

# Integrating Emerging Data Sources into Operational Practice

Capabilities and Limitations of Devices to Collect,  
Compile, Save, and Share Messages from CAVs and  
Connected Travelers

[www.its.dot.gov/index.htm](http://www.its.dot.gov/index.htm)

**Final Report—March 2018**  
**FHWA-JPO-18-626**



U.S. Department of Transportation

Produced by FreeAhead Inc. and Kimley-Horn and Associates  
U.S. Department of Transportation  
Office of the Assistant Secretary for Research and Technology

## Notice

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The U.S. Government is not endorsing any manufacturers, products, or services cited herein and any trade name that may appear in the work has been included only because it is essential to the contents of the work.

---

(Cover Image by iStockPhoto.)

**Technical Report Documentation Page**

<b>1. Report No.</b> FHWA-JPO-18-626		<b>2. Government Accession No.</b>		<b>3. Recipient's Catalog No.</b>	
<b>4. Title and Subtitle</b> Integrating Emerging Data Sources into Operational Practice— Capabilities and Limitations of Devices to Collect, Compile, Save, and Share Messages from Connected and Automated Vehicles and Connected Travelers				<b>5. Report Date</b> March 2018	
				<b>6. Performing Organization Code</b>	
<b>7. Author(s)</b> Roy Sumner, Douglas Gettman, Alan Toppen, Jon Obenberger				<b>8. Performing Organization Report No.</b>	
<b>9. Performing Organization Name and Address</b> FreeAhead Inc.      and      Kimley Horn and Associates PO Box 270                      7740 N. 16 <sup>th</sup> St. Suite 300 Orange, VA 22942              Phoenix, AZ 85020  Under Contract to: Cambridge Systematics, Inc. 3 Metro Center, Suite 1200 Bethesda, MD 20814				<b>10. Work Unit No. (TRAIS)</b>	
				<b>11. Contract or Grant No.</b> DTFH61-12-D-00042	
<b>12. Sponsoring Agency Name and Address</b> U.S. Department of Transportation ITS Joint Program Office—HOIT 1200 New Jersey Avenue, SE Washington, DC 20590				<b>13. Type of Report and Period Covered</b> Final Report	
				<b>14. Sponsoring Agency Code</b> HOIT	
<b>15. Supplementary Notes</b> The Government Task Manager for the United States Department of Transportation is Jon Obenberger					
<b>16. Abstract</b> Connected and automated vehicles (CAVs) and connected travelers will be providing substantially increased levels of data which will be available for agencies to consider using to improve the management and operation of the surface transportation system. This report describes 1) how this data may be handled; 2) what the future capabilities and potential future needs of traffic management systems and traffic management centers (TMCs) will need to be to collect, use and share this information; and 3) the capabilities that may be required to aggregate, assimilate, and transfer the data efficiently from the roadside equipment to the TMC. The report summarizes a range of hardware and software issues agencies should consider. The report describes requirements, technical issues, technologies, and practices that will be necessary to collect, use and share large volumes of messages from roadside devices to the TMC. Current intelligent transportation systems (ITS) devices on the roadside typically have a one-to-one relationship with the traffic management system or center, where each device sends the data collected locally to the system. In the future, the collection and sharing of messages from CAVs and connected travelers will likely need to accommodate the distribution of information for other systems and users to consume.					
<b>17. Keywords</b> Connected and automated vehicles (CAV), transportation systems management and operations (TSMO), roadside units (RSU), roadside equipment (RSE), emerging data sources, connected travelers, edge processing, connected infrastructure, big data tools and technologies, real-time data, data messages, data elements.				<b>18. Distribution Statement</b> No restrictions.	
<b>19. Security Classif. (of this report)</b> Unclassified		<b>20. Security Classif. (of this page)</b> Unclassified		<b>21. No. of Pages</b> 99	<b>22. Price</b> N/A

# Table of Contents

<b>Chapter 1. Introduction .....</b>	<b>1</b>
<b>Chapter 2. Collecting and Processing Emerging Data Sources with Roadside Equipment.....</b>	<b>5</b>
2.1 Introduction .....	5
2.2 Existing Conditions for Data Collection and Processing from Roadside Equipment.....	6
2.2.1 Traffic Management Systems and Centers for Freeway Traffic Management.....	6
2.2.2 Traffic Signal Systems on Surface Streets .....	8
2.2.3 The Potential for Using and Sharing Data with Emerging Sources .....	9
2.3 Roadside Equipment for Collection of Connected Vehicles and Connected Travelers Data .....	10
2.3.1 The Differences between Roadside Units and Roadside Equipment.....	10
2.3.2 Current Roadside Unit and Roadside Equipment Hardware .....	10
2.3.3 Roadside Unit Specifications .....	11
2.3.4 Current Roadside Equipment Product Capabilities .....	12
2.4 Edge Processing .....	12
2.5 Real-Time, Near-Real-Time, and Offline Data .....	13
2.6 General Objectives of Data Collection System Design.....	14
2.6.1 Minimizing Communications .....	14
2.6.2 Data and Information.....	17
2.6.3 Collect, Process, and Forward.....	17
2.6.4 Pedestrian Data .....	22
2.7 Traffic Management System and Center Design and Architecture Options .....	23
2.7.1 Conceptual Data Processing Architecture for TMC Functions.....	23
2.7.2 System Design Options to Enable Capturing and Sharing More Information.....	25
2.8 Business Case for Collecting, Using, Saving, and Sharing Data From Emerging Sources .....	26
2.8.1 Value Proposition .....	27
<b>Chapter 3. Data Collection .....</b>	<b>29</b>
3.1 Connected and Automated Vehicle Messages .....	29
3.1.1 Vehicle-to-Vehicle and Vehicle-to-Infrastructure Data Dictionary .....	30
3.1.2 Vehicle-to-Vehicle and Vehicle-to-Infrastructure Data Exchange Protocols .....	30
3.1.3 SENSORIS.....	31
3.2 Data Elements.....	31
3.2.1 Basics of Roadside Equipment Operation .....	33

3.2.2	Dedicated Short-Range Communication Range.....	34
3.2.3	Basic Safety Message .....	35
3.2.4	Other Message Types .....	36
3.3	Data Collection Issues .....	37
3.4	Communication Options.....	38
3.5	Probe Processes.....	39
3.5.1	Probe Vehicle Data Processes .....	39
3.5.2	Probe Data Management Process.....	42
3.5.3	Speed Profile Data .....	45
3.5.4	Further Concepts for Optimizing the Operation of RSEs with Probe Data Management.....	49
3.6	Impacts of Additional Messages at the RSE: Personal Safety and Mobility Messages .....	49
3.7	Roadside Equipment Limitations .....	50
3.8	Status of Roadside Equipment Capabilities, Data Collection, and Local Storage Issues .....	51
3.8.1	Roadside Unit Specifications .....	51
3.8.2	U.S. Department of Transportation Operational Data Environment (JPO-ODE).....	53
3.8.3	Roadside Equipment Deployments in Connected Vehicle Pilot Sites .....	55
3.8.4	RSE Software Platforms .....	58
<b>Chapter 4.</b>	<b>Data Compilation and Storage.....</b>	<b>65</b>
4.1	Data Compilation.....	65
4.1.1	When and Where the CAV and Connected Traveler Data Should Be Compiled.....	66
4.1.2	Three Levels of Data Compilation.....	68
4.2	Data Storage .....	68
4.2.1	Messages, Frames, or Elements? .....	68
4.2.2	Data Reduction Strategies .....	69
4.2.3	The Bottom Line: Vehicle Trajectories .....	73
4.2.4	Transitioning to the Use of Connected and Automated Vehicle Data .....	73
<b>Chapter 5.</b>	<b>Data Sharing .....</b>	<b>75</b>
5.1	Center to Center Methodologies for Sharing Data.....	75
5.2	Strategies for Sharing .....	76
5.3	Application Programming Interfaces .....	78
<b>Chapter 6.</b>	<b>Next Steps for the Collection, Compilation, Storage, and Sharing of CAV and Connected Traveler Data .....</b>	<b>81</b>
6.1	Findings.....	81
6.1.1	Real-Time Data .....	83
6.1.2	Near-Real-Time Data .....	84
6.1.3	Offline Data .....	84

6.2 Recommended Agency Actions ..... 85

    6.2.1 Integrating CAVs and Connected Travelers into Traffic Management Systems and TMCs  
          ..... 85

    6.2.2 Planning for Next Generation Traffic Management and TMCs ..... 86

**Appendix A. Connected Vehicle Applications ..... 87**

**Appendix B. Connected Vehicle Data Elements ..... 89**

**Appendix C. List of Acronyms ..... 91**

**Appendix D. References ..... 93**

## List of Tables

Table 1. Connected vehicle and connected traveler messages.....	19
Table 2. Speed and time between snapshots. ....	43
Table 3. Speed and distance between snapshots. ....	43
Table 4. Example of lossless compression for basic safety messages. ....	72
Table 5. Example strategies for sharing data.....	77

## List of Figures

Figure 1. Map. Dedicated short-range communications range.....	16
Figure 2. Flow chart. Comparison of generic components of edge processing in current traffic data collection operations and future RSE operations with CAV and connected traveler data.....	18
Figure 3. Diagram. Big data tools integrated into a traffic management center.....	24
Figure 4. Diagram. Illustration of traffic management system design options. ....	25
Figure 5. Diagram. Standard message frame, message, data frame, data element illustration. ....	33
Figure 6. Map. Speed profile data collection points.....	46
Figure 7. Diagram. Speed profile data collection. ....	47
Figure 8. Graphic. High-level conceptual diagram of the roadside unit.....	52
Figure 9. Diagram. Context diagram of a roadside unit. ....	52
Figure 10. Diagram. System architecture excerpt. ....	55
Figure 11. Diagram. Tampa-Hillsborough Expressway Authority connected vehicle pilot planned data flow. ....	58
Figure 12. Graphic. Vehicle-to-infrastructure hub concept. ....	59
Figure 13. Diagram. Vehicle-to-infrastructure hub detailed system view with candidate message handlers. ....	60
Figure 14. Graphic. Vehicle-to-infrastructure hub platform hardware and specifications. ....	61
Figure 15. Diagram. Vehicle-to-infrastructure hub core components. ....	62
Figure 16. Diagram. Vehicle-to-infrastructure hub plugin components.....	63

# Chapter 1. Introduction

This report focuses on roadside devices that are used to collect, process, analyze, use, share, and store messages from connected and automated vehicles (CAV) and connected travelers. For these messages to be used by traffic management centers (TMC) and traffic management systems (TMS) to more efficiently and effectively manage the transportation network, these messages and the data or information derived from them needs to be promptly collected, compiled, and made available to a variety of functions. This report provides agencies with the information needed to understand the capabilities and possible limitations of their current devices and systems along with what requirements and enhancements may be needed in new devices to handle large volumes of messages from CAVs and connected travelers. The report describes the range of issues to be considered in planning and designing the roadside system for remotely collecting, compiling, using, and sending messages from CAVs and connected travelers to central systems, hubs, and other systems and users.

The report describes the existing range of the potential types of messages, data, and information that CAVs and connected travelers may expect to be generated and used by TMSs and TMCs in the future. The report also discusses and provides examples of the analytical methods, technologies, and big data techniques that agencies may consider integrating into their systems in the near future. The potential to collect and integrate the use of data generated from CAVs and connected travelers offers the potential to substantially improve the capabilities and performance of TMCs.

This is the third in a series of three reports. The purpose of these reports is to assist agencies in considering the range of issues related to the planning and design of traffic management and TMC functions that will use data from CAVs and connected travelers. The reader is encouraged to consider the three Federal Highway Administration (FHWA) reports as a complete set. These reports are:

- *Report 1. State of the Practice Review* (FHWA-JPO-16-424) provides 1) a review of the state of the practice in big data tools and technologies; 2) an estimate of the volume and velocity of emerging data sources from CAVs and connected travelers over the next ~10 years; and 3) summarizes the issues that agencies will need to consider in collecting, storing, processing, and sharing data from CAVs and connected travelers to improve a variety of TMC functions and systems.
- *Report 2. Opportunities for Integration of Emerging Data for Traffic Management and TMCs* (FHWA-JPO-18-625) identifies specific use cases for CAV and connected traveler data in common traffic management and TMC functions and describes how these functions are similar and different across a broad range of characteristics including the data velocity, data volume, required processing speed, and geographic extent. TMC functions that will be enabled or enhanced by CAV and connected traveler data are grouped into three categories: real-time, near-real-time, and offline. Each of these three groups of functions will require different kinds of processing and storage functions from the big data ecosystem of software tools and technologies. A notional system architecture is described along with description of many key issues for agencies to consider in design, procurement, deployment, integration, and operation of big data tools and technologies with traffic management systems and TMC functions.
- *Report 3. Capabilities and Limitations of Devices to Collect, Compile, Save, and Share Connected and Automated Vehicles and Connected Traveler Messages* (FHWA-JPO-18-626)

discusses 1) the current state of the practice in roadside equipment (RSE); 2) existing standards for CAV and connected traveler messages; 3) potential approaches to data aggregation, compilation, storage and sharing (e.g., edge processing) to reduce the burden on the communications network; and 4) issues that agencies may need to consider in order to use data from CAVs and connected travelers to improve traffic management and TMC functions.

The intended audience of this report are individuals involved in, or responsible for, the planning, design, management, operations, or maintenance of traffic management systems and centers. The reader is assumed to have a general awareness of CAV communications technologies, or wish to gain a better appreciation of such data and messages. The report is quite detailed in the description of messaging standards, protocols, and data handling methodologies. Public agencies can use this report to help guide their assessment, planning, design, and consideration of technologies for collecting, processing, storing, and sharing data from CAVs and connected travelers.

This report 1) summarizes the current capabilities of RSEs; 2) identifies what guidance already exists to enable agencies to design and procure RSEs; and 3) discusses techniques for data aggregation, compilation, and sharing that could be used in RSEs for processing CAV and connected traveler data for use by traffic management systems and TMCs. The report discusses how RSEs could be used to collect, process, store, use, and send information to the traffic management system and connected devices, connected vehicles, and other components. The report illustrates the structure of the messages and the data elements that will be the primary source of information to enhance existing and enable new applications. The report describes how an agency may store or share data to facilitate analysis, use, and integration into the system or with the information shared by the system to other users or systems for a variety of real-time, near-real-time, and offline TMC functions. After reading this report, the reader will understand the current operational capabilities and limitations of RSEs to store, process, compile, and save connected vehicle data and what future capabilities and systems will be needed to use connected vehicle data for traffic management and TMCs. While FHWA-JPO-16-424 (*State of the Practice in Big Data Tools and Technologies and Emerging Data Sources*) discussed other types of emerging data sources (Light Detection and Ranging (LiDAR) point clouds, 3D video, etc.), this report focused on CAV and connected travelers data exclusively.

Chapter 2 discusses the system architecture of RSEs and the issues that arise when connected vehicles will be generating very large amounts of data. This chapter discusses how processing at the edge of the network can significantly relieve demand for storage at the TMC and communication bandwidth between the RSEs and the TMC. Reintroducing the earlier theme of real-time, near-real-time, and offline data from FHWA-JPO-18-625, chapter 2 describes the advantages of distributed processing as a mechanism to reduce communication requirements. The chapter ends with a discussion concerning the business case for RSEs from an agency perspective.

Chapter 3 discusses roadside units and roadside equipment. The chapter introduces the standards and provides the reader with the detail of the various data types and how they are structured into messages. The chapter describes in detail the probe processes which will allow agencies to gather new types of data from a greater geographical spread with finer resolution.

Chapter 4 concerns how the data can be compiled and stored. Issues concerning various storage and compilation are discussed. The chapter introduces the potential for the roadside equipment to act as a server. The chapter suggests a mechanism for compressing messages to reduce bandwidth and storage requirements.

Chapter 5 discusses concepts related to data sharing. Agencies that collect connected vehicle data at the roadside will likely need to share data with a variety of users at other traffic management centers for some applications. Strategies for sharing data between agency applications or roadside units and other external users who need the data are described.

Chapter 6 discusses the findings by data type and lists a series of issues where gaps in technical guidance exist and where future research and development efforts are needed to prepare guidance and other resources for public agencies to use in implementing agency-specific projects to take advantage of and use emerging data sources with RSEs and integrate that information into the active management and operation of the traffic management systems and TMCs.

# Chapter 2. Collecting and Processing Emerging Data Sources with Roadside Equipment

## 2.1 Introduction

The purpose of this chapter is to provide the reader an understanding of the options and design-related issues associated with collecting and processing data from connected vehicles, automated vehicles or other emerging sources for use in traffic management systems. The chapter focuses on the role of the RSE in receiving and transmitting data, and how roadside handling of data has evolved throughout the development of such systems. The design and configuration issues consider ITS devices, software, data management, and the communication options between field devices, traffic management centers, and hubs for data aggregation and distribution.

This chapter first discusses typical practices for using roadside equipment to share information with traffic management systems and TMCs that manage traffic on freeways and arterials. The reader will understand how the constraints of these existing systems may influence their ability to use RSEs to collect, process, and share data from emerging sources. The chapter then provides an overview of existing RSE hardware and software capabilities and logical designs for how new capabilities can be integrated with existing TMC and traffic management functions.

After reading this chapter, the reader will gain appreciation for the range of capabilities and how RSEs may operate, the concept of edge processing, and design issues to consider related to the collection, use, and dissemination of data between the RSEs and the TMC. Chapter 3 will then build on the content from this chapter with additional in-depth information related to the collection of the data.

This chapter focuses heavily on *local* collection of data from connected devices from an RSE using low-latency, high-bandwidth technologies such as dedicated short-range communications (DSRC), 5G wireless, and WiFi. Many considerations discussed in this report do not apply when using data collection methods such as cellular or satellite communications where local proximity between the data collection point and the data producer is not as critical. Many near-real-time and offline TMC functions can be enabled with cellular and satellite communications to connected vehicles and travelers. The issues discussed in this chapter related to individual RSEs are in some cases *compounded* for centralized data collection using cellular or satellite, and other issues are mitigated. These differences will be discussed further in the narrative of this chapter and in chapter 3.

## 2.2 Existing Conditions for Data Collection and Processing from Roadside Equipment

A key aspect that is addressed in the design of all traffic management systems is the consideration of what data will be collected, where it will be processed, saved, and transmitted between field devices and the TMC. This is of profound interest in the context of systems planning for and developing the capabilities necessary to collect and share messages with connected and automated vehicles and other sources of emerging data. Agencies implementing systems are not starting with a clean slate, they typically have an existing design and architecture which connects intelligent transportation systems (ITS) devices to the TMC. These designs were typically developed to meet the system's requirements with a minimum cost to deploy, operate, and maintain. The overlaying of requirements and installation of equipment to enable the collection, sharing, and use of these emerging sources of data will require significant integration with existing the system's hardware and software.

Current roadside hardware (traffic signals, ramp meters, dynamic message sign processors, and the like) most often has very little or no additional processing and memory availability to carry out any functions or tasks other than the purpose they were designed for; although the newest advanced traffic controller (ATC) standard is changing that paradigm. (<https://www.ite.org/standards/atcapi/referenceimplementation.asp>.) Processors in current roadside hardware typically have limited computational capabilities and solid-state memory to minimize the heat generated by the processor and risk of mechanical failure of hard drives. This is typically done so the equipment will survive for many years in high-temperature environment of a metal-encased cabinet with no air conditioning.

Communication systems in existing traffic management systems have a wide range of bandwidth capabilities, depending on when they were installed. Many agencies still rely on twisted copper pairs (serial) and dial-up modems to many field devices in remote locations. Such communications media has inherent and severe limitations on backhaul capacity and data transmission speeds. Modern standards of the last fifteen years rely on Internet protocol (IP) communications using fiber-optic cables, high-speed wireless systems, and IP over copper. Such communications media, particularly fiber-optic cabling, has much more growth potential for higher and higher data transmission capacity.

While there have been considerable improvements in the technologies for detection, communications, and analysis, in essence the principal features and functions of traffic management systems for both freeways and arterials has not fundamentally changed. It has been only in the last decade that the availability of new technologies (e.g., toll tags, Bluetooth/WiFi, radar, and video detection) has provided options for collection and use of data from emerging sources. The advent of the Internet, smart phones, and high speed cellular data services has similarly provided options for systems to consider how information is captured or disseminated.

### 2.2.1 Traffic Management Systems and Centers for Freeway Traffic Management

In the early days of traffic management systems, the data handling processes were *distributed* as much as possible. For example, a count station on the freeway that includes perhaps two loop detectors per lane will collect the presence or absence of a vehicle in the detection zone 10 times a second from every loop. Data collected is typically summarized into occupancy values for each zone and saved. The local

controller will then calculate the occupancy by lane. The processor in the local controller will then read these occupancy values and perform a range of checks and verifications. For example, if one loop fails, the processor will detect this, make assumptions about the adjacent lanes being the same as the failed lane, and amend the data accordingly while reporting on the loop failure. Such processes have been operating for several decades in TMCs across the world.

For current real-time transportation management systems, there seems no immediate need to transmit and store the raw data (individual vehicle occupancy data each 0.1s from each individual loop) received from the various ITS devices. For example, current side fire radar detectors that are used for measuring speed and counting traffic make internal computations, often on a once per second basis, exponentially smooth the data continuously, and then report the smoothed average speed and traffic counts every 20 to 60 seconds. Thus, the *near-real-time* data flows immediately to the RSE and then to the TMC, where it has an inherent, but tolerable, delay.

As data from connected and automated vehicles is available for traffic management systems to capture and use, agencies will need to integrate this information into their RSEs and systems. This will require agencies to redesign and develop the data bases, central computer hardware and software platforms, decision support subsystems, communication systems, software interfaces between system components, and the graphical user interface to the systems operational status, data, and control options. For example, currently the roadside equipment collects speed data from one single point and one direction on the freeway.

This data is then associated with a specific segment and is used as an input to incident detection algorithms and travel conditions monitoring and reporting, as well as for travel time calculations. If a RSE will collect and share data with CAVs or connected devices, it has the potential to collect and share data over the entire area the RSE covers, which may include vehicles or travelers of different roadways traveling in different directions. Like the 0.1s resolution occupancy from a single loop detector, for most applications it will not be necessary to transmit every data point from the RSE to the TMC.

Either the RSE or the systems TMC will need to initially parse and separate messages received from CAVs to determine the data contained in each type of message and allow for specific data elements to be used. The messages will need to be geofenced to determine what information may be appropriate for reporting or which data elements will be necessary to generate the necessary information (e.g., running averages or other summary statistics) and provided in the correct format to meet the requirements of the existing system or TMC. This capability would allow a RSE to capture and share messages with CAVs and devices covering both directions of the freeway, all approaches to intersections, and potentially spurious or conflicting information from streets that do not intersect, such as at underpasses and overpasses. Similarly, the single RSE would cover the dissemination of data to connected vehicles and travelers on all of these facilities.

Additional data could be made available by RSEs by collecting and using probe data messages received by vehicles and devices within range. Probe data messages, together with probe data management messages, provide the traffic management system or TMC the ability to access all of the differing parameters that the equipped vehicle is able to transmit. Probe data and other data, such as speed profiles, are by definition *near-real-time* (i.e., “warm”) since the vehicle requires time to generate and transmit this information from a range of data snapshot locations. This will be discussed in more detail in chapter 3.

## 2.2.2 Traffic Signal Systems on Surface Streets

Traffic management systems commonly have multiple communications services that poll several hundred field devices on a second-by-second basis. The largest traffic signal systems in New York, Miami-Dade County, the City of Philadelphia, the City of Los Angeles, and others have 10 or more such communication processes. Other legacy systems use field master controllers and dial-up connections to gather real-time data on demand.

Systems with master controllers typically have several (5 to 10) local traffic signals connected to an on-street master controller, which is typically co-located in one of the traffic control cabinets with the local traffic controller. This master controller synchronizes the controller clocks and typically maintains the time-of-day schedule of traffic control patterns for the group. When a user at the TMC wishes to observe status or make modifications to control parameters, a connection (typically a leased phone line with a low-speed modem) is made to the master and the master passes through the data from the local controller back to the TMC.

Master-based systems are quickly being replaced as fiber-optic, wireless, and Internet protocol over copper communication systems have become inexpensive. However, there are still many master-based systems in active use; particularly by State Departments of Transportation (DOT) that manage traffic control systems on State routes across vast geographic areas. Typical communication systems for existing traffic signal systems may not have the capability to collect, process, use, and share connected vehicle and connected traveler data for surface streets and the adjoining public-right-of-way.

The ability for traffic signal systems and controllers to collect, process, use, store, or send connected vehicle and traveler messages is considerably more complex than the data that is shared currently via different communication methods from a TMC to traffic signals or freeway detection stations. The functionality around which these devices were designed and procured has typically assumed only certain types of data with fixed formats and communication links designed for communicating only this data with the TMC. The rapid growth in popularity of video detection and pan-tilt-zoom video cameras for arterial traffic management has necessitated upgrading many center-to-field communication networks, but in most cases, the capabilities of existing communications systems will not be adequate for collecting and sharing connected vehicle data with RSEs at scale without distributed processing. An example of distributed processing from traffic signal control systems is discussed in the next subsection.

### ***Adaptive Traffic Signal Systems—an Example of Distributed Processing***

Current fixed time and actuated-coordinated systems have limited capabilities to react to changes in traffic conditions. To make improvements in operations and delay requires adaptive control. Agencies have been typically reluctant to install these systems due to the cost of installing and maintaining detectors and the communications system necessary to enable this sharing of data. Decreasing costs of video and non-invasive detection systems, as well as the costs of fiber optic and other high-speed communications systems have increased the use of adaptive control systems over the last ten years, particularly in the United States. Data collected and shared with connected and automated vehicles will enable adaptive control systems in various forms to use the data extracted from messages in place of obtaining data at specific locations using traffic detectors. This further increases the requirements on the capabilities needed from the roadside equipment (e.g., memory, processing, and support for different types of communications).

Some adaptive traffic control systems such as Split Cycle Offset Optimization Technique (SCOOT) use edge processing to reduce the burden of communications with a central processor. The system measures traffic data at the upstream intersections and sends this data to the central server which optimizes the signal timings for the downstream intersection. The information that is transmitted and used for optimization is called platoons. The data from the upstream platoons is used to optimize timing once per cycle. This platoon data is collected locally from detectors in each lane and local processes are used to create a platoon profile which incorporates the number of vehicles the timing. Only these parameters are sent to the server that uses this information to virtually move the platoon to the next intersection, and thus optimizing the timing prior to the vehicles arriving.

Other researchers have developed techniques to use connected vehicles data for adaptive signal control. One approach [1] is to use the probe data message technique to gather data going towards the intersection and minimizing the delay locally. Another [2] approach uses microscopic simulation together with the rolling horizon to again minimize the delay. Both of these approaches use edge processing and run algorithms locally to collect, compile, make decisions, and share messages at the RSE or system hub. Only summarized data is sent to a central processor for observation of status and control decisions.

This example of edge processing indicates a current and proven technique that is used to avoid communicating and processing large data sets at a central location when it is time-critical that the control decisions are returned to the field devices in a timely manner. It is likely that such distributed processing techniques will need to be applied to allow systems to collect, compile, use, and share data with CAVs and connected travelers.

### **2.2.3 The Potential for Using and Sharing Data with Emerging Sources**

Connected vehicles, automated vehicles, and other emerging sources of data (e.g., connected mobile devices) will provide a seminal change in how agencies' systems are designed to collect, compile, use, and share information with these sources. The geographical coverage of travel conditions data provided by emerging data sources will be ubiquitous where historically traffic management and TMC operations have relied on spot detection and video surveillance at selected key locations. The opportunity to electronically collect and share information from these emerging sources requires agencies to consider what additional technologies and communication capabilities may be necessary to enable this information sharing. If these systems can avoid relying on point detection technologies and current communication methods, they have the potential to substantially expand their service area.

After reading section 2.2, the reader should have an appreciation for the limitations of the capabilities of existing traffic management systems and TMCs, their communication systems, and the challenges that may arise with the addition of roadside equipment for collection and dissemination of data with connected travelers and vehicles. The next section 2.3 discusses the roadside equipment in more detail including current hardware and software specifications. After reading section 2.3, the reader will understand the capabilities of current devices and the need for additional work to define RSE specifications that include edge processing capabilities.

## 2.3 Roadside Equipment for Collection of Connected Vehicles and Connected Travelers Data

This section discusses roadside equipment in more detail including current hardware and software specifications. After reading section 2.3, the reader will understand the capabilities of current devices being used in active connected vehicle pilot programs, and the need for additional work to define RSE specifications that include edge processing capabilities.

### 2.3.1 The Differences between Roadside Units and Roadside Equipment

A definition is required for the commonly referred to roadside hardware often used in the descriptions and designs of connected vehicle applications. A *Roadside Unit (RSU)* consists of a wireless module that can communicate a DSRC message. Whereas, *Roadside Equipment (RSE)* consists of an RSU plus additional equipment and hardware/software that can provide processing capability, algorithm operation, communications, and operation of additional devices. It is important to distinguish between these two as the RSU is subject to licensing and Federal Communications Commission (FCC) regulations and will likely need to be certified by an approved authority. Agencies that specify RSUs as components of an RSE need to be aware that the RSU functionality of handling DSRC messages may need to be separately tested.

