applications, backhaul communications is not necessarily required, many widescale deployment of rural applications may be limited based on available power, backhaul network availability and funding to build out the infrastructure required to deploy applications requiring real time data inputs, like those required in the Spot Weather Warning application.

Mixed Fleet

In a mixed fleet environment there will be some safety benefits to vehicles that are equipped with OBUs, as the infrastructure is broadcasting information to the vehicle. These applications (speed zone and curve speed warning) would provide a Traveler Information Message (TIM) to the vehicle allowing the OBU to determine if the driver is exceeding the upcoming posted speed limit. The OBU would then provide a warning to the driver.

At two-way stop sign intersections, an appropriate application would be the Stop Sign Gap Assist. Equipment would need to be installed at stop sign controlled intersections which determines the location and speed of oncoming vehicles (e.g., using Radar/Lidar). This information, in addition to stop sign information and intersection map data, is broadcast in the vicinity of the intersection from an RSU. The vehicle OBU receives this information from the RSU and then provides a warning to the driver.

Full Fleet

In the full fleet environment, a large impact to safety, especially during construction and maintenance operations, is predicted. Roadwork vehicles can transmit their location through V2V and V2I communications. This information as well as specific information about roadway impacts can be sent directly to approaching vehicles, thus allowing the driver to move out of a closed lane or reduce their speed through a work zone. Secondary crashes have the potential to be significantly reduced under a full fleet environment.

RSUs at strategic locations with backhaul communications would allow additional applications that could collect passing vehicle data and then provide metric information to roadway agencies. Data such as traffic volume, probe-based traffic monitoring or probe-based pavement maintenance data could then be analyzed to further improve the roadway.

Planning for Connected Vehicles

Based on the expected timeline for DSRC-equipped vehicle penetration on the roadway, planning for a mixed fleet in urban and rural scenarios is essential.

While planning for connected vehicles, current systems need to be assessed to determine if they are compatible with CV requirements (i.e. Internet Protocol version 6 (IPv6), Power over Ethernet (PoE) capable, etc.). Based on the system compatibility, funding can be planned to upgrade the existing equipment to support a CV environment and deployment of CV technology (DSRC RSU). While identifying the status of existing assets, corridor prioritization based upon crash history, congestion, pedestrian use, bus routes, etc., can be conducted (further discussed in Section 2.3). With this evaluation and ranking of corridors, deployment of CV equipment can be planned to maximize use of funding for both urban and rural roadways.

Long-term planning should include routine evaluations of the technology, often referred to as State of the Practice studies. These evaluations would aid in providing knowledge of any potential changes to the national CV environment and allow for an analysis on impact to the region. When establishing a long-term plan for CV deployment, it is beneficial to consider including installation needs in other construction projects to potentially reduce costs (for example, infrastructure installation to a roadway improvement project).

As part of this planning effort, it is suggested that MPOs participate at the state level in any committees related to CVs and AVs. This is an opportunity for MPOs to help shape CV/AV policies and to provide the state with local concerns and input.

2.3. Corridor Prioritization

Criteria have been developed to assist in the planning of future V2I deployments in both rural and urban areas. The first step will be to apply the Initial Criteria to narrow down the numerous corridors in the region. The identified corridors can then be evaluated based on additional criteria (urban and rural) to be selected as per the user's interests. Identified corridors can be prioritized further by their existing infrastructure and alignment with the Transportation Improvement Program (TIP) and traffic impact study required improvements.

The DSRC Corridor Selection Interactive Map can be used to prioritize corridors in District 8-0 by selecting various overlapping layers. The map provides a pre-set layer that includes the initial criteria, zero-to-one-foot shoulders, and bicycle/pedestrian crash locations. In addition to the pre-set layer, other various criteria are able to be toggled on and off based upon the user's interest to select corridors. The map can be accessed at http://arcg.is/1Cnz45

Initial Criteria

1. **Non-Freeway** – Freeway use cases are very defined. Corridors/signalized arterials are capable of many different V2I applications, making them more suitable for early V2I development. While there are some very important Freeway applications, for the purposes of this effort, the focus will be on Non-Freeway segments to increase local involvement and to include bicycle and pedestrian applications.
2. **Federal-Aid System** – The majority of V2I deployments may qualify for similar federal-aid programs as ITS deployments (if the deploying agency meets certain eligibility requirements).
    a. Ask the question, "where can I put federal dollars?"

   The federal-aid roads in the GIS map were obtained through PennDOT.

Urban Corridor Criteria

1. **Safety** – A high concentration of the following crashes indicates that the corridor would be a prime candidate for V2I deployment.
    a. Red-light violation crashes (Angle, Head-on)
    b. Intersection proximity crashes
    c. Bicycle/Pedestrian crashes

   2015-2017 crash data was obtained from querying the Pennsylvania Crash Information Tool (PCIT) for each specified criterion.
2. **Transit/Bus Route** – By applying V2I technology to signalized intersections with transit signal priority, priority decisions can be optimized while considering vehicle type, passenger count, or adherence to schedule. Signalized intersections without transit signal priority on a transit/bus route should be considered for the addition of the transit signal priority V2I application. Transit routes were obtained through each of the transit providers in District 8-0.

