Guidelines for Applying Capability Maturity Model Analysis to Connected and Automated Vehicle Deployment

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16. Abstract

The Federal Highway Administration (FHWA) has adapted the Transportation Systems Management and Operations (TSMO) Capability Maturity Model (CMM) to describe the operational maturity of Infrastructure Owner-Operator (IOO) agencies across a range of important dimensions. Agencies can use the CMM to develop action plans to move agencies capabilities from one level to the next. In many respects, the connectivity of vehicles and travelers with infrastructure represents the next generation of TSMO advancement. Vehicle-to-infrastructure (V2I) technologies will provide enhancements to many existing TSMO applications and enable many new services that improve safety, mobility, and the environment. Implementation of V2I will require significant improvements in the essential capabilities for effective TSMO as well as require many improvements in agency maturity regarding organization, systems, technology, and business processes.

The capability maturity model presented in this report provides a template for IOOs to develop action plans supporting effective and efficient implementation of Connected Vehicle program capabilities. A wide range of agency activities in each key dimension are identified to form the basis for constructing a connected vehicle program plan, or moving an existing connected vehicle program to a higher level of maturity.

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Chapter 1. Introduction

The Second Strategic Highway Research Program (SHRP 2) L06 research determined that agencies with the most effective Transportation Systems Management and Operations (TSMO) activities were differentiated not by budgets or technology alone, but by the existence of critical processes and institutional capabilities tailored to the unique features of TSMO applications. For each of the key dimensions of capability, levels of improvement were identified for agencies to move from ad hoc activities through managed and integrated programs. This research was converted into a guidance tool based on the Capability Maturity Model (CMM). The TSMO CMM guidance is focused on broad, cross-cutting capabilities and is designed for applications related to comprehensive TSMO programs. The value of the TSMO CMM approach has been validated through its use in more than 50 state and regional self-assessment workshops. The TSMO CMM is also available as a web-based tool for self-evaluation.

Based on the success of this model, the Federal Highway Administration (FHWA) has adapted the TSMO CMM approach to develop specific capability maturity *frameworks* (CMF) for individual TSMO applications, including traffic incident management, traffic signal management, work zone management, planned special events, and road weather management. Tailored capability frameworks allow agencies and stakeholders to focus in on specific capability improvement needs within particular operational areas.

In many respects, the connectivity of vehicles and travelers with infrastructure represents the next generation of TSMO advancement. The core mission of infrastructure owner-operator (IOO) agencies to provide a safe and efficient transportation system will not change. Connected vehicles (CV) using vehicle-to-infrastructure (V2I) technologies will provide enhancements to many existing TSMO applications. In addition, V2I will enable many new services that improve safety, mobility, and the environment. Implementation of V2I will require significant improvements in the essential capabilities for effective TSMO as well as development of new capabilities. As automated vehicle technologies advance on a parallel path to CV technologies, driverless vehicles may also use V2I services to remain safe and efficient in their navigation of the roadway system.

The deployment of connected vehicles and V2I applications presents new challenges to IOOs, including:

- Developing the business case and developing consensus with stakeholders regarding policies and beneficial uses of connected vehicle data and applications.
- Deploying, staging, and establishing business processes for V2I applications.
- Integration of V2I into existing processes.
- Developing collaborative agreements across regions regarding equipment, data, and use of assets including new forms of public-private partnerships.
- Integrating new software systems with legacy systems.
- Managing new types of data and volumes of data with modern tools and technologies.
- Developing policies and compliance with legal requirements for licensing, security, and privacy.

- Determining how deployment performance will be measured.
- Determining funding plans and funding mechanisms.
- Developing staff capacity, technology training programs, and necessary management capabilities.

The capability maturity model for V2I presented in this report provides a template for IOOs to develop action plans supporting effective implementation of connected vehicle programs. This document complements a wide variety of other V2I guidance provided by U.S. Department of Transportation (DOT).

1.1 Audience for This Document

The primary audience for the content in this document are IOOs that will have responsibility for deploying, operating, and maintaining V2I infrastructure and applications. In some regions, this is the state DOT; in other regions, it could be a county, city, regional operations authority, transit system operator, or any combination thereof. In many cases, it will be appropriate for the Connected Vehicle CMM to be evaluated by a group of related agency partners. Which agencies have leadership roles, supporting roles, or information-only roles will be determined by your regional strengths and relationships. There is no “best” organizational structure for developing a connected vehicle program plan.

Experience with the TSMO CMM is not essential, but familiarity with the concepts behind the TSMO CMM is helpful to understand the foundation on which the Connected Vehicle CMM is based. For context, Chapter 3 summarizes the TSMO CMM. IOOs that have not yet gone through a TSMO CMM or another TSMO-related CMF will still benefit from the connected vehicle CMM. The steps and recommended actions in this document provide succinct and specific activities to advance agency capabilities for V2I.

Additional audiences that can benefit from this content include:

- Agencies responsible for developing and updating transportation improvement programs and capital improvement programs (e.g. metropolitan planning organizations and government councils).
- Agencies responsible for facilities parallel or intersecting to roadways with V2I functionality (e.g. transit operators).

The intent of the connected vehicle CMM process is to gather key stakeholders together for a self-assessment of agency capabilities. This process will also identify specific actions to advance capabilities of the agency in each of the dimensions. This is a proven process, and one that works well to engage the right stakeholder perspectives in identifying issues, challenges, and next steps.

Stakeholders to be engaged will largely depend on the specific V2I applications that IOOs are considering. Potential stakeholders for the connected Vehicle CMM assessment include:

- Traffic engineers.
- ITS engineers.
- Short-term capital budget planners.
- Long-term planners.

- Information technology (IT) staff including communications, software, and networking engineers.
- Traffic operations center managers and operators.
- Public information officers and public relations staff.
- Technology/systems maintenance staff.
- Partner agency (transit, rail, motor vehicle registration and licensing, technology coalitions) representatives.
- Human resources and training program representatives.
- Toll operations representatives.
- Equipment procurement and contracting representatives.

Ideally, an agency lead for the connected vehicle CMM will identify and assemble a core group of stakeholders to participate in the assessment and action plan development. This group could also serve to monitor progress on the action plan.

1.2 Overview of this Report

The goal of this report is to provide a foundational guideline for IOOs to develop plans for adopting and developing V2I technology into existing TSMO programs.

The report is divided into six sections:

- **Chapter 1: Introduction—**Basic overview and discussion of key audiences.
- **Chapter 2: Connected Vehicles and V2I Applications—**Background information on both connected vehicles and V2I applications; including brief description of how V2I applications enhance various areas of TSMO.
- **Chapter 3: Overview of the Capability Maturity Model—**An overview and background information on the existing TSMO CMM and an analysis of the connections between the CMM and V2I technologies.
- **Chapter 4: The Capability Maturity Model for V2I—**Definition of dimensions, levels of capability, and actions.
- **Chapter 5: Capability Maturity Actions for each CMM Dimension—**Details of actions in each dimension to advance maturity.
- **Chapter 6: Benefits of Having and Risks of Not Having Capabilities for V2I Applications—**An analysis of the benefits of having and risks of not having the capabilities detailed in Chapter 4.
- **Chapter 7: A recommended process for using the connected vehicle CMM—** Recommendations for how to use the content in this document to advance connected vehicle capability maturity in your agency.

Chapter 2. Connected Vehicles and Vehicle-to-Infrastructure Applications

Connected vehicles (CV) are vehicles that can communicate status information directly to other vehicles, road users, and roadside systems. Connected vehicle systems provide the capability for vehicles to identify threats, hazards, and delays on the roadway and provide drivers with alerts, warnings, and real-time information. (Kimley-Horn and Associates, Inc., "Traffic Management Centers in a Connected Vehicle Environment", TMC Pooled Fund Study, March 2014.) Key system components include advanced wireless communications, onboard computer processing, advanced vehicle sensors, Global Positioning System (GPS) data, and smart infrastructure. There are three basic types of connected vehicle applications: 1) Vehicle-to-Vehicle (V2V) which are principally for active safety purposes; 2) Vehicle-to-Other objects (V2X) which encompasses vehicle interactions with vulnerable road users such as pedestrians and cyclists; and 3) Vehicle-to-Infrastructure (V2I) which provides connections between vehicles and traffic management devices and management centers. This document is principally focused on IOO roles and capabilities for V2I.

V2I typically encompasses both vehicle-to-infrastructure communication and infrastructure-to-vehicle (I2V) communication. Normally, one-way communication is distinguished by labeling the initiator of the communications first—vehicle communication from a vehicle to the infrastructure's receiver is called V2I, while infrastructure communication sent to the vehicle's receiver is called I2V.

Both types of data exchange are considered in this document, as are applications that share information bi-directionally. Taken together, all three types of data exchange are referred to as V2I.

2.1 Connected Vehicles

The Connected Vehicle concept refers to the capability of the various elements of the modern surface transportation system (personal, transit, and freight vehicles, pedestrians, bicyclists, roadside infrastructure, transportation management centers, etc.) to electronically communicate with each other on a rapid and continuous basis. No personally identifiable information is shared between the vehicles. This communication can occur via several mechanisms. Dedicated short-range communications (DSRC) allow rapid communications (up to 10 times per second) between elements of a connected vehicle network, in particular for safety critical applications. Cellular phone technology is also anticipated to facilitate the use of many connected vehicle concepts. With safety as a primary goal, connected vehicle technology is anticipated to aid motorists in actively avoiding crashes and other incidents. Connected vehicle technology is distinct from vehicle automation, although the development of both technologies is a high priority for the U.S. Department of Transportation (U.S. DOT), and the concurrent development of both technologies is anticipated to provide reinforcing, synergistic benefits.

All types of connected vehicle systems are relevant and provide benefits for TSMO. Other types of connected vehicle systems include Radio Frequency Identification (RFID), Bluetooth MAC

address matching, WiFi address matching, parking system tags, and so on. For the purpose of this guidance, these types of connected systems are not considered.

Commercial Connected Vehicle or Telematics Systems

Commercial connected vehicles are based on cellular or satellite connections to a private cloud from the vehicle's infotainment system or third-party in-car systems for vehicle tracking and data collection.

Original Equipment Options and Aftermarket Devices—Nearly every automaker now offers connected car options. In this rapidly evolving area, automakers, telecommunications providers, technology companies, and content producers are establishing strategic alliances to provide the full range of services necessary for new and emerging products. According to a 2015 report by PricewaterhouseCoopers, the primary use cases for automakers and their partners are: (PricewaterhouseCoopers, "Connected Car Study 2015: Racing ahead with autonomous cars and digital innovation, 2015", Accessed at http://www.strategyand.pwc.com/reports/connected-car-2015-study.)

- Entertainment.
- Mobility management (e.g., navigation, traffic, incidents).
- Driver assistance/safety.
- Vehicle health monitoring/recalls/remote diagnostics.
- Driver health monitoring.
- Fleet management.
- Insurance premium evaluation.
- Automated driving.

These are potentially rich sources of data on driver and vehicular behavior, which can significantly benefit IOOs. HERE, TomTom, INRIX, Garmin, etc., have monetized vehicle status information (primarily location and speed) for sale to DOTs on a subscription basis, providing coverage in an area of influence (a state or region). These companies have sharing agreements with vehicle fleets (and in-dash navigation systems of some Original Equipment Manufacturers (OEM)), as well as data sharing agreements with private owners of aftermarket navigation devices. As of June 2016, HERE has published a connected vehicle data sharing standard, which may greatly accelerate the availability of trajectory-based commercial connected vehicle data to DOTs. (Texas A&M Transportation Institute, "Strategic Research Program: Big Data Scan", Accessed May 13, 2016, https://static.tti.tamu.edu/tti.tamu.edu/documents/161505-1.pdf.)

Many DOTs are now routinely purchasing this data to supplement their existing vehicle speed monitoring systems (i.e., in-pavement loop detectors, radar, and video) and pursuant to Section 1201 of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) requirements for the dissemination of real-time mobility information.

Communications Service providers—There are emerging efforts in the cellular industry to provide DSRC-like services by upgrading existing infrastructure. Recent research and development indicates that low-latency vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications may be able to be provided by use of Long Term Evolution (LTE) cellular phone towers by locating the switching hardware/software at the tower (AT&T Labs Research, "Enabling Vehicular Safety Applications over LTE Networks", Accessed May 13, 2016, http://web2.research.att.com/export/sites/att_labs/techdocs/TD_101260.pdf.) Generally, this is

referred to as 5G. Widespread adoption of 5G may be anticipated in the 2019 to 2022 timeframe. (IEEE Spectrum, "Autonomous Driving Experts Weigh 5G Cellular Network Against Dedicated Short Range Communications", Accessed May 13, 2016, http://spectrum.ieee.org/cars-that-think/transportation/self-driving/autonomous-driving-experts-weigh-5g-cellular-network-against-shortrange-communications-to-connect-cars.)

U.S. Department of Transportation Connected Vehicles Activities

Technology and Standards development—Open, standardized connected vehicle technologies have been supported by U.S. DOT for mobility and safety applications for more than 20 years. This program has a long history; and background details are available from National Highway Traffic Safety Administration (NHTSA), U.S. DOT, Government Accountability Office (GAO), American Association of State Highway and Transportation Officials (AASHTO), and other related sources such as FHWA-HOP-15-015. Open connected vehicle systems rely on DSRC technology to send vehicle status data (approximately 10 times per second) to other vehicles and infrastructure access points with very low latency from transmission to receipt. The low latency requirement is necessary for crash prevention.

Safety regulation—The National Highway Traffic Safety Administration (NHTSA) is responsible for regulating motor vehicle safety across all states and territories of the U.S. NHTSA has announced a notice of proposed rulemaking, which will likely mandate the use of connected vehicle technology in all new passenger vehicles sold in the U.S. starting with some models in 2019 and across all models by 2023. (https://www.federalregister.gov/documents/2017/01/12/2016-31059/federal-motor-vehicle-safety-standards-v2v-communications.) A similar rule for commercial vehicles (including buses) is expected to follow. The DSRC band (5.9GHz) is currently protected by the Federal Communications Commission (FCC) for licensed use of vehicle safety and mobility applications. The message definitions and technical interaction specifics are defined in SAE J2735 and related standards. (https://www.sae.org/standardsdev/dsrc/.) While the FCC has protected the DSRC band, individual users (for instance state DOTs) must register their intent with the FCC. A guide to this process is provided in *Recommended Practices for DSRC Licensing and Spectrum Management* (FHWA-JPO-16-267).

The deployment of V2I technologies is not mandated and is not coupled with the NHTSA advance notice of proposed rulemaking for V2V communications. A NHTSA rulemaking will not require state and local departments of transportation (DOTs) to deploy V2I technology, although it is important for you to understand what a decision to deploy V2I technology could mean to your region.

Guidance and additional documents are anticipated in 2017 and 2018, including a V2I Message Lexicon, a desk reference on V2I benefits estimation, and training materials.

CV pilot activities—Viability of DSRC technology was demonstrated by U.S. DOT's Connected Vehicle Safety Pilot program in 2014. Additional research and demonstration test beds in California, Florida, New York, and Virginia have evaluated the data exchange of Probe Data Messages (PDM) and Basic Safety Messages (BSM) for many TSMO and V2I functions. As of 2017, Connected Vehicle Pilot Deployment sites in New York, Wyoming, and Florida are preparing to demonstrate a wide range of safety and mobility applications and network and vehicle security mechanisms. (https://www.its.dot.gov/pilots/.)

The American Association of State Highway and Transportation Officials (AASHTO) has made a resolution that all 50 states in the U.S. are encouraged to have at least 20 roadside unit (RSU) devices deployed by 2020 at traffic signals. These RSUs should, at minimum, generate Signal

Phase & Timing (SPaT) messages for connected vehicles to use. (SPaT enables a variety of V2I applications including Intersection Collision Avoidance, Eco-Driving, and Transit Priority.) In addition, the V2I Deployment Coalition (AASHTO, ITE, and ITS America) has recommended that IOOs focus on the following V2I applications. (https://www.transportationops.org/twg-4-deployment-guidance.)

- Intersections (signalized and un-signalized).
- Curve Speed Warning.
- Work Zone Warning.
- Queue Warning.

IOOs must begin to prepare to use data from public connected vehicles for the wide range of TSMO functions.

2.2 Vehicle-to-Infrastructure Applications

Data from V2I sources can improve a wide range of TSMO practices and functions:

- Incident and event management—improved incident response and onsite monitoring of activities.
- Road hazard warnings—higher fidelity location information, more accurate confirmation of hazard types, more timely warnings.
- Speed warnings—specific recommendations to different vehicle types based on roadway conditions, more timely warnings.
- Traffic signal timing—better operation in oversaturated conditions, more timely updates to fixed timings, broad-based adaptive controls, reduced reliance on physical sensor devices and maintenance, shift towards in-vehicle data delivery, performance monitoring of signals with no physical links to DOT communications infrastructure.
- Freeway ramp metering—more accurate and coordinated corridor metering algorithms.
- Variable speed limits/recommendations and lane-use control strategies—more accurate and coordinated responses, shift towards in-vehicle signage reducing needs for infrastructure investments.
- DMS displays—more accurate messaging, shift towards in-vehicle signage for more personalized recommendations, reduced need for infrastructure investments.
- Work zone implementation—higher safety for workers and drivers, higher resolution maps of work zone geometries, real-time information on new zone locations, reduced need to manually update data.
- Broadcasted and Personalized Traveler information—higher fidelity information, more accurate and timely information, personalized recommendations.
- Congestion pricing, road user fees, and tolls—more granular toll rates, more accurate congestion prices, personalized tolls, and road user fees.
- Performance measurement, including weather and emissions monitoring—higher fidelity analysis, more comprehensive coverage of geography, reduced need for infrastructure investments.

- Asset management and maintenance —faster detection and response to equipment failures, potentially reducing the need for infrastructure investments through preventative maintenance.

U.S. DOT has characterized V2I applications into "bundles" as well as into broad functional areas. The U.S. DOT CV applications (over 75 specific applications) have been grouped into the following "bundles":

- V2I safety.
- V2V safety.
- EnableATIS (Next Generation Advanced Traveler Information Systems).
- Integrated Network Flow Optimization (INFLO).
- FRATIS (Freight Advanced Traveler Information System).
- MMITSS (Multimodal Intelligent Traffic Signal System).
- R.E.S.C.U.M.E. (Response, Emergency Staging and Communications, Uniform Management and Evacuation).
- Integrated Dynamic Transit Operations (IDTO).
- Applications for the environment: Real-Time Information Synthesis (AERIS).
- Road weather.
- International border crossings.
- Fee payments.
- Smart roadside.
- Agency data applications.