A *controller* as used in this report refers to a specific piece of equipment designed to operate an ITS device such as a traffic signal, or a message sign. It is likely that agencies will be conflating the RSU/RSE/controller functionality into one unit in the near future.

(<https://www.ite.org/standards/atcapi/referenceimplementation.asp>.) Current hardware can be found that incorporates faster processors, Ethernet communications, GPS signal handling, security applications, WiFi, 4G modems, and routing capability. In the same way that traffic signal controllers are now purpose-built devices, RSE vendors are currently providing RSEs that only handle connected vehicle applications. Later in development, more functionality may need to migrate from software on general-purpose hardware towards individual integrated circuits. The DSRC handling application of the RSU is essentially the same as the on-board unit (OBU) in the vehicle and therefore it is likely that this functionality will be first to migrate to an Application-Specific Integrated Circuit (ASIC). An ASIC is an integrated circuit customized for a particular purpose rather than for general processing.

### 2.3.2 Current Roadside Unit and Roadside Equipment Hardware

The technology that is used in roadside devices being implemented for collection and sharing of connected vehicle data follows the technological trends of faster processing, more processing, more memory, and lower power usage. Commonly found today are computers based on an ARM architecture (Advanced RISC Machine) (Reduced Instruction Set Computing). Processors with RISC architectures have fewer transistors than found in personal computers and this reduces their cost, power consumption, and heat generated. ITS developers purchase these processors as boards equipped with a variety of features such general purpose memory, flash memory, GPS, data ports, and other features. ARM processors are used in laptops, tablets, smart phones, and other embedded systems like traffic controllers. Over 100 billion ARM processors have been produced.

The memory associated with these processors can be expanded by the addition of separate boards or external storage devices (such as USB “thumbdrives”) to store additional data. As will be discussed in this section and future sections of this report, the storage requirements for RSEs will likely need to be significantly increased.

For example, the RSU being used by the Wyoming DOT as a part of the Connected Vehicle (CV) Pilot Study comprises:

- Quad-Core ARM R Cortex A9 processor at 1GHz.
- 1GByte RAM.
- 2MB Serial Flash.
- 4GB eMMC Flash.

The ARM architecture supports a wide range of operating systems. Linux and its derivatives are most commonly used in ITS systems. These processors meet the environmental requirements for roadside equipment and will allow for additional processing and data storage likely to be required for future connected vehicle applications. However, it is not known how well this hardware (i.e., processing speed) will scale when the penetration level of connected vehicles climbs to 20 percent, 50 percent, and further. It would be worthwhile to perform additional hardware research to identify the most powerful processor with the maximum storage that the operating system can support and then determining the maximum number of connected vehicle and connected traveler messages that could be collected, processed, and forwarded. In the next two sections, the current capabilities of existing RSUs and RSEs are discussed. The reader will understand how existing products are similar and different.

### 2.3.3 Roadside Unit Specifications

The USDOT has published a DSRC roadside unit specification [3] that defines the requirements for roadside units that can act as a network edge (The “edge” refers to the closest point between the vehicle and the infrastructure. In the case of DSRC functions for active safety, this is at the RSE. Since the processing must be done in microseconds, for, say, red-light running warning, it is not likely that the vehicle to infrastructure (V2I) data could be shipped to a TMC and then back to the vehicle in a timely manner. Those functions require deployment of the processing on the RSE) device for gathering and distributing messages with connected and automated vehicles and other emerging sources of data. The RSU is designed principally as a switch that can forward, store, and repeat messages that conform to the J2735 format. Much of the specification is concerned with the physical and interface characteristics and which standards need to be adhered to. The performance characteristics include basic safety messages with the transmit rate of 10 Hz and a data rate of 6 Mbps. This specification does not provide any guidance in terms of performance requirements that need to be met for processing the volume and various types of messages that will be needed in an environment of sending and receiving messages with CAVs and these other emerging sources.

The RSU specification does not provide facilities for the more extensive processing and storage requirements may be necessary as connected vehicles become more prevalent. The hardware (e.g., memory for storage, processing) and software that may need to be added to an RSU will be required to manipulate and send a large stream of messages and perform all of the requirements that may be necessary for a specific location (e.g., sorting, geofencing, parsing, storing, and generating and sending

messages). The RSE processor will need to meet the same physical and environmental specifications as an RSU.

### 2.3.4 Current Roadside Equipment Product Capabilities

The Multimodal Intelligent Traffic Signal System (MMITSS) [4] is a connected vehicle project involving traffic signals in California and Arizona. Both test beds RSEs with an 800 MHz iMX6 dual core processor with 1 GB of DRAM and 8 GB of flash memory. The Ann-Arbor Safety Pilot Model Deployment as well as the Crash Avoidance Metrics Partnership (CAMP) also use similar RSEs from the same vendor. In the California implementation of MMITSS, the applications are run on a separate Linux based computer connected to the RSE by Ethernet. The Arizona implementation uses a model that incorporates the processor within the RSE.

Other vendors provide an RSU that combines Bluetooth® (2.4 GHz) and DSRC (5.9 GHz) within one roadside device. A separate processor would be necessary for V2I applications using DSRC, while traditional travel-time metrics can be collected using the Bluetooth radio.

The New York and the Tampa CV pilot studies both use an RSE from the same vendor. The RSE includes a local WiFi hotspot which enables the device to connect to the signal controller, and an LTE cellular backhaul for data upload and download.

Other vendors are currently offering broad portfolios of V2X options which includes custom integration of specific functions and agency requirements including direct integration of Ethernet switches, WiFi, LTE/4G, GPS, differential GPS. As such, there is not yet any standard definition of what should be the minimum or desired range of capabilities of a RSE.

The requirements of an RSE will vary depending on both time of day, conditions with each location, and constraints or requirements of each system. It is desirable that the RSE design be expandable in terms of processing power and storage in order to accommodate the potential use to share and use data with connected or automated vehicles or other emerging sources. This general capability of an RSE is termed “edge processing” which will be discussed in the next section.

## 2.4 Edge Processing

In centralized architectures, the peripheral devices send their raw information to a central processor for analysis, control, and storage functions. In a *distributed* architecture, processing takes place at or near the peripheral devices and *summary* data is sent to the central processor. The trend, which is accelerating, is for both the quantity and size of the raw data to increase. This will certainly be true for data from emerging sources such as CAVs and connected travelers.

As the number of raw messages from connected vehicles and travelers increases, there will be a significant burden placed on the communication network as well as the capability of the RSE to process all of this data into information. As an analogy, in the early days (1980s) of centralized traffic signal control, all controllers were interrogated once per second and their status reported in detail back to the central system. In many systems, control signals were also relayed back from central to the field controllers each second.

As the processing capability of controllers increased, it became feasible and advisable to transfer much of the handling of the raw data to the signal controllers. Since this reduced the burden on the communication system, this allowed the central system to monitor more field controllers. Modern traffic control systems can now easily monitor and manage thousands of field devices due to distribution of processing to the edge devices. Current traffic signal controllers are now capable of many of the functions that that, in the early days, were performed only at the processor in the TMC.

As technologies continue to develop, data handling and processing will become faster and less expensive. These factors will enable more capabilities to be specified, deployed, and used in RSEs and at traffic signals, which will allow for more functions and decisionmaking now limited to the TMC to be more distributed. We have now moved from the early days of terminals providing access to a large mainframe computer to now a small central databases and smart phones with significant processing capability.

The trend towards greater use of edge processing will undoubtedly continue as traffic management systems and TMCs continue to develop. As the use of CAVs increases it may raise the expectation or allow agencies to take advantage of traffic management systems enabling the real-time exchange of messages. The use of edge processing will be different for different types of data coming from the connected devices. In the next section, the differences between edge processing for real-time, near-real-time, and offline functions is discussed.

## 2.5 Real-Time, Near-Real-Time, and Offline Data

It is important to distinguish between data that is needed in real-time or near-real-time from data that will be used for offline use (e.g., traffic analysis studies, assessing the effectiveness of operational strategies, emissions modeling, etc.). Continuing the nomenclature of different data types from FHWA-JPO-18-625 *Opportunities for Integration of Emerging Data for Transportation Systems Management and Operations*:

- Data is **hot** if it should be processed in real-time to be useful (i.e., a latency of less than one second from receipt to action). Real-time traffic management functions require hot data such as the processing of speed and position as close to the edge as possible. The lowest latency data type would be vehicle to vehicle (V2V) safety applications and certain V2I applications such as red-light running warnings. The edge processing of this data must occur on the RSE and the relevant information shared directly with the connected devices in real-time. In FHWA-JPO-18-625, such functions include hazard warnings, speed warnings, intersection collision avoidance, probe data collection, and electronic payments.
- Data is **warm** if it must not necessarily be processed in real time, but actions should be taken reasonably soon to provide benefits (i.e., less than a few minutes from receipt to action). An example application might be a traffic management system output that is driving a variable message sign or changing traffic signal timing variables, such as the cycle time, green time splits, or offsets. The edge processing of data from connected devices can accumulate many data elements together over a short period of time and appropriate geofenced areas. This information can then be processed locally at the RSE, or transferred back to a central processing function which needs information from many distributed locations to be effective. In FHWA-JPO-18-625, such functions include traffic signal control, incident management, metering, lane management, traffic information, weather monitoring, and parking management.

- “Offline” data analytics can use data that is **cool**. Generating and reporting on performance, assessing vehicle emissions (e.g., models), and asset management actions, for example, can operate with data that has been cleaned, processed, and stored. These actions are categorized as functions that do not rely on low latency communications. Actions on cool data might be taken every few hours, once a day, once a week, or even longer time periods. Such actions are much more likely to require information from many and perhaps all RSEs in an agency’s jurisdiction. Information from the RSE would be transmitted periodically to the TMC for centralized processing. In FHWA-JPO-18-625, such functions include emissions monitoring, performance management, and asset management.

Depending on an agency’s objectives for improving traffic management and TMC functions, it is likely that all of the above types of data will be necessary to be collected, stored, processed, and shared. This implies that the RSE will need many additional functions in the data collection and processing design. These issues are discussed in the following sections.

## 2.6 General Objectives of Data Collection System Design

As discussed in the previous section, RSEs will need additional functions to process, store, and share the three general types of data from connected vehicles and connected travelers. This section discusses several issues related to the design of this data collection and processing system:

- Minimizing communications.
- Processing messages, including the extraction of the relevant information from the data.
- The potential role and implications of collecting data from connected pedestrians.

Each of these topics are discussed in more detail in the following subsections.

### 2.6.1 Minimizing Communications

There are many recent references to the value of the enormous amounts of data that connected vehicles and connected travelers will generate. However, the information from all the sources has to be collected, stored, used, and transmitted for analysis and for sharing with other systems in order to reap such benefits. The reality is that most of the BSM data will only be used by the adjacent vehicles unless an agency decides to deploy a roadside unit within range to also receive and capture this information. The objective of the design of the system, design of a RSE, decision to deploy a RSE, and method to send information to the TMC are based on the need for the agency to collect, store and use the subject information in a manner which minimizes the capital, operating, and maintenance costs of the device and TMC. It is likely that enhanced capabilities in a RSE and/or field hub for the system will provide the agency with lower overall capital and operating costs for the system.

Consider figure 1 that illustrates an example of a busy urban location where an RSE has been installed at a position where it can cover several freeway ramps and arterial intersections. The figure shows a complex series of freeway ramps and merge points. In addition, there are several arterial roads with traffic signals. In order to effectively gather connected vehicle generated messages at one RSE in this example, it would potentially require significant processing and data storage capability to capture and send other types of electronic messages from traffic signals, probe data messages, and personal safety or mobility messages generated from devices being carried by pedestrians within range of an RSE.

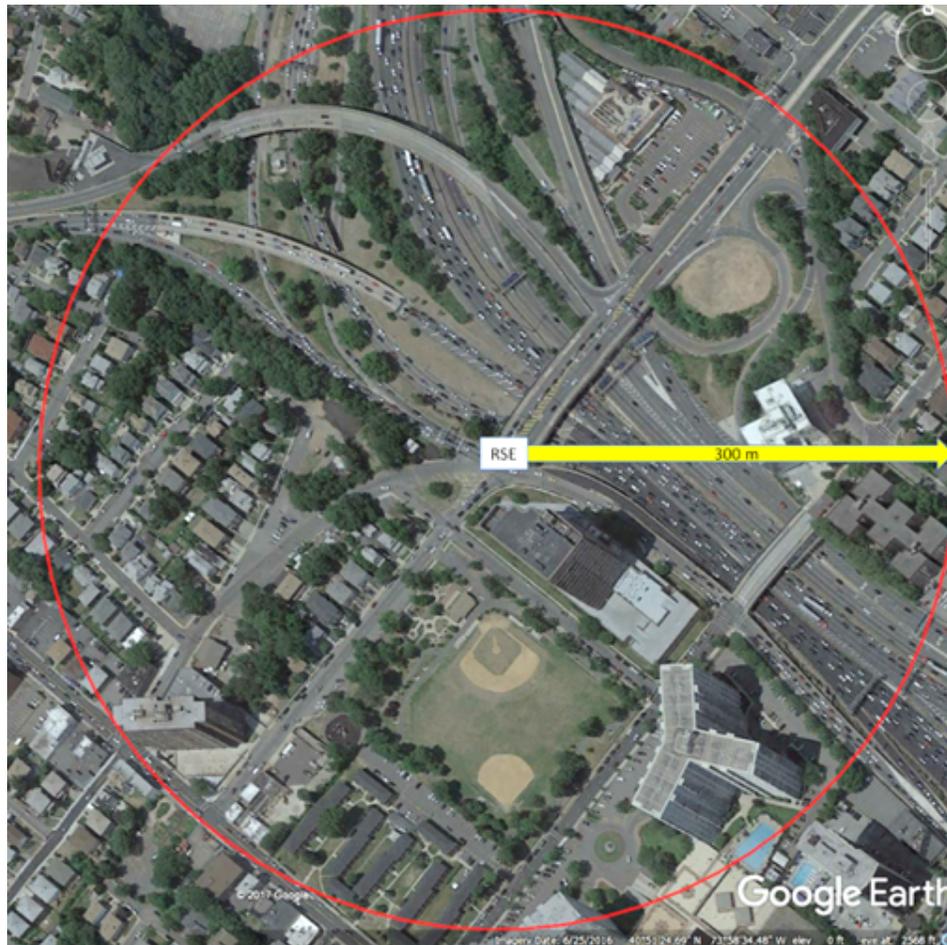
A modern communication link to an RSE based on gigabit Ethernet can transmit 1 billion bits per second or 125 MB/sec (8 bits per byte). The data stream is sent in frames and there are time gaps which reduces the real capacity to about 81 MB/sec. In the example of figure 1, there are approximately 300 vehicles that could be transmitting BSMs 10 times per second. In addition to the BSMs there are messages (e.g., traffic signal controllers, traveler information messages, probe data messages, etc.) which the RSE may have the opportunity to collect and use.

Using 3,000 BSMs /sec each of 100 bytes, with 10 bits per byte this will require a communication bandwidth of 3 MB/sec for BSM transmission alone. BSMs are considered to be approximately 50 percent of the total messages thus the connected vehicle data requirement for the messages to be stored or transmitted is in the order of 6 MB/sec approximately 0.5 TB per day (for just this one location). There will need to be additional allowance for monitoring outgoing messages and various management functions of the RSE. Furthermore, other ITS devices (most notably streaming video from CCTV cameras at ~1MB/s for HD quality) are likely to be collocated and these will have their own substantial requirements for communication bandwidth.

The simplest scenario or use case around which to design traffic management systems, the communication links, and RSE is to assume that all messages could be forwarded to a central repository for analysis. Current communication networks owned by transportation agencies that connect to roadside equipment typically use fiber optics to a nearby hub and then copper to the local device. Such connections are often being upgraded to fiber optics to accommodate video.

An RSE equipped with a single strand of fiber can currently support up to 10 GB/sec using a hardened Ethernet switch, although 1 GB/sec is the more typical bandwidth for switches available today. Higher capacity hardened switches are under development, and it is estimated that they will be available within five years. Such switches would provide much higher bandwidth and likely support all message transmission requirements, but at considerable agency cost.

Communication networks are typically designed to operate at a fraction of the maximum capacity to allow for peaks in the demand for bandwidth. In the context of traffic management, these peaks for communications capacity will coincide with the peak travel periods in the morning and evening rush hours. Considering this, large data demand leads to the development of systems that can meet the needs of the users while minimizing communications. It is realistic to assume that when multiple RSEs are connected to a traffic management center or hub where all the connected vehicle and other types of messages cannot fit into a single communication link nor can current processing facilities handle such loads. In five to ten years from now, the bottleneck may not likely occur at the RSE (assuming a next generation RSE with additional storage and processing capability) but rather the TMC.



Source: Google 2017.

**Figure 1. Map. Dedicated short-range communications range.**

### ***An Approach to Minimize Communication Bandwidth***

The design that attempts to minimize the communication between the TMC, field hubs, and RSEs will require significant processing and capabilities at these peripheral devices to perform the necessary functions required and within the requirements specified in the system design. Such edge processing needs to distinguish between the real-time, near-real-time, and offline data to ensure the RSE is procured with the capabilities which satisfy its design requirements. It is not feasible or practical for systems to collect, use, and send all of the data generated by CAVs and connected devices.

One solution would be to enhance the capability of a RSE to receive, process and respond with the messages needed based on the condition or request for information from a CAVs or connected devices. The data that is collected, processed, and stored for *real-time* functions would need to be processed and used at the RSE. Similarly, the data that is used for *near-real-time* functions could undertake the same processes at lower priority. Data that is only needed for *offline* analysis could be stored in its raw form

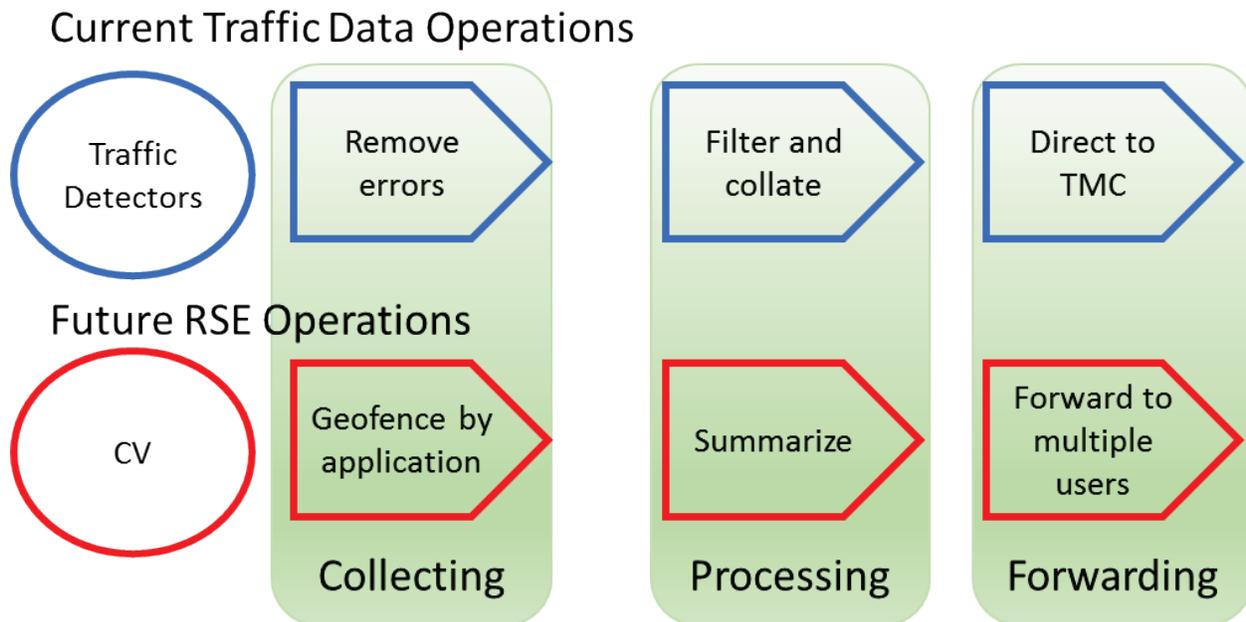
locally and submitted to the TMC when requested or on an established periodic basis. This concept of an agency designing and deploying a RSE with the capabilities necessary to meet the needs of the agency and connected devices is expanded on in the next chapters.

## 2.6.2 Data and Information

Throughout this report the terms data and information are used. Data refers to the bits and bytes of discrete elements within each electronic message. *Information* describes the result of processing data into a descriptive phrase (e.g., travel time) that is meaningful for some function. For example, the *data* indicating that a large number of windshield wipers are currently on can combine into the *information* that it is raining. The following subsections describe some of the key processes for turning data into information. After reading these subsections, the reader will understand that a significant level of data processing will need to occur at the RSE for real-time, near-real-time, and offline functions. Additional capabilities for data processing for *near-real-time* and *offline* functions will be needed at the TMC. Differences and similarities of the data processing requirements for each category of function (real-time, near-real-time, and offline) is described in each of the following sections.

## 2.6.3 Collect, Process, and Forward

The variety of messages, their frequency, and the geographical range of transmission means that an RSE could potentially receive a large amount of different types of electronic messages. The frequency, volume, and types of data to be collected will vary significantly when compared to the data typically collected by an ITS device. The objective is to collect, compile, and process the messages received to generate the data to meet the functional requirements of the system or intended users of the messages. There are two basic uses of the data. Firstly, the real-time and near-real-time needs of certain functions and secondly, archive data that will be used for offline functions. For each of these uses, the data needs to be cleaned, processed, and forwarded. These three functions are discussed in the following subsections.



Source: FreeAhead Inc. and Kimley Horn and Associates, 2018.

**Figure 2. Flow chart. Comparison of generic components of edge processing in current traffic data collection operations and future RSE operations with CAV and connected traveler data.**

### Collecting Data

Figure 2 illustrates the current processes that occur on the roadside and existing ITS devices and compares them with the processing that is likely to occur when RSEs with enhanced capabilities would be used to collect, process, and share information generated by CAVs and connected travelers. Currently the connection from an ITS device (e.g., an in-pavement sensor) to roadside equipment is often a direct physical connection. In some cases, there may be a local radio connection (e.g., a micro loop or sensor puck), however, the vendor product provides the connection making it transparent to the implementer.

The data collection and processing that occurs in current RSE devices is typically simple; data that does not meet the prescribed format is removed, repetitions are deleted, and error checking is undertaken. In order for an RSE to have the functional capabilities to collect, process, use, and share CAV and connected traveler data with different formats, additional processing will be needed. Firstly, there are multiple types of messages that will be received. The traffic management system design of this needs to accommodate all 15 message types, as well as other requirements of the RSE to support each real-time, near-real-time, and offline functions. It cannot be imagined what future uses will be made of the data and it is possible to envision functions that use every available message. Table 1 illustrates example usages for each message type.

**Table 1. Connected vehicle and connected traveler messages.**

Message Type	Example Usages
BasicSafetyMessage	Multiple V2V applications, traffic data, map generation, incident detection.
CommonSafetyRequest	V2V safety applications, measure of risk at intersections, nature of additional data requests for accident analysis.
EmergencyVehicleAlert	Tracking emergency vehicles, development of signal control strategies. Monitoring range of broadcast since emergency vehicles may have different broadcast power levels.
IntersectionCollisionAvoidance	Safety applications, signal control strategies, intersection design, and investment decisions.
MapData	When combined with BSMS can be used to enhance map accuracy.
NMEACorrections	Local corrections can be used to enhance accuracy of analysis.
PersonalSafetyMessage	Safety applications, risk analysis, origin destination studies. Determine local atmospheric conditions.
ProbeDataManagement	Multiple mobility applications
ProbeVehicleData	Mobility applications, divergent strategies, network management
RoadSideAlert	Can be logged to determine local environmental conditions such as icing.
RTCMcorrections	As National Marine Electronics Association (NMEA).
SignalPhaseAndTiming Message	Can be used in conjunction with probe data to determine current operation of traffic signals e.g., cycle failures.
Message Type—Continued	Example Usages
SignalRequestMessage	Can be used to optimize signal operations.
SignalStatusMessage	Provides priority when requested can be logged by RSE to determine operational effectiveness. Note signal controllers do not normally log data.
TravelerInformation Message	Monitoring traveler information.

*Source: SAE J2945.*

Since all messages contained elements that are potentially useful a ubiquitous design of a front-end parser that is sorting the data would be used. The data elements being parsed allows the capability of them being processed locally and forwarded to an application. In addition to parsing all the messages the initial cleaning process would verify the correct form of the message, remove duplicates, and apply any other verifications, such as security checks.

Some of the traffic management functions may need to apply geofencing at the RSE to assist with screening or limiting the data to be collected. Geofencing consists of drawing a boundary in software that defines an area of interest inside of which specific traffic management or data processing function can be performed. For example, a speed detector on a freeway may be a rectangle covering all lanes in which any BSMs may have this speed recorded and stored. Once the messages are parsed the position, heading and elevation will enable for the traffic management function or action to ascertain if a particular message meets its requirements for processing. In the complex example of figure 1, many geofences will be required to collect the correct CV generated messages for the many potential uses.

Connected vehicle messages are coded [5] in Abstract Syntax Notation One (ASN.1) which is a mechanism that defines the data structures at the interfaces between systems. SAE states “*This ASN.1 file is the precise source code used for SAE International Standard J2735. As part of an international treaty, all U.S. ITS standards are expressed in “ASN.1 syntax.” ASN.1 Syntax is used to define the messages or “ASN specifications.” Using the ASN.1 specification, a compiler tool produces the ASN library which will then be used to produce encodings....*”

Note again that message *formatting* is separate from the transmission media used to transmit the messages such as DSRC, WiFi, 5G, and cellular. Real-time applications require low-latency, high-bandwidth technologies such as DSRC, 5G wireless, and WiFi transmissions and thus the connected vehicle messaging standards have been designed for these purposes. Similar cleaning, processing, and forwarding issues apply with functions enabled with cellular communications but other message encoding formats may be more appropriate. These differences will be discussed further in chapter 3.

The BSM data will form the vast majority of the connected vehicle data. The main data frame of the BSM is the BSM core data element that is defined in the standard as:

```
BSMcoreData ::= SEQUENCE {
    msgCnt      MsgCount,
    id          TemporaryID,
    secMark     DSecond,
    lat         Latitude,
    long        Longitude,
    elev        Elevation,
    accuracy    PositionalAccuracy,
    transmission TransmissionState,
    speed       Speed,
    heading     Heading,
    angle       SteeringWheelAngle,
    accelSet    AccelerationSet4Way,
    brakes      BrakeSystemStatus,
    size        VehicleSize
}
```

There are many uses for this list of data elements as discussed in chapter 2 of FHWA-JPO-18-625 *Opportunities for Integration of Emerging Data for Transportation Systems Management and Operations* even though the message and its elements were primarily designed for safety applications. The *MsgCount* data element is used to provide a sequence number within a stream of messages with the same *DSRCmsgID* and from the same sender. The receipt of a nonsequential *MsgCount* value (from the same sending device and message type) implies that one or more messages from that sending device may have been lost. The *TemporaryID* allows the user of the data to create vehicle trajectories. The *TransmissionState* provides additional input to safety applications in the receiving OBU. For example, steering wheel angle can provide input to map correction applications and be an indicator of loss of vehicle control when compared with the heading. The *AccelerationSet4Way* data element is three dimensional plus rate of yaw. Linear acceleration and brake status can provide input to incident detection algorithms and vertical acceleration can provide input to highway condition monitoring functions. *VehicleSize* can aid in traffic classification counts.

### **Processing Data**

As discussed previously, traffic management systems currently use different type of detectors (e.g., video, radar, Bluetooth) to collect the data at the locations necessary for a specific traffic management function, operational strategy, or control plan. The primary source of data for these systems is from detectors which typically measure if a particular zone of the roadway is occupied in a binary fashion 10 times per second. This raw data is then processed to provide occupancy percentages or a binary presence indicator for each second.

The local traffic controller or roadside unit will process multiple values and average them to get an occupancy value at one zone for many seconds and/or it will process the beginning time of each event as input for a speed calculation. Current Bluetooth detectors process the MAC (Media Access Control) addresses (A MAC address is a unique identifier of a piece of networking equipment, such as a SIM card or Bluetooth chip in a smart phone or a network interface in a laptop. Where the IP address of a particular device can be changed to suit a particular network addressing scheme, a MAC address is a permanent identifier of the equipment that typically cannot be modified after manufacture) are sorted and duplicates removed. However, some systems use the number of Mac addresses and the duration of the occupancy at the detector as a source of additional traffic data. Similarly, the data is summarized over a short time period, saved, and transmitted to the TMC.

There will need to be significant processing within an RSE under a connected vehicle environment. Assuming the cleaning data processes has occurred, the input will consist of J2735 messages. These will be very variable in both type of message and length. The J2735 standard accommodates these variable length messages. However, this implies that the designer needs to be aware that there are likely to be more messages needed to produce the required number of data elements. For example, if only 33 percent of vehicles report longitudinal acceleration and if your application needs say  $n$  deceleration readings in a cluster to trigger an incident alarm then you will likely need at least  $3n$  readings.