3. **Freight network** – A freight network indicates that there is a diverse fleet of vehicles utilizing the corridor, which allows for diverse applications of V2I technology. The District 8-0 freight network and freight candidate routes were obtained by contacting PennDOT.
4. **Emergency Facility Locations** – Applying V2I technology to frequent emergency vehicle routes would allow for signal preemption to emergency vehicles and the accommodation of multiple emergency requests. Frequent emergency vehicle routes may be identified by the corridor's proximity to emergency resource locations. EMS and fire department locations were obtained through each County in District 8-0.

For MPOs that maintain a Congestion Management Process, if select corridors are identified as "high priority congested corridors" and conveyed to TCRPC, TCRPC can add this as an additional layer on the interactive map.

Rural Corridor Criteria

1. **Mix of 2-way stop and signals** – This would allow for a diverse set of V2I applications to be implemented with a minimal amount of infrastructure upgrades.
2. **Curvature of roadway** – The implementation of V2I technology at curves has the potential to reduce the number of roadway departure crashes. In 2017, there were 23,023 (18.0%) reported crashes in Pennsylvania related to the curvature of the road (2017 PA Crash Facts & Statistics Book). 2015-2017 curve crash data was obtained from querying PCIT.
3. **Spot weather issues (reoccurring bad weather crashes)** – With a significant number of reported crashes in Pennsylvania occurring during inclement weather conditions, V2I applications related to spot weather issue crashes have the potential to greatly reduce crashes due to local hazardous weather conditions by relaying local weather data to roadside equipment. In 2017, there were 25,406 (19.8%) reported crashes in Pennsylvania which occurred during inclement weather conditions (2017 PA Crash Facts & Statistics Book). Weather-related crash data from 2015-2017 was obtained from querying PCIT.
4. **Corridors with shoulders less than 1 foot** – Implementation of V2I technology at defined locations of departure crashes has the potential to provide additional safety countermeasures to standard road departure safety improvements. In 2017, there were 37,892 (29.6%) reported hit fixed object crashes in Pennsylvania (2017 PA Crash Facts & Statistics Book). In addition, comparing shoulder width data with speed limit data would allow for narrowing down roadways with minimal shoulders. District 8-0 shoulder width data was obtained by contacting PennDOT.

Feasibility of Implementation

If the selected corridor has existing compatible infrastructure and is aligned with the TIP, it is a prime candidate for implementation of V2I applications. If it is not, the desired V2I application may be used to justify adding compatible infrastructure to future projects.

1. **Compatible Infrastructure –** Modernized infrastructure already in place could greatly reduce the cost of implementing various V2I technology, without having to upgrade existing technology. The two pieces of infrastructure that may have to be modernized are:

   a. Modern advanced traffic signal controllers (types and model numbers vary by manufacturer)
   b. Robust high-bandwidth backhaul communication system

   Municipal fiber locations were obtained through the Traffic Signal Asset Management System (TSAMS) database. As TSAMS continues to be updated, the municipal fiber locations will become more refined and accurate. Locations of PennREN fiber was obtained through the PennREN Network Operations Center and Windstream fiber was obtained through Windstream Enterprise.

2. **Alignment with the Transportation Improvement Program (TIP)** – Corridors planned for significant investment in the TIP allow for greater V2I improvement possibilities. Additionally, projects in the preliminary design stage or before may be able to incorporate V2I applications into the design. The TIP layers in the DSRC Corridor Selection map show District 8-0 projects currently on the TIP. These data were obtained by contacting PennDOT.

2.4. Long Range Plan Integration

In planning for the long-term needs of the multimodal transportation system, there are several ways in which DSRC and related elements can be incorporated into the Long-Range Transportation Plan (LRTP) planning process. DSRC incorporation is detailed in the following sections related to priority corridor identification, stakeholder engagement, and plan integration.

Priority Corridor Identification

A corollary to selecting the appropriate selection criteria in urban and rural areas will identify priority corridors or networks as a criterion in DSRC investment. The DSRC Corridor Selection Interactive Map outlined in the previous section of this Guide should be used as a starting point for MPOs in identifying corridors or roadways where investments in DSRC and related technology should be included as projects are implemented. These priority networks would become part of the LRTP and would be factored into the project scope of work when projects are selected within the corridor for maintenance, mobility or safety improvements.

Stakeholder Engagement

Ensure operational interests are represented on the plan steering committee – LRTPs are typically guided by various multimodal transportation interests. As planning for highway transportation continues to segue from capacity building to more of an operations focus, these interests should be at the table as the plan is being updated. Related plans such as the Regional Operations Plan, TSMO Strategic Plan, and Congestion Management Process, should also be consulted as the LRTP is being updated for currency and to ensure the plan is drawing from the latest thinking as it pertains to transportation operations.