All of the applications have been conceptualized in a Concept of Operations and are at technology readiness level (TRL) 2 ("proof of concept" whereas many have been extended to levels 6/7 (prototype demonstrated in relevant environment or operational environment). (https://www.fhwa.dot.gov/advancedresearch/trl_h.cfm; https://www.its.dot.gov/pilots/cv_pilot_apps.htm.) Several of the applications are available as an open-source prototype on the U.S. DOT Open Source Applications Development Portal (OSADP). (https://www.itsforge.net/.) Many of the applications are being evaluated in the CV Pilot sites in New York, Wyoming, and Tampa. (https://www.its.dot.gov/pilots/cv_pubs.htm.)

Table 1. U.S. Department of Transportation Connected Vehicle applications.

Area	Application
V2I Safety	• Red Light Violation Warning (RLVW). • Curve Speed Warning (CSW). • Stop Sign Gap Assist (SSGA). • Spot Weather Impact Warning (SWIW). • Reduced Speed/Work Zone Warning (RSWZ). • 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.
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 (AERIS)	• Eco-Approach and Departure at Signalized Intersections. • Eco-Traffic Signal Timing. • Eco-Traffic Signal Priority. • Connected Eco-Driving. • Eco-Lanes Management. • Eco-Speed Harmonization. • Eco-Cooperative Adaptive Cruise Control. • Eco-Traveler Information Applications. • 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 Maintenance Decision Support System (MDSS). • Vehicle Data Translator (VDT). • Weather Response Traffic Information (WxTINFO).

Table 1. U.S. Department of Transportation Connected Vehicle applications (continuation).

Area	Application
Mobility (EnableATIS, MMITSS, RESCUME, FRATIS, IDTO, INFLO)	• EnableATIS (Advanced Traveler Information System 2.0). • Intelligent Traffic Signal System (I-SIG). • Transit Signal Priority (TSP) and Freight Signal Priority (FSP). • 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). • Freight-Specific Dynamic Travel Planning and Performance (FRATIS). • Drayage Optimization (DR-OPT).
Smart Roadside	• Wireless Inspection. • Smart Truck Parking.
Fee Payment	• Electronic Payment systems.
International Border Crossings	• Electronic credentialing systems.

Source: U.S. Department of Transportation.

2.3 Impacts of Vehicle-to-Infrastructure Applications on Transportation Systems Management and Operations Functions

One of the first steps in the development of a V2I strategy is identifying which applications to consider for "day one" and which applications to add over time. The selection of these applications should relate to the current TSMO program and the potential payoff from:

- ***Enhancing existing functions*** by use of V2I information.
- Providing ***new services*** to travelers through V2I.

V2I applications will enhance a variety of TSMO functional areas. Table 3 presents a range of TSMO functional areas (rows) and describes the key impacts of V2I applications on these TSMO functional areas (columns). The TSMO functional areas listed in table 3 are taken from the Connected Vehicle Pooled Fund Study "Traffic Management Centers in a Connected Vehicle Environment." (Kimley-Horn and Associates, Inc., "Traffic Management Centers in a Connected Vehicle Environment", TMC Pooled Fund Study, March 2014.) The key impacts and characteristics of V2I applications shown in the table include:

1. How, and to what extent, data from connected vehicles can ***enhance each function*** through V2I?

2. What ***penetration level*** of connected vehicles are needed to achieve enhanced functionalities?
3. Which ***agencies should be involved*** and the ***geographic/jurisdictional scope*** of the functionality?
4. What ***new requirements for data processing*** will need to be considered?

Not all applications require low latency, high bandwidth capabilities. Active safety functions require high data rates and low latency technology. Other applications may be accomplished with other types of communications. Table 2 classifies V2I applications by their speed:

- "Real-time" TSMO applications require rapid processing of connected vehicle data and trajectories as close to the edge as possible. (The "edge" refers to the closest point between the vehicle and the infrastructure. In the case of DSRC applications for active safety, this is at the RSU. Since the processing must be done in microseconds, for, say, red-light running warning, it is not likely that the V2I data could be shipped to a TMC and then back to the vehicle in a timely manner. Those applications require deployment of the application on the RSU.)
- "Near-real-time" applications functions may not require real-time processing, but need to have timely delivery and use within minutes.
- "Off-line" applications are those that may have data stored and processed for later use on the order of hours or days.

Table 2. Groupings of Transportation Systems Management and Operations functions by speeds.

Real-Time Functions (very fast)	Near Real-Time Functions (fast/medium)	Offline Functions (slow)
Roadway Hazard Warning	Traffic Incident Management	Emissions Monitoring
Speed Warning	Signal Control & Status Dissemination	Asset Management
Intersection collision avoidance	Metering	Performance Measurement
Probe Data Collection	Lane Management	
Electronic Payment	Traffic Information	
	Weather Monitoring	
	Parking Management	

Source: U.S. Department of Transportation.

Table 3. Key technical characteristics of how Vehicle-to-Infrastructure applications will affect Transportation Systems Management and Operations functions.

Potential to improve performance of functions	Will application augment existing or provides new functions	Number and location of RSUs and CVs to enable function	Level of involvement of local government regarding deployment and operations	Needed penetration rate of CVs to enable function	Need for agency to agency data sharing	Processing location needs	High Definition Mapping requirements	Processing speed requirements	Requires DSRC/RSUs
Traffic Incident Management									
Rapid identification and impact assessment Rapid dissemination via RSUs	Augments	Limited	Low	Low	Critical	One TMC	Low	Very Fast (<1 minute)	Depends on specific uses, but probably not
Roadway Hazard Warning									
Rapid identification and impact assessment Rapid dissemination via RSUs	New	Limited	Medium	Medium	Not critical	One TMC	Low	Very Fast (seconds)	Yes
Speed Warning									
Rapid identification and warning of unsafe speed Vehicle-specific and targeted	New	Limited—location specific	Medium	Low	Not critical	One TMC	High	Very Fast (<1 second)	Yes
Intersection Collision Avoidance									
Ability to improve safety at intersections	New	Benefits proportional to deployment	High	Low	Not critical	One TMC	High	Very Fast (<1 second)	Yes

Table 3. Key technical characteristics of how Vehicle-to-Infrastructure applications will affect Transportation Systems Management and Operations functions (continuation).

Potential to improve performance of functions	Will application augment existing or provides new functions	Number and location of RSUs and CVs to enable function	Level of involvement of local government regarding deployment and operations	Needed penetration rate of CVs to enable function	Need for agency to agency data sharing	Processing location needs	High Definition Mapping requirements	Processing speed requirements	Requires DSRC/RSUs
Signal Control and Status Dissemination									
At low penetrations, can be used to fine tune timing plans At high penetrations, can be used for real-time control	Augments	Benefits proportional to deployment	High	Low	Not critical	One TMC	High	Fast (<1 minute)	For most applications, yes
Probe Data Collection									
BSMs and PDMs used to estimate traffic flows on the network	Foundational data (Augments—Commercial; New—RSU/RSU)	Benefits proportional to deployment	High (DSRC); Low (Commercial)	Benefits proportional to deployment	Critical for cross-agency applications	One or multiple TMCs	Medium	Fast (<1 minute)	No
Metering									
At low penetrations, can be used to fine tune metering parameters At high penetrations, can be used for real-time control	Augments	Limited—location specific	Medium	Low	Not critical	One TMC	Low	Fast (<1 minute)	No

Table 3. Key technical characteristics of how Vehicle-to-Infrastructure applications will affect Transportation Systems Management and Operations functions (continuation).

Potential to improve performance of functions	Will application augment existing or provides new functions	Number and location of RSUs and CVs to enable function	Level of involvement of local government regarding deployment and operations	Needed penetration rate of CVs to enable function	Need for agency to agency data sharing	Processing location needs	High Definition Mapping requirements	Processing speed requirements	Requires DSRC/RSUs
Lane Management									
At low penetrations, can be used for feedback to Advanced Traffic Management System (ATMS) At high penetrations, can be used for lane control	Augments if existing; new if bypassing the construction of gantries	Benefits proportional to deployment	Low	Medium	Not critical	One or multiple TMCs	High	Fast (<1 minute)	No
Electronic Payments									
Can be used in lieu of transponders for toll payments Can be used to pay for parking or for road-user charging	Augments/New	Benefits proportional to deployment	Low	Medium	Not important	One TMC	Low	Medium (minutes)	Possibly
Traffic Information									
Can be used for targeted traveler information based on vehicle location and trajectory relative to incidents	Augments	Benefits proportional to deployment	Low	Low	Important	Multiple TMCs	Medium	Fast (<1 minute)	No

Table 3. Key technical characteristics of how Vehicle-to-Infrastructure applications will affect Transportation Systems Management and Operations functions (continuation).

Potential to improve performance of functions	Will application augment existing or provides new functions	Number and location of RSUs and CVs to enable function	Level of involvement of local government regarding deployment and operations	Needed penetration rate of CVs to enable function	Need for agency to agency data sharing	Processing location needs	High Definition Mapping requirements	Processing speed requirements	Requires DSRC/RSUs
Emissions Monitoring									
Even at low penetration, mobile emissions testing can provide better air quality data over a region and targeted emissions enforcement	New	Many	Low	Low	Not important	Multiple TMCs	Low	Slow (days/weeks)	No
Weather Monitoring									
Can be used to supplement ESS for wide area road weather monitoring	Augments	Many	Medium	Low	Important	Multiple TMCs	Low	Medium (minutes)	No
Asset Management									
Pavement condition monitoring is a substantial cost to agencies and could be supplemented from vehicle data	Augments	Many	High	Low	Not important	Multiple TMCs	Low	Slow (days/weeks)	No

Table 3. Key technical characteristics of how Vehicle-to-Infrastructure applications will affect Transportation Systems Management and Operations functions (continuation).

Potential to improve performance of functions	Will application augment existing or provides new functions	Number and location of RSUs and CVs to enable function	Level of involvement of local government regarding deployment and operations	Needed penetration rate of CVs to enable function	Need for agency to agency data sharing	Processing location needs	High Definition Mapping requirements	Processing speed requirements	Requires DSRC/RSUs
Parking Management									
At high penetrations, parking availability will enable better utilization of parking spaces, better real-time information, and potential reduction in emissions	Augments/ new	Many	High	High	Not important	One TMC	Low	Medium, Slow (minutes, trends—days/weeks)	No
Performance Management									
Even at low penetrations, a sample of vehicle data can supplement traditional sources to measure performance	Augments/ new	Many	Medium	Low	Important	Multiple TMCs	Low	Slow (days/weeks)	No

Source: U.S. Department of Transportation.

Finally, V2I technology will impact TSMO functions differently depending on whether the TSMO function can be enhanced by V2I, I2V, or I2V-V2I bidirectional functions—as these three categories are associated with different directions of data flow and infrastructure requirements and owners. Table 4 categorizes TSMO functions in groups of V2I only, I2V only, or bidirectional data exchange.

Table 4. Groupings of Transportation Systems Management and Operations functions by Vehicle-to-Infrastructure category.

V2I Functions	I2V Functions	I2V-V2I Bidirectional Functions
Probe Data Collection	Roadway Hazard Warning	Signal Control & Status Dissemination
Weather Monitoring	Speed Warning	Metering
Emissions Monitoring	Intersection Collision Avoidance	Electronic Payment
Asset Management	Traffic Information	Traffic Incident Management
Performance Measurement		Lane Management
		Parking Management

Source: U.S. Department of Transportation.

2.4 Summary

V2I is not mandated by U.S. DOT to be adopted by IOOs. The NHTSA proposed rulemaking for V2V equipment on passenger vehicles makes no presumptions about the availability of RSUs or V2I applications. The rate of market penetration of V2I may not be specifically linked to the deployment of V2V equipment. Assuming that V2V equipment is made mandatory starting in 2019, market penetration will be paced largely by fleet turnover. At the current rate of fleet turnover, market penetration of 50% will take 10-15 years. (National Renewable Energy Lab, nrel.gov; http://library.ctr.utexas.edu/ctr-publications/0-6849-p1.pdf.)

Capitalizing on V2I applications that require DSRC will depend on IOO deployment of RSUs. Some V2I applications can benefit from a modest rate of V2V and V2I deployment—while others require higher percentages to be effective. Those V2I applications which can operate through cellular communications can be deployed without special roadside infrastructure although this may require arrangements with private sector communication service suppliers, OEMs, nomadic device suppliers, and app developers. In either case, technology readiness levels (TRLs) are important to consider in strongly adopting an application as a focus area of a connected vehicle program. (https://www.fhwa.dot.gov/advancedresearch/trl_h.cfm.) Care should be taken to objectively evaluate maturity of applications and any technical, policy, or integration modifications that will be necessary to adapt a specific system to an agency's environment, systems, and processes. Even fully proven and mature applications may require modifications for specific uses and regional requirements.

Chapter 3. Overview of the Transportation Systems Management and Operations Capability Maturity Model Framework

3.1 Background

The Second Strategic Highway Research Program (SHRP 2) performed research focused on improving travel reliability and reducing congestion. A key effort was The SHRP 2 Institutional Architectures to Advance Operational Strategies Project (L06). This SHRP 2 research indicated that key indicators of TSMO program effectiveness were not only related to the level of funding and technology deployment of an IOO but also strongly related to agency processes, culture, and institutional capabilities. (http://www.trb.org/Publications/Blurbs/165285.aspx.)

The SHRP 2 L06 research suggested that development of TSMO plans must include more activities than a strategy to deploy IT systems and technology. Effectively capitalizing on systems and technologies requires a related set of improvements in business and institutional processes. Improvements to TSMO processes also needs to be appropriately planned and developed. Concepts from the Capability Maturity Model (CMM) were used to create a self-assessment framework for IOOs to identify their current levels of capability on a number of dimensions. Within each dimension, specific actions are identified for an IOO to improve TSMO within each dimension. (https://en.wikipedia.org/wiki/Capability_Maturity_Model.)

Audience and Objectives—The TSMO CMM was developed as a tool to be utilized by TSMO program managers and their teams. Managers identify the changes and actions required within each dimension to improve TSMO. While the principal users of the TSMO CMM have largely been state DOTs, local governments, Metropolitan Planning Organizations, law enforcement, and private service providers have also been involved in capability assessment and TSMO planning. The CMM for TSMO was subsequently adapted by AASHTO into a web-based self-assessment tool. (http://www.aashtotsmoguidance.org/.)

The TSMO CMM framework—Three dimensions of the TSMO CMM are process-oriented:

- **Business Processes,** including planning, programming, budgeting, and project development.
- **Systems and Technology,** including use of systems engineering, systems architecture standards, interoperability, and standardization.
- **Performance Measurement,** including measures definition, data acquisition, and use.

Three dimensions of the TSMO CMM are institutional:

- **Culture,** including technical understanding, leadership, outreach, and legal authority.

- **Organization and Staffing,** including organizational structure, staff development, and recruitment and retention.
- **Collaboration,** including relationships with public safety agencies, local governments and peers, MPOs, and the private sector.

For each of these six dimensions, four criteria-based "levels" of capability maturity are identified:

1. **Level 1—"Performed."** Activities and relationships are largely ad hoc, informal, and champion driven, substantially outside the mainstream of other DOT activities.
2. **Level 2—"Managed."** Basic strategies and applications are understood; key processes support the requirements for effective implementation; key technologies and core capacities are under development, but limited internal accountability and uneven alignment of accountability with external partners.
3. **Level 3—"Integrated."** Standardized strategies and applications implemented in a prioritized manner and managed for performance; Technical and business processes developed, documented, and integrated into DOT activities; partnerships aligned.
4. **Level 4—"Optimizing."** TSMO is considered a full, sustainable core DOT program priority, established on the basis of continuous improvement with top-level management support and formal partnerships.

Within each level, a set of actions and criteria are specified for improving TSMO effectiveness. An agency can determine their level by addressing the criteria of that level. To advance to the higher level the criteria of that level must be addressed. Actions in any dimension can be articulated by a common set of active verbs:

- *Commitment to perform* an activity (Level 1).
- *Ability to perform* an activity (Level 1 and moving from Level 1 to Level 2).
- Activity *performed* (Level 1, moving from Level 1 to Level 2, and Level 2 to Level 3).
- Activity *measured and analyzed* (moving from Level 2 to Level 3, and from Level 3 to Level 4).
- Activity *institutionalized* and continuously improved upon (moving from Level 3 to Level 4).

In order to raise capability maturity from Level 1 to Level 4 in any dimension, the same general progression of activities must be completed level by level. Levels cannot be skipped.

3.2 The Transportation Systems Management and Operations Capability Maturity Model Structure

Table 5 illustrates the TSMO CMM matrix. These criteria and actions are general and can be tailored to different users (multi-agency partnerships or metropolitan planning organizations, for example), or refined to address specific TSMO applications, such as traffic incident management. At the core of the CMM is the agency's evaluation of how the current status matches one of the four level descriptions. In many cases, an agency may find that the organization is "between" levels having completed some but not all actions at level 1 and some but not all actions at level 2. This is completely normal and natural, indicating strengths of the agency in some subareas and weaknesses in others. It is common for an agency to find they have different capability scores in each of the six dimensions.

Table 5. Transportation Systems Management and Operations Capability Maturity Model matrix.