If there are a substantial number of connected or automated vehicles or devices, it may not be possible for one RSE or detector to collect and forward all the received messages to a field hub or the TMC. The near-real-time data that is needed immediately by a traffic management function the RSE conducts or by a vehicle or connected device may require to be filtered, compressed, or concentrated in some manner in order to also be transmitted to the TMC with minimal latency.

### **Forwarding Data**

Within current systems, near-real-time data needs to have no higher resolution geographically than is needed traffic management functions which use the data. For example, if a freeway incident management application is monitoring vehicle trajectories to determine specific braking points within a section of freeway, the resulting action when an incident is detected to be severe enough is for the TMC to notify emergency services who deal with the incident. The position of the incident will be reported by the media and crowd sourced information providers. The data will also be used by other agencies, for example, environmental agencies associated with hazardous materials spills.

Navigation systems will read the data and provide advisory messages to drivers concerning re-routing. There would probably be no users of the data that would require location accuracy of perhaps 50 meters, however, there are many users including the information providers, directed motorists, who would want to know in which lane the incident occurred. The requirements for forwarding and sharing of information from the connected vehicle data will be different depending on its use in real-time, near-real-time, and offline functions.

After reading these subsections, the reader should understand that cleaning, processing, and forwarding connected vehicles and connected traveler data are all necessary elements of the design of the RSE and associated systems at the TMC. Connected traveler data from pedestrians is also an important element to consider in the design of future RSEs. Some unique requirements may result from large-scale collection of such information and a short discussion of such issues is provided in the following section.

### **2.6.4 Pedestrian Data**

The Personal Safety Message (PSM) is used to broadcast safety data regarding the kinematic state of various types of Vulnerable Road Users (VRU), such as pedestrians, cyclists, or road workers. SAE J2945-9 is the Vulnerable Road User Safety Message Minimum Performance Requirements. The definition VRU, in addition to pedestrians, includes wheelchairs, cyclists, and other vulnerable categories.

Receiving and processing of PSM data will also add complexity to the processing that may be required in the RSE. The information gathered from these messages will likely be used to support different traffic management and control functions carried out at nearby traffic signals or used to determine what messages may be appropriate to be distributed to connected mobile devices within range. The potential to collect, process, save, and share information with connected mobile devices is important to the discussion concerning edge processing and the capabilities which may be needed in the RSE and communication system needs to share information with a local hub or traffic signal or a the TMC. The RSE will also need to have the capability to collect, process, save, and share information for messages specific to connected mobile devices (e.g., PSM, Personal Mobility Message (PMM)) while also processing and distinguishing between messages received or sent to connected and automated vehicles.

In summary, data from connected vehicles and connected travelers will need to be cleaned, processed, and forwarded appropriately for real-time, near-real-time, and offline functions.

The goal of the design of the system architecture will necessarily be to reduce the communications load between the RSEs and the TMC to reduce cost and increase efficiency while meeting the objectives of the functions which use the information from the emerging data sources. Support for at-scale data collection and dissemination of information to VRUs adds additional complexity, which must be addressed

in the future. In the next section, system architecture options are discussed for integration of the data from connected vehicles and travelers with traffic management and TMC functions.

## 2.7 Traffic Management System and Center Design and Architecture Options

FHWA-JPO-18-625 *Opportunities for Integration of Emerging Data for Traffic Management and TMCs* describes how different big data related tools and techniques could be integrated within a single traffic management center in support of improving its performance, reducing costs, and minimizing the maintenance and operational costs of the agency. This description is repeated here together with the diagram illustrating the range of different tools which could be considered and the supporting data that would be exchanged between different TMC components. After reading this section, the reader will understand that the data cleaning, processing, and forwarding functions of the system will need to be appropriately distributed between the RSEs and the systems at the TMC.

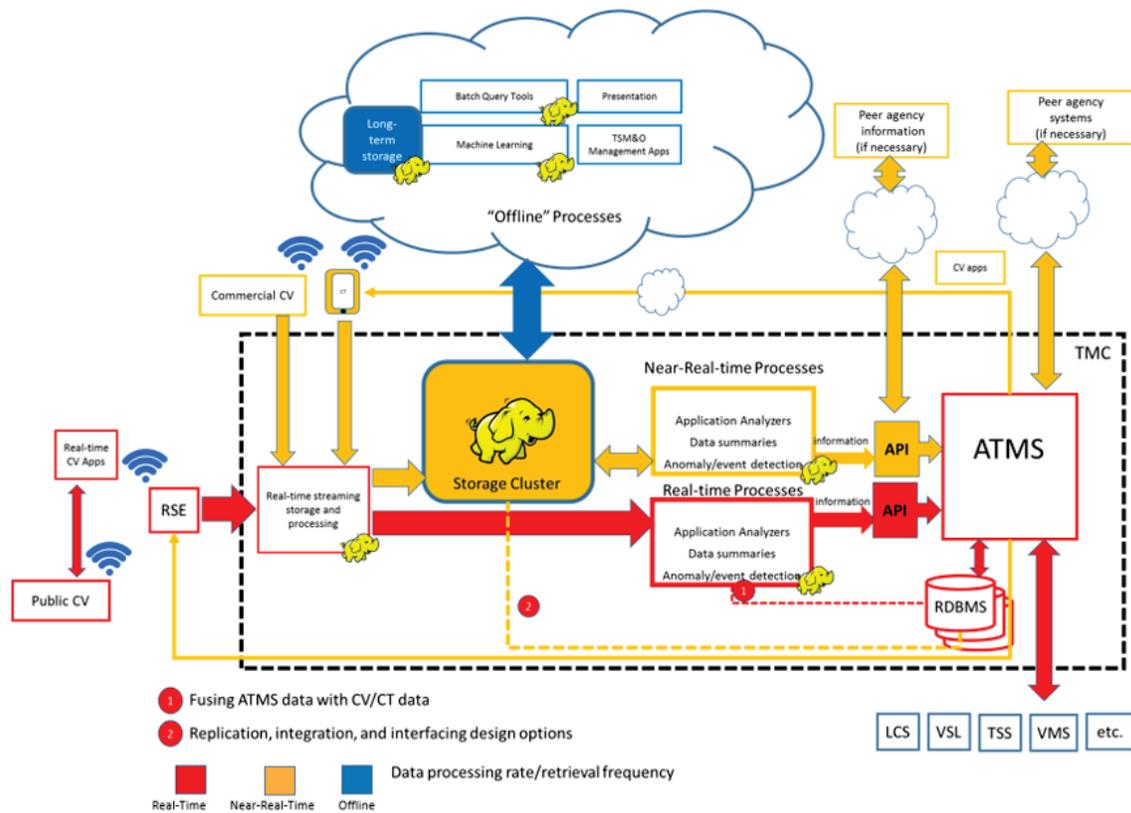
### 2.7.1 Conceptual Data Processing Architecture for TMC Functions

In figure 3, color is used to indicate data temperature or need for real-time, near-real-time, and offline data transmission and processing. Using the same definitions as earlier those shown in **red** are *real-time* components. Red lines and red boxes represent software components and data flows that process real-time data and have control actions that need to be taken within seconds. **Orange** components and arrows are *near-real-time* components. These elements have need to process data quickly and take actions on the order of minutes. **Blue** arrows and software components are *offline* elements.

These elements can process data on-demand, in batches, or even in daily updates. Components shown with the **yellow elephant icon** (the mascot of the Hadoop Distributed File System (HDFS)) are members of the big data ecosystem. These are the new technology elements that will be necessary to harness the value of the emerging data sources. These components are specifically designed for acquiring, storing, and processing massive data sets.

The components of this conceptual system will be discussed starting from left to right. As is typical in current system or TMC architecture, data from field equipment is usually brought back to the agency's Traffic Management Center through wire-line and/or wireless communication networks. It is assumed that messages received or sent via agency-owned RSEs will be connected to the system by this same communications network.

Connected and automated vehicles and connected mobile devices will exchange messages with agency RSEs, a Basic Safety Message, Probe Data Message, PSM, and other types of messages will be collected through the RSEs and the information processed will be transmitted to the TMC as they are received. We assume that *connected traveler* and *connected vehicle* data may also be delivered through cloud Application Programming Interfaces (API) to the TMC. Regardless of the communication system method used to send and receive data between the TMC and RSE, data will be shared in near-real-time. We represent this data being acquired by the same component as the data from the RSEs.



Source: FHWA-JPO-18-625, 2017.

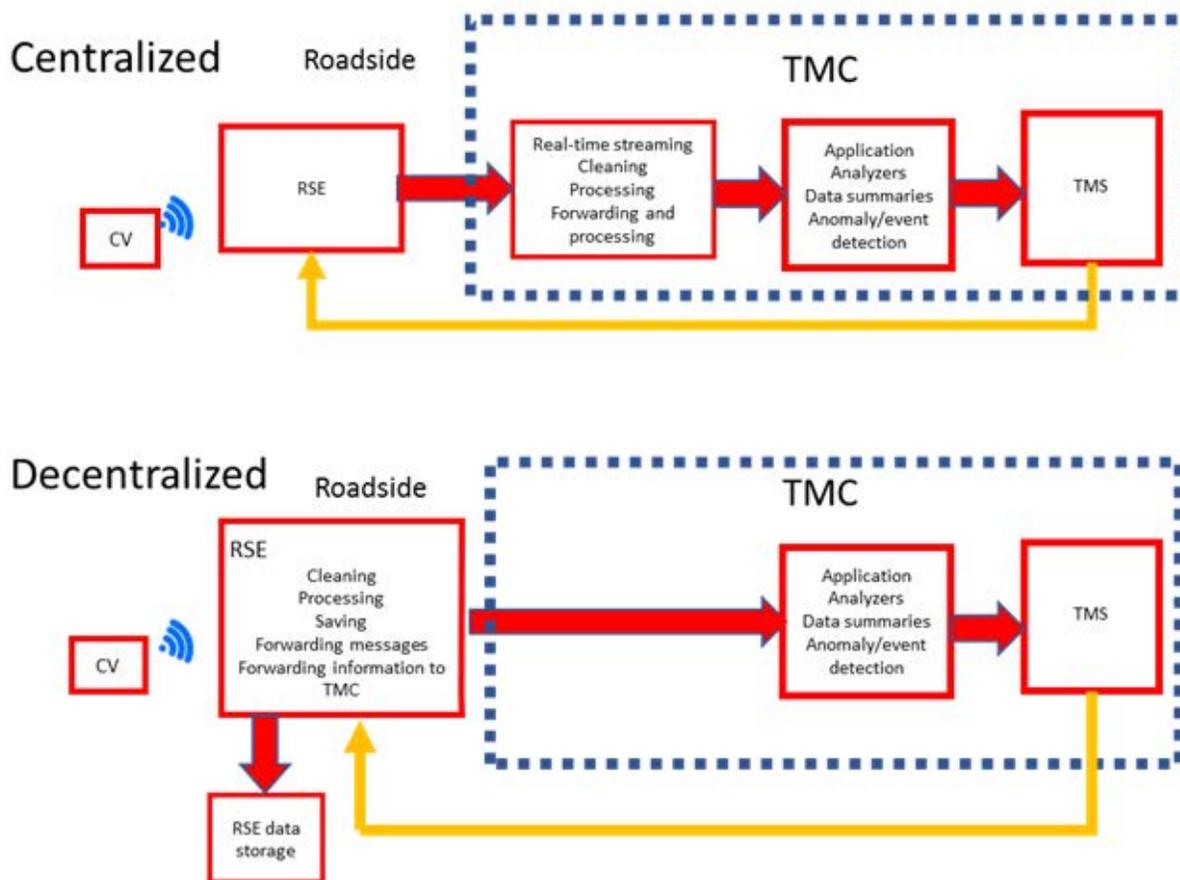
**Figure 3. Diagram. Big data tools integrated into a traffic management center.**

For the purpose of this illustration, we will assume that existing traffic management systems and TMC are represented as a single component (whereas in reality there are typically several and sometimes many back-office applications that constitute the TMS or TMC). This section will discuss in more detail the components of the systems architecture that provide the collecting, processing, saving, and forwarding of the data between the system and RSE. These processes take place on the edge that may be conducted in the RSE is on the left side of the diagram.

As the CAV market penetration increases, the design of traffic management systems and TMCs will need to have the ability to collect, compile and save information to improve traffic management functions. Figure 4 shows how a typical design where collected data is processed first at the roadside and then sent to the systems central control or TMC to further compile, process, save, or share. This design alternative requires significantly more communication system capacity and processing at the TMC than would be required at the roadside. This processing is defined in more detail in the later chapters of this report.

Figure 4 illustrates a design alternative which requires decisions being made on messages to share or the collection, processing, compiling, and sending information to the TMC. In a centralized approach, the RSE will forward relevant messages to the TMC. This is likely untenable due to the many issues discussed previously. A decentralized approach is likely required where much most of the data processing of the messages is done on the RSE and then forwarded to the TMC in the formats expected by the TMS API. The

specific interfaces between RSEs, the real-time streaming component, the analyzers, data summaries, and anomaly detection functions will need to be specified in the near future to prepare the information for use by legacy traffic management systems. This translation of the information from the new sources into formats that the legacy TMS can understand is encapsulated in the API box on the right-hand side of Figure 4.



Source: FreeAhead/KHA, 2018.

Figure 4. Diagram. Illustration of traffic management system design options.

## 2.7.2 System Design Options to Enable Capturing and Sharing More Information

There is a potential for different system design options to enable capturing, using and sharing more data. One example would involve a three-level architecture whereby multiple RSE are connected to local hub which is connected to the central system or TMCs. For example, when a system may have a significant number of RSEs these could be grouped in such a manner they can provide data to mid-level “hubs” that are located on high capacity communication system. This option may be an appropriate solution to minimize the communication requirements for the system by limiting the data that is required to be sent and received with the traffic management center.

This option may also be a solution where the data desired to be obtained is a long distance from the sources are a long distance from where the TMC where the traffic management functions are being run and decisions made on actions to be implemented. For example, if a State has only one traffic management center, a series of remote hubs (or virtualized hubs in a cloud-based solution) could then undertake some of the compiling and storage functions which would otherwise be required in either the RSE or TMC. However, the rationale for this design option is that it would be positioned to collect, process and save more data while minimizing the communication requirements, meeting the performance expectations of all system components, and being more cost effective to develop, operate, and maintain.

There are examples of legacy traffic signal control systems that use a three-level architecture. In this case an on-the-street master controller coordinates the operation of a series of controllers usually that are physically close to the master controller and have a communication connection to send and receive data and commands. The system design is to optimize travel (e.g., cycle length, offsets of signal timing plan) at each intersection and along the network or facility the signals are coordinating. In such systems, there is usually a central system that has multiple on-street masters under its control, where the central system shares information and coordinates their operation.

In the case of a traffic management system hub it may be feasible to simplify the requirements, design and cost of individual RSEs in a similar manner to a store and forward functionality and move the edge processing discussed in this report to the hub. Such a design and architecture approach would necessitate that both the hub and the traffic management center would be able to carry out the required traffic monitoring and management functions given the communication system connectivity and the ability to manage and coordinate between multiple hubs. In either case of a two-level or three-level architecture, the information from emerging data sources will need to be translated into data summaries and formats that the legacy TMS components can consume. This topic is discussed in more detail in chapter 3.

## **2.8 Business Case for Collecting, Using, Saving, and Sharing Data From Emerging Sources**

Local agencies such as cities and States that operate traffic management systems and TMCs have the opportunity to consider collecting, using and sharing data from a variety of emerging sources (e.g., connected vehicles, automated vehicles, connected mobile devices, crowd sourced) of data. Traffic management centers run by States typically rely on data obtained from some combination of traffic detectors, video surveillance, and reporting (e.g., 911 calls, other systems, police, and service patrols). Traffic management centers that are operated by cities typically run traffic signal control systems, are smaller and use fewer staff, and in some cases the TMC or central system is simply a set of workstations or application software on users' computers.

Cities and States do not generally develop software platforms for these systems. Rather they specify the functions and capabilities and procure their central system software through private vendors. Agencies may, in the process of procuring new or upgrading existing software, identify or specify new functionality or services to be supported by the software being procured. However, agencies almost always procure software that is developed by private companies which have limits on the use of the software, agencies are not able to make changes to the software, and the details of how many of the functions are carried out are often proprietary and not shared. Current software procurements for traffic management systems and TMCs are responded to by a handful of companies out of perhaps less than 20 viable competitors.

Even when a State has chosen to develop unique software and make publicly available so it may be enhanced (for example Maryland's CHART [6] and Georgia's NaviGator 511 [7]) by others, the software itself is developed by contractors and has limited documentation or did not use commercially available off-the-shelf or open-source software which is easy for other companies or agencies to modify. Public agencies have neither the staff nor the budget to develop such systems. The companies developing the software attempt to spread their development and maintenance cost across multiple procurements or agency directed and procured updates. As new technologies, techniques, and devices become available the manufacturers incorporate them into their products by funding this work through contracts with public agencies and then adding these features to other public agency procurements or upgrades paid for by current users.

## 2.8.1 Value Proposition

### *The Market*

The latest ITS Deployment figures from USDOT [8] indicate that of all of the 72,000 freeway centerline miles, only 17,000 report collecting real-time data, and 5000 miles operate managed lanes. There is little public agency information made available on arterial roads and only 23 percent of freeways have traffic monitored by TMCs. Private sector companies (TomTom, Garmin, Google, and others) continue to provide traveler information through their software applications which require download and use on a connected mobile device (e.g., tablet, smart phone, in-vehicle display). Currently these commercial systems have varying degrees of geographic coverage and often lack accuracy and timeliness of the information or events they report.

It is possible that these different traveler information service providers will be able to develop products that incorporate the use of data from emerging sources (e.g., connected vehicles, automated vehicles, and mobile devices) and provide services to both the users of these vehicles, devices, public agencies, or the traveling public. There are already joint developments between Bluetooth and DSRC vendors, for example, to make hybrid hardware/software products, and chip manufacturers are developing V2X products.

From the perspective of nationwide or even global companies, the market is so much larger than that available to highway agencies that they can have a valid value proposition for their products. This should be considered when defining what will be the role of the public agencies. As the developer and implementer of the RSEs the agencies will have the opportunity to determine how the data from their devices is collected, saved, used, or shared.

### *Future Operations*

The expected capabilities of the next generation of traffic management systems and centers should allow agencies to expand the systems area of coverage, enhance their active management and operation, share more information, and maintain or lower systems operating and maintenance costs. Connected vehicles and automated vehicles will provide data that will offer the opportunity for public agencies to:

- Expand their geographical coverage from the current areas, which are typically restricted to urban freeways and often only those parts that are congested or where they have telecommunication system deployed.

- Monitor travel conditions and detect incidents or unstable flow conditions in a timelier manner.
- Respond to incidents more efficiently if more information is available on the location and type of disabled vehicle and/or incidents occur.
- Emergency services to respond more accurately as they will be provided with information concerning the incident and the state of the vehicle.
- Proactively manage and control traffic based on current and projected travel conditions.
- Provide current and projected travel condition information to connected and automated vehicles.

Since the data from RSE's will not distinguish the city owned streets from the State-owned freeways there may be potential opportunity to combine city and State operation. This provides new coordination and control opportunities such as those used in the United Kingdom whereby the traffic signals at the top of freeway ramps are used to meter traffic onto the freeway from a single management center.

Future operations will also have the potential to incorporate the ability to use data from connected vehicles, automated vehicles, and other sources for new applications, such as surface condition monitoring, using the vertical acceleration of the wheels of connected vehicles, or gathering data from the vehicle to determine local weather conditions in the range of other applications that are discussed in subsequent chapters.

# Chapter 3. Data Collection

This chapter introduces the specifications and standards for CAV and connected traveler messages, and lists the range of messages and data elements expected to be available that a RSE may receive, send, process, and share. This chapter also includes description of the probe data and vehicle management process and how this data could be used by a traffic management system or TMC. Various current uses of RSEs are described, compared, and contrasted in this chapter.

After reading this chapter, the reader will understand the components of messages to be received from and shared with connected and automated vehicles. Chapter 4 will then build upon this content to discuss issues related to the compilation and storage of the information from RSEs at the TMC.

Chapter 3 is organized as follows:

- Discussion of connected and automated vehicle messages and formats.
- Discussion of data elements within the messages.
- Discussion of communication options for different types of messages.
- Detailed discussion of the probe data message and the probe data management process.
- Descriptions of current implementations of RSEs relative to message handling, data processing, and sharing and implications for future RSE and system design.

## 3.1 Connected and Automated Vehicle Messages

In general, messages exchanged between connected vehicles, connected travelers, RSEs, and the traffic management system or TMC have several basic purposes:

- Identifying the current location, speed, heading, and other detailed status data (e.g., windshield wipers on or off) of a vehicle, pedestrian, cyclist, or other conveyance.
- Request for a certain action to be taken by an infrastructure element, a vehicle, or another traveler.
- Information related to an action taken by an infrastructure element, another, vehicle, or another traveler.
- Configuration data related to infrastructure geometry and controls.
- Current information or advisories regarding the environment, such as travel conditions or weather.

These generic types of messages have been codified into standard message types over the last 15 years as connected and automated vehicle technology has been deployed to support traffic management functions. These standards are critical to enable the efforts of public agencies planning and enabling traffic management systems that share messages from a wide variety of vehicles from different OEMs, aftermarket OBUs, and connected traveler devices. Without such standards, the effort required to enable such data sharing would increase significantly if each OEM, device, and aftermarket OBU used different message types and formats.

It is assumed in this report that the messages exchanged between connected vehicles, connected travelers, RSEs and the TMC will adhere to existing standards. Although connected vehicles may be joined to the infrastructure using a cellular service, WiFi, 5G, or satellite rather than dedicated 5.9 GHz, the messages will still conform to the J2735/J2945 data dictionary and formats.

### 3.1.1 Vehicle-to-Vehicle and Vehicle-to-Infrastructure Data Dictionary

The J2735 Standard specifies a message set, and its data frames and data elements for vehicle-to-vehicle and vehicle-to-infrastructure data exchange. This is commonly referred to as a “data dictionary.” Although some portions of this standards are specifically focused on DSRC, the message set, and its data frames and data elements, have been designed, to the extent possible, to be of potential use for applications that may be deployed in conjunction with other wireless communications technologies such as WiFi, 4G/5G, satellite, and legacy cellular. This Standard therefore specifies the definitive message structure, encoding, and provides sufficient background information to allow readers of the standard to properly interpret the message definitions from the point of view of an application developer implementing the messages [9].

### 3.1.2 Vehicle-to-Vehicle and Vehicle-to-Infrastructure Data Exchange Protocols

The scope of the J2945 Standards is the information exchange between a host vehicle and remote vehicles, and between a host vehicle and the roadside, to address safety, mobility, and environmental systems. This standard provides performance requirements, recommended practices, use cases, and a variety of implementation processes and issues to be considered to support the systems being able to send and receive these messages. These processes are separate from the J2735 standard such that it remains purely a data dictionary. Thus, J2735 specifies *what is transmitted* and the suite of Standards in J2945 defines *how the data is handled*. As stated previously, both J2735 and J2945 are largely agnostic to the communications media being used to transmit the messages, except where the details of DSRC channelization and radio operation are concerned. The message formats and data elements within each message are not directly related to the communications media used to transmit them.

The J2945 suite of standards is in active development. Those that are being worked on include:

- J2945/0 DSRC Common Performance Requirements.
- J2945/1 On-Board System Requirements for V2V Safety Communications.
- J2945/2 DSRC Requirements for V2V Safety Awareness.
- J2945/3 Requirements for V2I Weather Application.
- J2945/4 DSRC Messages for Traveler Information and Basic Information Delivery.
- J2945/6 Performance Requirements for Cooperative Adaptive Cruise Control and Platooning.
- J2945/9 Performance Requirements for Safety Communications to Vulnerable Road Users.
- J2945/10 Recommended Practices for MAP/SPaT Message Development.
- J2945/11 Recommended Practices for Signal Preemption Message Development.
- J2945/12 Traffic Probe Use and Operation.

J2945/0 serves as the parent document for the J2945/ family of standards. It contains cross-cutting material which applies to the other J2945 standards, including guidance for the use of Systems Engineering (SE) and generic DSRC interface requirements content.

### 3.1.3 SENSORIS

SENSORIS is a European based standard that gathers data from vehicle sensors that currently exist in multiple different formats and provides a standardized interface such that vehicle data can be sent to the cloud for processing and analysis. It is being sponsored by ERTICO—ITS Europe which is Europe's ITS organization that promotes research and defines standards.

The SENSORIS specification [10] defines a series of sensor data messages and in what format they are encoded when submitted to the cloud for analysis. Such sensor data messages are related to one or multiple locations. The messages are time stamped to allow the user to determine whether these are real time or not. The messages contain information about the manufacturer, one company can for example have different values for different purposes, such as production group. The data elements include the physical aspects of the vehicle, fuel, path taken, events, vehicle dynamic information, signs and lanes recognized, proprietary information, environmental status, vehicle lane, and other elements, many of which are also included in J2735. One concept that is different in SENSORIS than J2735 is "Path" which defines a list of position estimates starting with the oldest which can be either short, or up to many hours where the vehicle data can be submitted much later as a delayed/batch submission.

The use of the SENSORIS standard data is predominantly associated with the manufacturer's sensors and their requirements to share data. Virtually all manufacturers are now global organizations and therefore this standard and its later developments should be harmonized and included with vehicles deployed within the U.S.

## 3.2 Data Elements

The data that is available within a connected or automated vehicle will vary by vehicle manufacturer, model, year, installed options, and other factors. The messages that can be shared with different types of vehicles, RSEs, and connected mobile devices will vary as well. Compounding this complexity will be the potential for aftermarket products that will provide a limited subset of what is available. It is assumed all of the current data elements that are incorporated into the latest published version of SAE J2735 will be available in some vehicles, but it is unlikely that any vehicle will have all of the data elements and most vehicles will only have some subset.

The source of the data elements included in the SAE J2735 Standard were originally derived from the Automotive Multimedia Interface Collaboration (AMI-C) [11] which as released in 2003 as a complete series of technical specifications to promote the standardization of common automotive information and entertainment system interfaces for motor vehicle communication networks. Since that time there have been significant additions designed to incorporate the data needs of the safety, mobility, and environmental applications that are under development.

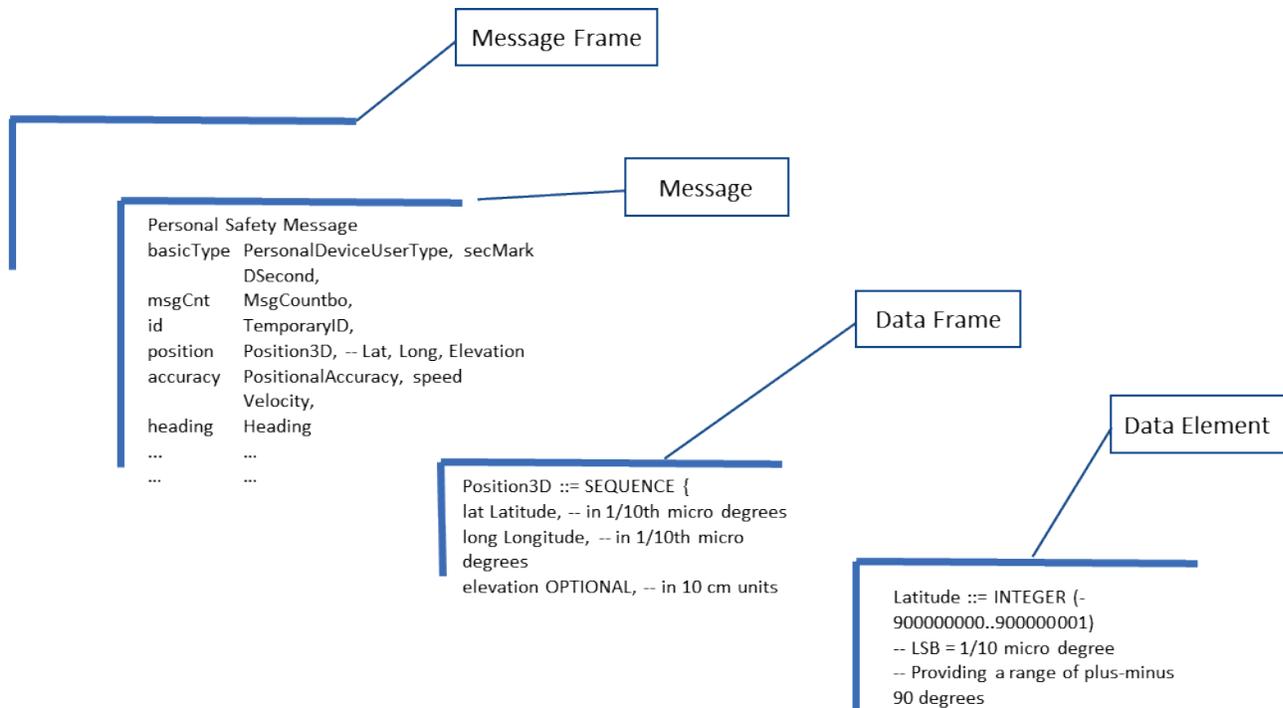
The latest version of standard is SAE DSRC Message Set Dictionary J2735-2016-03 [12] (Note again that the use of DSRC in the name of this standard does not indicate the messages cannot be conveyed over other communications media such as 5G, WiFi, cellular, or satellite). The standard comprises of a data

dictionary that is used to define the messages both V2V and V2I for both connected and automated vehicles. The physical and MAC layers of the transmission are defined in the IEEE (Institute of Electrical and Electronics Engineers) standard 802.11. The data that is transmitted is contained in a message frame that can hold both messages and regional information. Within each message there are data frames that are a collection of data related to each other as a group. These are referred to as *data elements* which are the smallest unit that is used.

