NATIONAL CONNECTED VEHICLE
FIELD INFRASTRUCTURE
FOOTPRINT ANALYSIS
Deployment Concepts

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1 INTRODUCTION

1.1 BACKGROUND

This technical memo is part of a study sponsored by the US Department of Transportation (USDOT) and Transport Canada and performed by the American Association of State Highway and Transportation Officials (AASHTO). The purpose of this study is to conduct analyses leading to a preliminary, general concept of a national connected vehicle field infrastructure footprint. Describing such a footprint satisfies many requirements in developing a policy foundation for the connected vehicle environment, including development of a set of desired outcomes which include:

- A description, for State and local investment and decision makers, of the justification for and value of deployment of connected vehicle infrastructure.
- A compilation of the possible data, communications, and infrastructure needs of the priority applications.
- A set of generic deployment concepts (at a high-level of engineering detail) that relate the infrastructure to the applications (or bundles of applications) and their needs under different operational conditions.
- A set of State- and local-based scenarios identifying how and where agencies might implement secure, connected vehicle infrastructure and what funding strategies they might use to support such deployment, and a synthesis of these scenarios into a preliminary national footprint of connected vehicle field infrastructure.
- A phased deployment plan which identifies the actions and funding strategies needed over a period of time for coordinated implementation of a national connected vehicle field infrastructure.
- Estimates of potential costs for deployment, operations, and maintenance.
- Estimates of workforce and training requirements; and identification of policy and guidance needs.
- Identification of implementation challenges and institutional issues and identification of the timing by which those issues need to be resolved to achieve deployment.

This technical memo specifically relates to the development of the generic deployment concepts.
1.2 DOCUMENT PURPOSE

The purpose of this document is to describe a set of high-level, generic connected vehicle infrastructure deployment concepts. The descriptions address potential infrastructure and application deployments in terms of the existing setting, connected vehicle field equipment, interfaces to related transportation equipment (e.g., traffic signal controllers), communications resources, security, and basic operations. The concepts have been developed around the applications identified in Task 4 of the study as they might be deployed in a variety of geographical and operational settings.

The deployment concepts are expected to form a basis for further analysis by both the USDOT and by State and local agencies. As such, they illustrate how applications, new and existing infrastructure equipment, power sources, and new and existing communications networks and equipment (i.e., fiber, cellular, microwave, modems, etc.) come together into snapshots of integrated connected vehicle deployments. For State and local decision makers, these deployment concepts are intended to provide enough detail to understand the implications of deployment—the required technologies, decisions, steps, personnel, knowledge and skill sets needed for deployment, operations, and maintenance. For the US DOT, the deployment concepts are intended to support further assessment of connected vehicle policy, planning, communications technology, deployment, operations, security, risk management, certifications and training.

In this context, the deployment concepts are informative rather than normative. The concepts are descriptions of potential connected vehicle infrastructure deployments, but do not constitute designs for such deployments. The state of connected vehicle technologies continues to evolve and could see extensive changes during the design, development and deployment of applications. Additionally, any eventual connected vehicle infrastructure deployments may be considered ITS projects and would then be subject to the relevant system engineering requirements in 23 CFR 940.111 and any similar regulatory requirement from FTA and FMCSA. The concept descriptions and illustrations herein should not be interpreted as design templates; they are intended solely to provide a basis for further discussion and analysis of potential deployments.

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1.3 **Document Overview**

Following this introductory section, Section 2 describes a set of deployment settings chosen to illustrate potential implementations of various applications requiring connected vehicle field infrastructure. These settings are:

- Rural Freeways and Arterials
- Urban Highway
- Urban Intersection
- Urban Corridor
- Freight Facility
- Smart Roadside Freight Corridor
- International Border Crossings (IBC)
- DOT Operations and Maintenance
- User Fee Collection

Section 3 identifies and describes considerations that are common to each of the settings. These include:

- Connected Vehicle System Architectures
- Connected Vehicle Data Needs and Standards
- Mobile Element, Field, and Center Components
- V2I Communications and Latency
- Communications Security
- Mapping Support
- Installation, Operations and Maintenance.

Section 4 identifies and describes potential costs for various elements of the connected vehicle infrastructure deployment.