Emphasize DSRC and operations in scenario planning – LRTPs may also consider multiple futures as part of an exercise in scenario planning. The plan may be used to convey the impacts that different courses of action could have on financing, land use, and capacity building versus operations or investments in DSRC.

Plan Integration

Incorporate DSRC as part of the LRTP's multimodal transportation profile and strategic directions – LRTPs are required to be responsive to Federal planning factors, one of which includes the requirement to *"Promote Efficient System Management and Operation."* This speaks directly to DSRC's role in optimizing the use of existing roadways. The LRTP should specifically include action strategies that would advance the use of DSRC within the region. Advancements in the evolution of DSRC and related technologies can be captured within the plan narrative as the LRTP is updated every four or five years.

Create a line item for DSRC-related improvements - The primary purpose of any LRTP is to advance an investment plan, or a portfolio of projects to be considered as future transportation programs are being developed. The MPO may wish to sub allocate a portion of its base funding or create a line item to fund specific DSRC-related improvement projects within the region.

Ensure operations are considered and incorporated into the project prioritization process – MPOs use various methods to evaluate the technical merits or economic development potential of candidate projects as part of the LRTP's project prioritization process. Some Planning Partners may use Decision Lens Software in collaboration with PennDOT or use other techniques with more analytical rigor. DSRC could be incorporated into these processes as an additional criterion to assist in project evaluation, and in giving greater weight to operational needs as candidate projects are being evaluated.

Future of DSRC Coordination Plans

While there are several communications technologies that could advance vehicle-to-infrastructure applications, such as Cellular V2X (C-V2X), and Cellular 5G, this Guide is focused on DSRC, which has been widely tested and deployed in the U.S. It is fully expected that the planning work associated with DSRC deployment will be able to be leveraged for these additional solutions. Section 1, as described in the Document Overview, goes into detail regarding C-V2X, 5G and DSRC.

This DSRC Coordination Plan can be used to provide benefits to the roadway network through the implementation of DSRC technology by:

Immediate Benefit

1. Helping MPOs in District 8-0 with identifying potential DSRC projects for their Congestion Management Process and Long-Range Plans

Potential Benefits

2. Being replicated in other PennDOT districts
3. Being implemented into the Statewide Long-Range Plan

Section 3. Cost & Design Considerations

3.1. Project Selection

In order to effectively reduce the cost of installing various DSRC V2I applications, it is recommended that a DSRC component is aligned with and added to a project already in the TIP. By adding V2I components to a TIP project, the design and construction costs may be reduced significantly. The following sections further discuss the stage at which a V2I component should be added to current or future TIP projects, as well as various types of projects that would be well suited for DSRC deployments.

Selecting the Right Project

The DSRC Corridor Selection Map should be used in conjunction with the PennDOT TIP Project Map to narrow down prospective projects within the desired area. See Section 2.3 for additional information on the recommended corridor selection process and how to use the DSRC Corridor Selection Map Tool. Links to both maps are provided below:

DSRC Corridor Selection Interactive Map – http://arcg.is/1Cnz45
PennDOT TIP Project Map – http://www.projects.penndot.gov/projects/TipVisMap.aspx

Some examples of current TIP projects that may be prime candidates for a DSRC component are provided in Table B.1 in Appendix B.

Project Lifecycle Timing

PennDOT's State Transportation Improvement Program (STIP) and TIP comprise the first four years of the Twelve Year Program (TYP), which outline the transportation improvement projects over those four years. While developed by MPO/RPOs, these projects intend to use federal and/or state matching funds to complete and allow for public involvement in the development of the plans, programs, and projects. As the public is heavily involved throughout the process, each TIP may be modified or amended as needs change.

Since DSRC and related technologies may be considered beyond the TIP/STIP in a LRTP, connected and autonomous vehicle technology, including DSRC should be incorporated into long range planning as tools to more effectively address safety and congestion issues through criterion to assist in project evaluation and better facilitate the addition to DSRC-related improvements to TIP projects. Additional information on DSRC LRTP integration is provided in Section 2.4.

The project delivery process goes through several collaborative steps where the addition of a DSRC component may be considered until environmental clearances have been completed. The steps where a DSRC component should be considered are indicated by the blue outline in Figure 4.

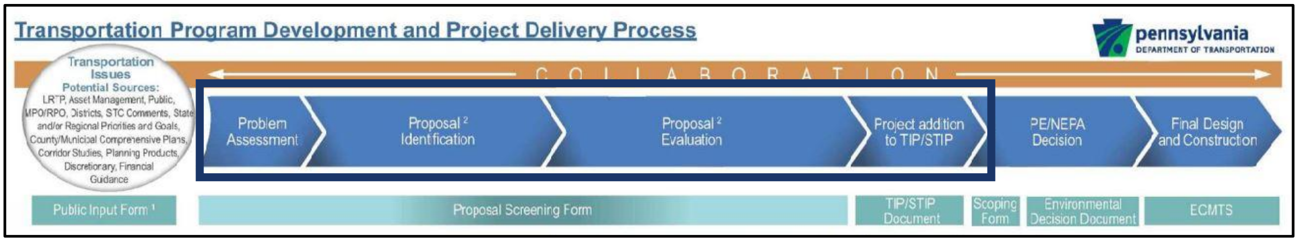


Figure 4 – DSRC Considerations Throughout the Project Delivery Process

Project Types

While identifying potential projects in which a DSRC component might be added, it is important to consider the type of project and the type of work being performed. Generally, an ITS project, with electrical/ITS contractor involvement, would be beneficial as the contractor would have experience of installing the ITS equipment. These contractors typically understand the intricacies of installing intelligent transportation devices and the coordination required with the device vendors.