There are 15 messages associated with data transfer for V2V or V2I in the Message Set Dictionary (J2735-2016-03):

- BasicSafetyMessage (BSM).
- CommonSafetyRequest (CSR).
- EmergencyVehicleAlert (EVA).
- IntersectionCollisionAvoidance (ICA).
- MapData (MAP).
- NMEAcorrections (NMEA).
- PersonalSafetyMessage (PSM).
- ProbeDataManagement (PDM).
- ProbeVehicleData (PVD).
- RoadSideAlert (RSA).
- RTCMcorrections (RTCM).
- SignalPhaseAndTiming Message (SPAT).
- SignalRequestMessage (SRM).
- SignalStatusMessage (SSM).
- TravelerInformation Message (TIM).

Other message types are also currently in development to support more V2V and V2I use cases. There are 156 data frames that may be contained in these messages, and 231 data elements that may be contained in the data frames. This structure is illustrated in figure 5.



Source: FreeAhead Inc. and Kimley Horn and Associates, 2018.

**Figure 5. Diagram. Standard message frame, message, data frame, data element illustration.**

As an example, figure 5 illustrates the message structure for a Personal Safety Message (PSM). The message frame allows the user to add regional information that might apply to a particular message. The message contains multiple data frames, the third of which is, for example, *position3D*. This data frame is shown in the next box and contains two mandatory elements (latitude and longitude) and one optional element (elevation). One mandatory element (latitude) is shown in the last box. Thus, a message by definition typically contains many data elements.

### 3.2.1 Basics of Roadside Equipment Operation

As introduced in chapter 2, a RSE is a complement of equipment at the roadside that will prepare, receive, and transmit messages to support the sharing of messages with CAVs, connected mobile devices, and other emerging sources of data. RSEs will likely be generally installed with other ITS devices to take advantage of power supply and communication systems, and other infrastructure-related facilities (e.g., traffic control cabinets).

The RSU component of the RSE could include at least one and possibly more 5.9 GHz DSRC radios, or similar roadside to vehicle radios such as WiFi or 5G. These radios support the low latency SAE J2735 Safety Messages in addition to the other message types. They also support the security credentials and management or allowed use of an important part of the connected vehicle. The RSUs communicate with the OBU that is in the equipped connected vehicle. The definitions of how RSUs communicate, frequency allocations, power levels, etc., specific to DSRC are defined in the FCC regulations [13]. Related standards for WiFi and 4G, etc. are maintained in other standards. The mechanisms by which the data is

transferred are defined in a series of IEEE standards [14]. The data dictionary of the messages that are transferred V2I and I2V are defined in the SAE standards [15].

### 3.2.2 Dedicated Short-Range Communication Range

When agencies consider using RSEs for their systems to send and receive messages with connected vehicles and travelers specifically use DSRC for communications, there are a variety of issues that the reader of this report should understand. Most important among the issues to consider when selecting DSRC as the method for message transmission is the range of communications between the RSE and the mobile data sources. There are a variety of factors that influence the range of DSRC transmissions including:

- The height of the antenna; on typical vehicles this can vary between low sports cars and large trucks. The radio propagation is affected by horizontal objects, particularly other vehicles in between one antenna and another.
- Antennas do not provide a uniform circular pattern when attached to a range of vehicles thus the range can be a function of the direction to the other antenna.
- 5.9 GHz has significant path loss and channel fading as a result operating at a high-frequency, particularly when the distance between antennas is significant and the number of transmitters on the channel becomes high.
- Operations at high frequencies are significantly affected by weather conditions, particularly rain and snow, which can significantly attenuate the signal.

DSRC is a line of sight communication system, which by definition limits the range according to surrounding vehicles, buildings, etc. Although its low latency makes it suitable for safety applications, different communication technologies such as cellular and WiFi can be used to send less urgent messages. Although SAE J2735 Messages are not restricted to the use of 5.9 GHz radio systems this chapter discusses issues related to DSRC communication mechanisms.

There have been a number of researchers that investigated the properties of 5.9 GHz DSRC for vehicle communications. The University of Alberta [16], for example, designed and tested a DSRC system. They concluded the following:

- During V2V testing with one stationary vehicle and the other vehicle moving, the DSRC connectivity had an effective range of 230 m (754 feet).
- For V2I, the average range was found to be 410 m (1345 feet).

The University of Auburn conducted research [17] on DSRC performance and measuring transmission characteristics over the range of distances 150, 300, 450, and 750 feet during sunny and rainy conditions. They found a reliable connection at 750 feet only during good weather conditions. During rain at 750 feet DSRC exhibited considerable data loss. They concluded that the maximum range of DSRC of 750 feet was reduced to 450 feet by rain.

Another of the issues that can arise is communication nulls, when interference between the signal reflected off the road and the signal received directly causes the received signal to drop. This was investigated by Honda [18], who developed a model to predict the power drop between two moving vehicles. Their results indicated they could gather data up to 1 km, however, there was significant signal

degradation of this distance. For the purposes of this report and analysis of received data, it is assumed that RSE's range is 300 m.

### **Range Deficit**

When a connected vehicle approaches an RSU and both the RSU and the OBU are operating at similar power levels the range of the RSU is often greater than the OBU. The RSU will often have a more effective antenna due to its height and design. There are several factors effecting power levels including signal reflections, multipath issues, and that the OBU is moving. This results in the OBU receiving a message, but its subsequent response does not reach the RSU. DSRC is a broadcast only system. Individual communication links are not supported and there is no facility for acknowledgments. This transmission range imbalance and can be compensated for by such mechanisms as repeating messages, monitoring power levels, and possibly antenna design.

### **3.2.3 Basic Safety Message**

As introduced in chapter 2, the basic safety message (BSM) is a message that is designed to support connected and automated vehicles sending and receiving messages in support of ensuring the safety of the completion of its trip. The BSM consists of a data frame titled BSMcoreData. This frame is always included in the message. There are multiple extensions which can be requested by other vehicles, however, from the perspective of the use of the data by the infrastructure ta, the focus will be on the BSMcoreData which comprises:

- **MsgCount**—used to determine if a message has not been received.
- **TemporaryID**—used to create vehicle trajectories can be randomized occasionally to prevent tracking.
- **DSecond**—time in milliseconds from known to the user community.
- **Latitude, Longitude, Elevation.**
- **PositionalAccuracy.**
- **TransmissionState**—the current condition of the vehicle's transmission neutral park etc.
- **Speed.**
- **Heading.**
- **SteeringWheelAngle**—could be used to compare with heading determine if skidding.
- **AccelerationSet4Way**—three orthogonal directions plus yaw rate.
- **BrakeSystemStatus**—brake applied status, plus ABS status, plus brake boost, plus traction control.
- **VehicleSize**—length and width.

The list above will comprise of the vast majority of connected vehicle data that will be available if it is collected by traffic management systems and TMCs. Each of the data elements is designed with the primary objective of sharing information with other vehicles. These data elements and how they are shared are not designed to provide information to support traffic management systems, consequently, the BSM messages will need to be manipulated prior to being able to use specific data elements for various traffic and travel management functions.

The BSM, by default, will be transmitted 10 times per second. In circumstances of heavy radio signal congestion on the transmission channels, the frequency of transmission may be reduced. The messages are broadcast to all within range and the nature of the transmission is not alterable by any infrastructure components.

### 3.2.4 Other Message Types

As listed at the start of section 3.2, there are many other message types that can be shared from vehicles and travelers to the RSE and vice-versa. The following messages can also be transmitted from an OBU to the RSE:

- CommonSafetyRequest (CSR).
- EmergencyVehicleAlert (EVA).
- PersonalSafetyMessage (PSM).
- ProbeVehicleData (PVD).
- SignalRequestMessage (SRM).

The following messages can be sent from the RSE to connected vehicles and travelers:

- EmergencyVehicleAlert (EVA).
- IntersectionCollisionAvoidance (ICA).
- MapData (MAP).
- NMEAcorrections (NMEA).
- ProbeDataManagement (PDM).
- RoadSideAlert (RSA).
- RTCMcorrections (RTCM).
- SignalPhaseAndTiming Message (SPAT).
- SignalStatusMessage (SSM).
- TravelerInformation Message (TIM).

The MAP, NMEA, and RTCM messages are static messages broadcast by the RSE that are not affected by collection of messages from connected vehicles and travelers. The SPAT message provides the current status of a traffic signal or ramp meter and is not affected by and RSE or other ITS device collecting messages from connected vehicles or travelers. In general, the data collected from the BSM and PVD messages are most important for the majority of the TMC and traffic management functions presented in chapter 2. Collecting, processing, and summarizing this data using edge processing approaches at the RSE and then sharing the information with the relevant algorithms and functions at either the RSE or at the TMC will result in the RSE being able to send out messages back to connected vehicles and travelers (EVA, ICA, PDM, SSM, TIM).

### 3.3 Data Collection Issues

DSRC, 5G, or WiFi can be used to collect connected vehicles and connected travelers data within range of the RSE. Thus, there will be potential overlap between data collected by traffic signals and traffic management systems. Although geofencing will be necessary at some part of the processing, prior to a specific function's use of the data, it will be coalesced into a group that is not neatly divided in the same manner that current systems collect, process, and store data by each system.

The associated complexities with collecting, compiling, and using specific data elements can be gained by considering figure 1 (section 2.6.1), as well as considering the current use of passing Bluetooth and WiFi devices as data sources. For example, the Bluetooth readers that are installed at intersections collect readings from the needed passing vehicles, vehicles passing in the opposite direction, mobile travelers walking around, busloads of tourists with multiple phones, etc. These complications can cause significant confusion and the need for early processing in order to separate data into the categories required by the specific functions. This requirement for processing leads to RSEs needing to have more computing, software, and communications capabilities. Edge processing, introduced in chapter 2, is discussed in more detail in the next section.

A second complexity associated with the lack of neatly defined geographical boundaries of jurisdiction is connected vehicles as receivers of traveler information. Early traveler information comprised of variable message signs and relatively stationary equipment that was limited in terms of the size of the message, and number and location drivers that received the information. Connected vehicles will allow specific messages to be directed towards travelers that can be customized according to their location and direction of travel.

Thus, instead of incident information being displayed on few variable message signs, the operator of the network will have the ability to send customized messages to a variety of locations, enabling drivers to make more informed decisions. On receipt of such messages, which could include revisions to the travel time, the information may be utilized by the navigation system in the vehicle to provide even more information on the conditions of different routes. This level of computation in near-real-time is likely to be beyond the capability of current legacy traffic management systems and TMCs.

The use of connected vehicle data will provide considerably more functionality than currently exists in RSEs, TMSs, and TMCs. Detectors for the current functions and areas of coverage supported by legacy traffic management systems are typically limited to dynamic information concerning the movement of vehicles, weigh stations, and toll collection. Although the initial efforts with connected vehicles is limited to safety functions between the vehicles and some of these traffic management functions, there is an extensive range of traffic information that has been explicitly included in the data standards to allow for the data to be used in the future when systems have the required capabilities. During the initial planning and development of these standards to support CAVs, over 90 separate applications were identified when the requirements of the motor manufacturers, transportation agencies, and other commercial interests were identified and included in these efforts. The early work linked the various data dictionary elements to these applications. The current version of the data dictionary (SAE J2735) includes:

- 17 different types of messages.
- 155 data frames that can be used to hold multiple data elements.
- 230 data elements.

Investigation of these applications and the data structures to support them provided an indicator of how extensive connected vehicles are likely to be as the data emerges. For a current list of applications, or Service Packages as they are now referred to, the reader is directed to the Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) [19]. This is defined as “*Service Packages represent slices of the Physical View that address specific services like traffic signal control. A service package collects together several different physical objects (systems and devices) and their functional objects and information flows that provide the desired service.*”

The ARC-IT specifies over 130 service packages and these are listed in appendix A. The architectural diagrams do not define how much of the data is processed in the site devices but merely states the raw data leaves the vehicle *and* defining traffic information flow as “...*Raw and/or processed traffic detector data which allows derivation of traffic flow variable ...*” leaving the implementer to decide at what point in the architecture to process which data.

## 3.4 Communication Options

There are a range of communication options that could be used by either connected vehicles, automated vehicles, or connected devices to and from the RSE, between the RSE and the traffic management center or hub, and between TMCs. These options include WiFi, satellite systems, and 4G/5G cellular. One issue with the use of cellular concerns payment since the cellular companies need an account to charge for provision of monthly service. This may be a suitable alternative for the personal safety and mobility messages which could be shared with mobile connected devices. DSRC is focused on low-latency active safety functions and may not be suitable for other functions.

Satellite systems are suitable for wide scale broadcast such as congestion data and traveler information. The communication options for each application need to be studied by the implementing agency to ensure bandwidth, capital costs, operating costs and latency needs are met. Most implemented communication networks are hybrids that use a variety of protocols and media. There is a wide range of combinations of devices and mechanisms for communicating connected vehicle data, for example:

- Installing WiFi in an RSE could be used for providing the connection from the RSE to local ITS devices such as weather stations, traffic detectors variable message signs. It is suitable for any device where the data is considered near-real-time and not require high-bandwidth.
- Bluetooth detectors send summary data over cellular modems often transmitting the first and last readings collected from each vehicle over the previous minute.
- Transmitting traveler information messages via Sirius XM for rural environments. This is a particularly apt use of satellite data since almost any other communication media too expensive.
- Portable personal information devices may communicate with both normal cellular and DSRC communications for different message types.
- Pedestrians in the crosswalk may be detected by LiDAR. The LiDAR system then generates personal safety messages that are broadcast via DSRC. Vehicles approaching the crosswalk broadcast BSMs via DSRC. The RSE runs a pedestrian application that receives the BSMs and then broadcasts them by WiFi. The OBU on a connected vehicle then runs a pedestrian collision warning application that calculates the trajectories and then warns the driver of a potential crash.

Standards such as the J2735 data dictionary do not proscribe DSRC, alternative communication such as cellular can be readily incorporated into the design of RSEs and TMSs to enable the sharing of data with

CAVs and connected travelers. Similarly, new technologies such as 5G networks are claiming higher capacity, higher speeds, and reliability over longer ranges. Installing the devices and taking advantage of these emerging data sources can occur regardless of the type of communication media.

The BSMs generated by a CAV are only available within the limits of the range of the RSE, which is normally 300 m. This means even if all received BSMs were received by all RSEs they still only provide detailed information on a limited portion of each vehicle's trip within the street network. The probe vehicle process has been explicitly designed to support a traffic management system obtaining information and sharing messages with CAVs in areas where the TMS currently may not have any coverage and is not actively managing traffic. In the future, probe vehicle data processes are likely to be of considerable utility to the operators of the network. For that reason, these processes are described in the next section.

## 3.5 Probe Processes

The ProbeVehicleData (PVD) message is particularly important when connected and automated vehicles rely on DSRC. The limited range or number of RSEs may influence the use of PVD messages to fill in the gaps in coverage should the use of the newer cellular data options (e.g., SENSORIS) become not viable due to technical, financial, or other limitations. Thus, it is possible that the collection of probe data messages will become a major source of data between CAVs and mobile connected devices to RSEs.

The probe management process involves sending the ProbeDataManagement (PDM) message from RSEs of the TMS to the vehicles to specify how the vehicle gathers data (i.e., at what frequency and including what detail). The messages generated by the TMS and sent from the RSE also has the potential to share data and the frequency of collection and delivery from the CAV or connected mobile device back to the RSE. The traffic management system or TMC can use the RSE to change the data collection from CAVs and connected mobile devices by modifying the probe data management message.

A simple example would be that when a sufficient number of a particular data type has been collected, the RSE could then send a probe management message telling the vehicles to stop sending additional messages regarding a particular status. This would be similar to a 911 operator informing citizens when they call to report a traffic crash that the crash has already been identified and emergency services have been dispatched, but this will happen automatically rather than over the phone. Other traffic management functions may have algorithms which based on the information compiled and current status or conditions, could for example, modify the probe data messages sent to ask vehicles to send messages containing different data elements by time of day.

### 3.5.1 Probe Vehicle Data Processes

The probe vehicle data messages are specifically designed to provide data to the owners and operators of the transportation network. There are two types of probe messages:

- **ProbeVehicleData (PVD)**—is designed to collect vehicle status data over a defined distance and/or time in a structured manner and to provide it to the infrastructure.
- **ProbeDataManagement (PDM)**—is designed to control the data within the PVD message, allowing the infrastructure applications to configure the data at its source.

Probe data is intended to be collected as a vehicle travel along the roadway system and then sent to an RSE. Additionally, the probe data message is by design anonymous as there is no personal information to

allow it to be identified. Probe data messages are comprised of “snapshots” of vehicle status over a length of time and distance. Note that the term “snapshot” does not imply that the status data is a video image or photo, but rather a glimpse of the vehicle’s speed, heading, etc. at a particular time and location. In the absence of any overriding probe management message (discussed later), probe data messages may be generated in three manners:

- **Periodically**—at intervals based on vehicle movement between RSEs.
- **Event Triggered**—these occur when the state of certain vehicle status elements change.
- **Starts and Stops**—these occur when a vehicle starts moving and stops moving.

These messages can consist of all probe data elements that are available on the vehicle along with the time, location, and heading when each snapshot was taken. Each of these approaches are discussed further in the following sections.

### ***Periodic Generation and Transmission of Probe Messages***

The intent of probe data messages is to periodically transmit messages on the performance of the vehicles trip as it travels between RSEs which have the ability to receive and process, save, or transmit these messages to a TMC. To do this, the default method for the periodic transmission of a probe message is designed to space the snapshots at regular intervals between RSEs. Although the default process is defined here, the process allows the RSE to request vehicles to change the frequency at which the snapshots are added to the PVD message.

The default method for generating periodic snapshots is to use time and the vehicle’s current speed to linearly space the intervals between snapshots. Although the method could use distance, the arguments for distance depend on uneven flow when incidents occur, however, most flow occurs when there are no incidents and thus using time as the default is expected to provide more uniform distribution of snapshots. As vehicle speed increases, the snapshot interval increases. This results in more widely spaced snapshots at higher speeds and closer spaced snapshots at lower speeds. This approach is used because, in general, RSUs will likely be further apart on higher speed roads. A capacity of 30 snapshots is assumed in the current standard following discussions with the vehicle manufacturers concerning onboard processing and is subject to change.

The following assumptions were used in the PVD standard to determine the default interval between snapshots:

- For the rural case at 60 mph (26.8 m/s), the RSE spacing is 10 minutes, or 600 seconds. When dividing this time by 30 snapshots it results in a snapshot interval of 20 seconds.
- For the urban case at 20 mph (8.9 m/s), RSE spacing is 2 minutes and the trip between RSUs would take 120 seconds or a snapshot interval of 4 seconds.

Thus, the snapshot interval is:

- 4 seconds if speed is  $\leq 20$  mph.
- 20 seconds if speed is  $\geq 60$  mph.

Between 20 mph and 60 mph a linear spread of snapshot intervals would be used, this is achieved by using the speed when a snapshot is taken to set a timer to count down to the next snapshot. The

exception to the above method is that periodic snapshots do not get collected after the vehicle is stopped. This is discussed in section 3.4.1

### ***Event Triggered Snapshots***

Event triggered snapshots could occur when there is change in vehicle status elements; such as when the state of a system changes change (e.g., windshield wipers go from off to on), when a value exceeds a specific threshold, or when a vehicle system undergoes a transition. The purpose of event triggered snapshots is to gather data on occurrences in the vehicle that are transitory by nature. An example of an event which would change the data to be compiled and included in a message is traction control switching from off to on. Multiple activations of traction control at adjacent locations could be used to indicate the location of a slippery road section. Another example could occur with a RSE sending messages requesting vehicles to send more frequent messages if traffic flow is projected to become unstable due to a variety of different events (e.g., crash, weather).

### ***Starts and Stops Snapshots***

Snapshots are also generated by stops and starts. Start and Stop events are defined as the following:

- A Stop is when there is no movement for a threshold stop time (default stop time threshold = 5 seconds) and no other stops have occurred within another threshold time (default last stop threshold time = 15 seconds). The latter being intended to prevent multiple counts when cars creep forward.
- A Start is when the vehicle speed exceeds a threshold (default start speed threshold = 10 mph (4.5 m/s)).

No snapshots are taken after a vehicle has experienced a stop event until the vehicle experiences a subsequent start event.

Starts and stops are useful indicators in a variety of traffic flow measures, including incident detection, clearance, and traffic signal operational measures such as cycle failures—where the queue does not completely dissipate during the green phase.

When a vehicle encounters an RSE that is requesting these messages, the OBU will respond with a one or more Probe Data Messages each comprised of several individual snapshots in the following order:

1. Event triggered snapshots are first in the transmission queue from the OBU to the RSE. Since these often relate to specific adverse conditions that are of interest to traffic operations, these are considered more critical than the other types of snapshots.
2. Stops and starts triggered snapshots are second and are needed to provide finer information on incidents and the various dynamic parameters concerning the traffic flow.
3. Periodic snapshots are third, oldest first.

Periodic snapshots may be tagged with short-lived PSN that is regularly changed to ensure privacy. There are other rules within the standard associated with privacy and anonymity.

### 3.5.2 Probe Data Management Process

This message is broadcast from the RSE to all vehicles. Its purpose is to change the snapshot generation characteristics of the OBU. For example, the OBU can be instructed to take snapshots more frequently and transmit them more often. It does not change the snapshot message.

Probe management is temporary. By default, a probe message management process ceases when a new RSE that supports probe messages is contacted by the vehicle. This case overrides the termination settings below.

Probe messages can be set to terminate as follows:

- A time-based duration expires.
- A distance-based length has been traversed.
- A vehicle is out-of-range of the current RSE.

When a probe management message terminates, the default conditions again operate in the OBU unless or until a new probe management message is received. Probe management messages can perform the following functions either singly or in combination:

- Control the production of snapshots by either distance or time.
- Direct the management message to vehicles moving in specified directions.
- Control how often snapshots are transmitted.
- Be applied to only a random sample of vehicles.
- Modify the thresholds of when event snapshots are triggered.
- Modify the thresholds of start/stop snapshots.

#### ***Time or Distance Periodic Snapshot Generation***

The first component of the Time or Distance Snapshot Generation element is a switch indicating if snapshot generation will be based on a time interval or distance interval.

If time is to be used, the message will have the capability of changing the default snapshot intervals as well as the speeds for these intervals:

- T1 = 4 seconds at S1 = 20mph.
- T2 = 20 seconds at S2 = 60mph.

Table 2 shows the default values for how often snapshots are collected as a function of the vehicle speed.

**Table 2. Speed and time between snapshots.**

Speed	Time Between Snapshots
$\leq S_1$	$T_1$
$>S_1 \ \& \ < S_2$	linear extrapolation
$>S_2$	$T_2$

Source: FreeAhead, 2017.

This will allow applications and users to fine tune the probe data being received. For example, if this is an urban freeway where the speeds are high but the RSEs are close together, then the 20 seconds at 60 mph may be changed to 10 seconds to provide a finer geographic resolution of the data.

An alternative method would be to enter a single time interval for  $T_1$  and  $T_2$ , thus taking snapshots at constant intervals, independent of speed, such as one per second ( $T_1 = 1$  and  $T_2 = 1$ ).

If distance is to be used, then a similar set of parameters can be sent, but instead the times ( $T_1$  and  $T_2$ ) would be replaced with distances ( $D_1$  and  $D_2$ ) in meters this is shown in table 3. In the same manner as the time calculation above, the distance used between speeds  $S_1$  and  $S_2$  will be linearly extrapolated. As before, two speeds ( $S_1$  and  $S_2$ ) can also be set, yielding the following:

**Table 3. Speed and distance between snapshots.**

Speed	Distance Between Snapshots
$\leq S_1$	$D_1$
$>S_1 \ \& \ < S_2$	linear extrapolation
$>S_2$	$D_2$

Source: FreeAhead, 2017.

This allows the operator to change the profile of the data collection policy to meet circumstances such as incidents. For example, an incident typically causes the traffic upstream of the incident to slow, but the downstream traffic flows fast. In this case,  $D_1$  can be made small to accommodate queue measurement and  $D_2$  made large to space out the snapshots downstream of the incident.

An allowed alternative method would be to enter a single distance interval for  $D_1$  and  $D_2$ , thus taking snapshots at constant distance intervals, independent of speed, such as once per 10 meters ( $D_1 = 10$  and  $D_2 = 10$ ). This would allow the user managing the probe data generation, given knowledge of the distance and direction to the next RSE, to evenly geographically space snapshots.

### ***Interval between Probe Message Broadcasts***

This parameter will control when the snapshots are transmitted back to the RSE as part of probe messages. This will allow the management message to request that probe messages be sent to the RSE at an interval other than the default (which is when a vehicle first enters range of an RSE). For example, this might allow an adaptive control system to request periodic snapshots be generated every two seconds and probe messages transmitted every four seconds (i.e., each probe message would contain only 2 periodic snapshots) while in range of the RSE.

### ***Termination of Probe Management***

This parameter is required to ensure that the OBU snapshot generation settings revert back from managed settings to the default settings. This parameter will contain data such that when the first of the following occurs, probe snapshot generation returns to the default settings:

- A time-based duration expires.
- A distance-based duration expires (i.e., a vehicle travels a certain distance).
- A vehicle is out-of-range of the current RSE for a threshold time (default 5 seconds)—i.e., after 5 seconds of no RSE signal is received then management process is terminated.

These values can be set independently, for example if time and out of range are not set, then distance only applies. For example, if distance were set at 1 km for westbound vehicles then is no new RSEs were encountered and no events or stops and starts occurred the OBU would collect one snapshot per kilometer for the next 30 km.

### ***Vehicle Status Element Triggers***

This parameter is used to adjust event triggered snapshot generation by adjusting the threshold of or transitions in various vehicle status elements which can be used as triggers.

For example, this parameter might include the vehicle status element for vertical acceleration, and a reduced threshold value. Thus, this would generate more snapshots that could be used as a roughness measurement. Another example would be to reduce the threshold of vertical g forces on each wheel to zero to calibrate road slope as a function of speed to determine adverse cambers.

### ***Vehicle Sampling***

The probe management message is a broadcast message. Therefore, all vehicles within range of an RSE receive this message and respond to it. However, it is possible to control the percentage sample of vehicles which will respond to any message by including in the probe management message a vehicle sampling parameter. This parameter has two digits (range 0 to 255), which represent the range of the last digit of the OBUs MAC address for those vehicles to which the management message applies.

For example, by setting the first value to 0 and the second value to 63, all those OBUs which that have a current MAC address that ends in the range 0 to 63 would use this probe management message, thereby yielding a sample of one fourth of all vehicles (MAC address is hexadecimal, much like an IP address, and the last digit can vary from 0 to 255 and over large populations are distributed randomly). A vehicle OBU with a MAC address ending in 64 or higher would not respond to this probe management message.

A statistically similar result could be achieved by using the values 64 and 127, also resulting in 1/4th of the local OBU population being affected. As a best practice, the issuer of the message should randomly vary the start and stop values selected to ensure that the burden of supporting the probe management message is evenly distributed among the entire OBU populations.

### ***Managed Vehicle Heading***

The probe management message will also include a parameter to indicate which direction-of-travel it applies to. The Managed Vehicle Heading parameter includes a heading value range, limiting its application to only vehicles which are currently traveling in that direction. Heading is described by dividing a range of 360 degrees into 16 different segments (each of which are 22.5° wide) and can be combined to define the required heading of the affected vehicles when entering the region.

For example, by setting the value to 0xFFFF, all possible headings are selected and therefore any vehicle receiving the probe management message will be affected. If a value of 0x0081 was used only those vehicles traveling directly east-bound would be affected, while a value of 0x8100 would indicate only west-bound vehicles, and 0x8181 would include both directions.