Dimensions	Level 1 Performed	Level 2 Managed	Level 3 Integrated	Level 4 Optimized
Business Processes (Planning and Programming)	Each jurisdiction doing its own thing according to individual priorities and capabilities.	Consensus regional approach developed regarding TSMO goals, deficiencies, B/C, networks, strategies, and common priorities.	Regional program integrated into jurisdictions' overall multimodal transportation plans with related staged program.	TSMO integrated into jurisdictions' multi-sectoral plans and programs, based on formal continuing planning processes.
Systems and Technology	Ad hoc approaches to system implementation without consideration of systems engineering and appropriate procurement processes.	Regional ConOps and architectures developed and documented with costs included; appropriate procurement process employed; systems engineering processes consistently used.	Systems & technology standardized and integrated on a regional basis (including arterial focus) with other related processes and training as appropriate.	Architectures and technology routinely upgraded to improve performance; systems integration/ interoperability maintained on continuing basis.
Performance Measurement	Some outputs measured and reported by some jurisdictions; no regular performance measurement related to TSMO.	Output data used directly for after-action debriefings and improvements, although these are limited; data is easily available and dash-boarded.	Outcome measures identified (networks, modes, impacts) and routinely utilized for objective-based program improvements.	Performance measures reported internally for utilization and externally for accountability and program justification.
Culture	Individual staff champions promote TSMO; value not widely understood beyond champions.	Senior management understands TSMO business case; recognition and appreciate of the value and role of TSMO.	Jurisdictions' mission identifies TSMO and benefits with formal program and achieves wide public visibility/understanding.	Agency commitment accountability accepted as formal, top level core program of all jurisdictions.

Table 5. Transportation Systems Management and Operations Capability Maturity Model matrix (continuation).

Dimensions	Level 1 Performed	Level 2 Managed	Level 3 Integrated	Level 4 Optimized
Organization/ Staffing	TSMO added on to units within existing structure and staffing—dependent on technical champions.	TSMO-specific organizational concept developed within/ among jurisdictions with core capacity needs identified, collaboration takes place.	Top level management position and core staff for TSMO are established.	Certification of operations core capacity positions including performances incentives.
Collaboration	Relationships are informal and on personal basis (public-public, public-private).	Regular collaboration at the regional level, collaborative approaches initiated for TSMO functions.	Rationalization/sharing/formalization of responsibilities among key stakeholders through co-training, formal agreements and incentives.	High level of TSMO coordination among owner/operators (state, local, private).

Source: U.S. Department of Transportation.

A key feature of the CMM is the relationship between levels and dimensions. The levels of capability are incremental, as each set of actions builds upon the previous. It is not really possible to jump from level 1 to 3 without progressing through level 2. In addition, the dimensions are interrelated. It is difficult to move ahead in one dimension without moving ahead in the others.

The CMM self-evaluation process—Figure 1 illustrates the CMM process as embodied in the AASHTO CMM guide. The key constructs include three steps:

1. **Self-evaluation:** identification of the "state of play" of the organization on each of the CMM dimensions.
2. **Capability level determination:** Identification of the capability level and the strategy for moving from the current level to the next.
3. **Improvement guidance:** identification of the selected actions within the strategy that are relevant to the agency's goals.

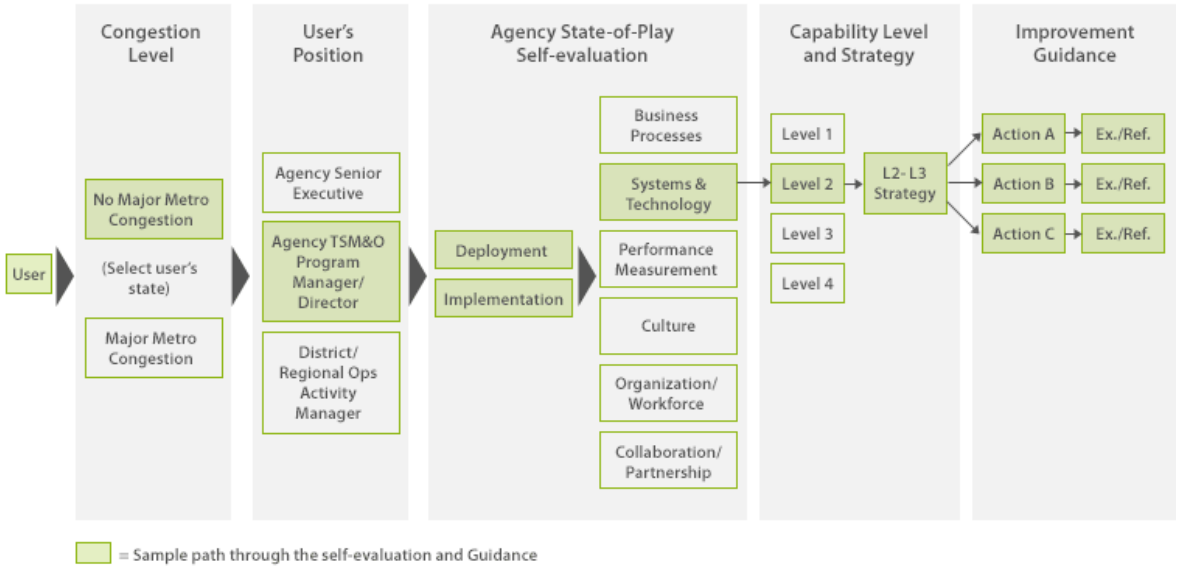

Figure 1. Flow chart. Structure of the Capability Maturity Model assessment approach.

(Source: U.S. Department of Tranportation.)

As of 2017, the FHWA has conducted ~60 CMM workshops across the United States to improve TSMO effectiveness. In addition, FHWA has supported ~30 agencies in using their CMM evaluation as the basis for development of a formal agency TSMO Program Plan.

The TSMO CMM workshops have suggested these general conclusions:

1. Use of the TSMO CMM dimensions provides an efficient means of improving TSMO program effectiveness by focusing on issues that are often overlooked.
2. Agencies exhibit a wide range of capability maturity across the six dimensions. While in general most agencies may have similar levels of capability in a given dimension, they often exhibit a different mix of specific strengths and weakness.
3. Most agencies have evaluated themselves at level 1 ("performed") or 2 ("managed") for business processes, systems & technology, and performance management.

4. A number of agencies self-assess their capability for organization and staffing, and collaboration at levels 3 and 4.
5. The applicability of CMM to specific TSMO applications suggests the robustness of the general logic of the dimensions and levels.

3.3 The Use of Capability Maturity Model in the Development of Transportation Systems Management of Operations Program Plans

As V2I functions augment many of the areas of TSMO and provide new services, V2I will likely be integrated into the TSMO program plan. Agency experience with TSMO implementation over the last decade has indicated that it is important to couple TSMO project planning for infrastructure deployment with the parallel development of the related process and institution capabilities. In addition, agency experience has indicated the importance of including TSMO into the agency's long-term multimodal transportation program.

The concept of a "TSMO program plan" has been developed based on consensus among leading transportation agencies. TSMO program planning involves three basic elements: strategic, programmatic, and tactical:

1. **Strategic:** The relationship of TSMO to the agency mission and the fundamental reasons for organizational commitment to TSMO;
2. **Programmatic:** The organizational structure and business processes to administer TSMO as a core program area; and
3. **Tactical:** The services, programs, technologies, and infrastructure to which an organization or geographic area commits to implement in order to support achievement of performance outcomes.

Transportation agencies with strong TSMO focus are developing TSMO program plans and integrating these plans into their agency transportation planning framework.

3.4 The Development of Capability Maturity Frameworks

The TSMO CMM self-assessment process focused on TSMO at the program level (across the common features of all applications). FHWA has since adapted the TSMO CMM into ***Capability Maturity Frameworks*** (CMF) for specific TSMO applications. The CMFs include traffic incident management, freeway traffic management, road weather management, traffic signal management and work zone management. These topic-specific CMFs include the same six dimensions, self-assessment criteria, and action identification processes.

There is broad consensus that the six dimensions in the TSMO CMM are appropriate for evaluating activities that are new, involve innovative technology, require unique performance measures, take place in real time, and are necessarily highly collaborative. All of these statements are true of connected vehicle programs.

Effective V2I applications will require capabilities in all six dimensions. For example, it is difficult to develop improved systems and technology without appropriate staff capabilities, and it is

difficult to judge whether any changes are having a significant impact without performance monitoring and management.

Dependence of V2I program effectiveness on capabilities development—The effectiveness of V2I programs will depend on a supporting structure of technical capabilities (business processes, systems and technologies and performance measurement) which, in turn, must be rooted in a foundation of collaboration, organization and staffing, and culture. Figure 2 illustrates this.

Figure 2. Chart. The dependence of Vehicle-to-Infrastructure effectiveness on dimensional maturity.

(Source: U.S. Department of Transportation.)

3.5 Challenges and Related Implications for Agency Capabilities

There are many issues that will be common in any connected vehicle program development including systems engineering, deployment, operations, and maintenance; and new capabilities.

IOO will need to employ systems engineering of new concepts and applications in considering:

- The rate of CV market penetration sufficient to support any particular application.
- The prototype status of applications and consensus on practical "day one" applications.
- Appropriate communications technology (DSRC/Cellular).
- Integration of new systems and software with legacy systems and software.

- Capabilities of IOOs to adjust processes to appropriately take advantage of new data streams.
- Use of V2I probe data beyond TSMO.

The development, deployment, operations, and maintenance of new V2I systems may place significant burdens on agency capabilities in the areas of:

- Policy development and compliance with legal requirements regarding licensing, security, and privacy.
- Management and integration of a Security Credential Management System (SCMS).
- Effectively coping with the complexities regarding infrastructure deployed among multiple jurisdictions.
- Influencing policy-makers to invest in V2I technology in light of funding constraints.
- Development of new business processes required for V2I and integration of V2I into existing processes.
- Managing new types of data and volumes of data with modern tools and technologies.
- Determining how V2I deployment performance will be measured.

Several V2I applications will involve coordination and collaboration with local IOOs, metropolitan planning organizations, and coalitions. In addition, there is a potential role for private service providers to collect and process data. This implies the need for capabilities in the areas of:

- Developing guidelines and collaborative agreements across regions.
- Establishing new forms of public-private partnerships (PPP).
- Consideration of partnerships and data packaging from third-party commercial providers.
- Developing and retaining specialized staff and knowledgeable management.
- Development of an appropriate organizational framework for coordination and allocation of authority and responsibility.

In the next chapter, the Capability Maturity Model for TSMO is introduced as baseline tool to organize the planning of a V2I program. This will be followed in Chapters 4 and 5 with the specific actions to elevate capabilities in the relevant dimensions.

Chapter 4. A Capability Maturity Model for Connected Vehicle Programs

4.1 Distinct Characteristics of the Connected Vehicle Capability Maturity Model

As noted in the previous chapter, the capability maturity model captures the key process and institutional capabilities associated with any transportation activity involving new technology and operational management. The development of a program to effectively capitalize on connected vehicle systems and technology must, therefore, include a focus on the development of the necessary capabilities.

Towards that end, the Capability Maturity Model (CMM) for Transportation Systems Management and Operations (TSMO) programs has been adapted to specific TSMO strategies, each with its own framework. These Capability Maturity Frameworks (CMF) follow the TSMO CMM with modifications tailored to the strategy. Similarly, the TSMO CMM has been modified in response to the specific characteristics of Vehicle-to-Infrastructure (V2I) applications for the connected vehicle CMM, such as:

- Some V2I applications are new TSMO services that have no precedent with respect to business process, systems and technology, and performance measurement. Their TRL level is below 8. (https://www.fhwa.dot.gov/advancedresearch/trl_h.cfm.)
- Many agencies have activities to complete at Level 1. Due to the uncertainties regarding technology and penetration rate, actions to move from a Level 3 to an “optimized” level are less well defined.
- There are fundamental differences in requirements for V2I and I2V applications, particularly with respect to systems and technology. Dedicated Short Range Communications (DSRC) and Cellular technologies have strengths and weaknesses for particular applications.

Many additional issues must be considered in the connected vehicle CMM, including:

- Deployment planning and funding mechanisms for V2I applications are re-directions or expansions of existing budgets.
- Business process development for V2I application areas includes both integration of V2I into existing processes and development of wholly new processes.
- New policies are required regarding use of data and privacy, a core component to many V2I applications.
- Collaborative agreements are required for multijurisdictional applications including lead/follow agreements and MOUs regarding equipment and application operations and maintenance.
- Organizational capacity for technology management including development, deployment, and operations must be addressed as applications are planned within an agency.
- New systems will need to be integrated with legacy systems.
- Data management is critical, including application of data tools and technologies.
- Performance measurement will be required for applications new to transportation agencies.

- Adjustments in agency culture, and organization and staffing will be needed to meet to the special demands of V2I.
- Data and communications security (both SCMS and other related provisions) must be considered at a much higher level than before due to the risks of hacking, spoofing, and misbehavior.

Certain V2I applications also have their own unique characteristics. New strategies that were not possible with conventional Intelligent Transportation System (ITS) involve new business processes, procedures, and protocols. Table 6 illustrates issues within each CMM dimension related to specific V2I application areas.

Table 6. Implications of Vehicle-to-Infrastructure applications on the Capability Maturity Framework dimensions.

V2I Applications	Business Process	Systems and Technology (both Field and Back-office)	Performance Measures	Collaboration	Culture, and Organization and Staffing
Traffic Incident Management	Modification of TIM procedures	Requires new ConOps and architecture, data fusion and analytics at the TMC	Ability to more precisely measure performance	Reduced dependency on law enforcement for first notification	Minor impacts
Roadway Hazard Warning	New services for mapping required	Requires new ConOps and architecture, data fusion and analytics at the TMC; may be DSRC	Reduction in secondary crashes	Not critical	Expansion in program, roles and staff expertise
Speed Warning	New service Role in enforcement vs advisories	Requires new ConOps and architecture, data fusion and analytics and communications to CVs and the TMC; may be DSRC	Ability to develop speed profiles	Communications with law enforcement	Expansion in program, roles and staff expertise
Intersection Collision Avoidance	Standardized deployment and operations procedures	Requires new ConOps and architecture, data fusion and analytics and communications to CVs and the TMC; DSRC dependent; SCMS critical	Reduction in crashes	Significant involvement with local government	Expansion in program, roles and staff expertise
Signal Control & Status Dissemination	Standardized deployment and operations procedures	Requires new ConOps and architecture, data fusion and analytics and communications to CVs and the TMC; likely DSRC dependent	Reduction in emissions, reduction in crashes	Significant involvement with local government	Expansion in program, roles and staff expertise
Probe Data Collection	Establishment of procedures to utilize data	Data collection, processing and archiving at the TMC	Ability to track asset condition	Significant involvement with local government	Expansion in program, roles and staff expertise
Metering	Not critical	Improve data for decision support systems	Ability to more precisely measure performance	Not critical	Not critical

Table 6. Implications of Vehicle-to-Infrastructure applications on the Capability Maturity Framework dimensions (continuation).

V2I Applications	Business Process	Systems and Technology (both Field and Back-office)	Performance Measures	Collaboration	Culture, and Organization and Staffing
Lane Management	New services for mapping required	Improve data for decision support systems	Ability to more precisely measure performance	Not critical	Expansion in program, roles and staff expertise
Electronic Payment	Not critical	DSRC dependent; SCMS dependent	Pricing	Regional pricing/ road user fee	Expansion in program, roles and staff expertise
Traffic Information	Not critical	Requires new ConOps and architecture, data fusion and analytics and communications to CVs and the TMC	New insights	Regional application	Not critical
Emission Monitoring	Significant modifications	Significant modifications	Ability to develop emission profile	Regional application	Expansion in program, roles and staff expertise
Weather Monitoring	Significant modifications	Significant modifications	Ability to develop local Road whether profile	Regional application	Expansion in program, roles and staff expertise
Asset Management	Significant modifications	Significant modifications	Support of asset management	Not critical	Expansion in program, roles and staff expertise
Parking Management	New services for mapping required	Significant modifications	New insights	Regional application	Expansion in program, roles and staff expertise
Performance Measurement	Significant modifications	Significant modifications	New insights	Regional application	Expansion in program, roles and staff expertise

Source: U.S. Department of Transportation.

4.2 Connected Vehicle Capability Maturity Model Dimensions

While V2I programs are dependent on the same dimensions of capability as other TSMO applications, the unique distinctions between V2I and I2V applications emphasizes the importance of certain dimensions. The adjusted TSMO CMM dimensions for the Connected Vehicle CMM is as follows:

- **Business Processes:** This dimension refers to issues related to planning, programming, and budgeting of resources as well as processes for data collection, exchange, and action. Business processes for V2I applications are especially important if the application area is not a TSMO area an agency currently uses and, therefore, has not already initiated efforts to advance business processes through TSMO program planning or related work. Agencies may need new roles at the IOO, such as real-time communications specialists, for some V2I applications. For most V2I applications, an agency will need an institutionalized approach to cybersecurity and privacy. In the short term, the IOOs may have significant legal and technical challenges. In the long term, it is anticipated that these challenges will evolve towards standards and best practices.
- **Systems and Technology:** This dimension refers to the use of systems engineering, systems architecture standards, interoperability, and standardization of equipment, software, and data centers. Most V2I applications have a significant impact on the capabilities needed for systems and technology development, both in the field and in the TMC. For agencies deploying V2I applications that are dependent on DSRC, they will need more skills and capabilities in technology and field devices than if they were developing a V2I program around cellular probe data. Therefore, the V2I CMF has divided systems and technology dimension into two sub-dimensions to discuss the related issues and actions separately:
    - **Systems and Technology—Field** refers to the devices deployed for V2I and I2V communications, in particular roadside unit (RSU) and on-board unit (OBU) interactions using DSRC. All V2I applications are technology intensive, but some may not require agency investments in field equipment when V2I data is available from commercial sources.
    - **Systems and Technology—Back-office** refers to the use of systems engineering, systems architecture standards, interoperability, and standardization of software in TMCs, data centers, and the cloud. V2I introduces challenges related to integration of new V2I systems with legacy ATMS, sharing of data and information between agency partners and coalitions, communications architectures, and analytics. SCMS and other security and privacy provisions.
- **Performance Measurement:** This dimension refers to the importance of performance measures definition, data acquisition, and utilization. Performance metrics are particularly important if the V2I application is in a TSMO area where your organization has no current experience and, therefore, has not already initiated efforts to advance performance measurement for V2I through TSMO program planning or related work. Performance measurement includes activities to measure the performance of the V2I application effectiveness as well as the use of V2I data to measure other systems and processes.
- **Organization and Staffing, and Culture:** This dimension combines two of the TSMO CMM dimensions. This dimension focuses on program management, organizational structure, staff development, and recruitment and retention. Culture refers to the importance of technical understanding, leadership, outreach, and staff empowerment within an agency. In the case of culture, efforts to advance an agency's culture towards V2I may significantly overlap with efforts to cultivate a culture that is conducive to TSMO advancement. A culture of innovation

is important for all V2I applications, but more so for applications that are new to an organization. Staffing and training issues are common across almost all of the V2I applications. Agencies will need specific new knowledge, skills, and abilities (KSAs); V2I functions are likely to elevate the importance of TSMO within an IOO program hierarchy by making the linkage between the TMC and the traveler more explicit. Agencies may need to make organizational changes to increase the direct responsibility of senior management and to ensure coordination across agency departments. Agencies may consider creating new roles or modifying existing roles.