Some specific types of projects would allow for a DSRC component to be added without greatly increasing the cost. These types of projects often involve a technological improvement or rewiring/designing of an intersection. The following are specific types of projects that would be ideal for incorporating a V2I component:

- **Traffic signal upgrades –** may involve installing new traffic signal equipment, backhaul infrastructure, etc.
- **Widening/redesigning intersections –** may involve adjusting wiring, installing conduit, installing new equipment, etc.
- **Safety Improvements –** may involve safety studies and various desired improvements to enhance safety through a corridor or at an intersection.
- **ITS Deployment –** may involve installation of various types of ITS devices to enhance traveler information dissemination and safety through a rural or urban corridor.

Project Funding

Projects funded through the Congestion Mitigation and Air Quality Improvement Program (CMAQ) may allow for the addition of a V2I component as the CMAQ program allocates funding to projects that show promise in reducing emissions. If the project type includes capacity or efficiency improvements it may qualify for the use of CMAQ funding.

3.2. Design Considerations

Existing (or planned) infrastructure and its surrounding environment are two important facets to consider while selecting optimal deployment locations. This section provides an overview of compatible infrastructure and DSRC unit placement that will assist in the selection of adequate locations for deployment.

Compatible Infrastructure

When identifying compatible infrastructure, the proximity to power, a network connection, and the unit placement requirements should be considered. In addition, having certain infrastructure in place at the deployment location can assist in the deployment of a V2I application. Some examples of compatible infrastructure are as follows:

- Mast arm traffic signals with a signal controller with SPaT configuration capabilities
- Highway lighting poles in close proximity to network connections
- Existing ITS devices & cabinets
- Metered power service and lightning suppression within cabinets
- Frequency and Interference analysis prior to site selection and detailed design

Unit Placement

While there are various options for RSU installation, there are several specific requirements that must be adhered to. Generally, an RSU should be installed at a location advance of the point where a vehicle must react to the anticipated application and with a clear line of sight for reliable communication between RSUs and OBUs. A clear line of sight means there should be no obstructions between the RSU and the roadway. Physical obstructions may include buildings, bridges, structures and vegetation.

In the case of intersections, the RSU should be placed to provide the most unobstructed line of sight to the roadway. It is common to be able to cover all directions of traffic with one RSU at an intersection, however a signal compatibility evaluation needs to be completed to ensure this RSU capability. Multiple RSUs, or at least signal repeaters may be required in urban, city locations where buildings can cause loss of signal in various directions, but in general, only one RSU is needed per intersection.

To obtain full coverage along a corridor, the RSUs will need to be placed no more than 3,000 feet apart. Each RSU has a 360-degree area of influence that covers 1,500 feet away from the device and should be mounted per the manufacturer’s recommendations, typically 25-35 feet above the roadway or on the traffic signal mast arm. While installation on a span wire is possible, it is not recommended unless there are no other mounting options available.

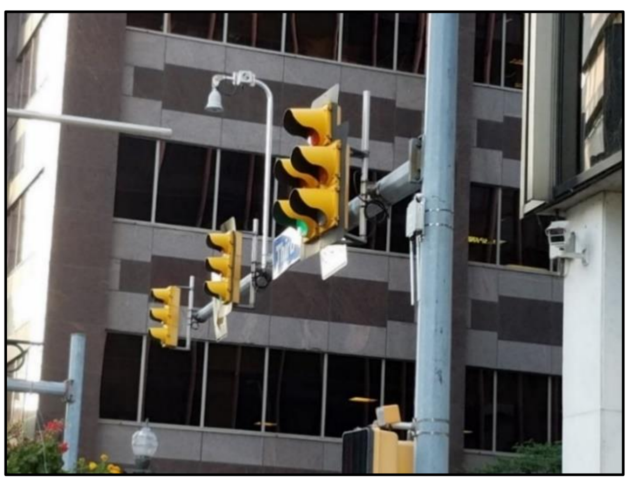
A control cabinet is required to house the communication and power equipment necessary to run the RSU, which should be located no more than a 300-foot maximum distance from the device. Below are two potential scenarios for utilizing existing control cabinets for RSUs:

- **Municipally-owned traffic signal cabinet –** An RSU controller will need to be installed in a separate PennDOT owned RSU control cabinet and connected to either a Power over Ethernet (PoE) switch or PoE injector (with DC power supply). The RSU should be integrated with an Advanced Traffic Controller (ATC) that supports the appropriate SPaT data to the RSU. The municipal traffic signal cabinet would provide power to the RSU control cabinet through a metered power service.
- **PennDOT-owned traffic signal cabinet –** An RSU controller would be installed inside the cabinet and directly fed via Ethernet using the correct file and network data transfer syntax between the devices.