The Appendix provides more detailed descriptions of some of the technologies and operational considerations supporting the infrastructure deployment.
2 Deployment Concepts

2.1 General Description

The concepts have been selected to illustrate connected vehicle infrastructure deployment in broad terms. Each concept illustrates geographical and application considerations that would influence the configuration of a connected vehicle deployment in a particular setting.

The deployment concepts were selected based on a thorough review of anticipated connected vehicle applications. An initial list of nearly 100 dynamic mobility, safety, environmental, and agency-focused connected vehicle applications was created. These applications were drawn from the Federal connected vehicle program, as well as work conducted through the Cooperative Transportation Systems Pooled Fund Study and by individual state and local agencies. In some cases, similar applications with different names were combined into one commonly-titled application.

Since the scope of this effort is focused on infrastructure, only the applications that require a connected vehicle field infrastructure were considered. V2V applications were not included in the analysis. Similarly, infrastructural support for V2V applications is presumed, but not explicitly addressed. In that context, the systems that address the security needs of V2V and V2I applications are discussed in the Section 3 Common Considerations as part of explaining the architectural interfaces. The application infrastructure will be required to work with the security infrastructure, but they may or may not share physical deployments. A more complete definition of the relationship between these infrastructural needs will necessitate further policy and technical research.

The final grouping of applications focused on possible geographical and operational settings. These settings were chosen to illustrate a diversity of potential application deployments using connected vehicle field infrastructure, recognizing that some attributes and considerations would be common to all or most of the anticipated settings.

These settings are:

- Rural Freeways and Arterials
- Urban Highway
- Urban Intersection
- Urban Corridor
- Freight Facility
- Smart Roadside Freight Corridor
- International Border Crossings (IBC)
- DOT Operations and Maintenance
- User Fee Collection

Under each setting, illustrations have been created to help practitioners visualize what a typical infrastructure deployment might look like. Each setting presents a likely scenario for equipment requirements, locations of equipment, interconnects to existing facilities and/or other infrastructure, and anticipated communications interfaces. Rather than creating detailed plans or an architecture, these drawings are intended to abstract the full set of application deployment requirements into what may be seen in “the real world” in a manner that is suitable for interested implementation stakeholders.

In addition to each drawing, the text further describes each setting, field infrastructure, communications, field management centers or information services, and a list of anticipated applications that could be supported in each setting. These descriptions focus on differences among the deployment settings.

As a guiding principle, it is generally assumed that applications requiring direct data communications between connected vehicles (mobile elements) and roadside infrastructure-based field elements will be carried out using Dedicated Short Range Communications (DSRC) technology. Where applications are supported by direct communications between connected vehicles and central elements (e.g. TMCs, other control centers, or other back-office facilities) then data communications will be carried out using cellular/LTE.

However, in some settings—including the Rural Roadway and Urban Highway settings—it is recognized that DSRC, cellular, or both DSRC and cellular could be used as the communication links with vehicles. Therefore, in these settings, each of the options is shown in the drawings and the alternative communications approaches described in the text. A further consideration used in the development of the concepts acknowledges the focus of this study on the infrastructural aspects of deployment. Therefore, while a cellular communication link may supplement or take the place of DSRC for an application in a given setting, DSRC is the more demanding case from the standpoint of infrastructure deployment by an agency and so is represented in the majority of the setting descriptions. Ultimately, it will be the decision of the deploying agency to select the most appropriate
communications architecture and technology based on their local needs and the requirements of the application(s) being deployed.

The deployment concept illustrations follow the descriptions of the settings in this Section 2. Section 3 describes additional characteristics that are common to all settings.

2.2 Rural Roadway

2.2.1 Current State

Rural roadways include arterials and freeways with higher speeds and infrequent intersections due to the low density of the surrounding land uses. Rural roadways may not follow linear segments or incorporate grid systems due to the locations of connecting towns and availability of right-of-way. Most intersections are un-signalized and have low-volume side street approaches, although some locations, such as rural highways, may have higher traffic volumes. The most common form of this roadway type is a two-lane undivided highway with intermittent warning signs of upcoming roadway conditions. Some of the most important needs for travelers in these areas are warnings of highway configurations that may present safety hazards (for example, curves, intersections and rail grade crossings), road weather information so travelers know if it is safe to take a certain route, and road work information to know if there are lane closures or detours.