- **Collaboration:** This dimension refers to the importance of relationships with public safety agencies, local governments, peers, MPOs, and the private sector. Probe data collection in particular will highlight the issue of cross-jurisdictional collaboration, particularly for DSRC RSU-OBU interactions and private I2V services.

4.3 Levels of Capability for Connected Vehicle Program Dimensions

The TSMO CMM was designed for the current state of TSMO maturity. TSMO strategies have been in various stages of implementation for over 25 years. While a focus on "institutionalization" is more recent, IOOs exhibit a wide range of levels of capability in the key dimensions ranging from start-up to advanced. Many agencies are already at levels 2 (managed) and above (integrated and optimized) on several TSMO CMM dimensions.

Unlike the current status of TSMO, almost all IOOs are at the very early stages of implementing V2I applications. Since CV technology for V2I is not yet common in the general vehicle fleet, and will not reach significant levels of market penetration for several years, the capability levels for the Connected Vehicle CMM have been adjusted to this reality.

The four levels of capability for the Connected Vehicle CMM have been defined as follows. Descriptive details are representative of typical activities at each level:

- **Level 1—Exploration**
  - Organizational awareness of V2I and related issues.
  - Concept of Operations being formulated.
  - V2I pilot being planned or implemented.
  - Limited expectations of benefits due to project scale.
- **Level 2—Program Initiated**
  - Current V2I pilot underway or completed.
  - Program strategy being developed.
  - Consideration for how V2I data can enhance other TSMO services.
- **Level 3—Program Integrated**
  - V2I is integrated into TSMO plans and systems are being modified to use V2I data.
  - V2I is being considered in the region's LRTP.
  - Implementation plan has been identified.
  - Changes to staffing and training have been identified and implemented.
  - Regional data sharing and partnerships have been formalized.

- **Level 4—Program Mainstreamed**
  - V2I mainstreamed into the agency's TSMO strategies.
  - Standards in place for equipment deployment.
  - Formalized use of V2I data and analytics for ongoing performance improvements.

As more agencies gain experience with V2I applications over the next 5 to 10 years, actions and capability descriptions of each level will become clearer.

4.4 Capability Maturity Model Framework for Connected Vehicle Programs

The Connected Vehicle Program CMM framework is illustrated in table 7. This matrix provides general description of capabilities for each level in each dimension.

Table 7. Connected Vehicle program capability maturity framework level assessment criteria.

CMM Dimension	Connected Vehicle Program Capability Level Self-Assessment Criteria			
	Level 1—Exploration	**Level 2—Initiated**	**Level 3—Integrated**	**Level 4—Mainstreamed**
1. **Business Processes**—Planning, programming and budgeting, workflows	Agency is considering or conducting V2I pilot project(s) and developing plans for business processes	Agency has conducted pilot project(s) and is now developing V2I plans, programs, budgets, and workflows	V2I plans, programs, and workflows are being implemented and institutionalized (e.g., integration in existing plans)	A Connected Vehicle program is established as part of normal agency operations
2. **Systems and Technology**				
Field	Agency has developed and deployed prototype V2I systems in field and at the TMC	Agency is developing a V2I systems plan, including back office and field components	Standardized approach to back office and field component deployment has been developed	V2I back office and field components fully integrated with TSMO systems
Back-office				
3. **Performance Measurement**—Data Collection, Processing, and Reporting	V2I performance measures, data, and analytics being identified	Performance measurement, data, and analytics processes are under development	V2I performance measurement system has been developed and utilized for routine TSMO operational management and reporting	V2I is fully integrated into the agencies performance measurement program, including both the performance of V2I as well as the use of V2I information regarding performance of other TSMO activities
5. **Organization and Staffing, and Culture**	Needs for changes in policy, staffing, organization, culture, and legal protections are being identified	Changes to staffing, organization, policy, culture, and legal protections being implemented	Modifications to organization, staffing, culture, and legal protections are accepted and institutionalized	Continuing improvements to staffing, organization, culture, and policy are routinely made
6. **Collaboration**—Public and Private Partnerships	Informal pilot program arrangements (public-public and public-private)	Public-private and public-public partnership needs and approaches have been identified	Public-private and public-public partnerships accepted and standardized	New and updated partnership arrangements mainstreamed

Source: U.S. Department of Transportation.

Chapter 5. Suggested Actions in Each Capability Maturity Model Dimension

5.1 Purpose

This chapter identifies the important activities to support the development of a connected vehicle program. By self-evaluation in each capability dimension, agencies will identify specific areas to focus on for improvement.

5.2 Intended Users

A single agency can conduct the self-evaluation process alone or a group of partner agencies can conduct the self-evaluation process together. An agency may elect to designate an agency representative to do the evaluation using their best judgment, or the evaluation can be conducted as a group of individuals with a variety of roles throughout the organization. Most agencies that have used the TSMO CMM have found significant value in evaluating their status on the various CMM dimensions as a group since the various topics touch a variety of staff roles and responsibilities. Alternatively, and perhaps more reflective of the collaborative nature of many V2I applications, agencies may find value in conducting the self-assessment as a group of peer and complementary agencies in a workshop setting.

5.3 Structure of the Capability Maturity Model Activity Tables

A separate table of potential activities is presented for each Connected Vehicle CMM dimension. The table for each dimension has the same structure as follows.

- **Columns—**The columns in the table represent the incremental levels of capability from 1 to 4.
- **Dimension framing considerations—**The rows of each capability matrix present a general description of the dimension including:
  - **Relevance**—how V2I introduces specific challenges and requirements.
  - **State of play—**the current status of the agency's capability level.
  - **Objective**—The goal of actions to improve capability maturity in this dimension.
  - **General Strategy**—a broad description of the strategies involved in advancing capability to the next level.
  - **Relationship to TSMO**—the degree to which V2I applications relate to existing TSMO applications in this dimension.
  - **Caveats—**Special considerations and dependencies that are specific to this dimension.

1. **Actions to get to the next level—**The enabling activities to improve V2I capability in this dimensions. The actions across rows at each incremental level of capability are dependent. That is, the actions in a row under each level column build on the sequential actions in the same row.
2. **Synergies—**Other dimensions in the Connected Vehicle CMM that are closely related to this dimension.
3. **Key stakeholders—**Agencies and groups that are important to include in decision making surrounding planning and actions for the dimension.
4. **Questions for consideration—**Questions for an agency to ask itself in its self-assessment and determination of maturity level for the dimension.

5.4 Use of the Action Tables in Agency Self-Evaluation

We recommend you consider all of the dimensions together using the following process.

- **Step 1: Determine your agency's current capability level—**Your status at a general level can be identified by reviewing the criteria of each level (table 7). If the majority of the criteria under that level have been met, the agency is likely at this level. If not, they are at the previous level.
- **Step 2: Identify priority dimensions—**All of the dimensions are essential and must be addressed to move the capability for V2I to the next level. It is possible that an agency will be at level 2 for some dimension and at level 1 for others. Priority should be placed on improving the capabilities in the lowest levels—as the research underpinning the TSMO CMM established that, given the interrelated nature of all six dimensions, it is critical to advance capability in the lowest level dimension(s) for an agency to move forward. Dimensions will take different orders of importance depending on the V2I application areas and functions that have been planned for implementation.
- **Step 3: Review actions for each dimension—**In some cases, an agency may have already completed one or more (but not all) of the actions to meet the criteria for a given level. For any given dimension, each new level of capability is designed to establish the basis for the subsequent step and therefore must be fully implemented before taking actions related criteria of the next level.
- **Step 4: Select initial actions within dimensions—**The actions are numbered according to a logical sequence within each level. In general, improving capability for that dimension involves following the sequence of actions as indicated, although specific circumstances may support some deviation from this sequence.
- **Step 5: Compile actions across dimensions into action plans to improve capability—** The actions within a level for a given dimension that have not been completed can be compiled into an action plan. You may choose to focus on one dimension, but all actions are relevant to move capabilities forward.

The combination of all actions at the given level for all dimensions will support a Connected Vehicle program plan.

Table 8. Capability levels for Business Process Dimension.

Planning, Programming and Budgeting, Workflows			
Achieving Level 1—Exploration Agency is conducting initial V2I pilot project(s) and developing plans for business processes.	**Achieving Level 2—Initiated** Agency has conducted pilot project(s) and is now developing V2I plans, programs, budgets, and workflows.	**Achieving Level 3—Integrated** V2I plans, programs, and workflows are being implemented and institutionalized (e.g., integration in existing plans).	**Achieving Level 4—Mainstreamed** A Connected Vehicle program is established as part of normal agency operations.
Relevance			
The introduction of pilot V2I applications brings the identification of requirements for planning, scheduling, budgeting, and project development.	The initiation of V2I systems and technology through time brings formalization of requirements for planning, scheduling, budgeting, and project development.	The integration of V2I systems and technology through time brings with it for the implementation of planning, scheduling, budgeting, and project development processes.	The mainstreamed use of V2I systems and technology requires formalized planning, scheduling, budgeting, and project development processes.
State of Play			
Agency is conducting initial V2I pilot project(s) and exploring implications and modifications to business process.	Agency is developing V2I plans, programs, budgets, and project development processes.	Agency has developed and is in the process of implementing a V2I operations plan together with programming, budgeting, and project development processes.	A Connected Vehicle program is established as the basis for continuing improvements—including updates to plans, programs, and funding strategies.
Objective			
Utilize pilot project(s) to identify the modifications and additions to business processes to accommodate V2I.	Develop the modifications and additions to business processes to accommodate V2I.	Implement modifications and additions to business processes to accommodate V2I.	Systematically integrate V2I-related business processes with TSMO activities.
General Strategy			
Identify partner's roles and responsibilities in pilot project development planning.	Develop a consensus-based regional approach to V2I pilot applications and deployment regarding planning, resource allocation and project development processes.	Move beyond pilots to develop an integrated Connected Vehicle program across priority TSMO functions.	Build out and update an integrated Connected Vehicle program across priority TSMO functions.

Table 8. Capability levels for Business Process Dimension (continuation).

Planning, Programming and Budgeting, Workflows			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Relationship to TSMO			
Limited direct impacts on many TSMO business processes.	Stronger consideration for how V2I applications may augment and improve existing TSMO business processes, while others may provide entirely new functions.	Direct impacts of V2I applications to augment and improve existing TSMO business processes, while others may provide entirely new business processes.	Full integration of V2I applications and data in TSMO business processes.
Caveats			
Formalized TSMO business processes are needed first before V2I impacts can be assessed.	V2I business processes build directly on those established for TSMO.	V2I business processes become foundational components of TSMO business processes.	V2I business processes and data integrally linked to TSMO business processes.
Actions to Get to the Next Level			
1. Identify peer and national dialogue opportunities regarding policy, planning, technical, and legal issues.	1. Participate in peer and national dialogue regarding policy, planning, technical, and legal issues.	1. Maintain involvement in peer and industry organizations and dialogue.	1. Maintain involvement in peer and industry organizations and dialogue.
2. Develop business case for TSMO regarding both public benefits and agency efficiency: a. Develop a communications strategy.	2. Develop business case for priority V2I applications regarding both public benefits and agency efficiency: a. Develop a communications strategy.	2. Disseminate business case to generate public and decision-maker support.	2. Communicate payoffs from TSMO and V2I to key stakeholders and public.
3. Develop consensus regional policy and planning framework for V2I implementation: a. Identify roles and resource commitments of partners/collaborators. b. Identify funding streams.	3. Develop consensus regional policy and planning framework for V2I implementation: a. Implement roles and resource commitments of partners/collaborators. b. Identify V2I implementation priorities and deployment roadmap.	3. Formalize MOUs: a. Regarding policy and roles and resource commitments. b. Update roadmap and staged V2I implementation plan for subsequent V2I increments.	3. Continue to update regional policy and planning framework: a. Changing roles and resources requirements. b. Incorporate V2I strategies into agencies' long-range planning. c. Expand consensus MOUs to other partners.

Table 8. Capability levels for Business Process Dimension (continuation).

Planning, Programming and Budgeting, Workflows			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Actions to Get to the Next Level (continuation)			
4. Identify costs and resources for implementation of initial V2I applications.	4. Identify resources for V2I implementation: a. Capital, operating, and maintenance costs. b. Funding sources, partnering and investment protocols and risks. c. Approach for estimating the impacts and benefits regarding safety, mobility, and environment. d. Investigate non-traditional vendor and suppliers.	4. Develop agency budgets: a. Create line item and budget for combined TSMO and Connected Vehicle programs. b. Work with peer states and research entities to develop approach to monitoring, data collection, forecasting, evaluating impacts of CV and V2I impacts.	4. Develop sustainable program: a. Identify sustainable funding sources for existing and new Connected Vehicle program areas. b. Monitor, forecast, and evaluate impacts of V2I.
5. Identify needs for ensuring privacy and security management.	5. Establish framework for ensuring privacy and security management: a. Legal and regulatory requirements for communications. b. Legal and regulatory requirements for back office systems. c. Security Credential Management System policies and procedures.	5. Finalize legal authorities, licenses, and relationships with security management entity.	5. Maintain legal authorities, licenses, and relationships with security management entity.

Table 8. Capability levels for Business Process Dimension (continuation).

Planning, Programming and Budgeting, Workflows			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Actions to Get to the Next Level (continuation)			
6. Develop initial pilot system deployment concept including ConOps, architecture, and system requirements: a. Define workflows and business processes. b. Define basic responsibilities of partners. c. Implement project(s).	6. Extend initial pilot system deployment concept including ConOps, architecture, and system requirements: a. Implement projects. b. Identify opportunities for V2I integration with existing TSMO devices, networks, and other system features. c. Review unique V2I project development issues and options related to procurement and/or partnerships. d. Develop application-specific real-time procedures and protocols. e. Define requirements for decision support systems.	6. Track performance and evaluate for cost effectiveness: a. Develop standard approach to device deployment. b. Improve project development process and utilize for continuing applications deployment. c. Review opportunities to reduce or replace other TSMO infrastructure. d. Standardize workflow agreements with partners. e. Extend decision-support system protocols to other applications.	6. Track performance/ evaluate for cost/effectiveness regarding mods and improvements: a. Utilize standard approach to device deployment. b. Improve project development process and utilize for continuing applications deployment. c. Implement approach to combined TSMO + V2I infrastructure. d. Maintain/extend project agreements with partners—public and private. e. Continue fine tuning decision-support systems.
Synergies			
Close relationship with systems and technology development.	Close relationship with systems and technology development.	Close relationship with systems and technology development.	Close relationship with systems and technology development.
Key Stakeholders			
TSMO program leadership, agency planners, and support consultants.	TSMO program leadership, agency planners, vendors, and support consultants.	TSMO program leadership, agency planners, vendors, and support consultants.	TSMO program leadership, agency planners, vendors, and support consultants.

Source: U.S. Department of Transportation.

Key questions for consideration in Business Processes:

Level 1
• Have we developed the business case for TSMO? • Have we engaged in the national dialogue for TSMO? • Do we understand the relationships between TSMO processes and V2I capabilities? • Do we routinely apply the systems engineering process for development and procurement of high-technology systems? • Have we identified a communications strategy for public and internal benefits of business process standardization? • Have we identified a regional consensus framework for policy and planning for V2I? If not, have we identified the right partners to develop such workflows? • Is it clear what V2I applications and functions will provide benefits to our specific regional issues? • Have we prioritized V2I applications for our agency? • Are V2I applications represented in agency planning documents? • Have we identified how regional processes and relationships among partner agencies will affect the implementation of business processes for V2I deployment? • Have we identified what costs and resources will be required for implementation of V2I? • Have we identified what agency or agencies will bear these costs and resources? • Have we outlined the requirements for security and privacy policies for V2I applications? • Have we formulated these requirements into a concept of operations? • Have we identified scope and scale of the business processes related to a pilot deployment(s)?
Level 2
• Have we developed the business case for V2I? • Have we engaged in the national dialogue for V2I? • Have we documented the relationships between TSMO processes and V2I capabilities? • Have we documented a communications strategy for public and internal benefits of business process standardization? • Have we developed a regional consensus framework for policy and planning for V2I? • Have we documented which V2I applications and functions will provide benefits to our specific regional issues? • Have we developed a plan to address regional processes and relationships among partner agencies for V2I deployment? • Have we developed a plan to secure the costs and resources will be required for implementation of V2I? • Have we gained agency buy-in for how these costs and resources will be borne? • Have we developed a plan for security and privacy management of V2I applications? • Have we developed a plan for implementation of the concept of operations? • Have we developed a plan form implementation of the business processes related to a pilot deployment(s)? • Have we identified roles and responsibilities within and among agency partners for implementation of the business processes?

Level 3
• Have we implemented the business case for V2I? • Are we contributing to the national dialogue for V2I implementation? • Have we implemented standard relationships between TSMO business processes and V2I data and applications? • Have we implemented a communications strategy for public and internal benefits of business process standardization? • Have we implemented a regional consensus framework for policy and planning for V2I? • Have we implemented V2I applications and functions successfully? • Have we implemented a regional process for V2I? • Have we implemented a standardized funding strategy? • Have we implemented a standardized security and privacy management strategy? • Have we implemented the concept of operations? • Have we moved forward from pilot deployment(s) to standardized processes?

Table 9. Capability levels for systems and technology—field dimension.