The following images are a few examples of optimal positioning of DSRC radios, where they have a clear line of sight without physical or vegetation obstructions between proposed RSU location(s) and all roadway approaches necessary for the CV application. As shown in the images, the DSRC antennas should be installed facing down toward the ground while the GPS antenna face up toward the sky.

DSRC radio installed on traffic signal mast arm

Highway pole mounted DSRC



Intersection signal pole mounted (not enough room on the signal mast arm)

3.3. Cost Overview

The cost of implementing a V2I application may vary depending on the specific application, surrounding infrastructure, and scalability (e.g., installing one unit vs. installing 100 units, etc.). To generalize the cost to correlate with likely scenarios, the cost overviews in Table 1 and Table 2 are based upon the following assumptions:

- DSRC components added to an existing project prior to environmental clearances
- Power is in the immediate vicinity of the installation location within the public right-of-way
- Local fiber is within the immediate vicinity and/or adequate communication service is available per each site (cellular, broadband wireless, or Wi-Fi services)
- Estimate does not include cost for backhaul connection services and application development
- Labor is included in the equipment cost
- Costs are high-level and do not include specific equipment requirements
- The DSRC equipment is not collocated with existing equipment (e.g., installing DSRC equipment in an existing cabinet)

Although there are several communication technologies that could advance V2I applications, such as cellular 5G, this section is focused on general costs for implementing DSRC equipment. In comparison to the following cost overview, cellular 5G operations would be very similar to a DSRC-based system in that dedicated equipment (RSUs) would be required to generate and receive data between vehicles and infrastructure. The differences lie in the equipment and backhaul communication configurations as some of the infrastructure costs will be borne by telecommunications companies. This however, may result in additional costs as public agencies will have no access to the data received unless a contract is signed with the private sector provider. Additional information on 5G is provided in Section 1.

Element Cost Breakdown for the Deployment of One DSRC Unit

The element cost breakdown for the deployment of one DSRC unit is provided in Table 1. The cost breakdown is organized into two sections; Planning and Design, and Equipment and Installation. These categories are then added to find a total, general cost of adding a V2I application to a project.

Table 1 – Element Cost Breakdown for the Deployment of One DSRC Unit

	Element	Description	Cost
Planning and Design	Radio Survey per site	Identification of radio interference and determination of the optimal location for the DSRC radio(s)	$700
	Map Generation	Highly accurate mapping of the intersection/location (as-built plans, Mobile LIDAR, survey crew, etc.)	$1,000
	Planning	Development of a general regional plan (data plan, security plan, and privacy requirements) for deploying a CV environment (5% of Construction)	$800
	Design	Design associated with deploying the DSRC infrastructure at a specific location	$8,000
	Total Planning and Design Cost		$10,500
Equipment and Installation (Completely Installed)	DSRC RSU Kit	DSRC radio unit, DSRC antennas, unit mounting hardware, PoE injector, wiring, mounting hardware, and configuration of the RSU	$3,500
	Communication Connection Equipment	Equipment necessary to connect to the current communication network - Fiber patch panel, manage switch	$1,800
	Power Connection Equipment	Service disconnect, meter socket	$500
	Additional Equipment and Installation	Device field enclosure and associated mounting hardware, etc., installation of all site components	$7,000
	Communication system integration & License	Communication to back office	$3,000
	Traffic Control	Basic traffic control during deployment of a DSRC radio unit 10% of Equipment and Installation	$1,500
	Mobilization	5% of Equipment and Installation	$700
	Total Equipment and Installation Cost		$18,000
	Construction Inspection	8% of Equipment and Installation Cost	$1,500
	Total Equipment and Installation Cost with Inspection		$19,500

Element	1 DSRC Unit
Planning and Design	$10,500
Equipment and Installation	$19,500
Total Cost for One DSRC Unit	**$30,000**

Deployment Cost Scalability

Scalability of deployment is a major factor while considering costs of installation. The more units deployed on a single project may greatly reduce design and installation costs per device. Equipment costs are less variable but may still reduce as the amount of devices increase. This would be specific to each manufacturer based on volume pricing. Table 2 was derived from comparing the cost of previous deployments and pilot programs. The References section of the document lists all deployments used while determining the values in Table 2.

Table 2 – Cost of Deployment per Number of DSRC Units

Element	Number of DSRC Units				
	1 to 9	**10 to 24**	**25 to 49**	**50 to 99**	**100+**
Planning and Design	$10,000	$9,000	$8,000	$6,000	$4,000
Equipment	$15,000	$15,000	$14,500	$14,500	$14,000
Installation	$5,000	$4,500	$4,000	$3,000	$2,000
Total Cost per DSRC Unit	**$30,000**	**$28,500**	**$26,500**	**$23,500**	**$20,000**

(Costs have been generalized for high-level planning purposes)

Additional Cost Considerations

Due to the variability of the surrounding infrastructure and environment at any deployment location, the cost of standard fiber optic cable and PoE cable were provided below. These costs, shown in Table 3, will vary based upon the length required to connect the DSRC equipment with the existing infrastructure in the surrounding area.