Minor rural roads are also included in this section, but are not specifically illustrated in this analysis since deployment on these roads would likely be linked to deployment on intersecting higher-capacity roadways. When there are deployments, they would include applications such as stop sign violation and gap assist applications for intersection approaches.

While some rural areas may have deployed ITS equipment this is not widespread, typically due to limited availability to communication or power. For the purposes of this setting description, it has been assumed no ITS infrastructure has been deployed.

2.2.2 Concept Description

The concept for the rural roadway setting focuses on safety applications conditioned by roadway configuration—such as curves, intersections and work zones—and on roadway conditions. Some of these applications would operate by providing information about the roadway strictly from the infrastructure—the roadside or a back office system. Other applications appropriate to a rural setting would collect probe data messages containing
location, speed, heading and other data (for example, traction control system actuations, air temperature, and windshield wiper state) from vehicles for aggregation and synthesis into traveler information.

**DSRC Concept**

The deployment of connected vehicle field equipment in a rural roadway setting could include a DSRC radio to communicate with a suitably-equipped vehicle. Appropriate installation locations for the DSRC roadside equipment (RSE) will be in advance of the point where a vehicle or operator must react to the particular situation and may therefore depend on performance requirements specific to the application. If the application is intended to provide a message to a vehicle operator, the placement of the RSE should be such that the location of the *message delivery to the operator* along the roadway is similar to the location of static signage that would provide a like message, according to the Manual on Uniform Traffic Control Devices (MUTCD).

If the deployed applications include collecting probe data, the data would be cached on the vehicle until it could be transmitted to an RSE. RSE placement for probe data collection could coincide with RSEs deployed for other purposes and would depend primarily on the geography over which data collection was desired.

In certain rural settings with clear lines of sight, DSRC radios could be expected to have a reliable communication range of up to one-quarter mile. However, terrain issues, such as hills, curves, and trees, would be expected to limit this range. This range is also dependent upon the power of the radio, the directionality of the antenna, and the height of the antenna. Other technical considerations are detailed in Section 3.

**Cellular Concept**

Vehicles equipped with cellular data (for example, LTE) modems would send information requests to a server at periodic intervals (e.g., every 100 meters or three seconds) as they travel along the roadway. The request would include the current location and direction of travel. The server would then provide back a message including any roadway alerts associated with segments or timeframes for which the driver would need actionable information. The vehicle system would then alert/inform the driver accordingly. The original request could also include vehicle operational data (speed, location, etc.) so that the message transaction would implement both probe data collection and roadway messages simultaneously.
This concept could support several potential applications in a rural roadway setting. The illustration in Figure 1 shows one example for a curve speed warning application using DSRC or cellular communications where advanced driver information is provided to help negotiate the downstream roadway conditions.

### 2.2.2.1 Field Infrastructure

The connected vehicle field infrastructure for a rural roadway setting would consist of connected vehicle field equipment that includes a DSRC radio and associated communication equipment mounted to a utility pole or sign pole. Power would be provided by a connection to a utility power drop providing utilization voltage of 120VAC at a service cabinet, or a solar panel providing DC voltage, mounted to a cabinet atop a warning sign pole. The use of solar power would be dependent on the area, especially in northern climates where daylight is limited in the winter and where panels get covered in snow, as well as the region’s predictability for cloud cover. Other power considerations are discussed in Section 3.8.

For a rural setting, available roadside infrastructure will generally be limited to existing utility poles or a new pole dedicated to connected vehicle applications as there are generally very few existing ITS device, traffic signal, or lighting installations.

### 2.2.2.2 Backhaul Communications

Backhaul communication in the form of copper or fiber line communications is typically not available in a rural setting as the roadway facility is often remote and far from an established wireline communications network. If cellular coverage or a state-operated communications network (such as 800 MHz radio) exists in the rural region of interest, these networks can provide any required communication capabilities to a back-office facility for remote monitoring or for applications where a backend server is utilized. The Common Considerations section discusses various backhaul technology alternatives.

If backhaul coverage does not exist, the connected vehicle rural applications would need to be localized in the case of DSRC just at the region of interest, and the roadside equipment would need to rely on localized updates to, for example, support security updates.