Field (RSUs, Right-of-Way, Spectrum, Site Assessment, Communications, Applications)			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Relevance			
The introduction of public V2I systems is dependent upon RSU deployment.	The introduction of public V2I systems is dependent upon RSU deployment.	Formalized design and deployment of field assets.	Systematic consideration of V2I field assets across TSMO functions.
State of Play			
No assets deployed.	Limited assets deployed in pilot locations.	Pilot assets deployed and expansion anticipated.	Significant field deployment across many V2I applications.
Objective			
Identify the actions necessary for V2I field equipment deployment.	Implement a standard action plan for V2I field equipment deployment.	Develop and mainstream standards for V2I field equipment deployment.	Institutionalized V2I field equipment deployment across many V2I applications.
General Strategy			
Deploy V2I field equipment in pilot deployment to gain experience.	Expand pilot size, add V2I applications, develop agency standards, follow national standards.	Move beyond pilots to an integrated Connected Vehicle program across priority TSMO functions.	Institutionalize Connected Vehicle program across priority TSMO functions.
Relationship to TSMO			
Many V2I applications require RSUs as currently envisioned.	Most V2I applications require RSUs as currently envisioned.	Revisions to field deployment strategy and standards due to emerging information and technology.	Institutionalized standards for field hardware/software.
Caveats			
Systems and technology deployment is heavily dependent on actions taken in other dimensions, notably business processes and collaboration.	Systems and technology deployment is heavily dependent on actions taken in other dimensions, notably business processes and collaboration.	Systems and technology deployment is heavily dependent on resources, capabilities, and industry roles.	Systems and technology deployment is heavily dependent on resources, capabilities, and industry roles.

Table 9. Capability levels for systems and technology—field dimension (continuation).

Field (RSUs, Right-of-Way, Spectrum, Site Assessment, Communications, Applications)			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Actions to Get to the Next Level			
1. Identify opportunities to participate in peer and national dialogue regarding technical specifications of field equipment.	1. Participate in peer and national dialogue regarding technical specifications of field equipment and standards development.	1. Maintain involvement in peer and industry organizations and national V2I dialogue.	1. Lead involvement in peer and industry organizations and national V2I dialogue.
2. Develop deployment approach for pilot project foot print including right-of-way, structure, power, backhaul.	2. Develop deployment approach: a. Review device footprint. b. Develop approach to securing right-of-way, structure, power, backhaul. c. Review other device requirements including interfaces to other field equipment.	2. Implement standard approach to device deployment: a. Revise approach based on lessons learned.	2. Utilize standard approach to device deployment.
3. Develop V2I pilot project use case, ConOps, system requirements, and architecture for field applications.	3. Develop detailed V2I use cases, ConOps, system requirements and architecture for field applications: a. Identify opportunities for V2I integration on existing TSMO devices, networks, and other systems. b. Understand mapping requirements for geolocation and RF site analysis.	3. Implement detailed V2I use cases, ConOps, system requirements and architecture for field applications: a. Revise due to lessons learned. b. Review opportunities to eliminate, reduce, or replace TSMO infrastructure. c. Develop and implement standard procedures for map development and RF site analysis.	3. Institutionalize V2I field deployment requirements: a. Develop and implement approach to combined TSMO and V2I infrastructure. b. Integrate map and RF site analysis in field equipment upgrades and replacements
4. Identify pilot project maintenance issues.	4. Develop approach to V2I field equipment maintenance.	4. Implement V2I maintenance and asset management approach.	4. Institutionalize V2I maintenance plan due to lessons learned.
5. Identify spectrum licensing need for pilot project.	5. License spectrum for V2I applications according to Federal practice guidelines, considering regional partnerships.	5. Expand licensed areas as appropriate; evaluate interference issues. Develop strategic approach to resolving interference.	5. Proactive approach to interference resolution and siting plan.

Table 9. Capability levels for systems and technology—field dimension (continuation).

RSUs, Right-of-Way, Spectrum, Site Assessment, Communications, Applications			
Achieving Level 1—Pilot	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Actions to Get to the Next Level (continuation)			
6. Track progress of related vehicle programs including first-mile, last-mile transit, AV bus rapid transit, AV high occupancy toll/managed lanes, transportation network companies (TNCs).	6. Study and identify synergies with automated vehicle programs including first-mile, last-mile transit, AV bus rapid transit, AV high occupancy toll/managed lanes, transportation network companies (TNCs).	6. Develop integrated strategy for V2I services with AV systems.	6. Institutionalized deployment of V2I systems with AV systems and suppliers.
7. Identify cybersecurity issues in field device deployment plans.	7. Implement cybersecurity approach for field device deployment: a. Security credential management system. b. Physical security protections.	7. Implement best practices for field device cybersecurity protections: a. Security credential management system. b. Physical security protections.	7. Systematically update cybersecurity protections.
Synergies			
Close relationship with business processes, and systems & technology—back office.	Close relationship with business processes, and systems & technology—back office.	Close relationship with business processes, and systems & technology—back office.	Close relationship with business processes, and systems & technology—back office.
Key Stakeholders			
TSMO program leadership, field device specialists, communications specialists, IT, support consultants.	TSMO program leadership, field device specialists, communications specialists, IT, support consultants.	TSMO program leadership, field device specialists, communications specialists, IT, support consultants.	TSMO program leadership, field device specialists, communications specialists, IT.

Source: U.S. Department of Transportation.

Key questions for consideration in Systems and Technology—Field

Level 1
• Are we aware of the national dialogue regarding and resources for V2I technical field specifications? • Have we identified a deployment approach for pilot equipment? • Do we have any legacy issues relevant to procurement of certain types of equipment? • Have we developed a pilot concept of operations and system requirements for field equipment? • Are there any issues with access to right-of-way? Power? Communications infrastructure? • Have we identified how the field equipment fits into our regional ITS architecture? • Have we identified spectrum licensing needs and procedures? • Have we identified how V2I pilot can integrate with other related technology programs at our agency? At peer agencies? • Have we identified issues with cybersecurity of field equipment? • Do we understand issues with RF siting and GPS/DGPS performance?
Level 2
• Are we participating in the national dialogue on V2I Technical field specifications? • Have we developed a deployment approach for pilot equipment? • Have we resolved issues with legacy equipment and procurement standards? • Have we implemented a pilot concept of operations and system requirements for field equipment? • Have we documented how the field equipment fits into our regional ITS architecture? • Have we licensed the spectrum appropriately? • Have we developed a strategy for identifying interference? • Have we developed a plan for integration of V2I with related technology programs at our agency? At peer agencies? • Have we implemented cybersecurity measures for field equipment? • Do we understand the operation of the SCMS? • Have we assessed RF siting and GPS/DGPS performance at all deployment locations? • Have we adapted necessary procurement procedures? • Have we updated vendor/supplier prequalified listings?

Level 3
• Are we contributing to the national dialogue on V2I Technical field specifications? • Have we developed a deployment approach for standardized equipment? • Have we standardized a concept of operations for field equipment? • Have we implemented the strategy and measures to resolve potential interference to the spectrum? • Have we integrated V2I with related technology programs at our agency? At peer agencies? • Have we standardized cybersecurity measures for field equipment? • Have we standardized RF siting and GPS/DGPS performance assessment procedures? • Have we implemented an equipment replacement process in anticipation of technology obsolescence cycles?

Table 10. Capability levels for systems and technology—Back Office dimension.

Back-Office (Software, Hardware, and Communications for Processing, Storage, Use, and Sharing)			
Achieving Level 1—Exploration	**Achieving Level 2— Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Relevance			
The introduction of pilot V2I applications is dependent upon application of relevant back office prototype software.	The introduction of public V2I systems is dependent upon availability of systems to process, analyze, store, and take action on V2I data.	Formalized deployment of systems in a back-office to process, store, analyses, and use V2I data.	Systematic consideration of V2I back office software across TSMO functions.
State of Play			
No systems deployed.	Pilot system(s) deployed with minor or no integration with other TSMO systems, software, or processes.	Prototype and pilot systems deployed and processing V2I data with some integration with other TSMO systems, software, and processes.	Enterprise systems deployed for processing and use of V2I data with full integration with other TSMO systems, software, and processes.
Objective			
Identify the actions and timeline necessary for piloting V2I back office systems deployment.	Identify the actions and timeline necessary for V2I central systems procurement, development, and deployment and future integration with existing and new TSMO systems, software, and processes.	Development and implementation of V2I central systems and equipment deployment integrating with existing and new TSMO systems, software, and processes.	Systematic integration of V2I central systems in TSMO systems, software, and processes.
General Strategy			
Deploy prototype V2I back office equipment in pilot deployment(s) to gain experience.	Expand V2I back office software from pilot deployment(s).	Move beyond pilots to develop an integrated V2I software strategy across priority TSMO functions.	Build out and update integrated V2I software systems as an integral component of priority TSMO functions.
Relationship to TSMO			
Pilot V2I deployments will help establish back office system requirements for integration with other TSMO systems.	Develop V2I back office software systems for processing, analysis, use, and sharing of V2I data with other TSMO systems and software.	Revisions to central systems deployment strategy and standards due to new information as it becomes available, such as through successful peer implementations at level 2.	Revisions to central systems deployment strategy and standards based on lessons learned; new functional processes based on successful peer implementations at level 3.

Table 10. Capability levels for systems and technology—back office dimension (continuation).

Back-Office (Software, Hardware, and Communications for Processing, Storage, Use, and Sharing)			
Achieving Level 1—Exploration	**Achieving Level 2— Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Caveats			
Systems and technology deployment is heavily dependent on actions taken in other dimensions, notably business processes and collaboration.	Systems and technology deployment is heavily dependent on actions taken in other dimensions, notably business processes and collaboration.	Back-office systems and technology deployment is heavily dependent on IT and software trends.	Back-office systems and technology deployment is heavily dependent on IT and software trends.
Actions to Get to the Next Level			
1. Identify opportunities for participation in peer and national dialogue regarding technical specifications of back office systems.	1. Participate in peer and national dialogue regarding technical specifications of back office systems.	1. Maintain involvement in peer and industry organizations and dialogue.	1. Maintain involvement in peer and industry organizations and dialogue.
2. Identify impacts of pilot V2I operations on TMC legacy back-office systems.	2. Identify upgrades to TMC legacy back-office systems for V2I operations (interfacing, replacement, or augmentation).	2. Complete TMC operations plan and V2I information integration with legacy back-office systems.	2. Systematic program plan for ATMS back-office upgrades utilizing V2I data and applications.

Table 10. Capability levels for systems and technology—back office dimension (continuation).

Back-Office (Software, Hardware, and Communications for Processing, Storage, Use, and Sharing)			
Achieving Level 1—Exploration	**Achieving Level 2— Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
3. Review back-office data processing, storage, and interfacing tools and technologies.	3. Plan for V2I data processing tools and technologies: a. On premise, software/platform/infrastructure as a service hardware and application deployment. b. Identify deficiencies in data sharing technology, systems, and processes necessary for holistic view of operations. c. Identify enabling regional applications. d. Identify adjacent and complementary agency partners. e. Asset management requirements. f. Software maintenance requirements.	a. Implement back-office data management plan with V2I information Develop data sharing technology, processes, and systems for sharing V2I data. b. Implement cross-jurisdictional V2I applications. c. Asset management and software maintenance plans.	3. Systematic plan to revise and adjust back-office data tools and technologies as technology advances: a. Institutionalize data sharing strategies for cross-jurisdictional V2I applications.

Table 10. Capability levels for systems and technology—Back Office dimension (continuation).

Back-Office (Software, Hardware, and Communications for Processing, Storage, Use, and Sharing)			
Achieving Level 1—Exploration	**Achieving Level 2— Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Actions to Get to the Next Level			
4. Identify decision support system needs from pilot experiences.	4. Formalize requirements for decision support system functions enabled by V2I data.	3. Implement initial decision support system(s) for V2I applications.	4. Institutionalize decision support systems across V2I applications.
5. Review needs for high-definition digital maps of RSU sites.	5. Evaluate synergy of high-definition digital regional maps with RSU site mapping requirements.	4. Develop technical approach to updating RSU site maps from master HD regional map assets	5. Implement system for updating RSU site maps, revise, and adjust as technology changes.
6. Identify issues in cybersecurity and Personally-identifiable information (PII) protections in the V2I pilot data collection, storage, and use.	6. Address issues in cybersecurity and PII protections related to V2I data collection, storage, and use.	5. Implement best practices for cybersecurity and PII protections for V2I data sets.	6. Systematically update cybersecurity protections.
Synergies			
Close relationship with systems and technology development—back office and business processes.	Close relationship with systems and technology development—field and business processes.	Close relationship with systems and technology development—field and business processes.	Close relationship with systems and technology development—field and business processes.
Key Stakeholders			
TSMO program leadership, TMC and ATMS specialists, IT, support consultants, system vendors.	TSMO program leadership, TMC and ATMS specialists, IT, support consultants, system vendors.	TSMO program leadership, TMC and ATMS specialists, IT, system vendors.	TSMO program leadership, TMC and ATMS specialists, IT, system vendors.

Source: U.S. Department of Transportation.

Key questions for consideration in Systems and Technology—Back Office:

Level 1
• Are we aware of the national dialogue on V2I back office technical specifications? • Do we have existing standards for common TSMO back office systems? If not, can we develop them? • Have we identified impacts of V2I operations on legacy systems in the TMC? Other centers? • Do we understand the role of data tools and technologies for processing, storage, and use of V2I data? • Are there any barriers or legacy requirements (OS, hardware, IT) that will impact selection of certain back office systems for V2I? • Have we articulated needs for decision support systems that may result from the outcomes of pilot deployments? • What deficiencies in current TSMO operations could be improved with V2I back office systems? • Do we understand the issues with management of high-definition maps of RSU sites? • Do we understand the issues related to cybersecurity and PII protections of V2I pilot data collection, storage, and use? • Do we understand how existing asset management systems might be utilized? • Do we need new back-office systems for asset management? • Do we understand what may be needed for back-office software maintenance? • Do we have a preferred IT procurement strategy (IaaS, PaaS, DaaS, on-premise deployment, etc.)?
Level 2
• Are we active in peer to peer sharing of V2I back office technical specifications? • Have we developed a plan to integrate V2I operations with legacy systems in the TMC? Other centers? • Are there any barriers to standardizing back office systems? • Are my IT policies and procedures adequate for V2I back office system requirements? • Do I need new processing hardware, communications, or other infrastructure and building capacity (rack space, power, etc.)? • Have we developed a plan for use of data tools and technologies for processing, storage, and use of V2I data? • Do my current vendors or in-house resources have the necessary skills and abilities to deliver back office systems for V2I? • Are my current procurement processes adequate for acquisition of evolving technologies? • Are my current staff adequate for operation of new V2I back office systems? Do they need additional training or outsourcing? • Have we developed a plan for development of decision support systems using V2I data? • Have we developed a plan for management of high-definition maps of RSU sites? • Have we implemented cybersecurity and PII protections of V2I pilot data collection, storage, and use? • Have we implemented asset management software for new V2I field devices? • Have we implemented a V2I back-office software maintenance strategy? • Have we implemented the preferred IT procurement strategy for V2I back-office software?

Level 3
• Are we formalizing V2I back office technical specifications? • Are we formalizing IT policies that accommodate potential new models for PPPs? • Have we implemented systems that integrate V2I operations with legacy systems in the TMC? Other centers? • Have we implemented data tools and technologies for processing, storage, and use of V2I data? • Have we implemented decision support systems using V2I data with other TSMO functions? • Have we implemented a strategy for management of high-definition maps of RSU sites? • Have we developed and implemented best practices for cybersecurity and PII protections of V2I pilot data collection, storage, and use? • Are we continuing to update our IT procurement, asset management, and software maintenance plans to reflect best practices?

Table 11. Capability levels for Performance Measurement dimension.

Metrics, Analytics, Evaluation, Reporting, Management			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Relevance			
The development of a performance management program is essential to evaluate pilot V2I project.	The development of a performance management program is essential to both justify and guide V2I deployment.	The development of a performance management program is essential to both measure and revise V2I deployment.	Institutionalization of performance management programs is essential for mainstreaming any TSMO programs, including V2I.
State of Play			
No specific V2I performance measures have been developed.	Approach for performance measurement and management process for V2I including related data requirements and support analytics and reporting is under development.	A V2I performance measurement system has been developed—including the necessary support resources.	V2I is fully integrated into the agencies performance measurement program—including both the performance of V2I as well as the use of V2I information regarding performance of other activities.
Objective			
To develop an understanding of performance management for V2I.	To establish the basis for benefits achieved versus the costs and risks.	To demonstrate that benefits outweigh the costs and risks.	Institutionalization of a performance based plan for management of field assets and central applications.
General Strategy			
Define the data, analytics and reporting needs for performance management.	Develop the metrics, analytics and reporting processes for performance management.	Implement the performance management process.	Institutionalize performance management as routine within agency culture.
Relationship to TSMO			
If no TSMO performance measurement approaches exist, develop them first.	Without metrics, data, analytics, and program goals for V2I are ad hoc and unsustainable.	Metrics, data, and analytics demonstrate maturity of V2I programs.	Use of metrics for program adjustments demonstrates goal-based program implementation.
Caveats			
Value of performance measurement depends on culture incentivizing utilization for management.	Value of performance measurement depends on culture incentivizing utilization for management.	Value of performance measurement depends on culture incentivizing utilization for management.	Value of performance measurement depends on culture incentivizing utilization for management.

Table 11. Capability levels for Performance Measurement dimension (continuation).

Metrics, Analytics, Evaluation, Reporting, Management			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Actions to Get to the Next Level			
1. Review agency performance measurement program and approach to meeting both MAP-21 and internal agency requirements regarding TSMO and V2I applications.	1. Review agency performance measurement program and approach to meeting both MAP-21 and internal agency requirements: a. Include V2I support of TSMO performance measures and performance measures of V2I systems.	1. Revisit agency performance measurement program and approach to meeting both MAP-21 and internal agency requirements: a. Include V2I support of TSMO performance measures and performance measures of V2I systems.	1. Institutionalize performance measurement for both capacity and operational improvements using V2I data for TSMO measures and measures of V2I performance.
2. Analyze pilot V2I applications role in providing both operational and asset management data based on probes.	2. Review priority V2I applications with respect to their role in providing both operational and asset management data based on probes: a. Identify contexts where V2I probe data may replace data collection systems based on roadway detection and surveillance infrastructure. b. Secure agreement from state DOT partners (PSAs and local governments) regarding changes involved in use of V2I data in systems operations.	2. Integrate new V2I applications for providing both operational and asset management data based on probes: a. Develop a program plan where V2I probe data may replace data collection systems based on roadway detection and surveillance infrastructure. b. Make adjustments in surveillance and detection as related to V2I probe data availability and the related roles of key stakeholders in TSMO.	2. Institutionalize the use of V2I operational and asset management data based on probes for performance assessment: a. Potential for systematic retirement of physical detection and surveillance based on sufficient probe penetration levels. b. Institutionalize adjustments in the roles of key stakeholders in TSMO regarding sources and uses of data for both real-time operations and performance improvement.