Table 3 – Additional Cost Considerations

Additional Elements	Cost
Standard Fiber Optic Cable	$5.50 per LF
Power over Ethernet	$2.66 per LF

General equipment inspection may be conducted semi-annually similarly to other ITS devices in the field. Additional elements, such as security, operations and maintenance, and a software subscription would occur annually and should be considered upon deployment of the V2I system. The recurring costs upon deployment are provided in Table 4. In addition, there would be an increase in maintenance costs if there is a need for new V2I application system maintenance, or if there is a need to replace a specific hardware component.

Table 4 – Recurring Costs Upon Deployment

Recurring Elements	Annual Cost
Semi-annual inspection of radio communication, power, mounting brackets, and bolt tension	$600.00 per site (assume $150 per hour, 2 hours per device, semi-annually)
Annual software subscription	$200 per site
Production Security Certificates by V2X technology device and message-set type	Up to $3,500 per site (high level estimate, contract to be negotiated by deploying Agency with production Security Credential Management Systems (SCMS) National Architecture conformant supplier
Operation and Maintenance (includes power, maintenance, license/maintenance agreements)	$1,000 per site

3.4. Ownership and Maintenance Responsibilities

As V2I applications are integrated through TIP projects, their ownership and maintenance responsibilities will likely be similar to that of current PennDOT-owned ITS devices. This means that the V2I equipment would be owned and maintained by PennDOT, while signal equipment and the surrounding infrastructure would be owned and maintained by a municipality. Due to the difference in ownership and maintenance requirements, all PennDOT-owned DSRC and required communication equipment would likely be stored in a separate cabinet from an existing, municipally-owned, cabinet. In addition, a Memorandum of Understanding (MOU) between PennDOT and the Municipality would be necessary to facilitate maintenance between the various equipment.

Several ownership and maintenance scenarios and requirements involved with the installation of DSRC equipment are identified in Table 5. In the table, Scenario 3 is the most analogous to the installation of ITS devices and is likely the preferred ownership and maintenance scenario for V2I applications.

Table 5 addressed the following by ranking the combination of the need and the effort involved for each element on a high, medium, or low basis.

- **Data Sharing Agreement –** An agreement between PennDOT and the municipality to share data obtained through the RSU.
- **Memorandum of Understanding (MOU) –** An MOU would moderate maintenance and communication agreements between PennDOT and Municipality personnel and equipment.
- **TE 160 (Application for Traffic Signal Approval) –** This form would require various level of modifications based upon alterations to the existing signal cabinet.
- **TE-972 and TE 973 (Responsive and Preventative Maintenance Records) –** These forms would require various level of modifications based upon maintenance agreements between PennDOT and the municipality.
- **Additional Maintenance Cost –** The cost of maintenance of the DSRC equipment would vary based upon equipment and power/communications ownership. If a PennDOT owned DSRC Unit is accessing power/communications through the municipality, there would be a cost reimbursement from PennDOT to municipalities for additional, albeit minimal, electrical usage.

Ownership and maintenance responsibilities and scenarios will be further developed through pilot programs and early deployments of V2I applications. Through these deployments, the following questions are anticipated to be answered:

- Who is responsible for registering CV devices with the FCC?
- What happens if a PennDOT line gets cut?

Table 5 – Ownership and Maintenance Scenarios

Ownership Scenarios			Data Sharing Agreement Need	MOU Need	TE-160 Mod.	TE-972 TE-973 Mod.	Additional Municipal Maintenance Cost
	Element	Owner					
1	DSRC Equipment	Municipality	High	Low	High	High	High
	Equipment Cabinet	Municipality					
	Power/Communication Source	Municipality					
2	DSRC Equipment	PennDOT	Medium	High	High	Low	Low (Reimbursement from PennDOT)
	Equipment Cabinet	Municipality					
	Power/Communication Source	Municipality					
3*	DSRC Equipment	PennDOT	Medium	High	Low	Low	Low (Reimbursement from PennDOT)
	Equipment Cabinet	PennDOT					
	Power/Communication Source	Municipality					
4	DSRC Equipment	PennDOT	Low **	Medium	Low	Low	None
	Equipment Cabinet	PennDOT					
	Power/Communication Source	PennDOT					

***Scenario 3 will likely be the most preferred typical installation situation between PennDOT and the Municipality**

****If the municipality requests data access, the need/effort would be medium**

Appendix A – Current Pilot Programs

Appendix A provides links to several USDOT designated Pilot programs and the USDOT Smart City Challenge.