### ***Start and Stop Threshold Settings***

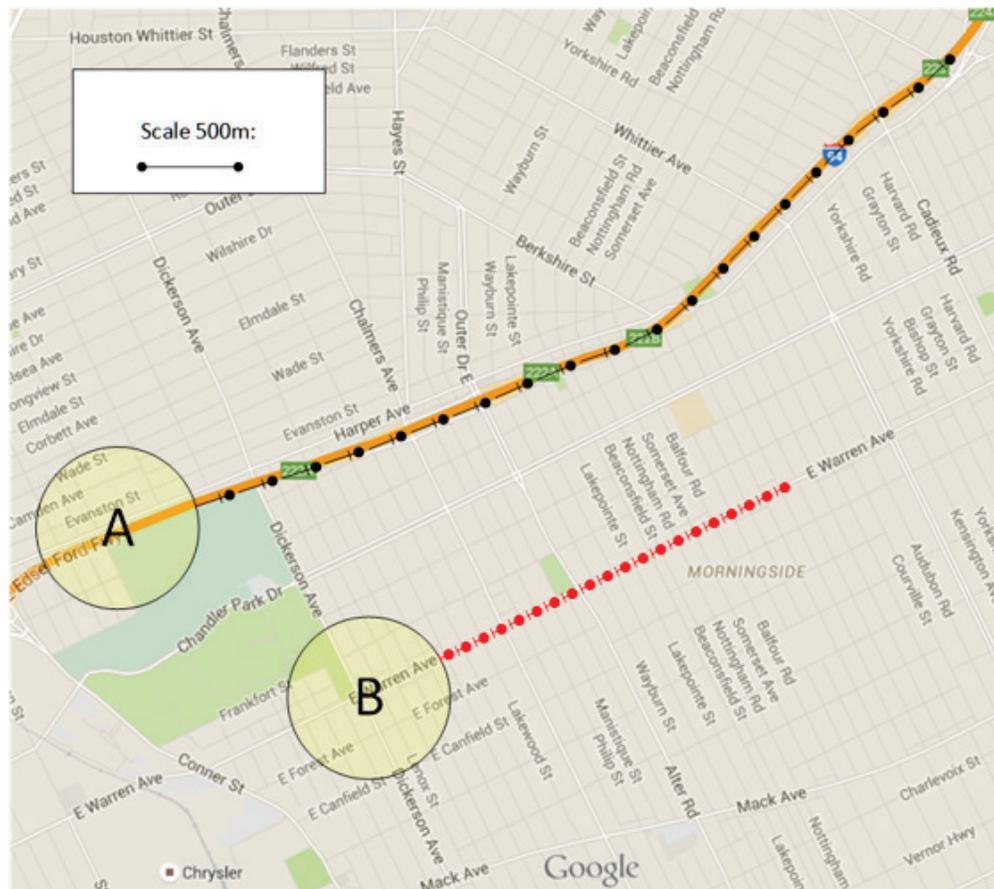
The management message allows the start and stop thresholds to be modified. The default stop time threshold is 5 seconds and the default last stop threshold time is 15 seconds. The default start speed threshold is 10 mph. These three values can be modified at by the local RSE. The default values may be inappropriate for the case of ramp metering where the start stop thresholds are greater than the vehicle metering rate.

Thus, the probe process provides the operator the network with the ability to gather specific data elements according to their needs, from whichever sections of the network they wish to gather the data. It allows them to sample population to reduce the size of the data stream. It is likely that as connected vehicles systems advance, the RSE will be responsible for some probe management tasks in the local environment, such as adaptive signal control or roadside messages, such as icy bridge ahead. In addition to probe messages to extend the network coverage, there is the potential to use the speed profile data as described below.

## **3.5.3 Speed Profile Data**

### ***Introduction***

In a connected vehicle environment, the BSM can be read by both vehicles and infrastructure receivers within a range of 300m. The process defined here extends the range by using the vehicle to measure speeds in the opposite direction and appending this data to the BSM transmissions.



Source: Google 2017.

**Figure 6. Map. Speed profile data collection points.**

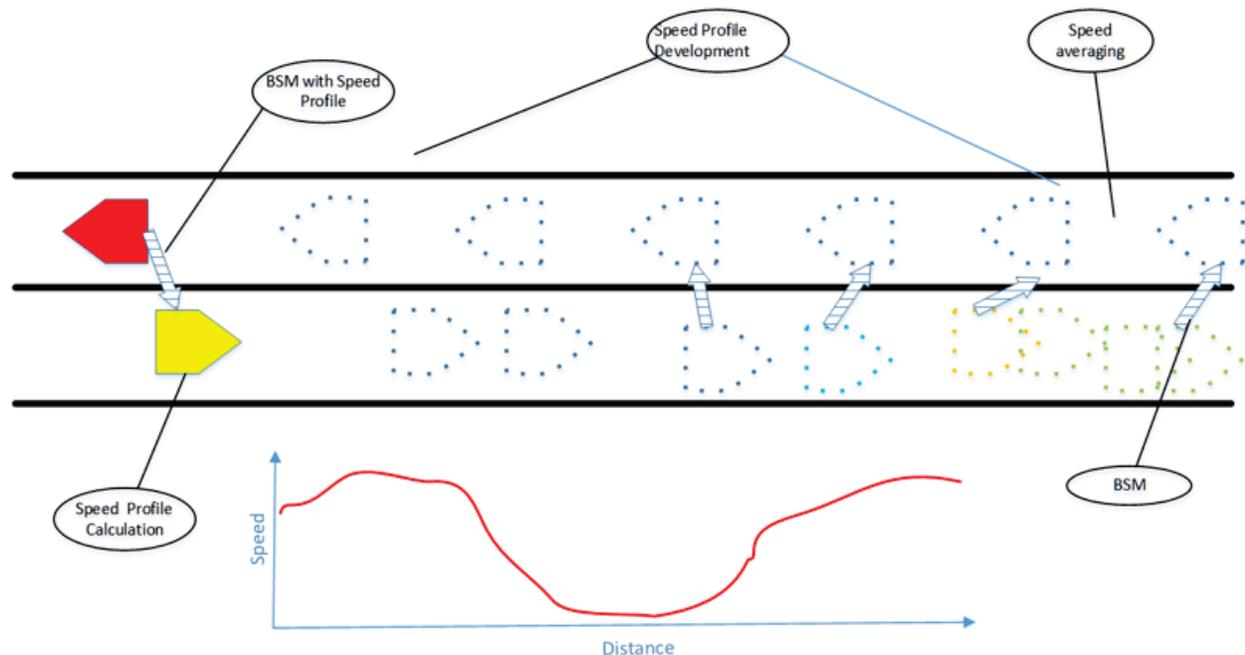
Consider a vehicle or device at position A in figure 6 that can read a BSM within the surrounding 300 m. The BSM of a vehicle entering the range of A could be configured to gather speeds from the opposite direction thus providing these speeds to the receiver at A. In this example, if the vehicles are traveling at 32 m/s (72 mph) on the freeway, then the speeds will be gathered at the positions shown by the black circles on I-94. For illustration, this example uses 20 speeds collected at five second intervals. The technique significantly extends the range of traffic data gathering which can be used by all devices and vehicles that wish to use BSM data. In the case of an arterial system with the vehicles traveling at 14 m/s (31 mph) then the range is extended but at a less distance as illustrated by the device at B on the arterial Warren Avenue.

Vehicle A would have data in real-time from the BSMs within the range shown by the circle, the extended data would be delayed by the travel time taken for this collection. However, for many of the applications associated with mobility this delay may be considered acceptable.

Figure 7 illustrates the data from one vehicle entering the range of the receiver. In practice, there will be multiple vehicles providing a range of data on a continuous basis. This will allow the receiving vehicle to superimpose the data and provide a reliable estimate of the speed profile ahead. In addition, this

extended data will be available in all directions. For example, if there were a DSRC equipped traffic signal controller at intersection shown by circle B in figure 1, that controller would be able to capture extended vehicle queues in all directions. If there were a DSRC receiver connected to the network at position A, this technique would be able to provide speed data for an extended range in either direction.

Thus, in a mature system of connected vehicles each vehicle would be constantly streaming data collected from behind them to the opposite direction vehicles who are then receiving information concerning the road ahead. In the near term, when penetration levels of connected vehicles and roadside equipment will be relatively low, the speed profile data also helps to “fill in the gaps” in coverage between roadside devices when connected vehicles share the data using V2V while passing each other in opposite directions on the same roadway. This data can supplement existing traditional roadway sensor data such as from radar and embedded loop detectors.



Source: FreeAhead Inc. and Kimley Horn and Associates, 2018.

**Figure 7. Diagram. Speed profile data collection.**

Figure 7 illustrates how the data flow would operate. The red vehicle moving to the left has been gathering speed data from the right moving vehicles and developing a speed profile as it moves down the road. The yellow vehicle moving right reads the speed profile data from the red vehicles BSM and then develops the speed profile for the road ahead which can be used in its mobility applications.

Such a technique would allow the development of new vehicle applications such as in-vehicle dynamic rerouting using the speed profile data and applying it to the routing algorithm within the vehicle's navigation system. It would also allow the network operator to have speed data from areas of the transportation network that would otherwise not be covered by roadside equipped DSRC receivers. It would extend the range of engine management systems.

### ***Why Use Speed?***

This technique could be applied to any of the data elements that exist within the BSM. However, it is important that the size of the BSM be kept as small as possible in order to function well for its safety applications. By using speed and assuming a fixed time between each reading, it is possible to re-create the speed profile with the minimal data size added to the BSM. Since the time between each speed reading is fixed at 5 seconds, then the distance between readings can be readily calculated and the corresponding cumulative distances ahead of the subject vehicle can then be calculated. Thus, minimal data can provide a speed profile.

### ***Minimal Message Size***

The current speed value in the BSM that vehicles will receive is an integer 0-8191 in units of 0.02 m/s (0.045 mph). Nothing like this resolution is needed for this application. For a speed average value for mobility applications, 1.0 m/s (2.2 mph) is sufficient and is comparable with the accuracy from existing roadside speed detectors. If this is encoded as an integer with a maximum value of 31 m/s (69.3 mph) [20] then only 5 bits are needed for each value and thus if the data element had a fixed string of 20 values then 100 bits or 13 bytes is required. Although not insignificant, since the message need only be sent at 1 Hz, the impact on the bandwidth would be small.

### ***Use Cases Supported by Speed Profile Data***

SpeedProfile data from probes could be used for a range of traffic management functions including:

- **Signal Control**—The data could be used for adaptive traffic signal control, since the status of queues would be known. For example, at the start of green the lead vehicle would measure zero velocity on the queued vehicles in the opposite direction. This could then be broadcast back to the RSE and the traffic controller could use the queue length to optimize the green time of the phase servicing the queue.
- **Eco-Driving**—SpeedProfile Data could be used for engine management and reducing speeds when approaching downstream queues. For example, in vehicle operations such as reducing power or changing air-conditioning settings could use the speed trajectory as an input to save fuel and reduce engine wear.
- **Queue Warning and Speed Harmonization**—Could have their range significantly extended by using speed profile data, without the need for significant processing of individual BSMs either on each RSE or at the TMC since the SpeedProfile is an aggregation of the information necessary for determining where the back of the queue resides.
- **Traveler Information**—Derived from the Queue Warning and Speed Harmonization messages relevant to vehicles approach the queue locally, the SpeedProfile information can also be used to inform vehicles of incidents many miles ahead on their route. Warnings and higher-resolution details could be given earlier concerning incidents ahead.

The speed profile data would be valuable real-time information that could be added to Part II of the BSM. As part of the BSM it could be read by any process in the RSE that is collecting and processing BSMs. Since the speed profile data element may only be added to a selection (yet to be determined) of the BSMs (say, one reading each 5s or 50 BSMs, as discussed in 3.5.3), the amount of additional data would have almost no impact on communications bandwidth requirements when compared with the bulk of the BSM data.

In the New York City Pilot Study where BSMs are collected on board the vehicle, the focus of the requirement is safety. In this case, the data is written into a local rotary file and when a potential safety event has occurred the 10 seconds of data before and after the event are recorded. In the Tampa connected vehicle pilot study, they reduced the data by first employing a geo-fence inside the OBU which significantly reduced the number of messages transmitted to the RSE. In the Wyoming pilot study, they adopted a plan of logging BSMs at 10 Hz for the last one minute and transmitted this detailed data if an event of interest to the study occurs. Otherwise only one BSM is logged every 30 seconds.

### 3.5.4 Further Concepts for Optimizing the Operation of RSEs with Probe Data Management

CAVs and connected travelers traveling in the same direction at the same time will transmit messages to RSEs that contain data that is largely the same. The probe data collection process (i.e., the probe data management message) and RSEs and TMSs can develop and use algorithms to optimize the capture and transmission of vehicle-based messages (e.g., BSM) and associated data. These algorithms could arrange and send messages based on the current or projected conditions.

For example, vehicles near an incident location or currently experiencing a weather event would be requested to provide high-resolution trajectories and more elements of the optional data elements in the BSM while vehicles in other uncongested (and less interesting from a traffic management perspective) would be requested to only send periodic updates on vehicle status. While this concept is focused on changing the way that messages are sent from vehicles to the RSE, similar concepts for aggregating redundant information on the RSE are discussed further in chapter 4. Such data compilation strategies will be critical to reduce the burden on the communications network between the RSEs and the TMC.

## 3.6 Impacts of Additional Messages at the RSE: Personal Safety and Mobility Messages

The safety and mobility messages for connected travelers are designed to enhance the safety and performance (e.g., convenience, travel time) of travelers sharing and using data from mobile devices carried by pedestrians, cyclists, and other vulnerable road users (VRU). While electronic messages generated by vehicles will require significant edge processing by RSE, the collection of data from pedestrians, cyclists, and other VRUs will further stress the ability of the RSE to collect, process, store, and share information. Data compilation strategies previously identified will need to be used if large volumes of connected traveler data are to be collected in addition to a data stream from CAVs. In the SAE J2735 family of message standards, the data from VRUs is encapsulated in two message types; the PSM and PMM. These messages are defined [21] as follows:

- The PSM is patterned after the BSM for vehicles. The BSM transmits a vehicle's position, speed, and heading, among other information. Surrounding vehicles use this information in various applications to increase safety by, for example, avoiding collisions. The PSM will provide similar information about the position of an individual carrying a mobile device. The PSM includes mandatory data elements of device type, position, temporary ID, velocity, and heading. In addition, there are a wide range of optional elements such as path protection and various user requests and status values. The PSM will notify vehicles of the presence, for example, of a pedestrian in a crosswalk or of a runner in the street. Like the BSM, PSM is intended to be

broadcast on using DSRC because it is specifically focused on collision avoidance between VRUs and vehicles.

- The PMM will enable new applications benefitting a variety of users. PMM messages will be sent to the vehicle via 5.9GHz, DSRC frequency band (if within range), cellular, or WiFi to send a single or ad-hoc travel group travel ride/travel request. It is expected to contain information about the traveler's destination and their requirements for travel (schedule constraints or mobility issues such as the need for wheelchair storage or a bicycle rack) similar to a traveler trip planning request message used in transit applications with the difference being that the PMM would be applicable to any type of vehicle so as to be truly multimodal. A vehicle having received a PMM and agreeing to pick up the passenger(s) will send a PMM response.

The D2X Hub developed by USDOT and available on the OSADP supports the exchange of PSMs and PMMs. (<https://www.itsforge.net/index.php/component/ars/repository/traveler-information/D2X%20Hub%20v1?Itemid=668>) Currently the PSM is included as a standard message in SAE J2735, but the PMM has only been proposed for inclusion as a standard message type. There is a significant likelihood that if pedestrian safety applications were widely available that PSMs and PMMs could present challenges with ensuring the successful operation of a RSE that is also expected to collect other messages associated with the vehicular transportation network.

### 3.7 Roadside Equipment Limitations

The systems engineering process typically begins with the identification of user needs. Clearly not all traffic management and TMC functions need to be supported by every agency. Similarly, not all connected vehicle and connected traveler messages need to be collected at every RSE, or at all. Agencies looking to enhance traffic management and TMC functions with connected vehicle and connected traveler data should first identify what data will be of value and then determine what capabilities of the RSE will be necessary to achieve their objectives. The development of current RSEs based on the ARM processor described earlier in chapter 2 is likely to be overwhelmed by the processing and storage requirements of connected vehicles if anything and everything that can be collected is collected, stored, processed, and shared.

Historically, processes have achieved increased speeds and a broader range of functionality by moving processing from general-purpose operating systems into specific software/hardware components that are optimized for a particular function. For example, the initial personal computer provided on one board with one processor, all the computational and storage needed for the machine to work. Today, multiple processing cores increase computational ability, graphics processors drive monitors, separate board components handle communications, and there are multiple storage options that contain processing capability. It is likely that the development of RSEs will follow the same path of optimizing the various functions. In an RSE specific functions that are repetitive and suitable for individual software/hardware solutions could include:

- Message handling, sorting the multiple messages and storing them individually.
- Security, running the USDOT-developed Security Certificate Management System (SCMS) or whichever security system or requirements (e.g., credential management, certificate verification) become the requirement for sending and receiving messages with connected and automated vehicles and connected mobile devices.
- Processing messages, enabling the functionality of data compiling, geofencing, averaging, and statistical computations.

- Communications, supporting the cueing on processing and transmission of messages according to the various user needs.

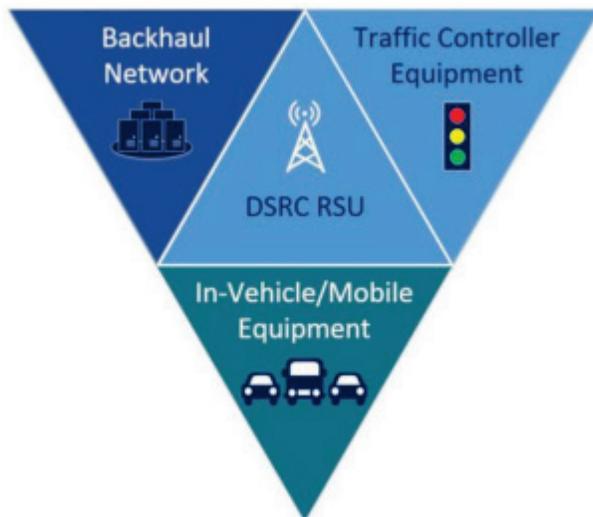
Hardware/software design that is demand dependent allows the implementer to readily configure a software platform of multiple uniform devices which are configured to address the local load or desired functions and operating condition. If there is a processor within the RSE unit that supports the security function and it is being overloaded, providing additional processors can balance the load in support of meeting a desired level of performance. Dividing the RSE processing into independently processing functional components will probably allow for a scalable solution if each of the major functions are performed on a separate hardware platform in the TMC to allow the processing that is only required at the RSE to be inserted to meet the assumed demand. Load balancing computing [22] can be implemented in a variety of manners, some virtual and others requiring multiple hardware components. Such an approach will provide potential solutions to any computing or processing constraints that may be encountered with an RSE. However, these and other technologies for data analytics and processing at the TMC will require highly specialized technical knowledge which should be integrated into the planning and design of the system.

## 3.8 Status of Roadside Equipment Capabilities, Data Collection, and Local Storage Issues

This section provides an overview of current capabilities and practices with using RSUs and RSEs. This section first reviews the latest USDOT RSU specifications, highlighting language related to data storage and processing requirements, it reviews current practices with requirements, design, and data management requirements. This section then provides an overview of how a software application can be developed or the functions which could be integrated into the software for a RSE to support the translation of data received or sent to a CAV or connected device. Finally, recommended practices and key issues to consider in the planning, design and operation of a RSE to send and receive messages and carry out whatever functions or tasks may be required for a specific location or conditions that may take place are discussed.

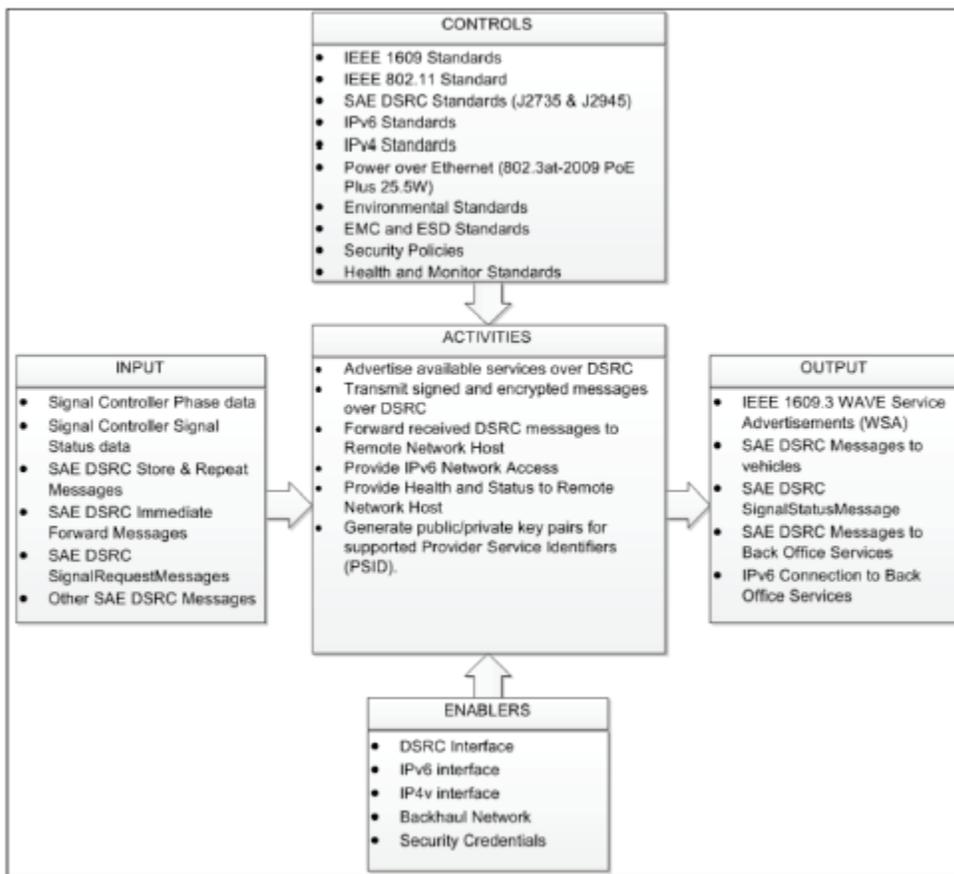
### 3.8.1 Roadside Unit Specifications

This section will focus on the current practices and information available to support the identification of data collection, processing and local storage issues that may be appropriate to consider in the planning and design of RSU or RSE devices. It is notable that the RSU specifications referencing processing/database write capabilities do not give clear storage and processing requirements that would support edge processing as defined in the most current USDOT specifications (version 4.1, updated April 28, 2017) [1]. Figures 8 and 9 illustrate the key elements affecting the RSU (again, not the RSE, but specifically the radio unit) including the inputs, outputs, controls, activities, and enablers. For the purposes of improving traffic management functions and TMCs, the capabilities of the RSU are the conduit between the data arriving from the OBUs to the edge processes running on the RSE that process, store, aggregate, and share data with the TMC. Similarly the RSE passes the messages that are intended to be shared back to connected vehicles and connected travelers through the RSU.



Source: Leidos.

Figure 8. Graphic. High-level conceptual diagram of the roadside unit.



Source: Leidos.

Figure 9. Diagram. Context diagram of a roadside unit.

### **Storage Capabilities**

USDOT specifications for RSUs [1] note that the device must “contain internal computer processing and permanent storage capabilities.” These specifications also note that RSUs procured for deployment may be subject to additional requirements based on the local design and policies of the procuring agency.

### **Database Write Capabilities**

USDOT RSU v4.1 specifications do not mention database write capabilities beyond the ability to contain permanent storage within the device.

### **Communications Capabilities**

RSUs transmit messages known as Application Layer Protocol Data Units (PDU) formatted in accordance with SAE J2735 using one of two mechanisms [1]:

- **Store and Repeat** messages are downloaded from a back-office service and stored on the RSU. These messages are static messages for transmission to passing vehicles such as a Curve Speed Warning (CSW) message noting the geometry of a downstream curb and speed for traversing the curve. These messages include Transmit Instructions defining how often a message should be transmitted, when the message should start and stop being transmitted, the channel used for transmission, the Provider Service Identifier (PSID) the message is associated with, and whether the message should be signed or encrypted.
- **Immediate Forward** messages are transmitted by the RSU as they are sent. These are dynamic messages from ancillary devices connected to an RSU; for example, signal phase and timing (SPaT) messages would be Immediate Forward messages. These messages also include Transmit Instructions defining the channel to be used for transmission, associated PSID, and whether the message should be signed or encrypted.

## **3.8.2 U.S. Department of Transportation Operational Data Environment (JPO-ODE)**

Since 2007, USDOT has operated a CV Test Bed in Southeast Michigan (SEMI) [11]. This Test Bed was implemented to serve as a test facility for CV technologies for USDOT and the auto industry. Part of this project was the development of the Operational Data Environment (ODE).

([https://www.its.dot.gov/factsheets/pdf/ITSJPO\\_ODE.pdf](https://www.its.dot.gov/factsheets/pdf/ITSJPO_ODE.pdf)) The ODE is now being used in the Wyoming CV Pilot. The development of the ODE revealed several key takeaways that are relevant to the use of RSEs and edge processing for enhancing traffic management functions through the use of connected vehicle and connected traveler data

- The initial Safety Pilot in 2012 showed that the storage on RSUs would quickly be exceeded if data is not downloaded semi-regularly to a back-office server. The RSE should thus be used as a data aggregator and processor
- The latest ConOps for the JPO-ODE includes functional requirements for processing and storage that must take place on the RSEs, but is silent on minimum specifications for memory or processing power. Agencies will need to develop requirements for data processing and memory/storage based on needs for traffic management functions both on the RSE and at the TMC.

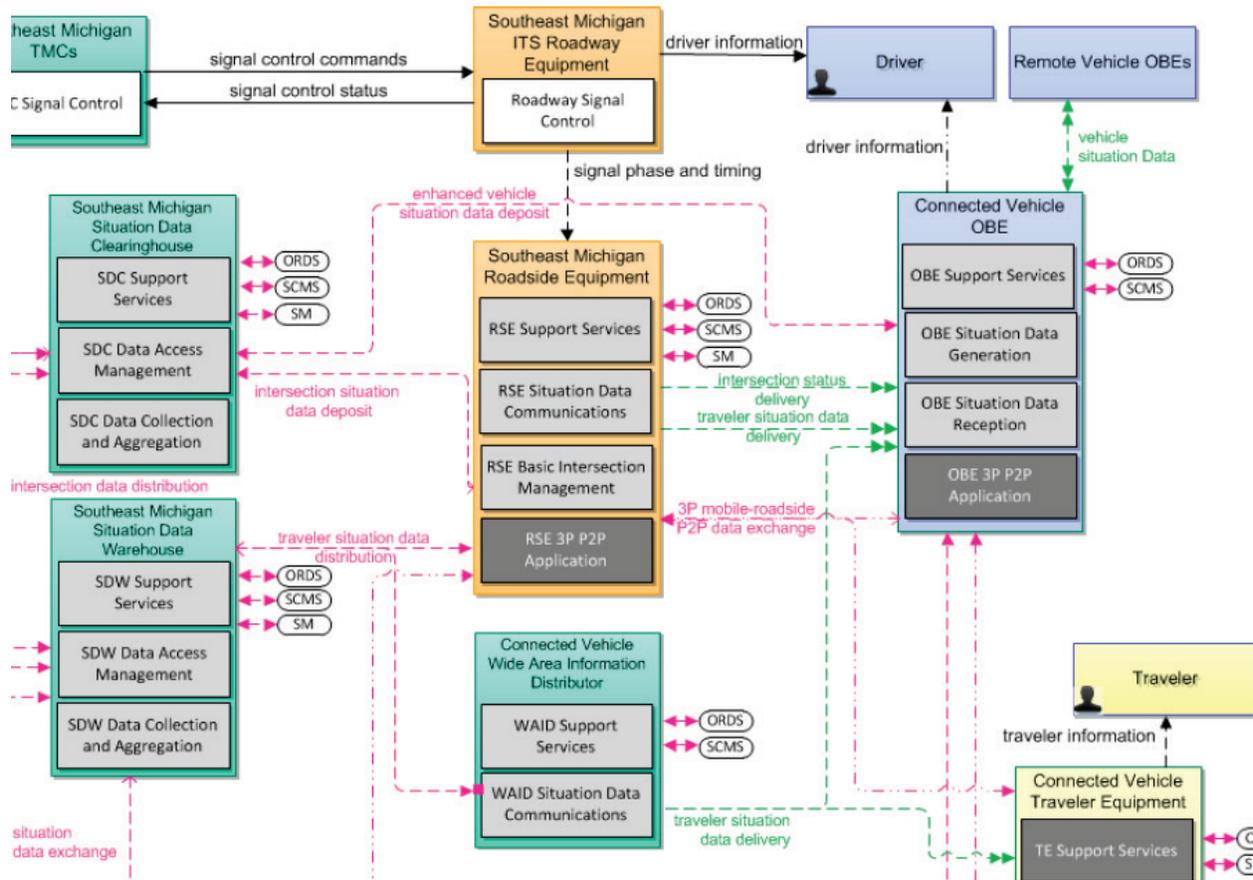
- Since RSUs are typically co-located with the DSRC antenna(s) 25-30 feet from the ground, they are not an appropriate location for storage of data in the event that traditional communications retrieval of the information fails
- Large amounts of the stored data from connected vehicles is redundant, particularly at traffic signals when vehicles are sitting motionless while the traffic light is red. Appropriate data reduction methods should be developed to reduce unnecessary storage of redundant data elements.