Table 11. Capability levels for Performance Measurement dimension (continuation).

Metrics, Analytics, Evaluation, Reporting, Management			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Actions to Get to the Next Level (continuation)			
3. Identify performance metrics, supporting data collection and analytics appropriate to measure effectiveness of start-up V2I applications.	3. Identify performance metrics, supporting data collection and analytics appropriate to measure effectiveness of start-up V2I applications: a. Identify data collection opportunities via V2I and related analytics that support other TSMO activities. b. Review and secure consensus with respect to use of performance data as agency policy and secure buy-in from system managers. c. Identify staffing and other costs associated with V2I-related data collection, analysis, and communication.	3. Utilize performance metrics, supporting data collection and analytics appropriate to measure and report effectiveness of V2I applications: a. Continue to identify data collection opportunities via V2I and related analytics that supports other TSMO activities and activities outside of TSMO. b. Review impact of the actual utilization of V2I-related performance measures on system management. c. Update staffing and other costs associated with V2I-related data collection, analysis and communication and search for economies.	3. Routinize accountability and remedial actions for V2I performance goal attainment: a. Routinize data collection opportunities via V2I and related analytics that supports other TSMO activities. b. Institutionalize use of real-time performance information (including provision of V2I probe data) for systems operational improvement. c. Continue to seek efficiencies and performance measurement and review benefit/cost considerations.
4. Identify V2I pilot costs and impacts tracing system and collect data.	4. Track V2I-related costs and impacts: a. Include capital operating and maintenance) and impacts (crash reduction, travel time delay, improvements in reliability). b. Develop reporting formats and dissemination strategies.	4. Develop sustainable approach to cost and impact monitoring: a. Include both in-house and outsourcing approaches. b. Report key V2I performance to all key stakeholders— internal and external.	4. Maintain sustainable approach to cost of impact monitoring: a. Review opportunities and look for efficiencies. b. Report key V2I performance to all key stakeholders—internal and external.

Table 11. Capability levels for Performance Measurement dimension (continuation).

Metrics, Analytics, Evaluation, Reporting, Management			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Synergies			
Performance management without a strong culture of performance reporting and responsibility have minimal impact.	Performance management without a strong culture of performance reporting and responsibility have minimal impact; back office tools and systems.	Performance management without a strong culture of performance reporting and responsibility have minimal impact; back office tools and systems.	Performance management without a strong culture of performance reporting and responsibility have minimal impact; back office tools and systems.
Key Stakeholders			
Connected Vehicle program managers and planning staff in real-time systems operators.	Connected Vehicle program managers, IT, back office systems specialists.	Connected Vehicle program managers, IT, back office systems specialists.	Connected Vehicle program managers, IT, back office systems specialists.

Source: U.S. Department of Transportation.

Key questions for consideration in Performance Measurement

Level 1
• Have we reviewed the MAP-21 performance measurement requirements? • Have we identified how we will use existing TSMO systems to meet MAP-21 requirements? • Have barriers to basic performance measurement needs been removed? What strategies can be identified to remove those barriers? • Have we identified how V2I data may supplement other TSMO performance measurement efforts? • Have we identified if/when V2I data collection may replace other data collection efforts? • Have we identified what V2I data could enhance certain TSMO performance measurement practices? • Have we identified what performance metrics will be used to measure V2I deployment performance? Are they realistic?
Level 2
• Have we implemented systems for meeting MAP-21 requirements? • Have we developed a plan and concept of operations for integration of V2I data with other TSMO performance measurement systems? • Do we have consensus and buy-in from stakeholders on our performance management plans? • Have we implemented performance measurement systems for V2I applications? • Have we developed a plan for staffing and other related costs of an ongoing performance measurement program? • Have we developed a plan for tracking, monitoring, and reporting impacts and costs of V2I applications? • Have we identified any use cases for V2I data outside of TSMO?
Level 3
• Have we institutionalized the use of performance measurement for V2I application assessment? • Have we implemented adjustments to V2I application deployment based on benefit-cost performance? • Have we implemented use cases for V2I data outside of TSMO? • Are we routinely reporting on V2I application performance to key stakeholders (internal and external)?

Table 12. Capability levels for Culture, and Organization and Staffing dimension.

Culture and Leadership, Organizational Structure, Staff Capacity			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Relevance			
V2I applications require changes in policy, new Connected Vehicle program institutions and appropriate organization and staff training.	V2I systems deployment requires people with organizational motivation, organizational responsibility, appropriate training and skills, and leadership.	V2I systems deployment requires people with organizational motivation, organizational responsibility, appropriate training and skills, and leadership.	V2I systems deployment requires people with organizational motivation, organizational responsibility, appropriate training and skills, and leadership.
State of Play			
No Connected Vehicle organizational structure, specific positions, nor staffing has been established.	Some Connected Vehicle organizational structure, specific positions, and staffing have been established.	An organizational concept and appropriate staffing and training for V2I has been established.	Appropriate Connected Vehicle organization and staffing are in place.
Objective			
To recognize the need for necessary changes to technical understanding, agency culture, legal protections, organization, training, and leadership to enable effective pilot V2I deployment.	To identify necessary changes to culture, organization, staff training, and leadership to enable effective V2I deployment.	To carry out necessary changes to culture, organization, training, and leadership to enable effective V2I deployment.	To continue to adjust culture, organization, training, and leadership to mainstream effective V2I.
General Strategy			
Evaluate current TSMO organization for likely fit of Connected Vehicle responsibilities.	Identify deficiencies in current organizational attributes that need improvement for effective V2I deployment.	Implement revisions to current organizational attributes for effective V2I deployment.	Institutionalize innovation in TSMO culture and align organization capabilities to deliver benefits from V2I.
Relationship to TSMO			
Formalization of TSMO staffing, capacity, and organizational structures suggested before developing similar plans for V2I.	V2I and TSMO overlap in terms of staff orientation, capacity, and organizational structure.	V2I and TSMO overlap in terms of staff orientation, capacity, and organizational structure.	V2I and TSMO fully integrated in terms of staff orientation, capacity, and organizational structure.

Table 12. Capability levels for Culture, and Organization and Staffing dimension (continuation).

Culture and Leadership, Organizational Structure, Staff Capacity			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Caveats			
Inertia of organizational structures, particularly in the public sector, can be challenging to overcome.	Efforts in TSMO organizational structural changes help smooth further modifications for V2I.	Organizational changes are typically uncomfortable; continual reorganization reduces productivity.	Leadership vision needs empowered and capable staff.
Actions to Get to the Next Level			
1. Identify staff champions for V2I.	1. Identify and support staff champions for V2I.	1. Expand, support and reward champions with authority, budgets, and staff to direct initial deployment programs.	1. Spread championship throughout agency — V2I is embedded inherently in TSMO.
2. Identify Connected Vehicle organizational structure issues: a. Review pilot experience. b. Review experience in peer jurisdictions. c. Align with agency priorities.	2. Identify organizational structure issues: a. Identify needs for clear roles and relationships, coordination among units involved with V2I pilot application, equipment, and functions in initial deployment. b. Identify issues associated with reporting and accountability regarding agency vertical hierarchy layers and representation of TSMO in V2I issues at policy and resource allocation level.	2. Reorganize as appropriate to reduce stove-piping and authority conflicts: a. Provide clear authority/responsibility for additional applications regarding V2I applications, equipment, and functions. b. Modify reporting and accountability relationships so that appropriate representation at agency policy and resource allocation level is ensured.	2. Evolve and update organizational structure: a. Maintain clear relationships among all collaborative partners of responsibilities for V2I applications, equipment, and TSMO functions appropriate for expanding program. b. Continue to evolve reporting and accountability relationships for maximum effectiveness

Table 12. Capability levels for Culture, and Organization and Staffing dimension (continuation).

Culture and Leadership, Organizational Structure, Staff Capacity			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Actions to Get to the Next Level (continuation)			
3. Review core capacity KSAs needs for V2I specialty areas, such as systems engineering, data management, communication, software/hardware.	3. Review core capacity KSAs needs and job specs needs for V2I specialty areas, such as systems engineering, data management, communication, software/hardware versus internal staff availability: a. Identify training needs for core capacity positions. b. Review career development opportunities for Connected Vehicle core capacity positions and posture regarding recruitment and retention. c. Review tradeoffs for in-house core staff capacity building versus outsourcing. d. Establish agency participation in national V2I and TSMO technical and professional development organizations.	3. Develop position descriptions for key Connected Vehicle core staff capacity positions and review recruitment needs, including peer co-development (note that *new* positions need not be developed specifically for V2I responsibilities; existing position descriptions may be augmented or modified): a. Access training resources and develop managed training program. b. Develop program for retention of key staff, including professional development, advancement opportunities, rewards. c. As appropriate, undertake outsourcing and public-private partnerships in conjunction with development of appropriate outsourcing management procedures and approaches. d. Maintain agency participation in national V2I and TSMO technical and professional development organizations.	3. Establish sustainable process to adjust roles consistent with operations experience: a. Institutionalize training for existing and new staff. b. Develop retention and succession plans, including professional development, advancement opportunities, rewards. c. Continue to evolve efficient outsourcing and public-private partnerships is appropriate. d. Continue agency participation in national V2I until a technical and professional positions.

Table 12. Capability levels for Culture, and Organization and Staffing dimension (continuation).

Culture and Leadership, Organizational Structure, Staff Capacity			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 4—Mainstreamed**
Actions to Get to the Next Level (continuation)			
4. Create stakeholder/decision-maker outreach/communications plan to foster understanding of V2I business case within agency, policy-makers, and the public.	4. Create stakeholder/decision-maker outreach/communications plan to foster understanding of V2I business case within agency, policy-makers, and the public.	4. Conduct stakeholder outreach program to foster understanding of business case within agency, policy-makers, and the public.	4. Institutionalize communications of business case and progress updates.
5. Evaluated need for changes needed in agency in values and priorities and culture regarding fostering innovation and embracing technology.	5. Identify changes needed in agency in values and priorities and culture regarding fostering innovation and embracing technology.	5. Implement changes (policy, staff empowerment, reduction of ‘‘red tape’’) that foster innovation and embracing technology.	5. Revise cultural approaches (policy, staff empowerment, reduction of ‘‘red tape’’) that continue the ability of the agency to deliver innovation faster.
Synergies			
Performance measurement; business processes; collaboration.	Performance measurement; business processes; collaboration.	Performance measurement; business processes; collaboration.	Performance measurement; business processes; collaboration.
Key Stakeholders			
Connected Vehicle program managers, TSMO program managers, management.	Connected Vehicle program managers, TSMO program managers, management.	Connected Vehicle program managers, TSMO program managers, management.	Connected Vehicle program managers, TSMO program managers, management.

Source: U.S. Department of Transportation.

Key questions for consideration in Culture, Organization, and Staffing:

Level 1
• Do we have a champion for a Connected Vehicles program? • Is this champion in our organization? • Does our organization embrace technology and innovation? Is there a commitment from leadership to advance technology? • Are there tangible steps to take to promote a culture that embraces technology? • What groups or divisions will have primary involvement in deploying, operating, or maintaining V2I infrastructure? • What basic skills are needed, and does our staff have these skills? • What specific technical areas do we have that can support V2I? - System engineering - Design - Deployment/Integration - Data management - Operations - Maintenance - Analytics • Is there flexibility to acquire agency staff with these skill sets (i.e., redefine roles, expand technical staff groups)? • Do we have a mechanism to obtain these skills if they cannot be addressed by current staff or roles (i.e., contract/outsource, training) • Are there any operational or policy limitations on our agency deploying V2I? • Are we active in national V2I and TSMO organizations (or activities) where we are hearing about peer agency programs and experiences, national trends, and emerging technologies? • Are there any barriers to participating in these national activities?

Level 2

- Is there momentum with agency leadership to continue to expand and advance V2I capabilities?
- Are champions at a level to make decisions and commitments to continue to advance V2I?
- Do champions have the necessary budgets and resources to implement actions on the Connected Vehicle program plan?
- Are staff empowered to make suggestions or do they have a level of decision-making authority to be able to continue to expand V2I capabilities?
- Are there barriers to core group coordination to advance V2I? Is there strong justification for realigning internal reporting/organization to promote better collaboration?
- Is there support to modify core staff descriptions to integrate specific V2I and technology requirements?
- Can agency positions be added or expanded to meet known V2I technology requirements?
  - System engineering
  - Design
  - Deployment/Integration
  - Data management
  - Operations
  - Maintenance
  - Analytics
- Are there related positions within the agency that could be transitioned to focus on V2I?
- Are there retention challenges with highly trained staff? Can positions/compensation/ requirements and career path be adjusted to meet the needs of this technical staff?
- Can supplementing resources (outsourcing) be sustained to allow for continued V2I integration and expansion?
- Are there innovative P3 arrangements that can be explored and put in to place? Are there any barriers to P3 for V2I at the agency?
- Is there a commitment to continued outreach to support awareness of V2I benefits to agency leadership, regional decision-makers, and the public?
- Can internal training programs be expanded to include V2I capabilities and technical training?
- Are there internal barriers to continued implementation, integration, and expansion of V2I capabilities?

Level 3

- Are our training programs continually improved and revised based on performance data?
- Is V2I accepted as a core element of our agency mission based on performance results?
- Is our organizational structure and staffing continually evaluated based on effectiveness?
- Is the agency working to remove or reduce barriers to organizational and procedural efficiency—and to prevent new barriers from developing?
- Are compensation and benefits of agency staff continually revised commensurate with responsibilities to ensure retention?

Table 13. Capability levels for Collaboration Dimension.

Public and Private Partnerships and Peer Agency Relationships			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 3—Mainstreamed**
Relevance			
V2I systems deployment and operations involves a range of stakeholders—both public and private.	V2I systems deployment and operations involves a range of stakeholders—both public and private, and significant synergy between peer and complementary agencies.	V2I systems deployment and operations involves a range of stakeholders—both public and private, and significant synergy between peer and complementary agencies.	V2I systems deployment and operations involves a range of stakeholders—both public and private, and significant synergy between peer and complementary agencies.
State of Play			
Key participants are not involved in V2I-specific collaboration.	Some stakeholders are involved in V2I-specific collaboration.	Formal collaboration roles and responsibilities for V2I has been established.	Regular collaboration is fully established and improving on a continuing basis
Objective			
Identify the critical roles of and relations among key V2I systems deployment stakeholders.	To identify the critical roles of and relations among key V2I systems deployment and operations stakeholders.	To establish the critical roles and relationships to V2I systems deployment and operations stakeholders.	To institutionalize the critical roles of and relations among key V2I systems deployment and operations stakeholders.
General Strategy			
Identify roles and requirements and discuss the concept of operations with potential participants.	Identify how collaborative approaches can be embedded directly into V2I deployment strategies.	Implement procedures and protocols among key stakeholders in V2I implementation.	Institutionalize roles, procedures, and protocols among key stakeholders in continuing V2I implementation, expand to other regional partners.
Relationship to TSMO			
Key collaborators in TSMO are substantially the same as in V2I, with an increasing potential role for private sector stakeholders.	Key collaborators in TSMO are substantially the same as in V2I, with an increasing potential role for private sector stakeholders.	Collaboration strategies for V2I influence collaboration strategies for broader TSMO activities.	Collaboration in V2I and TSMO becomes synonymous.

Table 13. Capability levels for Collaboration Dimension (continuation).

Public and Private Partnerships and Peer Agency Relationships			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 3—Mainstreamed**
Caveats			
Effective V2I requires consideration of new and changed roles.	New and changed roles are tested in V2I implementation.	New and changed roles for collaborators are revised due to experiences.	Roles and responsibilities are appropriate for all stakeholders and collaboration is implicit.
Actions to Get to the Next Level			
1. Identify key participants in V2I applications—public and private.	1. Develop consensus among key public-sector stakeholders to align objectives, and performance measures of achievement (see performance management).	1. Implement collaborative approaches to V2I applications deployment.	1. Institutionalize collaborative approaches to V2I applications deployment and expand incrementally to additional partner agencies.
2. Review ConOps associated with pilot V2I applications experience regarding roles and responsibilities.	2. Review ConOps associated with pilot V2I applications: a. Review regarding roles and responsibilities of key public sector stakeholders (see systems engineering dimension). b. Identify needs for changes in roles and responsibilities—and impact on public-sector collaborators resources and physical capacity regarding pilot V2I applications.	2. Update ConOps and related roles and responsibilities: a. Revise responsibilities of key partners as new applications are added. b. Formalize roles and relationships via memorandum of understanding and stakeholders agreements.	2. Update ConOps and related roles and responsibilities: a. Revise responsibilities of key partners as new applications are added. b. Review Opportunities for potential reallocation/reconfiguration of interagency roles and responsibilities for life-cycle efficient TSMO.

Table 13. Capability levels for Collaboration Dimension (continuation).

Public and Private Partnerships and Peer Agency Relationships			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 3—Mainstreamed**
Actions to Get to the Next Level (continuation)			
3. Review opportunities for multijurisdictional peer cooperation (including multistate) regarding all key aspects of V2I applications development (systems, business processes, performance).	3. Review opportunities for multijurisdictional peer cooperation (including multistate and multi region) regarding all key aspects of V2I applications development (systems, business processes, performance): a. Identify necessity or opportunities resource sharing among key stakeholders as related to right-of-way, device deployment, and continuing operational responsibilities. b. Identify potential common core staffing needs for critical KSA-related workforce training among partners in V2I and TSMO applications.	3. Maximize peer collaboration regarding common priority applications, use cases, standards, interoperability among partners locally and with peers outside state: a. Develop resource sharing agreements as appropriate regarding technical, financial and staff resource to generate required resources and minimize duplication. b. Establish workforce co-training program for key staff positions across jurisdictions.	3. Develop formal mechanism to maintain commonality regarding applications, use cases standards interoperability among local and peer partners: a. Review and modify resource sharing agreements on a continuing basis as appropriate. b. Formalize sustainable co-training program within jurisdictions and through peer relationships with other jurisdictions.