CV Pilot Deployment Program – The CV Pilot Deployment Program seeks to combine connected vehicle and mobile device technology in innovative and cost-effective ways. The goal of this program is to enhance safety, improve traveler mobility and system productive, and reduce environmental impacts. As the Pilot Sites advance through stages of deployment; guidance documents, technical assistance webinars, and reports, that may be of value to early deployers of CV technology have been created. These documents can be found at https://www.its.dot.gov/pilots/technical_assistance_events.htm

NYCDOT CV Pilot – NYCDOT is utilizing connected vehicle technology to help New York City reach its Vision Zero goals to eliminate traffic related deaths and reduce crash related injuries and damage to vehicles and infrastructure. To reach their safety goals, the City deployments are primarily safety applications. More information on the NYCDOT CV Pilot can be found at https://www.cvp.nyc/

THEA CV Pilot – The Tampa Hillsborough Expressway Authority (THEA) and its partners aim to transform the experience of downtown Tampa by preventing crashes, enhancing traffic flow, improving transit trip times and reducing emissions of greenhouse gases. Buses, streetcars, and hundreds of privately-owned vehicles have been equipped with OBUs, allowing them to receive information within their vehicle. This pilot is focusing on various applications related safety, mobility, agency data, and the environment. More information on the THEA CV Pilot can be found at https://www.tampacvpilot.com/

Wyoming DOT CV Pilot – The program led by WYDOT is intended to develop various connected vehicle applications (both V2I and V2V) to improve traffic management and traveler information practices as well as reduce the impact of adverse weather on I-80. The pilot includes the deployment of approximately 75 RSUs and 400 OBUs. More information on the WYDOT CV Pilot can be found at https://wydotcvp.wyoroad.info/

USDOT Smart City Challenge – In December 2015, mid-size cities across America were asked to develop ideas for an integrated, smart transportation system utilizing data, applications, and technology to improve the transportation of people and goods. There were 78 applicant cities that presented their challenges and potential solutions. Seven of the applicants were named finalists and worked with the DOT to further develop their ideas. More information on the smart city challenge can be found at https://www.transportation.gov/smartcity

Appendix B – Example 2019 TIP Projects in PennDOT District 8

Table B.1 lists some of the TIP projects in which an addition of a DSRC component may be beneficial. (As such, it does not convey a recommended priority.) This table was exported from the PennDOT TIP Project Map and further filtered and vetted based upon location, improvement type, and the project description.

Table B.1 – TIP Project Examples

Project ID	Category	Title	County	Improvement Type	Description
102975	TIP	Hanover Street Crossing	Adams	RR Warning Devices	SR 1015 (Hanover Street) at CSX Crossing Oxford Borough Install RR warning devices
47521	TIP	Nyes/Devonshire Hts Safety	Dauphin	Intersection Improvement	Traffic Signal Installation along with roadway realignment Intersection of Nyes Road and Devonshire Heights Road Lower Paxton Township
92945	TIP	US 322 & Chambers Hill Rd	Dauphin	Intersection Improvement	Intersection of US 322 (Paxton Street), SR 2019 (Grayson Road), and SR 3006 (Chambers Hill Road) Swatara Township Intersection Improvements
94913	TYP	Trindle/St Johns Church	Cumberland	Intersection Improvement	Intersection of PA 641 (Trindle Road) and State Route 2029 (St Johns Church Road) Hampden Township Turn Lanes, Signal Timing, and Update Pedestrian Access
102384	TIP	Chambersburg Signal Imp.	Franklin	Existing Signal Improvement	"Upgrade of signals and interconnect improvements 56 Signalized intersections in Chambersburg Borough Guilford and Hamilton Twp Franklin County"
80119	TIP	PA 72 Inter. Corr. Imp.	Lancaster	Intersection Improvement	PA 72 from SR 4011 (Fruitville Pike) to SR 4013 (Graystone Road) and the intersection of PA 722/741 City of Lancaster, Manheim Twp. and East Petersburg Borough. Improve intersections and traffic signals
90221	TIP	ITS - Lancaster Phase 2	Lancaster	Traffic System Management	Install ITS equipment US 30 & PA 283 Lancaster County
90490	TIP	PA 272 Intersection Impvt	Lancaster	Intersection Improvement	PA-272 from Bylerland Road to East Miller Road Providence Township Improve corridor intersections.
106587	TIP	ITS - Lancaster Phase 4	Lancaster	Traffic System Management	Install ITS equipment US 30, US 222 & PA 283 Lancaster County
94936	TIP	US422 Safety Project	Lebanon	Corridor Safety Improvement	Intersection and Safety Improvements US 422 from PA 645 to Martin Drive Jackson Township and Myerstown Borough
85655	TIP	PA 34 & PA 850 Intersect.	Perry	Safety Improvement	PA 34 & PA 850 Intersection Carroll Twp. Safety Improvements
20652	TIP	Camp Betty Washington	York	Safety Improvement	Widen and Resurface State Route 2005 (Camp Betty Washington Road) from State Route 2002 (Springwood Road) to PA 124 Springettsbury and York Townships
108933	TIP	N. George St.Ped & Bike Safety Improvements	York	Pedestrian Facilities	Reducing travel lanes and lane widths George Street from North St. to Dewey Avenue York City; North York Borough