### ***RSE/RSU Concept of Operations (2014)***

USDOT released an updated Concept of Operations (ConOps) for the SEMI Test Bed in 2014 [11] given needs to support evolving program objectives, enhanced operations support, and research supporting future deployments. This ConOps details requirements for RSEs to include:

- **RSE Support Services** provide for the exchange of information with the three SEMI Test Bed Support services:
  - **Object Registration and Discovery Service (ORDS)**—the RSE should reach out to the ORDS to register its current location (geofence and cyber-address) and update this information upon any change in cyber location or public credentialing.
  - **Security Credential Management Service (SCMS)**—the RSE should retrieve all necessary security credentials, decryption keys, and the latest certification revocation list (CRL), storing any information received and ensuring that any expired keys or CRLs are discarded.
  - **Service Monitoring (SM).**
- **RSE Situation Data Communications** includes field elements that distribute information to vehicles for in-vehicle display. This information may be provided by a TMC (e.g., variable information on traffic and road conditions) or it may be determined and output locally (e.g., static sign information, ramp metering signals). This includes the interface to the center or field equipment that controls the information distribution and the short-range communications equipment that provides information to passing vehicles. The RSE should be able to request and accept Traveler Situation Data Bundles from the SEMI Situation Data Warehouse, process these retrieved bundles, and broadcast these to passing CV OBEs via a managed broadcast playlist.
- **RSE Basic Intersection Management** uses short-range communications and interfaces to local ITS field devices to support CV applications at signalized intersections. This application communicates with approaching vehicles and ITS infrastructure (e.g., traffic signal controller) to provide intersection status (SPaT) information to both vehicles and other interested centers.
- **RSE 3P peer-to-peer (P2P) Application** refers to a high-level generic application that provides some roadside service relevant to nearby vehicles or their occupants and involves bidirectional communication between two entities.

These data flows are illustrated in figure 10. These elements of RSE specifications and requirements are mostly relevant to the ability of the RSE to send data *out* to connected vehicles and connected travelers from TMC functions (represented by the Situational Data Warehouse “Traveler Situation Data Bundles” and the provision for bi-directional communication between a vehicle and the RSE).



Source: SEMI Test Bed Concept of Operations [11].

Figure 10. Diagram. System architecture excerpt.

### 3.8.3 Roadside Equipment Deployments in Connected Vehicle Pilot Sites

Since 2015, USDOT's ITS Joint Program Office (JPO) has been leading a CV Pilot Deployment Program at three pilot sites around the country [5]:

- New York City (through NYCDOT).
- Tampa (through the Tampa-Hillsborough Expressway Authority (THEA)).
- Wyoming (through Wyoming DOT).

The purpose of these pilot deployments is not to design RSEs, but to illustrate and evaluate the benefits of various connected vehicle and connected traveler applications. The various documents produced by each site do have some relevant requirements for RSE and TMC to RSE communications and processes, including the system requirements [6, 7, 8] and the Tampa and Wyoming Data Management Plans [9, 10]. Both the Tampa and Wyoming DMPs as well the System Requirements for all three sites generally view the RSEs as two-way communications portals between the OBUs and TMC, with limited expectations for storage and processing at the RSE device.

The main takeaways from the pilots' design activities are as follows:

- The pilots view RSUs generally as 2-way communication portals/translators rather than storage/processing engines (to be done at a TMC or a separate RSE),
- The requirements for the RSU storage, processing, and communication were made without explicitly considering what the ultimate demand of messages from CAVs might be many years into the future. The Tampa/Wyoming Data Management Plans do include the consideration of potential situations where the amount of messages could potentially exceed the capabilities of the RSU.
- Data aggregation, edge processing, and limitation of communications between the RSE and the TMC have not been strongly addressed (nor were these issues assumed to be addressed in the conduct of the demonstrations).

More detail on each pilot site's specific designs is provided in the following subsections for the interested reader.

### ***RSU/RSE Operational Requirements for the New York City Pilot Site***

NYCDOT's CV pilot includes 353 RSUs deployed throughout the boroughs of Manhattan and Brooklyn supporting a suite of applications geared toward crash reduction and safety applications for pedestrians and motorists. This pilot intends to provide a demonstration and evaluation of the benefits of CV technology in a dense urban environment [8]. The pilot's System Requirements document focuses on the use of Aftermarket Safety Devices (ASD) built into the vehicles with which they are associated. Various CV applications are hosted on the ASDs themselves, which have data processing and storage capabilities such as in-vehicle temporary recording and event logging. These records are downloaded to RSUs when available via DSRC; the RSUs then forward BSMs and other messages to the NYCDOT TMC for "initial post-processing." At the NYCDOT TMC, a Data Distribution System (DDS) will be responsible for collecting, processing, and distributing near-real-time CV data such as BSMs, MAP, SPaT, and TIM messages.

### ***RSU/RSE Operational Requirements for the Tampa Pilot Site***

Tampa's CV pilot, through the Tampa-Hillsborough Expressway Authority (THEA), includes a suite of applications focused on improving operations and safety at the entry/exit point for a reversible lane system downtown as well as other applications related to vehicular interactions with pedestrians, transit, and non-CV passenger vehicles in mixed traffic. The pilot will use RSUs that have either already been certified or can demonstrate through self-certification that they met the USDOT RSU specifications.

The RSUs are expected to host a number of applications in the Tampa CV pilot. Data collection and transmission requirements are noted in the System Requirements document and further defined in the pilot DMP [10] and illustrated in figure 11. For example, the End of Ramp Deceleration Warning (ERDW) application estimates the queue length of each lane and broadcasts a recommended speed to vehicles in advance of the queue to applications running on vehicle OBUs. For transit signal priority, when a bus OBU sends a message to the RSU TSP application (via DSRC), the RSU converts this message to a bus priority request message, sending this to the TSP application installed on the master server at the TMC. For PSMs, the RSU must be able to convert a PSM into a BSM (and vice-versa) for communication between vehicles and pedestrians. The RSUs will also host applications such as the 2-phase signal control operations at the reversible express lanes entrance and a pedestrian safety app for issuing an

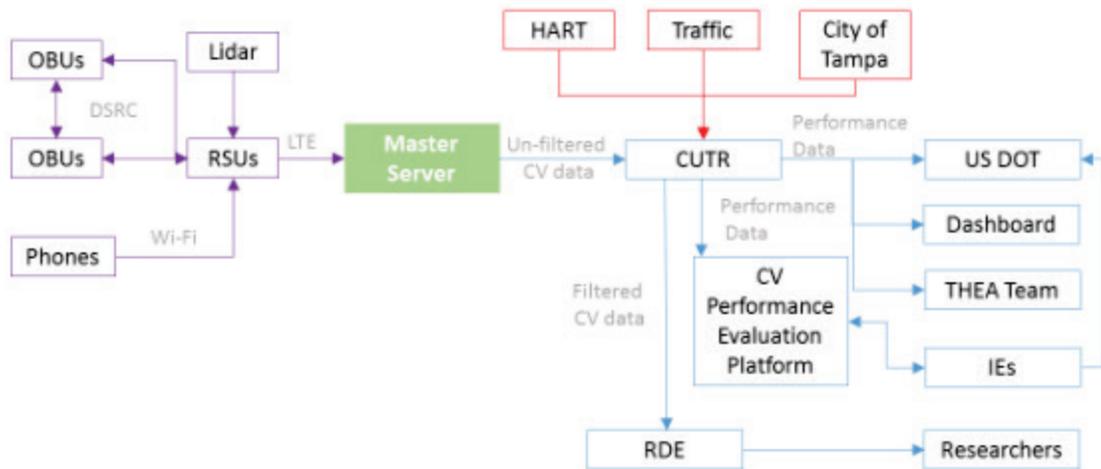
alert if a bus or streetcar is about to proceed. The System Requirements document includes a section on Information Management requirements, including requirements for RSUs:

- RSUs will save data they generate/transmit and receive (e.g., infrastructure safety messages, BSMS, PSMs). Once data from a vehicle OBU is downloaded to an RSU, the OBU will delete the data from its storage. Messages (i.e., alerts) transmitted and received by RSUs shall be stored on a storage device connected locally to the RSU.
- Data locally stored on RSUs shall be transmitted to the THEA master server through a secure communications connection. RSUs will delete data from their local storage once downloaded to the master server over the network between the RSU and the servicer (fiber if available; otherwise LTE).
- The frequency at which data locally stored on the RSUs is transmitted to the THEA master server shall be determined based on the RSU's storage capacity.

Note that these elements basically address the needs for *offline* traffic management and TMC functions that can use archived data.

The Tampa DMP includes a Data Collection Analysis of the volume of data likely to be generated over the course of the pilot study, which includes an assessment of potential roadblocks to the intended goal of collecting and retaining as much CV data as possible. The DMP provides estimates for BSM data received by RSUs and the average amount of data transferred via LTE per RSU per day (currently estimated at just over 1 GB/day per RSU for the study). The DMP does note an approach for cases during operational testing where there are breakdowns in transmission, receipt, and collection of BSM data:

- One frequently-discussed potential problem is that as equipped CVs encounter the first RSU in the study area, this first RSU will not have sufficient time while the vehicle is in range to download the CV's OBU data collected outside of the study area (especially if there are many OBUs within range of the RSU at the same time). If this issue is encountered, the current plan is to install additional RSUs that would provide an opportunity to receive data at intervals.
- Should the projections of the overall amount of BSM or other data prove to be underestimated and create transmission or storage issues, the DMP's first contingency is to employ a modified data logging approach for OBU data collected outside of the defined study area. If these problems persist, the next step would be to filter out all "out of study area" data.
- As part of the final design of the OBUs and RSUs, a prioritized data filtering process is being developed to account for data overload issues.



Source: THEA Data Management Plan.

**Figure 11. Diagram. Tampa-Hillsborough Expressway Authority connected vehicle pilot planned data flow.**

### **RSU/RSE Operational Requirements for the Wyoming Pilot Site**

Wyoming DOT's CV pilot includes the deployment of approximately 75 RSUs along Interstate 80 (I-80), supporting applications focused on reducing the impacts of adverse weather and aiding freight operations. This includes interfaces with public work fleets (snowplows).

The Wyoming DOT System Requirements and DMP both denote RSUs functioning as two-way communication portals between CV's and WYDOT's Operational Data Environment, which is hosted at the WYDOT TMC. High-level requirements for the ODE are captured in the Concept of Operations for the USDOT Southeast Michigan CV test bed [11], including requirements for validation, integration, sanitization, and aggregation. The WYDOT DMP does note that RSUs will include application support, data storage, and other support services to enable CV applications, such as security certificates.

The WYDOT DMP notes that CVs will continuously broadcast BSMs at a frequency of 10 Hz, some of which will be saved and stored on the OBU. All messages received by the CVs (BSMs, TIMs, etc.), whether coming from another OBU or an RSU, will be stored on the OBU. When the OBU passes an RSU, data stored on the OBU will be transmitted via DSRC and then deleted from the device. The RSU would then transmit this data to the ODE. The DMP also developed preliminary data storage estimates, noting that the data storage required for interactions among CVs dwarfs other data storage estimates when it comes to designing the data storage system; however, this amount of data itself is highly dependent on how often CVs will be traveling within range of each other and sharing information. Data storage at the vehicle level will be constrained by OBU data capacity; during the detailed system design process, options to possibly limit the data collection in these circumstances will be examined.

### **3.8.4 RSE Software Platforms**

As the connected vehicle program has evolved, software for the RSE has continued to evolve into standardized approaches for handling common functions. Agencies considering implementation of CAV

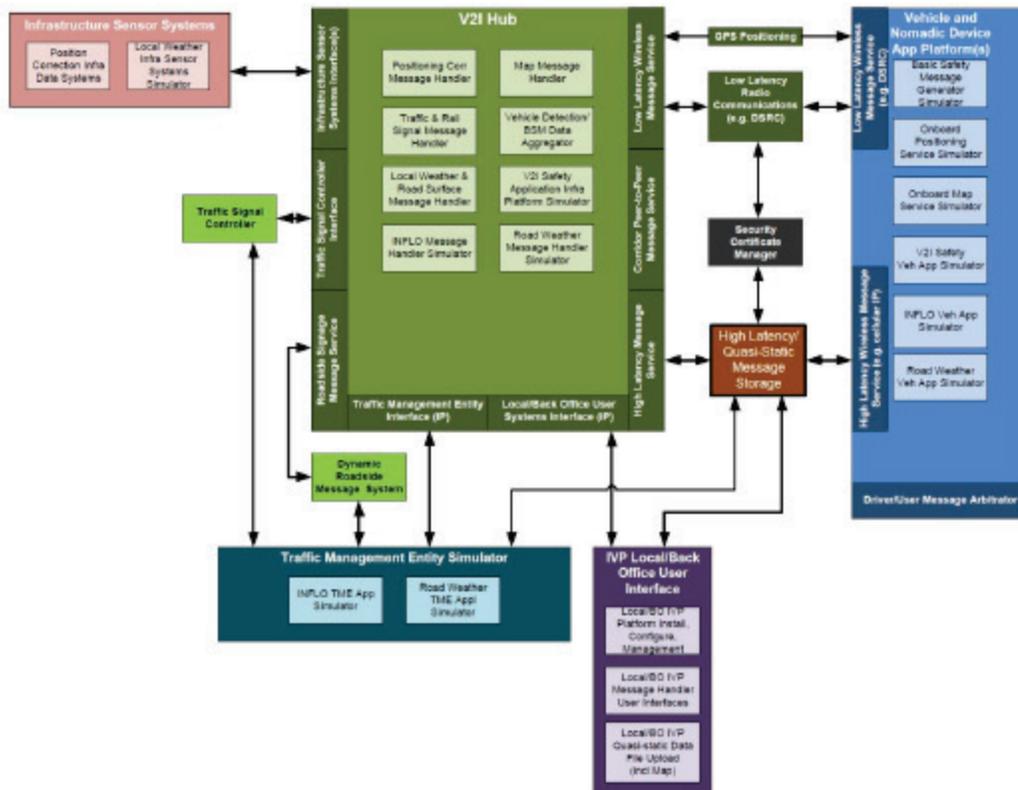
and connected traveler applications using RSEs today should consider using existing software platforms rather than developing new applications “from scratch.” The Integrated Vehicle-to-Infrastructure Prototype, also known as the V2I Hub, is one such software platform that interfaces with the RSU as well as a variety of ITS field equipment (such as signal controllers, DMS, RWIS, etc.) [2, 12]. (“V2I Hub,” “Integrated Vehicle Prototype,” and “IVP” are terms that are used interchangeably by USDOT.)

This open-source software platform was developed by USDOT to facilitate the exchange of data in a format that can be understood by both vehicles and infrastructure devices [3]. The V2I Hub translates messages from vehicles and infrastructure into formats that each can understand; it also “acts as a data aggregator/disseminator for infrastructure components of a CV deployment” [3]. The V2I hub is intended to simplify integration for jurisdictions by translating between different standards and protocols and incorporating a modular design, thereby enabling use of jurisdictions’ existing transportation management hardware and systems, as illustrated in figures 12 and 13. Agencies may find the software platform of value as a starting point for development of other RSE functions, such as the data aggregation and processing functions discussed in this report. The open source and freely modifiable “plug in” architecture will also allow TMSs to integrate additional functions and components as needed, without needing to develop additional interfaces to GPS, security credentials, and message formatting.



Source: Battelle.

**Figure 12. Graphic. Vehicle-to-infrastructure hub concept.**



Source: Battelle.

**Figure 13. Diagram. Vehicle-to-infrastructure hub detailed system view with candidate message handlers.**

The V2I Hub Software Design Document (SDD) [13] provides an overview of user needs for the V2I Hub, which specify that multiple applications require a *local* communication and computational/processing platform (i.e., the RSE) for the following:

- Message handling across multiple interfaces—integrating data from multiple sources and compiling messages for delivery to vehicles, drivers, and nomadic devices via multiple communication methods; obtaining and aggregating data from multiple vehicles and nomadic devices and delivery to a Traffic Management Entity (TME); distribution of TME messages to local vehicles
- Local infrastructure-based computation and processing—for example, local computation of safe speeds or stopping distances using real-time weather and road condition data; aggregation of vehicle weather data for efficient communication to the TME for weather-responsive traffic management; MMITSS “intersection level” functions including management of MAP and SPaT broadcast messages, tracking of equipped vehicles, serving priority requests, and interfacing to the traffic signal controller.

The V2I Hub SDD denotes the hardware selected to support the initial V2I Hub platform development and deployment: the Advantech UNO-2184G (illustrated in figure 14), an industrial-grade, commercial off-the-shelf automation computer with extensive input/output functionality as well as ample processing power to handle the needs of the targeted V2I applications, key message routing, and administrative needs of the

core V2I Hub platform functionality. The SDD provides key specifications for hardware and software, including recommendations for processor type, internal memory, hard drive storage, port requirements, and software requirements. The V2I Hub SDD lays out a system architecture detailed in the following sub-sections.

- UNO-2184G-D44E
  - 4 x 10/100/1000Base-T RJ-45 ports
    - Intel Core i7-2655LE 2.2GHz
    - 4 GB DDR3 SDRAM
    - 80 GB SSD HD
    - 2 x RS-232 ports with DB9 Connectors
    - 2 x RS-232/422/485 with DB9 Connectors
    - 6 x USB 2.0
- Ubuntu 14
  - MySQL Server
  - Apache Web Server



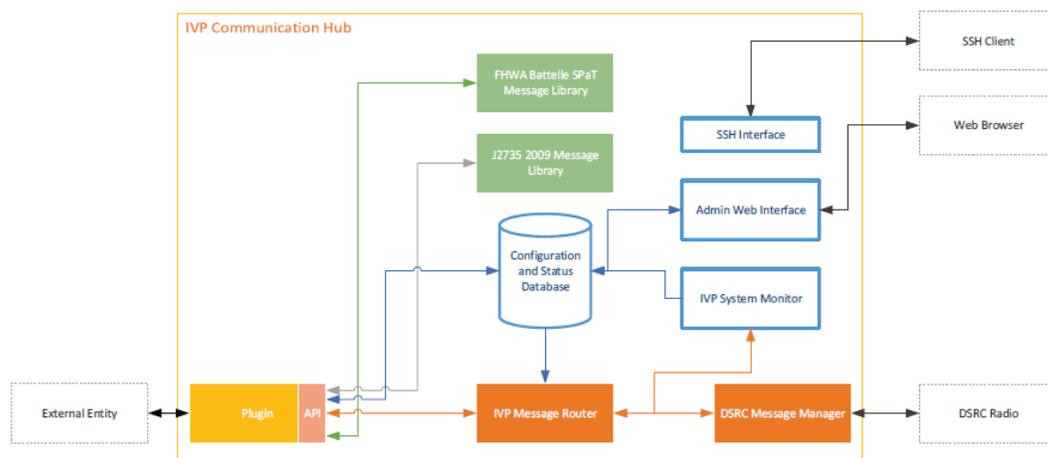
Source: Advantech.

**Figure 14. Graphic. Vehicle-to-infrastructure hub platform hardware and specifications.**

### ***Vehicle-to-Infrastructure Hub Core Components***

The V2I Hub primary functions are to manage message routing among the application-specific (plugin) components. Notably, the core components include a *Configuration and Status Database*, a MySQL database with entries for each of the plugins installed on the V2I Hub along with their configuration. Statistics and status are also stored in this database. The core components also include a V2I Hub Plugin API, which the SDD refers to as the “foundation of all plugins in the V2I Hub platform.” The Plugin API has the functionality to subscribe and publish messages, read configuration information, and decode messages using the message libraries also contained within the core components.

The core components also include a V2I Hub Message Router, DSRC Message Manager, a V2I Hub System Monitor, Admin Web Interface, message libraries, and secure shell (SSH) interface. Figure 15 provides a diagram of the architecture of the core components.



Source: V2I Hub SDD.

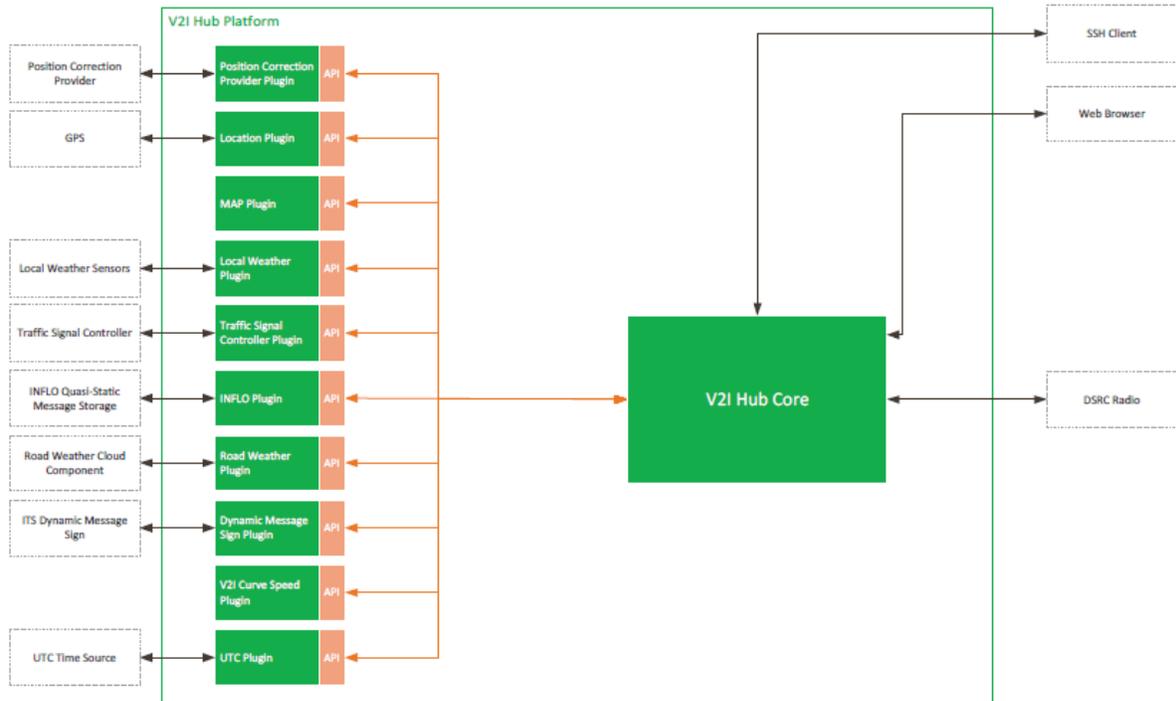
**Figure 15. Diagram. Vehicle-to-infrastructure hub core components.**

### **Vehicle-to-Infrastructure Hub Plugin Components**

The V2I Hub Plugin Components represent the application-specific pieces of code on the V2I Hub platform. These plugins are responsible for processing data extracted from external peripheral components, generating status or other information that is published to the V2I Hub Router (in the core components), or controlling/communicating with external components based on processing performed or messages received from other plugins. The V2I Hub Plugin Components currently include the following:

- Generic GPS plugin, Position Correction Plugin, and UTC Plugin.
- MAP and SPaT Generator Plugins.
- DSRC Message Manager Plugin.
- INFLO Plugin.

Figure 16 provides a diagram of the architecture of the V2I Hub Plugin Components:



Source: V2I Hub SDD.

Figure 16. Diagram. Vehicle-to-infrastructure hub plugin components.

# Chapter 4. Data Compilation and Storage

The discussion in this chapter concerns compilation and storage which can take place at the RSE or at other locations in the traffic management systems or TMC. The ability to collect and use CAV and connected mobile device data is an opportunity for these systems and TMCs to explore conducting new functions, sharing information with these emerging sources, and assessing how this information could enhance how existing systems operate. For example, a traffic signal controller sending data to a TMC is usually restricted to signal phase and timing data, status of the clock and other relevant messages.

In the CAV environment, vehicle trajectories may be used in the active management and operation of traffic signal timing plans and summaries of traffic flow may be sent to the TMC instead of each RSE transmitting every single BSM and PSM. Different functions will have similar but different approaches to compilation and storage. The mechanism of using RSEs for collecting and sharing data will often collect data from multiple facilities. This practice may necessitate distribution from the collection point to multiple systems or each system will need to share information with each other. After reading this chapter, the reader will gain understanding of some potential approaches to data collection, compilation, aggregation, saving, and sharing information both on the RSE and at the TMC.

## 4.1 Data Compilation

Much of the initial collection, handling, saving, and sending of messages with CAVs data can be performed at the RSE. An RSE may ultimately be receiving and sending a wide range of messages with CAVs and connected mobile devices. The messages to be received or exchanged require specific data elements (e.g., time, position) or controls (e.g., security credential verification). If any of these electronic messages are to be used for traffic or travel management related functions, data elements in the messages must include the heading of the vehicle. The active management and operation of traffic signals, will benefit from being able to calculate the characteristics (e.g., flow profiles) of vehicles arriving at the intersections. Both probe messages and BSMS can be used to obtain the current trajectory of a vehicle by using the ID of the vehicle together with the sequence of data on the vehicles trip that is contained in the message.

The ability to integrate CAV and connected device data into the management and use of traffic management functions will require RSEs to collect, process and use data compiled from messages received in real-time and transmit messages to users (e.g., CAVs and connected travelers), the TMC, and other devices (e.g., the traffic signal controller). The processing and sending of messages will require either the RSE or TMC where messages are compiled, data extracted, used and saved to have the functional capabilities to generate a wide range of data elements (e.g., geo-fence boundaries, frequency of sampling). For example, detecting a queue on a ramp using CAV data may require the use of BSMS from the majority of the vehicles at an on-ramp to develop a trajectory representing traffic flow at the ramp and/or where the traffic merges with the freeway mainline flow.

The use of these messages to support identifying possible weather events may require large areas of coverage but only require sample messages from CAVs at a much lower rate. Therefore, it may not be

necessary for a system, TMC or RSE to send entire messages based on the information to be shared or functions to be conducted. The exchange and processing of messages may require a traffic management system or TMC to develop and use an intermediate point in the system (e.g., “hub”) to collect, compile and distribute information and messages. This approach was investigated earlier in [23], and [24]. The broad types of functions or services a RSE, system, or TMC would need include:

- **Administrative**—allowing users to determine administrative access restrictions, registration, communication logging, data storage, backup, and status reporting.
- **Management**—allowing the agency with authority to remotely monitor, control, and manage the operation of a RSE as needed.
- **Location or Map Identification**—allowing the system to update or process requests to change maps with asset related information and locations. The system or RSE would have the ability to determine the map and location information contained within messages received from or distributed to CAVs or connected mobile devices
- **Positioning functions**—distributing GPS corrections corresponding to the RSE location and providing logs as appropriate for differential correction.
- **Probe data**—provision of the service to collect and forward probe data messages and allow operators to perform probe data management remotely.
- **Time**—provide services to ensure sufficient accuracy in transmitted messages and logged data.
- **Server functions**—allowing registered applications to request data elements by geographical and temporal functions providing streaming data. In addition, allow local storage of raw data on an ad hoc basis.

The inclusion of local storage at an RSE would likely require writing the data to a circular file stored on an external device interfaced with the RSE or the capability needed to store data need to be specified and built into the RSE to allow it to send or allow a system or TMC to access and retrieve stored data. An implication of this decentralization is that there will be additional complexity in design, architecture, software platform, and communication network used to enable the collection, use and sharing of this data. A typical region may have a fiber-optic network installed within or adjacent to a freeway right-of-way that may be owned and operated by the State or toll authority. An RSE is likely to be collecting data which may span multiple facilities where there may be an interest from other agencies to obtain information on the portions of facilities which are managed by another agency. The system design and requirements should consider and incorporate these needs to share information with other stakeholders; where appropriate, deemed practical, and when the resources exist to develop data sharing functions.

#### 4.1.1 When and Where the CAV and Connected Traveler Data Should Be Compiled

It is critical for essentially all traffic management and TMC functions that are expected to be enhanced through use of the CAV and connected traveler to know the location and time of the occurrence. This may seem trivial, but the accurate determination of location and time is safety-critical for V2V and certain V2I applications, and of course any processes that are attempting to generate summaries of data by location or comparing results across the network at a common time. These considerations have been addressed in the development of the J2735 standards. The data element of J2735 that is used for time is the DE\_DSecond which consists of integer values from zero to 60999, representing the milliseconds within a minute. The J2735 standard for the BSM states:

*“The value contained in the DSecond data element must refer to a known point in time within the DSRC system that is shared or understood by the user community. This point in time is typically the moment when the position determination was made for most messages (such as the BSM). Other measurements present in the same message (speed, heading etc.) should be aligned to that moment insofar as possible in the implementation.”*

The RSU is required to contain a GPS unit that is used for positioning and timing so it can accurately match incoming BSMs with its own understanding of what time it is. This is particularly important so that data from connected vehicles and travelers that does not have an accurate timestamp can be rejected. Therefore, the RSU time, together with the Dsecond value, will enable the receiver of the data to know *when* it was collected in Universal Coordinated Time (UTC) time.

The BSMs use latitude, longitude, and elevation to define from *where* the data was collected. Latitude and longitude are defined in 1/10th integer micro degrees, as a 31-bit value, and with reference to the horizontal datum then in use. The DE\_Elevation data element represents the geographic position above or below the reference ellipsoid. The number has a resolution of 1 decimeter and represents an asymmetric range of positive and negative values.