Table 13. Capability levels for Collaboration Dimension (continuation).

Public and Private Partnerships and Peer Agency Relationships			
Achieving Level 1—Exploration	**Achieving Level 2—Initiated**	**Achieving Level 3—Integrated**	**Achieving Level 3—Mainstreamed**
Actions to Get to the Next Level (continuation)			
4. Identify opportunities to engage in dialogue with private-sector technology and service: a. Review with relation to specific applications. b. Review peer experience.	4. Identify opportunities to engage in dialogue with private-sector technology and service providers regarding state of the practice: a. Identify potential role of private-sector technology and service suppliers and business models regarding pilot V2I applications, including tradeoffs regarding in-house versus outsourcing. b. Conduct preliminary discussions private-sector entities regarding roles in V2I applications development and services delivery.	4. Develop approaches for regular and sustainable relationships with private-sector technology and service providers state-of-the-practice and partnership opportunities: a. Develop PPP mechanisms as appropriate, including procurement, contracting, performance management, and resource-sharing. b. Execute PPP contracts as appropriate.	4. Mainstream regular and sustainable relationships with private-sector technology and service providers state-of-the-practice and partnership opportunities: a. Evaluate and modify PPP mechanisms as appropriate for maximum efficiency. b. Execute PPP contracts as appropriate.
Synergies			
Collaboration requires consensus regarding performance objectives and coordinated staff training.	Collaboration requires consensus regarding performance objectives and coordinated staff training	Collaboration requires consensus regarding performance objectives and coordinated staff training.	Collaboration requires consensus regarding performance objectives and coordinated staff training.
Key Stakeholders			
Connected Vehicle program managers at peer and complementary agencies, private sector vendor representatives, TSMO program managers, technical staff.	Connected Vehicle program managers, TSMO program managers, management, technical staff.	Connected Vehicle program managers, TSMO program managers, management, technical staff.	Connected Vehicle program managers, TSMO program managers, management, technical staff.

Source: U.S. Department of Transportation.

Key questions for consideration in Collaboration:

Level 1
• Is there regional interest or established goals that will be achieved through V2I? Are multiple agencies interested in advancing V2I capabilities? • Have potential roles and responsibilities been identified for implementing or piloting V2I capabilities? • Is there a forum for partner agencies to collaborate / discuss / obtain consensus on potential V2I applications? • Are there opportunities to leverage existing processes among agencies (business processes, planning, procurement, system engineering, and operations) to initiate V2I capabilities? • Do some partner agencies have fewer barriers to certain processes? How might this influence planning? • Are there regional processes that would need to be factored in to piloting V2I capabilities (i.e., Transportation Improvement Plan, programming cycles, and flexibility to fund near-term improvements)? • Are there partner agencies with staff who have skill sets that would align with V2I capabilities? • How aligned are partner agency missions with regard to TSMO and V2I? Is there a consistent interest and leadership support among partner agencies? • How involved is the private sector in different TSMO initiatives? Are there barriers to engaging the private sector in some capacity as part of a V2I pilot? What are those barriers?
Level 2
• Has a Concept of Operations identified potential changes in agency or partner roles as a result of V2I capabilities? • Are there established relationships among partner agencies for other TSMO initiatives that V2I can leverage? Are these formal relationships (agreements) or informal relationships (volunteer collaborators)? • Do partner agencies already share resources (staff, project, funding) to advance other TSMO initiatives? • Can existing PPPs be leveraged? • Can future project development/programming cycles be leveraged for continued implementation and expanded V2I capabilities?
Level 3
• Can collaborative implementation be sustained? - Are roles clearly defined, and is there a process for changing roles as the region or partnership gains experience? - Is there a process for adding new public or private partners? - Are these roles institutionalized (part of standard operating procedures, formalized in an agreement, and understood by leadership)? • Are there opportunities to share knowledge/lessons learned among partner agencies? • Can training programs be developed and implemented across multiple agencies? • Can formal resource sharing agreements be developed to allow technical, financial and staff resources to better collaborate? • Can public-private partnerships be expanded with distinct roles for public and private partners? Will procurement be the responsibility of one agency or a consortium?

Chapter 6. Benefits of Having and Risks of Not Having Capabilities for Vehicle-to-Infrastructure Applications

Vehicle-to-Infrastructure (V2I) applications are expected to have a range of user and agency benefits. However, the benefits cannot be captured unless the applications are effectively implemented. Transportation Systems Management and Operations (TSMO) research and experience has demonstrated that effectiveness is closely related to capabilities in the Capability Maturity Framework (CMF) dimensions. Therefore, the general risk associated with lack of key Connected Vehicle (CV) Capability maturity Model (CMM) capabilities is loss of much of the potential user benefits. Conversely, the general benefit of developing V2I capabilities is capturing the full potential of benefits to the users of the transportation system.

Specific benefits for travelers include increased safety at intersections and on roadways, proactive notifications to travelers, and enhanced situational information to users of the road network. Benefits to agencies include the ability for V2I data to fill data gaps agencies have today, enhance notifications of hazards or impacts to the road, and support for regional traffic management strategies. Many of these benefits are directly related to the degree of market penetration of vehicles equipped with CV capabilities, as well as the level of agency deployment of Dedicated Short Range Communications (DSRC) Roadside Unit (RSU) infrastructure.

When considering benefits/risks of having (or not having) capabilities to support V2I, it is important to understand the relationship to broader agency TSMO objectives. For example, regions or agencies that are focused on improving traffic incident management (TIM) will see V2I capabilities as a complement to the coordination, improved procedures, and existing incident data exchanges among responders that might have already been implemented. There will likely be an increased level of support to advance capabilities for TIM through additional program elements such as V2I, which could translate into resource commitment to maintain DSRC RSU infrastructure, support for expanding data sharing relationships, and recognition of the impact on TIM performance measures.

This section discusses the benefits of having these capabilities as well as the risks of not having agency capabilities for V2I.

6.1 Benefits of Vehicle-to-Infrastructure Applications

User Benefits

While there is little empirical data to date, example benefits of V2I are expected to demonstrate improvements to:

- **Safety—**individual traveler safety as well as safety at intersections and on corridors. These applications are being designed to supplement or replace driver reaction time to hazards, thereby reducing crashes, reducing the potential for secondary crashes, and supporting agency analytics for high-crash locations.
- **Mobility—**real-time system management based on traffic strategies that adapt to current conditions, enhanced data to inform agency strategy implementation, corridor and regional benefits, reduced delay, improved signal operations (intersections and meters) enabled by real-time volumes/trajectories and vehicle classification.
- **Environmental benefits—**improved agency monitoring of environmental conditions, improved decision-making capabilities for agencies to mitigate environmental impacts of delay, reduced delay for individual travelers based on enhanced information of route options and alternatives.

6.2 Agency Benefits

Agencies will see benefits of improved safety and mobility of the system as a whole. Reducing crashes, reducing crash severity, and reducing the potential for secondary crashes has significant benefit on safety and mobility, as well as on agency resources (transportation, law enforcement and other TIM responders). An additional benefit to agencies is that V2I data will serve as an important data source to support improved agency decision-making and system analysis. V2I data will support enhanced analytics of intersection and corridor operations, allow for improved safety analysis capabilities as well as inform real-time operations strategies for systems that require operator intervention. Over time as penetration levels rise, V2I data may obviate the need for some assets for traffic detection and surveillance.

From an environmental perspective, V2I capabilities are expected to help reduce environmental impacts of delay by reducing delay at intersections, on freeway entrance ramps, and by mitigating delay due to recurring and nonrecurring congestion. Environmental monitoring applications are intended to provide broader monitoring capabilities of vehicle emissions, helping to identify areas that are posing a high level of environmental risk. V2I data can support this level of monitoring and compliance, and can provide this information to agencies for real-time reporting.

V2I has the potential for benefits across a range of TSMO applications providing there is a sufficient density of RSU deployment and an appropriate level of market penetration of equipped vehicles. Traveler benefits cited in these TSMO areas will largely be limited to travelers in equipped CV. TSMO benefits include:

- **Traffic Incident Management—**V2I data can support decisions for dynamic strategy implementation for metering, traffic signal control, and active applications (such as variable speeds and lane management). There is the potential to address current gaps in incident detection and verification for corridors that are not instrumented with agency infrastructure, such as arterials or highways outside of traditional freeway management system infrastructure coverage. This can improve response to incidents by providing more granular and real-time data on impacts, help inform agency response resource needs, and address an

important gap of notifying of 'all clear' when response is complete and the road network is restored to prior traffic flow. Data can support post-incident debriefings for improved response strategies for future incidents. For travelers, V2I data can provide trajectory specific information about incidents ahead, impacts, restrictions, delay and potentially support dynamic alternate routing.

- **Work Zones—**V2I applications and data can help to adjust traffic management strategies based on actual active work zone conditions and restrictions. V2I capabilities can support analysis of work zone safety and operations, as well as provide travelers with advanced warning of actual conditions. Most messages provided to travelers are static (work zone ahead, expect delays), even when using technologies like dynamic message signs. V2I can tailor information provided to agencies and alerts to travelers based on real-time work zone conditions.
- **Planned Special Events—**For Planned Special Events, V2I applications can provide information to travelers during ingress, and also provide information to non-event travelers in the surrounding area. V2I data can support route guidance to parking areas, alert travelers of lane restrictions and provide alerts on speeds approaching the event ingress area. For egress, V2I applications can support traveler notifications for appropriate egress routes. Data can be used by agencies to analyze event traffic management strategies, parking operations, and inform future strategies. This data can address an important gap of limited data available on arterials near major event locations.
- **Road Weather Management—**Many agencies use environmental sensor stations to obtain information about road weather conditions, weather impacts on roads (ice, rain, fog), and use this information to inform weather response strategies and resource needs. Agencies will issue broad notifications to travelers using dynamic message signs, highway advisory radio, media alerts, social media, 511, and other tools. V2I data can enhance this information by providing location-specific pavement conditions information, helping agencies to precisely identify hazardous locations as well as rapidly changing road weather conditions. This will help to supplement current forecast data as well as data from environmental sensors. V2I data can supplement data where environmental sensors are not deployed, such as on arterials and at intersections, and can inform changes to traffic signal control to respond to current weather conditions.

6.3 Benefits of Having Vehicle-to-Infrastructure Capabilities

The deployment of V2I applications alone without the related capabilities to fully capitalize on them is not likely to realize expected benefits. Capabilities refer to those agency processes, collaborative operations processes, and how agencies use the V2I data to inform operations and improve system performance. Capabilities demonstrate a commitment to elevating operations, and that commitment translates into several key dimensions, including:

- **Business Processes—**integrating V2I applications into corridor plans, planning for data processing enhancements and programming for RSU infrastructure installation with or without other corridor improvements. It also includes planning and funding allocation for RSU and data processing maintenance needs.
- **Systems and Technology (Field)**—V2I field equipment, when significant numbers of equipped vehicles are available, can reduce or eliminate the need for other types of detection and monitoring systems, such as loops. A key benefit is the ability to gather data on networks not typically instrumented by agency detection systems, such as arterials or highways outside of freeway management system boundaries. V2I field equipment provides the opportunity for applications and services that TSMO agencies could not provide before.

- **Systems and Technology (Back Office)—**V2I data can improve a wide range of TSMO functions by integration of the data with legacy systems. Back-office software for processing, storage, and interfacing will be required to enable enhancements to existing and new TSMO functions. Agencies will gain new experience with advanced software tools for managing large and fast data sets as V2I data presents orders of magnitude more information to the TMC then available ever before.
- **Performance Management—**V2I data will provide for a robust data set to support a range of TSMO and regional performance metrics. Real-time data can support rapid strategy assessment and implementation, rather than after-action reviews of what happened using data that is not currently transmitted live or live data that is not currently used. Automation strategies for system responses to real-time data can be implemented on a broader scale than today.
- **Culture, and Organization & Staffing—**This includes training for staff on new technologies, training for operators on how to interpret and use the V2I data, and acquiring staff skill sets for appropriate levels of data analysis. Data storage will need to be upgraded and adequately sized for real-time and archived use. It will require updates to maintenance staff processes for maintaining RSU equipment and communications connections.
- **Collaboration—**V2I data has the potential to support one or many transportation agency operations. It could require agencies to collaborate on strategies for V2I data sharing and use, as well as require internal collaboration (such as with Information Technology departments and policies). Internal collaboration also can benefit planning groups (and modeling functions) by providing a robust data archive.

The specific capabilities in each of the key dimensions requires specific managed changes. There will be changes needed to acquire staff skill sets for advanced data processing and management, and current funding and programming processes will need to be modified, in many instances, to be able to adapt to the needs for equipment installation, integration, and maintenance. Updates to key agency management activities, including advanced traffic management systems, traveler information systems, and data processing and management systems will be needed to maximize the benefits of V2I. Other infrastructure, such as communications networks and controllers, will need to be assessed and potentially upgraded. All of these changes require specific capabilities across the CMM dimensions—many of which will have to be developed beyond their current level.

Table 14 provides a summary of potential benefits and risks of having V2I capabilities across a range of applications.

Table 14. Key benefits of having and risks of not having Vehicle-to-Infrastructure capabilities.

Business Process, Organization and Staffing	Mobility, Safety, and Environmental	Other
Traffic Incident Management		
Benefits		
Rapid identification and impact assessment	Incremental improvements to existing methods	Addresses gap of incident clearance notifications
Rapid dissemination via RSUs	Addresses data gaps in areas not instrumented with monitoring/ detection	
Improved responder notifications and resource allocation based on response needs	Improved information about evolving scene clearance and surrounding traffic	
Risks		
New processes needed for augmenting existing procedures with V2I data	Limited data availability outside of agency instrumented areas	Potential for limited use of data by non-transportation TIM partners
Roadway Hazard Warning		
Benefits		
Rapid identification and impact assessment	Reduction in crashes and secondary crashes, resulting in incremental improvements to other metrics	Addresses gap of notifications in non-instrumented areas
Rapid dissemination via RSUs	Improved traveler awareness of upcoming hazards	
	Reduction in crashes and secondary crashes, resulting in incremental improvements to other metrics	
Risks		
Wholly new business processes required	Safety benefits depend on traveler compliance	Faulty reporting reduces consumer confidence
Need for filters and thresholds to address multiple notifications	Lack of advanced warning of road hazards	
Speed Warning		
Benefits		
Rapid identification and warning of unsafe speed	Reduction in crashes, resulting in incremental improvements to other metrics	Measure compliance of speed warning information
Vehicle-specific and targeted	Proactive notifications to travelers of excess speed	
Inform agency of recurring speed issues at specific locations	Benefits depend on driver compliance	
Share data between transportation and enforcement agencies		
Risks		
Wholly new business processes required	Safety benefits depend on traveler compliance	Faulty reporting reduces consumer confidence

Table 14. Key benefits of having and risks of not having Vehicle-to-Infrastructure capabilities (continuation).

Business Process, Organization and Staffing	Mobility, Safety, and Environmental	Other
Intersection Collision Avoidance		
Benefits		
Ability to improve safety at intersections	Benefits proportional to deployment	Can support analysis of high risk intersections
	Can support prevention rather than just enforcement	
	Collision Avoidance can be deployed at sensitive locations (school zones, work zones)	
Risks		
Wholly new business processes required	Requires equipped vehicles and two-way communication to enable crash prevention	Faulty reporting reduces consumer confidence
	Enhanced capabilities (left turn and crossing) require high level of penetration	
Signal Control and Status Dissemination		
Benefits		
At low penetrations, can be used to fine tune timing plans	Benefits proportional to deployment	Visibility of TSMO to the public
At high penetrations, can be used for real-time control		
Risks		
New processes needed for augmenting existing procedures with V2I data	Real-time decision-making and control requires higher penetration	Agency detector systems still required to supplement low penetration rate
Staff time to adjust signal timing is required for non-adaptive systems		
Probe Data Collection		
Benefits		
BSMs and PDMs used to estimate traffic flows on the network	Benefits proportional to probe data availability and quality	Visibility of TSMO to the public
Reduced need for operating and maintaining agency monitoring and detector infrastructure	Improved coverage of traffic flow conditions, addressing current gaps in coverage for arterials and non-urban highways	
	Supports predictive traffic flow information	

Table 14. Key benefits of having and risks of not having Vehicle-to-Infrastructure capabilities (continuation).

Business Process, Organization and Staffing	Mobility, Safety, and Environmental	Other
Probe Data Collection		
Risks		
Current systems need to be configured to use probe data	Time critical applications require a fast data processing rate	Need a sustaining funding source if procuring from a third party
Policy change might be needed for agency to procure data		
Data processing standards needed to enable data sharing among agencies		
Metering		
Benefits		
At low penetrations, can be used to fine tune metering parameters	Incremental improvements to systemwide metrics above existing methods	Improved acceptance of ramp metering by local agencies
At high penetrations, can be used for real-time control	Real-time queue information can inform metering rates and reduce delay on ramps	
	Metering rates can reflect vehicle types (commercial vehicle, bus)	
	Enable corridor-wide coordination	
Risks		
Requires staff training for monitoring ramp operations	None identified	None identified
Lane Management		
Benefits		
At low penetrations, can be used for feedback to ATMS	Benefits proportional to deployment	Data can support bottleneck analysis
At high penetrations, can be used for lane control	Can support active traffic management applications, including work zones, dynamic lane operations	
Can limit the need for agency detection infrastructure and associated maintenance	Can provide end of queue warning	
	Supports freeway arterial coordination and diversion strategies	
	Reduce bottlenecking by providing proactive lane assignment and management	
Risks		
Will require RSU deployment on adjacent arterials to support freeway traffic rerouting	Requires sufficient density of RSUs to enable some functions (queue warning)	Faulty information or instructions reduces consumer confidence

Table 14. Key benefits of having and risks of not having Vehicle-to-Infrastructure capabilities (continuation).