References

Section 1. Defining the Technology

General:

https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety
https://transportationops.org/spatchallenge

CV and AV Background:

https://local.iteris.com/cvria/html/applications/applications.html
https://transportationops.org/spatchallenge/resources/Implementation-Guide
https://news.itu.int/to-5g-or-not-to-5g-automotive-safety-may-hang-in-the-balance/
https://static.tti.tamu.edu/tti.tamu.edu/documents/0-6848-1.pdf
https://www.researchgate.net/publication/308664115_Market_Penetration_Model_for_Autonomous_Vehicles_on_the_Basis_of_Earlier_Technology_Adoption_Experience
https://ieeexplore.ieee.org/document/8255748/?part=1
https://www.infineon.com/cms/en/about-infineon/press/market-news/2017/INFPMM201702-034.html
https://cyberlaw.stanford.edu/files/publication/files/15CPB_AutonomousDriving.pdf
https://spectrum.ieee.org/cars-that-think/transportation/self-driving/autonomous-driving-experts-weigh-5g-cellular-network-against-shortrange-communications-to-connect-cars
https://www.its.dot.gov/research_archives/connected_vehicle/connected_vehicle_standards_progress.htm

DSRC and 5G:

https://www.siemens.com/content/dam/webassetpool/mam/tag-siemens-com/smdb/mobility/road/connected-mobility-solutions/documents/its-g5-ready-to-roll-en.pdf
https://ieeexplore.ieee.org/document/6519550/
http://www.fdot.gov/traffic/Doc_Library/PDF/USDOT%20RSU%20Specification%204%201_Final_R1.pdf
http://www.5gamericas.org/files/3215/1190/8811/5G_Services_and_Use_Cases.pdf

Section 2. V2I Deployment Impacts and Priorities

General:
https://www.cargroup.org/wp-content/uploads/2017/03/Planning-for-Connected-and-Automated-Vehicles-Report.pdf
https://ops.fhwa.dot.gov/publications/fhwahop18014/chap3.htm

V2I Applications:
https://www.its.dot.gov/pilots/cv_pilot_apps.htm
https://rosap.ntl.bts.gov/view/dot/26495
https://rosap.ntl.bts.gov/view/dot/26499
https://rosap.ntl.bts.gov/view/dot/3440
http://www.cts.virginia.edu/wp-content/uploads/2014/05/Task2.3._CONOPS_6_Final_Revised.pdf

2017 Pennsylvania Crash Facts & Statistics:
https://www.penndot.gov/TravelInPA/Safety/Documents/2017_CFB_linked.pdf'

Smart City Challenge:
https://www.transportation.gov/sites/dot.gov/files/docs/Smart%20City%20Challenge%20Lessons%20Learned.pdf

Projected Penetration Rate
https://www.its.dot.gov/research_archives/connected_vehicle/pdf/DSRCReportCongress_FINAL_23NOV2015.pdf
http://www.nhtsa.gov/staticfiles/rulemaking/pdf/V2V/Readiness-of-V2V-Technology-for-Application-812014.pdf
https://ecfsapi.fcc.gov/file/60001841106.pdf

Vehicle Manufacturers
http://techblog.comsoc.org/2018/05/07/gm-and-toyota-back-dsrc-to-link-connected-cars-to-smart-traffic-lights-ford-bmw-other-auto-makers-favor-5g/
https://www.statista.com/statistics/199983/us-vehicle-sales-since-1951/
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https://corporatenews.pressroom.toyota.com/releases/toyota+and+lexus+to+launch+technology+connect+vehicles+infrastructure+in+u+s+2021.htm
http://gmauthority.com/blog/2018/06/cadillac-plans-to-bring-v2x-technology-to-new-crossover-by-2023/
http://gmauthority.com/blog/2019/02/two-v2x-communication-standards-fight-for-supremacy/

Section 3. Cost & Design Considerations

Project Selection:
http://www.dot.state.pa.us/public/PubsForms/Publications/PUB%2010/Pub%2010A/March%202018%20Change%20No.%201.pdf

Design Considerations:
https://www.its.dot.gov/presentations/2017/CAV2017_AdvTechTransport.pdf
http://www.westernstatesforum.org/Documents/2017/Presentations/UDOT_Leonard_FINALc_DSRC.pdf
https://itsforge.net/data/repo/docs/V2I_Hub_Deployment_Guide.pdf

Cost Overview:
https://www.itscosts.its.dot.gov/ITS/benecost.nsf/SummID/SC2014-00325?OpenDocument&Query=Home
https://www.itscosts.its.dot.gov/ITS/benecost.nsf/ID/C2AB1F4F44AF0A0C85258331005E2154?OpenDocument&Query=CApp
https://www.itscosts.its.dot.gov/ITS/benecost.nsf/SummID/SC2014-00329?OpenDocument&Query=Home
Standard equipment costs were based upon ECMS price history

CMAQ Funding:
https://www.fhwa.dot.gov/environment/air_quality/cmaq/policy_and_guidance/2013_guidance/