Similar to the BSM message, the probe data messages use the frame for position vector that incorporates time, latitude, longitude, elevation, and heading. If the functions that are included in the RSE software also include the geographical inquiry features described earlier in chapter 2 then if a remote user/application requires data their initial inquiry will be to obtain geographical status from the RSE of which information is available at what locations.

Such geographical inquiries would then be made most efficiently from the RSE. If this were not done, then a central server would be required to keep track of each RSE and its geographical coverage. It would be more efficient for the RSE to act and respond to an external request from a CAV or connected mobile device that wants to acquire information or a message. For example, traffic management system may issue a probe data request for vehicles to submit information on antilock brake system activations, temperature, and windshield wiper activity within a specific geographic boundary. This request could be for one or all RSEs to obtain and submit this information.

### **Real-time and Near-Real-Time Data**

Arriving connected vehicle data is effectively streamed as it arrives asynchronously over a single radio frequency. Real-time data could be considered as the initial stream of messages directly from the vehicle. Near-real-time data such as probe messages could be delayed by several, and perhaps many, seconds. Any delay may be due to either compiling and preparing the information to transmit or post-processing to accumulate the data into trajectories or averages or other short-term results requested by the system if the RSE has the required capability.

These examples of hot and warm types of data would be distributed from the RSE to the system as they are created. For example, a State traffic operations center may request certain geo-fence locations of speed data, acceleration, and heading as input to an incident detection algorithm. If the function using this data is for the TMC to detect incidents, it may be appropriate for the RSE to transmit all messages received without any processing or assessment to reduce the time to detect incidents. The utility of the probe data management message should be considered if an agency considers integrating CAV data into their TMC and the algorithms used to detect incidents, since if an incident is detected, the TMC could

issue a probe management message to refine the information being reported in CAV messages generated from vehicles to enhance the monitoring of the incident and identify in more detail how the incident is influencing traffic on the facility.

### **Offline Data**

The cool or “offline” data, consisting of messages to be stored for data analytics purposes, could likely be stored either locally at a RSE, or at an agency that has a directly connected fiber optic line to the physical RSE. How long these messages can be stored will be dependent upon urban density, communication capacity, market penetration, range of the RSE, and other variables. However, for urban RSEs with a 10 GB network communication connection, it is likely that such raw data could be shared for the first few years of operations, during which other technologies may be developed to improve communication bandwidth.

## **4.1.2 Three Levels of Data Compilation**

This three-level structure of data compilation (real-time, near-real-time, and offline) is similar to the current operations of the Regional Integrated Transportation Information System (RITIS) at the University of Maryland. The three main components of RITIS are real-time data feeds (hot), a near-real-time Web site (warm), and a data archiving process (cool). The RITIS provides access to a wide range of transportation data, together with analysis and visualization tools, and a detailed archive of raw data.

Large-scale situational awareness sites, such as RITIS and other large-scale projects such as integrated corridor management (ICM) projects, will be sharing data across institutional boundaries and between traffic management centers more often as they develop. Although each agency will necessarily have their own data storage solutions for internal functions, there will be need to share certain portions of that data with neighboring agencies. These might be public safety, transit, air quality, or planning agencies, and such data would likely to be shared in a compressed form.

This is discussed in more detail in chapter 5. Many agencies have some experience already with center to center (C2C) sharing for traffic management typically using the AASHTO/ITE Traffic Management Data Dictionary (TMDD) Standard for Center to Center Communication. However, this does introduce a requirement where additional design work is needed. As new data elements evolve it would be advisable they be added to the J2735/J2945 standards. Data compilation has significant impacts on the storage requirements which will be discussed next.

## **4.2 Data Storage**

### **4.2.1 Messages, Frames, or Elements?**

Consideration should be given to how data is stored. The data is received as messages. The messages contain frames and the frames contain data elements (refer to figure 5). Traffic management and other related system functions typically require the use of *data elements*, but each element needs a location in time to make it useful. To store data as messages would require any future use of this information to inquire and access data elements across multiple messages.

In addition, these messages will contain multiple elements that are not used by the function and may therefore be inefficient to be accessed, used, and/or transmitted. To store the data as frames alone would not suffice since many of the data elements are not necessarily in a frame. Storing the data as elements associated with their time and location would allow each function or request to obtain information to only access the data elements it requires.

If data is stored as elements alone, then any information concerning the association between data elements is lost. For example, if a probe data message is divided into its elements, relationships between windshield wipers activation and temperature in a particular vehicle would not be known. However, if data is stored as elements, then a traffic management function or application could gather the specific data elements it may need from multiple messages. Acceleration of vehicles is an example of the value of supporting this method of accessing and using specific data elements since acceleration data may be reported in different messages. However, such associations between data contained in messages generated by an individual vehicle can be generally accommodated by using the temporary ID assigned to messages sets to associate data for access or use.

Since the association between data with one vehicle can be accommodated, it may be beneficial to store the data as elements. This approach allows elements of the same type from different messages to be grouped together. For example, if the RSE is responding to an inquiry from a TMC, CAV or connected device requesting weather data, it would be able to read elements such as temperature and windshield wiper activations from a single query, even though the data had been retrieved from multiple message types.

## 4.2.2 Data Reduction Strategies

A range of data reduction techniques may be appropriate to allow systems or TMCs to minimize data storage requirements and communications bandwidth. Storing CAV trajectories along with the RSEs position would allow latitude and longitude to be stored as minutes and seconds since they will have the same number of degrees as the RSE. Similarly, the time from the RSE together with Dsecond can be stored enabling UTC time to be reconstituted by functions at the TMC.

The data reduction that could occur at the RSE should meet the minimum requirements specified for either the RSE, the systems, or the TMC such that the system design and requirements were developed based on assessment of the configuration and functions to minimize the overall development and operational cost, optimize performance, and perform the required tasks. Some functions such as signal control would require real-time and near-real-time data. Others such as weather applications would require near-real-time data. Large-scale data analytics applications would make use of “cool” offline data stores. With respect to data reduction, an RSE could operate as follows:

- **Real-time data:** once per second: stream data to registered applications including:
  - RSE GPS full-time and full position.
  - Requested raw data element1, short time and position.
  - Requested raw data element2, short time and position, etc.
- **Near-real-time data:** once per minute: batch file including:
  - RSE GPS full-time and full position.

- Matrix of requested data elements.
- Average of data elements from the last minute.
- Other mathematical manipulation such as exponential smoothing.
- **Offline data:** files as requested, possibly highly compressed:
  - Requests could be on a regular basis such as once per hour or once per day (perhaps at off-peak times, such as during the middle of the night when bandwidth will be less utilized by near-real-time processes) to gather specific data for a particular element of the CAV trajectories.

Real-time data being needed for a traffic management function should generally be pared and compressed as much as possible to minimize communication load and ensure timely delivery. Near-real-time data can afford to be processed and have some basic statistics applied. Offline data requires no reduction whatsoever since any processes that compress the information may induce data loss by removing the information needed for analysis of the relationships of the various traffic parameters at the TMC.

### ***Time-Based Processes for Data Reduction***

Time-based processes include sampling, for example, every  $n^{\text{th}}$  BSM, or using the sampling processes built into probe data collection. For transitory events such as a quickly moving string of BSMs associated with an individual vehicle, using even just the first or last reading has proven to be useful for real-time data. If the data is essentially unchanged (the vehicle travels at more-or-less the same speed and heading during the entire trajectory) then there would probably be no loss of information. Applying lossless compression processes (described below) will ensure that all the information that can be obtained from the data can be retrieved.

### ***Application-Specific Processes for Data Reduction***

In the same way that current smart phone applications have components that reside in both the mobile device and at a central server, it is possible to distribute components of traffic and data management functions to an RSE. For example, if a traffic management center's functions includes detecting incidents, it could collect all the BSMs and probe messages, parse out the time, position, speeds, and accelerations at the RSE, and then transmit this information to the TMC for use in its algorithm to detect incidents. The processing of the speeds and accelerations would likely look for processes that smooth and filter the incoming data and then look for anomalous deceleration data combined for a preset number of vehicles for certain speed conditions.

These types of approaches are typically implemented by selecting a suitable time and location for which the data is accumulated and tested, perhaps every 30 seconds across all lanes in 500 m segments. In this example, there is little reason why the local processes should not provide the summary data alone to the central application. The central application would then be able to look at the data across multiple RSEs on a route and come to the correct conclusion about the location of the incident. This approach allows communication and storage loads to be minimized, and the raw data would not be transmitted at all to the TMC.

This approach is applicable to near-real-time data as well, but is not suitable for research needs and offline data analytics where each detailed parameter may need to be analyzed. For example, if a researcher wished to develop a model of traffic that was to predict the rate at which backward moving shockwaves move as a function of traffic density, it would be necessary to gather the dynamic data from a

long section of interstate from multiple RSEs over the same time period. The data collected would need to be geo-fenced to limit the data to the road of interest. All the raw data could be gathered to determine if factors such as weather or surface condition affect the result. In this example, long-term data storage is needed and multiple RSEs would be utilized.

The RSEs processing load would be to geo-fence the data and forward the appropriate messages to the TMC application. There are two options; the first would be to install high capacity communication lines from the appropriate RSEs to a storage point, and the second would be to store the data locally. It is possible currently to buy environmentally hardened solid-state drive storage that can operate between -40° C to +85° and hold 8 TB of data. Considering the cost of increasing the communications capacity, it is likely that significant amounts of local storage could be less expensive.

### ***Reporting by Exception—Potential Use in Near-Real-Time Applications***

Reporting by exception has been advocated and used in some applications in the past, but with limited success. This process involves the source (in this case the vehicle or a local process running on the RSE) knowing what “normal” conditions are like, determining when variations from normal occur, and then transmitting the information to the TMC only when variations from normal are detected. In the Advance [26] project, for one, the database held within the test vehicles to define “normal” experienced significant issues when being updated. Variables such as “congestion” can be quite noisy, so difficulties arise when using reporting by exception.

For example, a section of road may be congested for a few days or a week, which then becomes the “new normal” because traversing the road updated the database to indicate that congestion was the typical condition of that road section. When the congestion was not there, vehicles were still spuriously diverted to alternate routes, which then became part of the preferred route. However, there may be individual data elements where reporting by exception is a preferred option. For example, if a fleet is monitoring an engine parameter, sending the data attached to each probe message when it is normally operating would not be efficient, but sending by exception could be preferred.

### ***Compressing Connected and Automated Vehicle Data—Requirements for Offline Applications***

There are a range of compression techniques that could be applied to connected vehicle data including both lossy and lossless. In lossy compression, the data is corrupted to an extent; for example an image or a video will be fuzzier than the original video. Lossless compression ensures data integrity and is more suitable for connected vehicles data.

It is likely that compression techniques for one data message may not be suitable for another message type. Consider the application of a variation of run-length encoding (RLE) on a stream of BSM data. As described earlier the BSM consists of the following data elements:

- MsgCount.
- TemporaryID.
- DSecond.
- Latitude, Longitude, Elevation.
- PositionalAccuracy.
- TransmissionState.

- Speed.
- Heading.
- SteeringWheelAngle.
- AccelerationSet4Way.
- BrakeSystemStatus.
- VehicleSize.

For much of the time most of the vehicles continue straight ahead at the same speed. Therefore, when the BSM message is broadcast at 10 Hz, many of the data elements will remain unchanged during normal traffic flow. Consider a two second duration with 20 messages, as illustrated in table 4. For the vast majority of the two second block of data, the only change is likely to be the position (latitude longitude and elevation). For most of the time, messages 2 through 19 will not provide useful data. However, when there is a significant change in the data it is important that the appropriate application receives it with minimum delay.

**Table 4. Example of lossless compression for basic safety messages.**

Data Element	Time (tenths seconds)																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
MsgCount*	D	<i>Not useful vehicle data</i>																		D
TemporaryID	D	<i>Typically unchanged</i>																		D
DSecond	D	<i>Increments by tenths</i>																		D
Latitude, Longitude, Elevation	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
Positional Accuracy	D	<i>Typically unchanged</i>																		D
TrasmissionState	D	<i>Typically unchanged</i>																		D
Speed	D	<i>Typically no significant change</i>																		D
Heading	D	<i>Typically no significant change</i>																		D
SteeringWheelAngle	D	<i>Typically no significant change</i>																		D
AccelerationSet4Way	D	<i>Typically no significant change</i>																		D
Brake System Status	D	<i>Typically unchanged</i>																		D
VehicleSize	D	<i>Unchanged</i>																		D

Notes: D indicates new Data.  
 MsgCount\* used to indicate new message.

Source: FreeAhead.

A compression technique based on *run length encoding* could reduce the size of the bandwidth and storage needed for BSMs by approximately 80 percent. Such a technique could allow the requester of the data to determine the time between full BSMs being transmitted to meet the requirements of their application. Development of open source compression/decompression techniques specifically tailored to the storage and transmission of connected vehicle messages should be considered as a research gap to be filled.

Table 4 illustrates where there are opportunities for significant reduction in bandwidth requirements, however, each individual data element may also have other compression mechanisms applied to them. This could lead to further savings in both storage and communication requirements. Routinely applying compression techniques does require that the processing capability of an RSE would need to be increased.

This lossless compression technique is designed to allow transmission and storage of the data in such a manner that no information is lost during the process. This requirement will be needed to develop new mechanisms for operating traffic networks. For example, should an end-user of the data wish to investigate a mechanism for predicting in real-time where crashes are most likely, the application will need to gather traffic conditions, detailed information on vehicle operations, and weather conditions?

This information will need to be in its rawest form to mathematically search for relationships that could lead to such predictions. This could be useful for the transportation network operator in placing and routing safety service patrols. To develop such algorithms, the TMC would need to gather detailed data for a considerable amount of time (e.g., months and perhaps years). Lossless compression of BSM trajectories and batch forwarding of the data at regular intervals would be more effectively than streaming individual trajectories to such an “offline” function.

The central issue in developing data reduction techniques is developing a clear definition of what the needs of each TMC function will be. In this report and previous reports, we have advocated that commonalities of application needs exist among real-time (apps that must run on the RSE itself to be effective), near-real-time, and offline applications. However, there are specific differences between applications in each category that will need detailed designs developed in further work.

### 4.2.3 The Bottom Line: Vehicle Trajectories

Near-real-time and offline TMC functions will be significantly enhanced by knowing vehicle trajectories (both PDMs and strings of BSMs of each vehicle while in view of the RSE). The vehicle trajectory is merely a series of time stamped points in a 3D space.

Storing full latitude, longitude, elevation, and time for multiple points will require significant data storage capacity on the RSE. Preliminary work has already been done in the coding of the MAP message in J2735 to define the path upstream of an intersection through the stop bar and to the egress points that generally describes the range of the RSE. This coding is done by defining a starting point and then defining the offset for each consecutive mapping point.

A similar process could be adopted for vehicle trajectories by providing full position and time data at the starting point and then encoding the offset in position and time (which has a smaller size than storing the entire position and UTC time stamp for each point), thus allowing the full vehicle’s trajectory of its path within the range of the RSE to be reconstituted. The temporary ID would be used to determine that the same vehicle is represented by each point on the trajectory. While it will occur that some vehicles in view of the RSE will change their ID mid-stream (i.e., the current SCMS provisions require that this is done approximately every five minutes), the RSE application that generates the trajectories can either snap the partial trajectories back together or this reconstitution can be done by the TMC function without any compromise of privacy.

### 4.2.4 Transitioning to the Use of Connected and Automated Vehicle Data

Agencies that are adopting and working to integrate connected and automated vehicle data with the capabilities and designs of their existing traffic management system and TMC, will have existing databases that will need to be merged with this new information. This was discussed in some detail in chapter 3 of FHWA-JPO-18-625 *Opportunities for Integration of Emerging Data for Traffic Management and TMCs*. As agencies pursue the integration of data from CAVs with current traffic management

systems and TMCs, it is likely the agency may experiment with or sample CAVs sharing messages with ITS devices prior to the central system being designed to accommodate the new information directly. Therefore, there are likely to be several phases for a transition:

- An example of a possible initial phase could be when a RSE delivers trajectories of BSMs and PDM data directly to the TMC. The TMC could consider using the data for both near-real-time and offline use and use the data compilation and storage concepts discussed in this chapter. This would allow the system to convert the trajectory data into the format(s) (e.g., spot mean speeds, etc.) expected by the TMS. The TMC could receive more data from a wider geographical area than the current system supports. This information derived from CAV trajectories could in the longer term replace the need for certain types of traffic detectors or sensors.
- A transition phase where the TMS function(s) are modified and enhanced to use the trajectory data compiled from messages received from connected and automated vehicles directly, instead of assuming the CAV data is just a replacement of traditional sensors.
- A third phase when the data from messages generated by connected vehicles is sufficiently ubiquitous that many of the conventional sensors could be decommissioned without significant loss of functionality.

For example, consider a TMS function designed to monitor travel conditions, detect regimes of unstable traffic flow, identify possible incidents, implement any applicable traffic management or control strategies, or provide pre-trip or en-route roadway condition messages to drivers. In the initial phase the data contained in messages generated by connected vehicles will simply supplement the existing traffic detectors. With the proper functional capabilities, the RSE could geo-fence the appropriate BSM trajectories, parse the messages, extract the speed data, convert it to the legacy format, and then transmit (or respond to a poll message as is more typical in legacy systems) the message to the applicable traffic management functions at the same intervals (e.g., every 30 seconds) expected by the legacy system.

The traffic management system or TMC could then post messages on variable message signs, highway advisory signs, and pre-trip travel condition reporting. In the transition phase, additional data, such as deceleration, could be added to the traffic management systems incident detection function. The RSE would then send both the converted speeds and connected vehicle trajectories incorporating speed and deceleration.

The traveler information component could then start to distribute more specific traveler information messages to equipped vehicles and connected travelers and continue to support variable message signs. In the third phase, the conventional traffic detectors could likely be abandoned, the RSE would stop sending the legacy speed data, and the new incident detection algorithm would locate traffic anomalies and the traveler information would be sent to connected vehicles on a geographically specific basis in order that drivers only receive relevant information. At such a time, variable message signs might also be able to be retired.

This transition will constitute a continually increasing burden on the computational and storage ability of the RSE, some of which cannot be designed into the current specifications without additional experience of the CV pilots and other testbeds over the next few years.

# Chapter 5. Data Sharing

The purpose of this chapter is to discuss issues related to sharing of data with connected and automated vehicles and connected devices by a traffic management system or TMC. As data sharing in by these systems is commonplace, the objectives of this chapter are to illustrate how these emerging sources of data could be integrated into existing methods of sharing data, what may be different, and what agencies need to consider or address. After reading this chapter, the reader will gain an appreciation of these technical issues to consider and what may require additional investigation or analysis as next steps. The data sharing functions of a traffic management system or TMC described in this chapter assume that these practices are integrated into the agencies policies and procedures for managing data or sharing information.

The introduction of data from CAVs and connected devices will necessitate potentially more complex methods to ensure the desired levels of performance are achieved associated with the sharing of data to support current traffic management and TMC functions. There is a range of potential users of an agency's CAV data that includes:

- **Regional users**—including neighboring States, transit authorities, metropolitan planning organizations, regional fleet operators, and other forms of transit service providers.
- **Local users**—city and county DOTs, roadway maintenance departments, transit authorities, planning departments, public safety, emergency medical and other first responders, and local commercial businesses distinct from regional or national businesses providing the same services in multiple jurisdictions across the U.S..

The utility of sharing information varies significantly based on the conditions unique to each situation. For example, if the application is to monitor the condition of a fleet of transit vehicles, it is likely that the routes to be covered will extend into multiple jurisdictions. Each local agency responsible for managing traffic along the routes served by the transit provider will need to electronically share the desired data in a manner which complies with the policies, procedures, and requirements of each agency and their associated systems.

## 5.1 Center to Center Methodologies for Sharing Data

There are a variety of mechanisms for sharing data from one transportation management system to another which may or may not require the use of standards. In order for the widest range of systems to be integrated without an undue burden of additional software development for each project, standards such as the National Transportation Communications for ITS Protocol (NTCIP) have been developed in a consensus-based process to allow remote monitoring and control of roadside and other transportation management devices in a manner that is both interoperable and interchangeable between device manufacturers. Other processes are applicable such as JavaScript Object Notation (JSON) that is standard file format using human readable text allowing communication between a browser and a server.

There are also legacy mechanisms such as File Transfer Protocol (FTP) and flat files with comma separated variables available for use in a spreadsheet. These techniques have been developed for the relatively slow and not very data intensive world of conventional traffic detectors, variable message signs, traffic controllers, and traveler information. The current NTCIP 2306 center to center standard (now more than 10 years old, and based on technology from 2003) is already limited in its functionality to share near-real-time status information for traffic signals from one agency to another when the number of devices exceeds more than a few hundred, since all of the statuses are appended into a single XML file that must be generated, sent (via Simple Object Access Protocol (SOAP)), and unpacked each second.

Modern methodologies as discussed in chapter 4 of FHWA-JPO-18-625 *Opportunities for Integration of Emerging Data for Traffic Management and TMCs* will likely be required to share data with agency partners when CAV data is included. The sheer size of the information as it builds up over time will require NoSQL technologies such as the Hadoop Distributed File System (HDFS) to store it, and the velocity at which the information is delivered will require technologies such as Apache Spark to deliver it to other centers for near-real-time applications. These technologies will enable interesting new applications such that perhaps an algorithm in one location can be applied multiple times in parallel across data stored in multiple locations, including locations at adjacent and partner agencies.

It is anticipated that such processing will also be able to improve traffic operations by finding relationships between variables not obvious to individual traffic management centers with limited geographic purview. For a given set of circumstances such as weather, traffic flow conditions, percentages of trucks, and so on a particular network, personalized traveler information messages might be able to be generated back to connected vehicles, enhancing integrated corridor management and alleviation of congestion across both freeways and arterial streets. Without the fusion of connected vehicle data shared from agency partners, such applications could not be achieved.

Sharing of CAV data with partner agencies will also enable much more extensive and detailed modeling and improve the predictive capabilities of such models and decision support systems. Currently microscopic modeling of traffic flow using programs such as CORSIM and Paramics can be used in an on-line mode (e.g., San Diego ICM) to estimate the effects of changes on the network on traffic flow. However, when these models are run there is little information on how the predicted changes in the network compared with what actually occurred. In a connected and automated vehicle environment, it will be much more possible to model a network using live data and compare the predicted output with the actual data received from the CAVs and connected travelers. These results could be used to calibrate the model assumptions to make the resulting future predictions and assessment of diversion strategy options in incident conditions significantly more accurate.

## 5.2 Strategies for Sharing

Strategies for sharing data between agencies will vary widely depending on the data types, formats, urgency, available bandwidth, needs of each agency, and costs to develop and maintain the mechanisms for sharing of this information. However, as tools are developed and technologies change which enable the cost-effective sharing of data it will likely become commonplace in the same way that image compression and video compression tools enabled successful commercial services such as Amazon Prime Video and Netflix. To illustrate examples of how sharing may work, table 5 includes a range of applications taken from the example use cases being developed to illustrate the use of probe data.

Key to data type: **real-time**, **near-real-time**, and **offline**.

**Table 5. Example strategies for sharing data.**

Application	Types of data	Compilation method	Shared with:
Mobility Data to TMC	Dynamic vehicle parameters including event data such as ABS activations and speed position heading. Where available BSM messages.	Single exponential smoothing every minute.	Commercial suppliers of traffic data such as WAZE. Adjacent jurisdictions with traffic management centers for
Roadway Condition Monitoring	Position, vertical acceleration, ABS events, traction control events.	Compressed raw data to keep accuracy.	Maintenance departments planning resurfacing.
Adaptive Signal Control	Speed, position, heading, timestamp.	Vehicle trajectories approaching signalized intersection.	Traffic signal controller optimizing timing plans.
Weather Model Input	Temperature, wiper activations, external lights, ABS and traction control events.	Temperature wiper on a sampling basis. ABS and traction control compressed raw data	National Weather Service.
V2V Mobility Data	Speed profiles, including position speed and heading data.	Compressed speed profile messages.	Receiving vehicles, inputs to navigation systems and traveler information messages.
Local Map Development	Speed position heading.	Averaged over very long sample periods, then differentially corrected.	Local algorithm in RSE used to enhance MAP message.
Origin and Destination (OD) Matrix	Timestamp, position, ID.	Raw data, small sample compression not required	transportation planning models requiring OD matrix.

**Table 5. Example strategies for sharing data (continuation).**

Application	Types of data	Compilation method	Shared with:
Fleet Vehicle Maintenance Data	Timestamp, position, ID, various vehicle monitoring parameters, passenger count.	Raw data, small sample compression not required	Transit authorities, fleet managers.
Third-Party Data	Timestamp, position, ID, BLOB.	Proprietary BLOB compressed.	Applications such as snowplow monitors, transit vehicle monitoring and safety service patrols.
Stationary Vehicle Warning	Object detection, position.	Raw data, small sample, average position	Traveler information message to other vehicles
Situational Awareness	Object detection, position.	Raw data, small sample, average position	Traveler information message to other vehicles

Source: FreeAhead Inc. and Kimley Horn and Associates, 2018.

### 5.3 Application Programming Interfaces

An Application Programming Interface consists of a set of tools for building software systems that connect to other software systems. An API typically exposes a method by which an external software system can obtain information from another program or send control commands to the other system to enable certain functions. For example, most video cameras have a vendor-specific API that allows other software systems to select PTZ presets or obtain snapshot images. Any number of external systems might connect to this API once it is put in place and little to no coordination with the system vendor is required to use it. This is also similar to many open data policies of governments where data sets are made available on the Internet for anyone to use without any coordination with the providing agency.

In the case of CAVs and connected travelers, a series of standardized APIs needs to be developed that will allow center-to-center data sharing of the various types of summaries and aggregations listed in table 5. These APIs will probably and necessarily be different than the software-to-software connections between legacy ATMS and RSEs, or from RSEs to real-time streaming data acquisition tools at the TMC. A modular software platform and system architecture similar to that used by the V2I and D2X hub projects for RSEs may be a model that could be followed for developing generalized, open-source or modular

platforms for TMCs which could be easily configured, modified, scaled, and adjusted for specific agency uses and needs.

While the content will likely be the same between the RSE and the TMC and from the TMC to other users for the typical applications in table 5, the center to center APIs will be different in particular because the center to center data sharing will aggregate information across all of an agency's CAV and connected traveler data and may contain complex aggregations across certain data elements, geo-fences, frequency, and other parameters for certain routes and areas of interest for agency and commercial partners. Such design activities will require close cooperation between the partners initially and the use of scalable systems, such as those built on modern big data tools and technologies. Use of scalable systems will minimize the operations and maintenance burden on agencies as the volume and velocity of the CAV and connected traveler data flowing through the APIs will continue to grow over time.

Modern APIs used by big data commercial systems such as Twitter typically now “push” data using JSON API standards or more generally Web API standards after the endpoint software has subscribed to certain topics, geofences, and other requirements such as #hashtags. The debate of push versus pull methods will continue as many big data tools and technologies continue to use both. Pull methods are also typically used when the data requests may be modified, sometimes frequently, by the software doing the requesting. This will likely be true for some center to center requests. Detailed design of these data interfaces will be needed in the coming years to ensure that scalability of the services is maximized, while balancing initial agency costs for communications bandwidth, cloud computing resources, and software development/procurement.

# Chapter 6. Next Steps for the Collection, Compilation, Storage, and Sharing of CAV and Connected Traveler Data

The purpose of this chapter is to summarize the findings from the previous five chapters and identify what agencies should consider in preparing their traffic management systems and TMCs to take advantage of the opportunity to share and use data from CAVs and connected travelers. When information from CAVs and connected travelers is available at scale, agencies systems which attempt to use and share information with these vehicles and devices, will need to be able to facilitate this exchange. After reading this chapter, the reader will have an appreciation for the issues to consider in the design, planning, and implementation of revisions to TMSs and TMCs and the RSEs to enable them to collect, use and share electronic messages with CAV and connected travelers.

## 6.1 Findings

This report focused on 1) summarizing the current capabilities of RSEs; 2) identifying what information exists to enable agencies to consider the role of RSEs in the design and procurement of TMSs; and 3) exploring how agencies could use RSEs to take advantage of emerging data sources. The principal finding of this report is that there needs to be a significant increase in the capabilities of the RSE to position TMSs to take advantage of using and sharing data with CAVs and connected travelers. Without additional capabilities for edge processing and storage on the RSE, the disparate users of the data will not be able to take advantage of its potential. These changes in RSE capability and functionality will need to be developed iteratively on both the hardware and software components.

Current RSE specifications (as described in chapters 2 and 3) do not address the potential value of using different data aggregation strategies at the RSE to successfully relay connected vehicle data or compiled information back to the TMC. Many current communication networks have limited bandwidth and may require significant improvements to enable exchanging all of the data collected from CAVs and connected travelers which would be cost prohibitive. This report explored the range of issues associated with CV messages, formats, and content to explain the various issues to consider the collection, processing, use, and sharing of data by traffic management systems and how different that motivate the need for data aggregation.