Business Process, Organization and Staffing	Mobility, Safety, and Environmental	Other
Electronic Payments		
Benefits		
Can be used in lieu of transponders for toll payments	Benefits proportional to deployment	Can inform road pricing strategies
Can be used to pay for parking or for road-user charging		
Risks		
Fee collection requires a high penetration rate of equipped vehicles and high density of RSUs	None identified	Proven systems and technologies already exist
		Need to maintain parallel systems until there is a sufficient CV penetration rate
Traffic Information		
Benefits		
Can be used for targeted traveler information based on vehicle location and trajectory relative to incidents and hazards	More precise information specific to traveler's location and trajectory	Can inform traveler decision-making
Private sector could support part or all of the traveler information system	Support for dynamic routing	
	Proactive advanced warning of specific hazards	
	Can support regional coordination of traffic information	
Risks		
Transition from current systems (dynamic signs, detection) will be long	Some traffic information is not time-critical (advanced notice of work zones); critical information can be addressed through other systems (intersection collision avoidance, lane management)	Regional coordination strategies require multiple agencies deploying RSU equipment
Agency strategy could be redundant to capabilities from OEMs		

Table 14. Key benefits of having and risks of not having Vehicle-to-Infrastructure capabilities (continuation).

Business Process, Organization and Staffing	Mobility, Safety, and Environmental	Other
Emissions Management		
Benefits		
Even at low penetration, mobile emissions testing can provide better air quality data over a region and targeted emissions enforcement	New capability for regional air quality assessment	Can support multiple agency objectives (state and local environmental compliance agencies)
Support for regulatory compliance	Supports proactive response to regional air quality issues	
Real-time data vs. latent updates		
Risks		
Environmental information and impacts not integrated with operations	Agency response to environmental hazardous conditions is not timely	Competitive nature of future funding opportunities
Weather Management		
Benefits		
Can be used to supplement ESS and current forecasting capabilities for wide area road weather monitoring	New capability for micro-weather assessment; reduction in crashes; improvement to systemwide mobility metrics through rerouting and departure time management	Visibility of TSMO to the public
Dynamic updates based on changing conditions		
Improved response staff resource allocation		
Risks		
Weather data and information is limited to specific groups	Limited specific alerts provided to travelers—focus on general weather hazard alerts	Lack of feature reduces consumer confidence
Staffing and resources allocated on a reactive basis	Specific safety risks not communicated to travelers	

Table 14. Key benefits of having and risks of not having Vehicle-to-Infrastructure capabilities (continuation).

Business Process, Organization and Staffing	Mobility, Safety, and Environmental	Other
Asset Management		
Benefits		
Pavement condition monitoring is a substantial cost to agencies and could be supplemented from vehicle data	Higher degree of infrastructure reliability and good repair	Other uses in complementary departments outside of TSMO
Improved information for agency planning and programming for maintenance and asset lifecycles	Mitigate risks to travelers of infrastructure failures	
Risks		
Risk of slow rate of change and adoption by non-TSMO groups	No enhanced capabilities provide little safety benefit to travelers	Inefficient use of public funds
Competing processes already established for some asset and infrastructure monitoring	Impact for increased delay as a result of major asset replacement rather than proactive repairs	
Not expected to reduce maintenance resource needs, but will redirect (preventive vs. reactive)		
Parking Management		
Benefits		
At high penetrations, parking availability will enable better utilization of parking spaces and better real-time information	Improved parking guidance to specific locations	Potential for data sharing between parking operations and road network operations
Improve planning for parking operations and management strategies	Improved parking availability information	
	CVO applications could provide enhanced information to trucks about available parking and locations	
Risks		
Requires a high penetration rate for equipped vehicles	Increased delay due to cars (and trucks) looking for available parking	Potential for conflicts with public/private data sharing about parking availability (private entities not wanting to indicate no parking)
	Safety issues with trucks parking in unsafe locations (ramps)	

Table 14. Key benefits of having and risks of not having Vehicle-to-Infrastructure capabilities (continuation).

Business Process, Organization and Staffing	Mobility, Safety, and Environmental	Other
Performance Measure		
Benefits		
Even at low penetrations, a sample of vehicle data can supplement traditional sources to measure performance	Improved performance reporting and real-time use of performance data	Improved alignment across multiple groups/agencies performance reporting
Can provide performance data from a wider sample of the network (roads not currently instrumented)	Improved environmental compliance reporting	
	Real-time response to safety issues on the road network	
Risks		
Performance measures not consistent or available	No changes to traffic management strategies in response to actual conditions	Wasted public funds
Static measures providing after-the-fact data rather than real-time performance information	Improvements to safety and mobility are slow	

Source: U.S. Department of Transportation.

6.4 Risks of Not Having Vehicle-to-Infrastructure Capabilities

There are several different types of risks associated with the absence of needed capabilities or the deployment of fewer V2I assets and functions due to limited funding, program maturity, or other shortcomings of connected vehicle program planning. The most basic risk is the foregone opportunities to capitalize on the potential payoffs as described in the benefits section. Additional risks associated with not having each capability include:

- **Program inefficiencies and cost overruns—**V2I can help to promote efficiency and cost management. RSUs can replace current costly (and aging) detection systems, V2I data can be used by multiple groups (TSMO, Planning, Maintenance), and can help to inform better resource allocation.
- **Tort Liability—**There is a risk in localized and regional strategies for the potential of implied cause of incidents. Crash-focused applications require split-second data transmission rates between vehicles and infrastructure. Equipment malfunctions, data latency, or other risks could raise issues of liability.
- **Failure of local V2I to coordinate with national technical standards and OEM activities—**For V2I to be effective, vehicles need to interact with systems that are standard from one corridor or one region to the next. To mitigate this risk, deploying agencies need to insist on and use national technical standards.
- **Lack of authority to utilize probe data or profit from its use—**Some agencies today do not have legal authority to purchase and use probe data. Similarly, some probe data procurement agreements limit the ability of an agency to use data for certain functions or to share data. Similar issues and risks could be encountered with V2I data.
- **Lack of financial sustainability of effort (inefficient investment)—**There needs to be a commitment to operating and maintaining the field equipment, updating field equipment enablers (such as communications and controllers), as well as a financial and resource equipment to implement the necessary data processing and management capabilities. Current traffic management and control software and systems also will need to be modified to enable enhanced V2I capabilities. Without support and financial commitment to the unique needs of V2I capabilities, initial investments will not yield the desired benefits
- **Difficulty in attracting, training, retaining needed technical staff capabilities—** Operations and analysis in a V2I environment will require different skill sets from staff. There will be an increased emphasis on data processing, management, and analytics, which does not fit with traditional agency civil engineering requirements. Often, these skill sets are in demand across various sectors, so competition will be challenging. Training materials are not yet available for these systems, and will need to be developed in order to provide specific training to staff. Retaining trained staff in these specialized fields also poses a risk.
- **Union and civil service issues regarding staffing, position descriptions, compensation, and working hours—**Many transportation agencies use union staff for specific positions. Any modifications to skill set requirements, staff position descriptions or compensation could risk opposition from unions. There will need to be an elevated level of coordination to address these potential risks.
- **The need to execute legal agreements with other public or private entities—**Many collaborative agreements are already in place among transportation agencies and between transportation agencies and the private sector. Current private sector agreements and contracts include supporting certain TSMO functions (traffic management center operations, system maintenance), data, systems engineering, and traveler information among others.

Among public agencies, there are mutual aid agreements, shared operations agreements, data sharing and use agreements, and others. V2I introduces a new level of real-time data, higher quantities of data, and more specific data than agencies have used before. Legal departments will need to be involved in updates and modifications to current agreement strategies. In some instances, legislative approval might be required.

- **Failure to communicate objectives and activities to the public and decision-makers—** V2I introduces a new risk of the perception of 'big brother'. While many agencies have integrated specific outreach messages about current capabilities—such as anonymous probe data, use of CCTV cameras, etc.—there is the risk of the public and key decision-makers/managers not understanding what V2I is, benefits and business case of V2I, and how data is acquired, stored and used. There will need to be a focused and consistent set of messages about the business case and about specifics of V2I data acquisition and use. The public interest and support will be critical to ongoing funding and sustainability of the program. Messages to the public must be communicated about the enhanced safety and mobility benefits being provided by using these technologies.
- **Data privacy—**Maintaining data anonymity will be a critical factor in operations as well as public perception of the system viability. This will require establishing security systems, as discussed below.
- **Security of systems from hacking or unlicensed use—**Related to data privacy, cybersecurity presents an important set of risks related to the security of systems from hacking or unlicensed use. A security and credential management system (SCMS) must either be supplied locally or by a national entity. Maintaining data anonymity and data security will be a critical factor in operations as well as public perception of the system viability. There is a paramount safety risk to the public of not providing a highly secure system. The development and management of such a system requires special capabilities that the agency must develop, acquire, or collaborate to secure.

Chapter 7. Moving Forward

The Connected Vehicle (CV) Program Capability Maturity Model (CMM) is designed to help agencies comprehensively assess their Vehicle-to-Infrastructure (V2I) capabilities and identify actions to advance their levels of capability. However, determining how to start this assessment—or how to start implementing these actions once an agency has completed the self-assessment exercise—may still seem daunting. This chapter provides some important considerations and recommendations for approaching or launching into a Connected Vehicle Program CMM self-assessment.

7.1 The Basis for Improvement—All Dimensions are Vital

The basis for improvement of any program has three basic components: 1) a supporting institutional framework; 2) processes that support the program; and 3) the "Program" itself—as shown in figure 3.

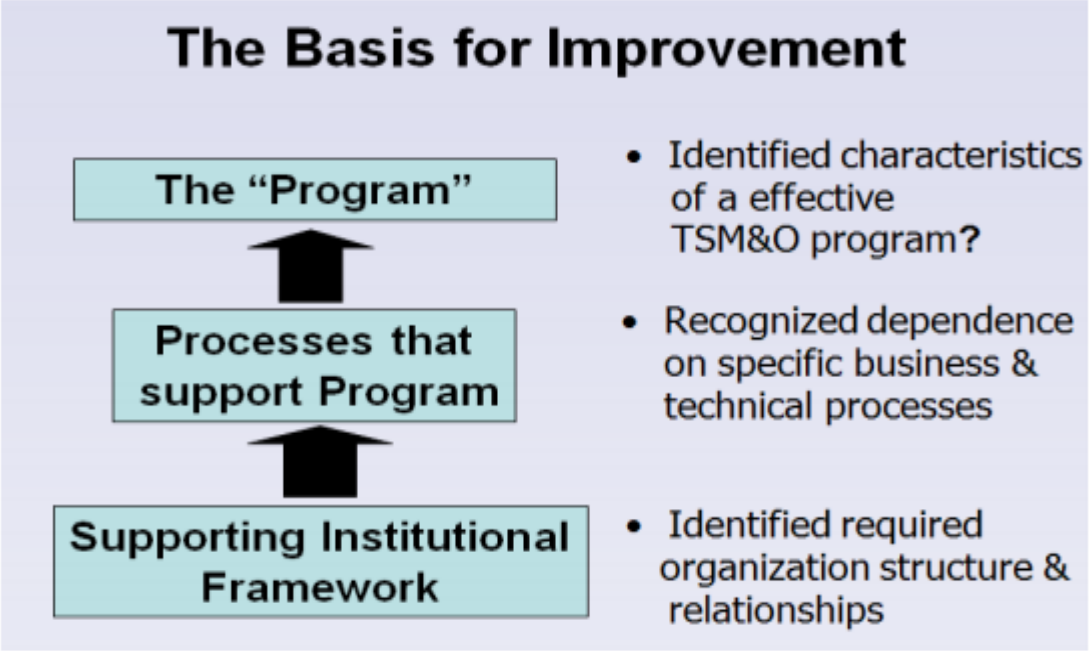

Figure 3. Chart. The basis for improvement in any organizational capability.

(Souce: U.S. Department of Transportation.)

The foundation of any successful program is first the institutional framework to support the activity. In the context of V2I, this will require developing the necessary organizational structure and functions for Transportation Systems Management and Operations (TSMO). After these enabling actions, the business processes for using and applying V2I data to TSMO practices will follow more readily and be more effective due to the strong foundation. These processes will, in turn, ensure that the program functions at a high level initially, and continues to adapt and improve as technology advances, connected vehicle penetration levels rise, and new applications and functions are identified.

Developing these foundational elements is, of course, the focus of much of the connected vehicle program CMM, so completing a CV CMM self-assessment is a significant step towards improvement. However, it is important to keep in mind that some of the dimensions are inherently more difficult to deal with than others, yet they all must be addressed to move forward. Omitting improvement in any one dimension may inhibit continuous improvement in effectiveness of a connected vehicles program.

7.2 A Holistic and Programmatic Approach

In 2017, many states/regions feel that they have "plateaued" in deployment of freeway management applications. The application of V2I technologies represents a natural next step in the provision of mobility and safety services that improve congestion and safety. However, not unlike TSMO strategies, V2I applications will require new planning and programming approaches, particularly with the need for collaboration with local agencies and transit. Agencies might consider coordinating V2I program planning with TSMO program planning as a natural combination, but should be careful not to consider treating V2I as another "device" to be deployed like a ramp meter or a dynamic message sign. This treatment may not appreciate the full potential of V2I applications and data.

I2V applications such as curve speed warning and intersection collision avoidance have limited geographic purview and operate like an isolated device. However, the regional data that may be available through comprehensive collection of anonymized vehicle trajectories unlocks wholly new areas of application and enhancement of many existing TSMO practices. In many long-range planning processes, an "unconstrained" future is envisioned for the planning horizon. That is, if funding was not an issue, what would be built and developed to meet our regional mobility, safety, and environmental goals? Then this ultimate plan is considered in the context of realistic funds available for construction, equipment deployment, and operations and a cost-constrained plan is derived. A similar approach might be applied to Connected Vehicle Program planning. A holistic program plan may be developed considering many potential applications and pared back to consider what might be accomplished with more realistic budgets and resources.

7.3 Suggestions for How to Approach the Connected Vehicle Program CMM Self-Assessment Process

Where do I start? Agencies in the early planning stages may take the following steps:

1. Convene a statewide or regional workshop to educate stakeholders, partners, and potential partners on V2I.
2. Discuss priorities, opportunities, and barriers to V2I applications in each of the TSMO areas.
3. Determine a short-list of high-priority applications and a longer list of secondary-priority functions that address regional issues, challenges, and goals. While many goals are generic, tailoring the connected vehicle strategy to regional hot-button issues is typically helpful in gaining broader buy-in from decision-makers and associated agency departments.
4. Review the activities in Level 1 of the self-assessment tables and identify priority actions.
5. Develop a project plan to implement the actions.

If most activities in Level 1 have been accomplished, focus energies on levels 2 and 3. How can we move our initial efforts to a statewide system? How can we integrate pilot activities with other regional programs? Additional steps to further these initial steps may include:

- Convene a statewide or regional workshop to formalize connected vehicle strategy from deployment testing and evaluation to program level considerations.
- Identify actions at level 1 that have not yet been completed.
- Explore the integration of current or proposed TSMO program plans with V2I data and application program plan. Explore synergies with other programs such as transit technology, automated vehicles, mobility hubs, smart cities, and tolling.
- Formalize the agency policies on V2I applications and develop a prioritized V2I action plan.

The results of the self-assessment process will likely identify a significant list of actions. The next step will be to prioritize the completion of those actions to achieve the desired outcomes within a reasonable schedule. In many program planning activities, it may be helpful to link the completion of key milestones with other related activities. Could the V2I infrastructure and programs be in place by the opening of a new stadium? Reconstruction of a bridge or major interchange? Roll-out of other programs such as managed lanes? Working backwards from a common deadline for other facilities or programs may motivate actions and reveal the schedule for activities that have dependencies on the connected vehicle roadmap.

7.4 Relationships of Connected Vehicle Program Planning with Automated Vehicles

In 2017, agency planning for automated vehicles is becoming another popular topic for IOOs. The topic of automated vehicles is quite likely to be a point (or many points) of discussion in V2I self-assessment workshops since there are many misconceptions related to automated vehicle capabilities and requirements. While most automated vehicles in development by private companies today do not require connectivity, synergies of V2I services with automated vehicles may become especially important in the future. For example, automated micro-transit vehicles may require connected vehicle technologies to safely cross intersections (i.e. traffic signal preemption or priority). Automated vehicles may use SPaT broadcasts to assist with driving near traffic signals. Work zones may be negotiated more safely by automated vehicles using data available through V2I. Many other synergies will likely be identified. While this Connected Vehicle CMM does not expressly address issues related to automation, many of the same program-level considerations that apply to connected vehicles apply to agency development of automated vehicle program plans:

- Development of champions, organizational structures, and business processes to handle new agency functions, systems, and roles.
- New planning and programming approaches may be required.
- Collaboration with agencies outside of TSMO will be important.
- Performance measures will be needed to measure outcomes and identify benefits.

While there are still many uncertainties regarding timing and availability of both connected and automated vehicles, both technologies are likely to be a significant component of the transportation landscape over the next decade. IOOs considering connected vehicle program plans and the V2I self-assessment may find value in considering implications for automated vehicles at the same time.

List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
API	Application Programming Interface
ATM	Advanced Traffic Management
ATMS	Advanced Traffic Management System
BSM	Basic Safety Message
CCTV	Closed-Circuit Television
CMF	Capability Maturity Framework
CMM	Capability Maturity Model
CV	Connected Vehicle
DMS	Dynamic Message Sign
DOT	Department of Transportation
DSRC	Dedicated Short Range Communications
FHWA	Federal Highway Administration
FTP	File Transfer Protocol
GB	Gigabyte
GIS	Geographical Information Systems
GUI	Graphical User Interface
HD	High-Definition
HDFS	Hadoop Distributed File System
IaaS	Infrastructure-as-a-Service
ICM	Integrated Corridor Management
IoT	Internet of Things
IT	Information Technology
ITS	Intelligent Transportation Systems
LAN	Local Area Network
LCS	Lane Control System
MTA	Los Angeles Metropolitan Transportation Authority
NHTSA	National Highway Traffic Safety Administration
NOCoE	National Operations Center of Excellence
NTCIP	National Transportation Communications for Intelligent Transportation System
OSADP	Protocol Open Source Application Development Portal
PB	Petabyte
PDM	Probe Data Message
PeMS	Caltrans Performance Measurement System
RSU	Roadside Unit
RWIS	Road Weather Information System
SPaT	Signal Phase & Timing
TB	Terabyte
TMC	Traffic Management Center
TMDD	Traffic Management Data Dictionary
TSMO	Transportation Systems Management and Operations
WAN	Wide Area Network
VSL	Variable Speed Limits
U.S. DOT	United States Department of Transportation

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