One key finding discussed in chapter 2 was that processing at the edge of the traffic management system will be necessary to significantly reduce demand for storage at the TMC and communication bandwidth between the RSEs and the TMC. Individually forwarding each BSM from the RSE to the TMC is not likely to be a viable strategy for success when the penetration level of CAVs and connected travelers increases

and thus the number of electronic messages that could be collected increases significantly. In some ways, the future design and architecture of the traffic management system which includes RSEs may resemble 1980s and 1990s-era traffic management systems, with intermediary processing points (the RSEs themselves, for one, but potentially other distributed processing points or hubs that deal with several, or perhaps many, RSEs collocated geographically) that assimilate the information from the CAV and connected traveler data and forward summaries, aggregations, and compressed data back to the TMC for near-real-time and offline applications.

The reader is also referred back to figure 1 in chapter 2 to highlight the multi-jurisdictional issues that will arise with many RSEs. Based on the range of most DSRC RSE antennas (300m+), data from arterial streets, freeways, and nearby pedestrian areas may be mixed together. Similar issues will be experienced with other communications media including WiFi and 4G/5G. Geofencing strategies, at minimum, will need to be deployed on the RSE to help sort out the relevant information (e.g., direction of travel, location of vehicles within roadway) for processing to allow specific information to be identified and used for specific traffic management functions.

Chapter 3 discussed data collection, message formats and standards, probe management processes, and summarized existing approaches to data aggregation, compilation, storage, and processing on RSEs. A reader looking to compare and contrast the various equipment selections and approaches may find section 3.9 helpful. Both PVD and SpeedProfile message types will likely be quite valuable for near-real-time and offline TMC applications, particularly if the density of RSEs does not accelerate at the same pace at which CAVs and connected travelers are being used. In particular, if PSMs become prevalent from smart devices carried by pedestrians, cyclists, and other vulnerable road users, these messages could significantly add to the challenges faced by RSEs that attempt to collect, process, and store all the data within range, particularly in dense urban settings.

Chapter 4 discussed strategies for data compilation and storage. At minimum, data compression will be necessary for offline applications that may need to retain all of the detailed history of BSM trajectories, PDMs, and other message types. Certain application-specific aggregation strategies will likely be required for near-real-time and local real-time applications. Most notably, the chapter concludes that individual BSMs should be probably collected together as trajectories for each vehicle (as well as other users such as pedestrians and cyclists) and transmitted to the TMC after the vehicle has exited the range of the RSE for use by near-real-time applications.

In addition, the RSE will need to have much more “intelligence” to handle a wide variety of electronic *message types*. Each message type that could be collected will also contain a wide variety of *data elements*, and each message generated by and shared with CAVs and connected travelers *will not uniformly have the same content*. These complexities will require the RSE to compile and process the messages to access, aggregate and summarize the data that can then be forwarded to a hub or TMC. This will require additional memory, processing, and storage capabilities at the RSE (and perhaps orders of magnitude more storage than existing RSEs).

Since much of this data will then be sent to a variety of near-real-time functions which are performed at the TMC, communications bandwidth in many systems will need to be significantly increased, or many of the traffic management and control functions will need to be conducted at a hub or RSE. To support this functionality, the RSE will also need to have a registration system that will limit access to only authorized processes. The V2I Hub software is a good example of how a flexible and adaptive “plug-in” software architecture and platform might be used for this purpose.

The RSE will need to be aware of its geographical coverage to provide registered processes with the coordinates within which they can make their own geofenced queries. Note that the current RSU specification does require that a GPS unit is incorporated; although many applications will require differential corrections (RTCM) for highly-accurate positioning. The RSE will be able to map the incoming messages and potentially report the coverage area allowing the administrator for the system to visually determine if there are areas that are insufficiently covered by the DSRC, WiFi, or 5G signal.

The hardware configurations developed by vendors according to the specifications developed by public agencies to procure these devices are likely to change as the messages from CAVs and connected travelers become available over time. Agencies are encouraged as they redesign existing TMSs or design next generation TMSs, to also monitor information regarding changes and increasing capabilities of RSEs. Future changes to the design or specifications for RSEs may include developing separate hardware/software components designed for specific requirements and functions (such as data aggregation and compression), much in the same way that the newest traffic signal controller cabinet standards provide separate hardware components for conflict monitoring, communications, detection, and signaling.

In addition, RSEs will need to support the functionality of the SCMS and other requirements that may be necessary in the future associated with these systems collecting, processing, using, and sending electronic messages. The SCMS provides the security certificates that are attached to messages as part of the digital signature used to prove that the message is trustworthy. This report mentioned but provided only limited information on the implications for SCMS processes on the design and performance of RSEs. The reader is advised to continue to explore and use the latest information which may be available in support of SCMS and other methods which may be appropriate to use in support of sharing and using electronic messages with CAVs and connected travelers.

Finally, chapter 5 discussed concepts related to sharing of CAV and connected traveler data owned by one agency with other partner agencies and commercial entities. Big data tools and technologies and appropriate software APIs will likely be required for such interfaces, particularly for sharing CAV and connected traveler data with other centers for near-real-time applications. Existing traffic management industry practices and standards are probably not adequate for sharing of connected vehicle data from potentially hundreds of RSEs communicating with a large number of CAVs and connected travelers in a jurisdiction or with other agencies or service providers.

The following sub-sections outline the findings of this report relative to the role of the RSE in real-time, near-real-time, and offline functions for traffic management and TMCs.

### 6.1.1 Real-Time Data

A significant increase in the processing capability of the RSE will be required in the event that (potentially many) safety-critical real-time functions will be installed on the RSE. If real-time functions are included in an agency's system design, all incoming messages need to be processed immediately in order that the RSE can determine which data elements of each message are necessary for real-time functions and which data elements are not. Based on all of the other communications between the RSE and the TMC for *near-real-time* and *offline* functions, it will not likely be possible to transmit real-time data from the RSE to the TMC and return control actions back to the roadside with low enough latency to have the desired effect (i.e., send a warning to the vehicle or change control displays such as traffic signal colors). Additional "plug in" software API's or modules will likely need to be added to the software platform used for the system or at each RSE to enable data translation and streaming analytics.

Many real-time functions of the RSE are likely common to functions of the OBE; including message handling, geofencing, and compressing and storing data elements. Many of these functions are likely to be made available on the open source application development portal to allow for others to use or jointly share in the development of the software for RSEs or the system which will allow other agencies and manufacturers to benefit.

It can be envisioned that future real-time models of the transportation network could be driven by real-time status data from CAVs and connected travelers. Such a model might be used at the TMC in a decision support system to estimate the consequences of various types of operator actions and provide highly-granular and specific traveler information to individual vehicles. When these applications have been developed, it is likely they will require significant increase in the bandwidth of the communications network between each RSE and the TMC.

### 6.1.2 Near-Real-Time Data

It is suggested in the near term for near-real-time legacy TMS functions that the data transmitted from the RSE to the TMC could replicate the data from traditional sensors (e.g., loop detection stations on freeways, for one). This would require the RSE to include functions and processes to generate data summaries, such as spot speeds, and respond to the TMC function as if it were a traditional sensor system. This would significantly decrease the communication loading between the RSE and the TMC, particularly during peak periods of travel when the density of CAVs and connected traveler within range of the RSE will be highest.

A second interim step would then be to provide aggregations (e.g., perhaps one-minute summaries of all vehicle trajectories just exiting the range of the RSE) of connected vehicle data to the TMC via data acquisition technologies based on big data tools (e.g., Apache Spark, Kafka, etc.). As the market penetration of connected vehicles increases, scalable modern technologies will be necessary to handle the extreme loads. New algorithms would then be developed to manipulate the data elements and augment the legacy TMS applications with new information. In perhaps ten years or more, new generation TMS applications would likely become available that directly manipulate the CAV and connected traveler data without relying on legacy traffic measurements such as spot mean speed.

Other near-real-time data, such as data elements needed for weather models, can likely be sampled and summarized from all of the variety of messages received at each RSE. For example, temperature measurements may only require a thin geographical spread of readings to obtain sufficient accuracy but may also require all event data such as antilock brake activations to be sent to the weather model.

### 6.1.3 Offline Data

Additional uses of CAV and connected traveler data may be identified in the future. Thus, the CAV and connected traveler data intended for use by Offline functions at the TMC will probably need to consist of all the raw messages received by the RSE. However, since there is no significant urgency in transmission of the information, the data can be highly compressed for storage and transmission. Customized compression methods such as those discussed in chapter 4 (see table 4), may be helpful in reducing the size of the data without any loss of information. The RSE will likely need significantly more data storage capacity and possibly big data storage based on big data technologies, such as NoSQL.

It may also be advisable only to collect, process, and store offline data when requested by a TMC function, such as for an academic research study. Such on-demand storage and communication of offline data will minimize the impacts of offline functions on the need to upgrade communications networks. Offline data can also be transmitted from the RSE to the TMC off-peak (i.e., in the middle of the night), when other near-real-time data streams will not be significant.

## 6.2 Recommended Agency Actions

### 6.2.1 Integrating CAVs and Connected Travelers into Traffic Management Systems and TMCs

Agencies considering integration of CAV and connected traveler data with traffic management functions and TMCs are referred to FHWA-JPO-18-629 *Guidelines for Applying the Capability Maturity Model to Connected and Automated Vehicle Deployment* to assess the various dimensions (business processes, systems and technology, performance measures, collaboration, culture, organization & staffing) relative to their readiness for undertaking feasibility studies, pilot projects, and program development. The Capability Maturity Model is a framework for assessing if an agency is *exploring* CAV functions (level 1), *initiating* CAV programs (level 2), *integrating* CAV and connected traveler data with existing traffic management and TMCs (level 3), or ready to *mainstream* (level 4) CAV and connected traveler data with traffic management and TMCs.

This report substantially focused on detailed technical issues related to systems and technology (RSE capabilities, software processes and systems, communications networks, and data standards), but the other dimensions of agency capabilities are equally as important to the success of integration of CAV and connected traveler data with traffic management systems and TMCs.

Agencies in the early planning stages for integrating CAV and connected traveler data with traffic management and TMCs may take the following steps:

1. Convene a statewide or regional workshop to raise awareness and discuss with potential stakeholders, partners, and partners on topics associated with the integration of CAVs and connected travelers with traffic management systems and TMCs.
2. Discuss priorities, opportunities, and barriers to integrating CAV and connected traveler data to enhance the active management and operation of traffic management systems and TMCs.
3. Determine a short-list of high-priority CAV and connected traveler data that improve traffic management and TMCs and a longer list of secondary-priority data that address regional issues, challenges, and goals. While many goals are generic, tailoring the ability to compile data and information from CAVs and connected travelers to augment current performance monitoring, reporting, and programs.
4. Review the activities in level 1 (exploration) of the self-assessment tables and identify priority actions.
5. Develop a project plan to implement the actions.

If most activities in level 1 (exploration) have been accomplished, focus energies on levels 2 (initiation) and 3 (integration). 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 a strategy to integrate CAVs and connected travelers into traffic management systems and TMCs as a basis for determining what other possible strategies could be pursued or expansions of services supported by these systems or enhancements made to the traffic operations programs of agencies.
- Identify actions at level 1 that have not yet been completed.
- Gather technical experts, system integrators, and TMC staff together for detailed technical planning of capabilities for use of CAV and connected traveler data with legacy TMS and sharing with agency partners.
- Explore the integration of current or proposed traffic management and TMC program plans with a CAV and connected traveler 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 and develop a prioritized action plan for integration of CAV and connected traveler data into traffic management systems and TMCs.

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 for improving traffic management and TMCs. Could the ITS and traffic management system infrastructure (RSEs, communication links, and software) 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 CAV and connected traveler system roadmap.

## 6.2.2 Planning for Next Generation Traffic Management and TMCs

RSEs will be a key element in the use of data from CAVs and connected travelers to improve traffic management functions in next generation TMSs and TMCs. Several specific actions are needed to accomplish such goals:

- Develop a multi-year plan to integrate collection, processing, etc. of CAV and connected traveler data from RSEs with the development of next-generation TMS functions, to include the specification of big data tools and technologies in the processing, storage, and sharing of data and information
- Use modular and easy to modify software platforms for the RSE in the implementation of data aggregation, data compression, and other processing algorithms
- Identify how PVD and PDM processes may support collection of data between areas of RSE coverage
- Support the development of flexible and modular software platforms and APIs between RSEs and TMSs, and for data sharing from TMSs to CAVs, connected travelers, and other agency stakeholders and centers
- Evaluate how existing communication networks will be able to support future CAV and connected traveler data. Where limitations exist, develop a plan for upgrading such communication links or developing other data collection architectures (e.g., interim hubs) to accommodate the lower bandwidth communication links.

# Appendix A. Connected Vehicle Applications

Source: Connected Vehicle Reference Implementation Architecture.

Commercial Vehicle Operations	Infrastructure Monitoring
Carrier Operations and Fleet Management	Parking Management
Freight Administration	Parking Space Management
Electronic Clearance	Smart Park and Ride System
CV Administrative Processes	Parking Electronic Payment
International Border Electronic Clearance	Regional Parking Management
Freight Signal Priority	Public Safety
Roadside CVO Safety	Emergency Call-Taking and Dispatch
Smart Roadside and Virtual WIM	Routing Support for Emergency Responders
Freight-Specific Dynamic Travel Planning	Emergency Vehicle Preemption
Road Weather Information for Freight Carriers	Mayday Notification
Freight Drayage Optimization	Vehicle Emergency Response
HAZMAT Management	Incident Scene Pre-Arrival Staging Guidance for Emergency Responders
Roadside HAZMAT Security Detection and Mitigation	Incident Scene Safety Monitoring
CV Driver Security Authentication	Roadway Service Patrols
Fleet and Freight Security	Transportation Infrastructure Protection
Electronic Work Diaries	Wide-Area Alert
Intelligent Access Program	Early Warning System
Intelligent Access Program—Weight Monitoring	Disaster Response and Recovery
Intelligent Speed Compliance	Evacuation and Reentry Management
Data Management	Disaster Traveler Information
ITS Data Warehouse	Public Transportation
Performance Monitoring	Transit Vehicle Tracking
Maintenance and Construction	Transit Fixed-Route Operations
Maintenance and Construction Vehicle and Equipment Tracking	Dynamic Transit Operations
Maintenance and Construction Vehicle Maintenance	Transit Fare Collection Management
Roadway Automated Treatment	Transit Security
Winter Maintenance	Transit Fleet Management
Roadway Maintenance and Construction	Transit Passenger Counting
Work Zone Management	Transit Traveler Information
Work Zone Safety Monitoring	Transit Signal Priority
Maintenance and Construction Activity Coordination	Intermittent Bus Lanes
	Transit Pedestrian Indication
	Transit Vehicle at Station/Stop Warnings

---

U.S. Department of Transportation  
Office of the Assistant Secretary for Research and Technology  
Intelligent Transportation Systems Joint Program Office

Vehicle Turning Right in Front of a Transit Vehicle	Standard Railroad Grade Crossing
Multimodal Coordination	Advanced Railroad Grade Crossing
Transit Stop Request	Railroad Operations Coordination
Route ID for the Visually Impaired	Reversible Lane Management
Transit Connection Protection	Speed Warning and Enforcement
Integrated Multimodal Electronic Payment Support	Drawbridge Management
Connected Vehicle System Monitoring and Management	Roadway Closure Management
Core Authorization	Variable Speed Limits
Data Distribution	Speed Harmonization
Map Management	Dynamic Lane Management and Shoulder Use
Location and Time	Border Management Systems
Object Registration and Discovery	Traveler Information
Privacy Protection	Broadcast Traveler Information
Security and Credentials Management	Personalized Traveler Information
Sustainable Travel	Dynamic Route Guidance
Emissions Monitoring	Infrastructure-Provided Trip Planning and Route Guidance
Eco-Traffic Signal Timing	Travel Services Information and Reservation
Eco-Traffic Metering	Dynamic Ridesharing and Shared Use Transportation
Roadside Lighting	In-Vehicle Signage
Electric Charging Stations Management	Vehicle Safety
HOV/HOT Lane Management	Autonomous Vehicle Safety Systems
Eco-Lanes Management	V2V Basic Safety
Eco-Approach and Departure at Signalized Intersections	V2V Situational Awareness
Connected Eco-Driving	V2V Special Vehicle Alert
Low Emissions Zone Management	Curve Speed Warning
Traffic Management	Stop Sign Gap Assist
Infrastructure-Based Traffic Surveillance	Road Weather Motorist Alert and Warning
Vehicle-Based Traffic Surveillance	Queue Warning
Traffic Signal Control	Reduced Speed Zone Warning / Lane Closure
Connected Vehicle Traffic Signal System	Restricted Lane Warnings
Traffic Metering	Oversize Vehicle Warning
Traffic Information Dissemination	Pedestrian and Cyclist Safety
Regional Traffic Management	Intersection Safety Warning and Collision Avoidance
Traffic Incident Management System	Cooperative Adaptive Cruise Control
Integrated Decision Support and Demand Management	Infrastructure Enhanced Cooperative Adaptive Cruise Control
Electronic Toll Collection	Automated Vehicle Operations
Road Use Charging	Weather
Dynamic Roadway Warning	Weather Data Collection
	Weather Information Processing and Distribution
	Spot Weather Impact Warning

# Appendix B. Connected Vehicle Data Elements

From SAE J2735.

AccelerationConfidence	DrivingWheelAngle	J1939-71-Tire Location
AdvisorySpeedType	DSecond	J1939-71-Tire Pressure
AllowedManeuvers	DSRC_MessageID	Threshold Detection
AmbientAirPressure (Barometric Pressure)	Duration	J1939-71-Tire Pressure
AmbientAirTemperature	DYear	J1939-71-Tire Temp
Angle	ElevationConfidence	J1939-71-Trailer Weight
AnimalPropelledType	Elevation	J1939-71-Wheel End Elect. Fault
AnimalType	Extent	J1939-71-Wheel Sensor Status
AntiLockBrakeStatus	ExteriorLights	LaneAttributes-Barrier
ApproachID	FuelType	LaneAttributes-Bike
Attachment	FurtherInfoID	LaneAttributes-Crosswalk
AttachmentRadius	GNSSstatus	LaneAttributes-ParkingLane
AuxiliaryBrakeStatus	GrossDistance	LaneAttributes-Sidewalk
BasicVehicleClass	GrossSpeed	LaneAttributes-Striping
BasicVehicleRole	HeadingConfidence	LaneAttributes-TrackedVehicle
BrakeAppliedPressure	Heading	LaneAttributes-Vehicle
BrakeAppliedStatus	HeadingSlice	LaneConnectionID
BrakeBoostApplied	HumanPropelledType	LaneDirection
BumperHeight	IntersectionID	LaneId
CoarseHeading	IntersectionStatusObject	LaneSharing
CodeWord	IsDolly	LaneWidth
CoefficientOfFriction	Iso3833VehicleType	Latitude
Confidence	ITISextPhrase	LayerID
Count	J1939-71-Axle Location	LayerType
DDay	J1939-71-Axle Weight	LightbarInUse
DeltaAngle	J1939-71-Cargo Weight	Longitude
DeltaTime	J1939-71-Drive Axle Lift Air Pressure	MAYDAY_Location_quality_code
DescriptiveName	J1939-71-Drive Axle Location	MAYDAY_Location_tech_code
DHour	J1939-71-Drive Axle Lube Pressure	MergeDivergeNodeAngle
DirectionOfUse	J1939-71-Drive Axle Temperature	MessageBLOB
DistanceUnits	J1939-71-Steering Axle Lube Pressure	MinuteOfTheYear
DMinute	J1939-71-Steering Axle Temperature	MinutesDuration
DMonth	J1939-71-Tire Leakage Rate	MotorizedPropelledType
DOffset		MovementPhaseState
DrivenLineOffsetLarge		MsgCount
DrivenLineOffsetSmall		MsgCRC
		MultiVehicleResponse

MUTCDCode	RadiusOfCurvature	ThrottlePosition
NMEA_MsgType	Radius	TimeConfidence
NMEA_Payload	RainSensor	TimeIntervalConfidence
NMEA_Revision	RegionId	TimeMark
NodeAttributeLL	RequestedItem	TimeOffset
NodeAttributeXY	RequestId	TractionControlStatus
NumberOfParticipantsInCluster	RequestImportanceLevel	TrailerMass
ObjectCount	RequestSubRole	TransitStatus
ObstacleDirection	ResponseType	TransitVehicleOccupancy
ObstacleDistance	RestrictionAppliesTo	TransitVehicleStatus
Offset_B09	RestrictionClassID	TransmissionState
Offset_B10	RoadRegulatorID	TravelerInfoType
Offset_B11	RoadSegmentID	UniqueMSG_ID
Offset_B12	RoadwayCrownAngle	URL_Base
Offset_B13	RTCM_Revision	URL_Link
Offset_B14	RTCMmessage	URL_Short
Offset_B16	Scale_B	UserSizeAndBehaviour
OffsetLL-B	SecondOfTime	VehicleEventFlags
OffsetLL-B	SegmentAttributeLL	VehicleHeight
OffsetLL-B	SegmentAttributeXY	VehicleLength
OffsetLL-B	SemiMajorAxisAccuracy	VehicleMass
OffsetLL-B	SemiMajorAxisOrientation	VehicleStatusDeviceTypeTag
OffsetLL-B	SemiMinorAxisAccuracy	VehicleType
PayloadData	SignalGroupID	VehicleWidth
PedestrianBicycleDetect	SignalReqScheme	Velocity
PersonalAssistive	SignPriority	VerticalAccelerationThreshold
PersonalClusterRadius	SirenInUse	VerticalAcceleration
PersonalCrossingInProgress	SpeedAdvice	VertOffset-B07
PersonalCrossingRequest	SpeedConfidence	VertOffset-B08
PersonalDeviceUsageState	SpeedLimitType	VertOffset-B09
PersonalDeviceUserType	SpeedProfileMeasurement	VertOffset-B10
PivotingAllowed	Speed	VertOffset-B11
PositionConfidence	SSPindex	VertOffset-B12
PrioritizationResponseStatus	StabilityControlStatus	VINstring,
Priority	StationID	WaitOnStopline
PriorityRequestType	SteeringWheelAngleConfidence	WiperRate
PrivilegedEventFlags	SteeringWheelAngleRateOfChange	WiperStatus
ProbeSegmentNumber	SteeringWheelAngle	YawRateConfidence
PublicSafetyAndRoadWorkerActivity	SunSensor	YawRate
PublicSafetyDirectingTraffic	TemporaryID	ZoneLength
SubType	TerminationDistance	Zoom
PublicSafetyEventResponder	TerminationTime	
WorkerType	ThrottleConfidence	

# Appendix C. List of Acronyms

<b>AASHTO</b>	American Association of State Highway and Transportation Officials
<b>API</b>	Application Programming Interface
<b>Apps</b>	Applications
<b>ATM</b>	Advanced Traffic Management
<b>ATMS</b>	Advanced Traffic Management System
<b>BSM</b>	Basic Safety Message
<b>CCTV</b>	Closed-Circuit Television
<b>CICAS</b>	Cooperative Intersection Collision Avoidance Systems
<b>CV</b>	Connected Vehicle
<b>DMS</b>	Dynamic Message Sign
<b>DOT</b>	Department of Transportation
<b>DSRC</b>	Dedicated Short Range Communications
<b>ESS</b>	Environmental Sensor Stations
<b>FHWA</b>	Federal Highway Administration
<b>GB</b>	Gigabyte
<b>GID</b>	Geometric Intersection Description
<b>GIS</b>	Geographical Information Systems
<b>GUI</b>	Graphical User Interface
<b>HD</b>	High-Definition
<b>HDFS</b>	Hadoop Distributed File System
<b>IaaS</b>	Infrastructure-as-a-Service
<b>ICM</b>	Integrated Corridor Management
<b>IoT</b>	Internet of Things
<b>IT</b>	Information Technology
<b>ITS</b>	Intelligent Transportation Systems
<b>LAN</b>	Local Area Network
<b>LiDAR</b>	Light Detection and Ranging
<b>LCS</b>	Lane Control System

<b>MTA</b>	Los Angeles Metropolitan Transportation Authority
<b>NHTSA</b>	National Highway Traffic Safety Administration
<b>NOCoE</b>	National Operations Center of Excellence
<b>NTCIP</b>	National Transportation Communications for Intelligent Transportation System Protocol
<b>OSADP</b>	Open Source Application Development Portal
<b>PB</b>	Petabyte
<b>PDM</b>	Probe Data Message
<b>PeMS</b>	Caltrans Performance Measurement System
<b>RDBMS</b>	Relational Database Management System
<b>RAID</b>	Redundant Array of Independent Disks
<b>RAM</b>	Random-Access Memory
<b>RITIS</b>	Regional Integrated Transportation Information System
<b>RSE</b>	Roadside Equipment
<b>RWIS</b>	Road Weather Information System
<b>SPaT</b>	Signal Phase & Timing
<b>SQL</b>	Structured Query Language
<b>SRM</b>	Signal Request Message
<b>TB</b>	Terabyte
<b>TMC</b>	Traffic Management Center
<b>TMDD</b>	Traffic Management Data Dictionary
<b>TSMO</b>	Transportation Systems Management and Operations
<b>VSL</b>	Variable Speed Limits
<b>WAN</b>	Wide Area Network

# Appendix D. References

1. Sumner, Roy. Adaptive Signal Control with VII. 15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual Meeting, ITS America, 2008.
2. Noah J. Goodall, Brian L. Smith, and Byungkyu (Brian) Park Traffic Signal Control with Connected Vehicles. Published in Transportation Research Record: Journal of the Transportation Research Board, vol. 2381, 2013, pp. 65-72. Available at <http://dx.doi.org/10.3141/2381-08>.
3. Dedicated Short Range Communications Roadside Unit Specifications FHWA-JPO-17-589 April 28, 2017.
4. Multimodal Intelligent Traffic Signal System—Phase II: System Development, Deployment and Field Test. Final Report.
5. [http://standards.sae.org/j2735asn\\_201603/](http://standards.sae.org/j2735asn_201603/).
6. <http://chart.maryland.gov/about/overview.asp>.
7. <http://www.511ga.org>.
8. <http://www.itsdeployment.its.dot.gov/Results.aspx>.
9. [http://standards.sae.org/j2735\\_201603/](http://standards.sae.org/j2735_201603/).
10. [https://its.cms.here.com/static-cloud-content/Company\\_Site/2015\\_06/Vehicle\\_Sensor\\_Data\\_Cloud\\_Ingestion\\_Interface\\_Specification.pdf](https://its.cms.here.com/static-cloud-content/Company_Site/2015_06/Vehicle_Sensor_Data_Cloud_Ingestion_Interface_Specification.pdf).
11. <http://ami-c.org>.
12. [http://standards.sae.org/j2735\\_201603/](http://standards.sae.org/j2735_201603/).
13. Federal Communications Commission (FCC) 47 Code of Federal Regulations (CFR) Parts 0, 1, 2, 90, and 95 amendments for Dedicated Short-Range Communications Services and Mobile Service for Dedicated Short-Range Communications of Intelligent Transportation Service in the 5.850-5.925 GHz Band (5.9 GHz Band).
14. IEEE P1609.2,.3 and.4. In addition, IEEE 802.11-2007.

15. SAE J2735 2009-11: Dedicated Short Range Communication (DSRC) Message Set Dictionary.
16. Design and Validation of a Small-Scale 5.9 GHz DSRC System for Vehicular Communication. Fraaz Kamal, B.Sc., Edmond Lou, Ph.D., and Vicky Zhao, Ph.D.
17. An Empirical Study on Ad Hoc Performance of DSRC and Wi-Fi Vehicular Communications. Seungbae Lee and Alvin Lim. International Journal of Distributed Sensor Networks. Article 482695.
18. Experimental Characterization of DSRC Signal Strength Drops.
19. <http://local.iteris.com/arc-it/index.html>.
20. Note that one of the five bit values will be required to indicate no value.
21. Devices, Connected Vehicles, and Infrastructure Task 4 / Task 10: System Architecture and Design Document Final Report—October 27, 2017 FHWA-JPO-17-476.
22. [https://en.wikipedia.org/wiki/Load\\_balancing\\_\(computing\)](https://en.wikipedia.org/wiki/Load_balancing_(computing)).
23. Vehicle Infrastructure Integration, National System Requirements, U.S. Department of Transportation. February 2007, version 1.2.1.
24. U.S. DOT Southeast Michigan test bed 2014 concept of operations. Version 1.0 December 29, 2014.
25. <http://www.cattlab.umd.edu/>.
26. ADVANCE ADVANCED DRIVER AND VEHICLE ADVISORY NAVIGATION CONCEPT Illinois Department of Transportation, Federal Highway Administration, Motorola, Illinois Universities Transportation Research Consortium, American Automobile Association. Insights & Achievements Compendium, Document # 8465.ADV.01 -DRAFT-.

U.S. Department of Transportation  
ITS Joint Program Office—HOIT  
1200 New Jersey Avenue, SE  
Washington, DC 20590

Toll-Free “Help Line” 866-367-7487

[www.its.dot.gov](http://www.its.dot.gov)

FHWA-JPO-18-626



U.S. Department of Transportation