### 2.2.2.3 Management Centers and Information Services

Within the rural roadway setting, communications to a remote facility would enable vehicle-related data collection capabilities that could support other
applications. Data collected from vehicles could include weather and road condition data with other probe data and might be used, for example, to create roadway warnings for other vehicles.

Although some rural interstate locations may be the exception, a rural setting is assumed to have relatively low traffic volumes, resulting in a low to moderate level of connected vehicle data. This will affect backhaul bandwidth and data warehousing requirements for collection and storage of data desired for historical analysis or use in other applications. In developing backhaul and storage requirements, consideration should be provided to analyze rural routes that experience seasonal traffic volume fluctuations. These roadway facilities may require added communications, processing, and storage capabilities. Storage capacity for redundancy and to satisfy data retention policies must also be considered. A connected vehicle equipment installation used in this capacity is similar to a traffic count station whereby data is not required to be near real-time but can be obtained periodically from the field site.

2.2.3 Applicability

Applications that may be supported by a connected vehicle infrastructure deployment within the illustrated rural roadway setting include, but are not limited to:

- Motorist Advisories and Warnings (emergencies, weather, variable speeds, curve speed, oversize vehicle)
- Stop Sign Assist
- Intersection Violation Warnings
- Reduced Speed Work Zone Warnings
- Dynamic Eco-routing based on roadway conditions or congestion issues
Figure 1 - Rural Roadway Deployment Concept
2.3 **Urban Highway**

2.3.1 **Current State**

Urban highways are part of the principal arterial system that carries some of the highest traffic volumes and proportion of total urban travel. These roadways provide connections within urbanized areas, to outlying suburban centers, and ultimately to rural roadways. In urbanized areas, which typically have populations greater than 50,000, these highways are fully or partially controlled access facilities due to high traffic volumes and roadway speeds. AASHTO separates urban highways into three categories: interstates, other freeways, and other principal arterials (with partial or no control of access).

In many cases, ITS deployments exist on the urban interstate network and provide the appropriate operating agency with the means to monitor and optimize their regional freeway system. ITS infrastructure on an urban interstate typically supports traveler information (e.g. dynamic message signs, highway advisory radios), traffic control (e.g. ramp meters), data collection (e.g. vehicle data stations, traffic cameras, weather stations), user fees (e.g. tolling, congestion pricing), commercial vehicle services (e.g. weigh stations), and control centers (e.g. traffic management center, active traffic management). These ITS systems rely heavily on dedicated communication systems typically installed within the freeway right-of-way. Traveler information and data collection will be the focus in this concept with specific applications falling under each of these two system types.

Traveler information systems disseminate useful information to users of the urban highways. Congestion management and traffic incident management are typically key focuses of such systems; they may also provide information about work zones. For congestion management, agencies have implemented ITS systems intended to spread demand across the highway network, attract users to mass transit, and make effective use of the existing freeway capacity. For traffic incident management, ITS systems typically detect and promote the removal of incidents, restoring urban highway capacity in a fast and safe manner. For work zones, the traveler information both tries to alleviate congestion associated with the zone and to protect workers.

A typical traveler information system installation consists of a display such as a dynamic message sign or website application, a communication network which includes cabinet, associated equipment, and backhaul communications, and a control center that delivers traveler information to the system.
Data collection systems provide operators at management centers a means to evaluate the conditions or performance of the urban interstate network. Traffic data detectors, such as inductive loops, radar, and video imaging, provide speed, occupancy, and, in some cases, travel time data. Closed-circuit traffic cameras help detect and verify incidents and congestion; information that can then be distributed to the web or other forms of media. These examples of data collection systems consist of detection equipment, a communication network, and a control center that receives and evaluates traveler information from these installations.

2.3.2 Concept Description

The concept for this urban highway setting is focused on support for traveler information and data collection systems using DSRC or cellular technology. Safety-focused applications such as work zone or weather advisory warnings would also likely be deployed for urban highways. Other examples of typical applications in this setting are described in section 2.3.3 below.

**DSRC Concept**

Vehicles equipped with DSRC would receive and transmit data periodically along the highway system when the vehicles are within range of an RSE. For example, roadway alerts, arterial management recommendation messages, and traffic information would be provided over a backhaul link from a regional Traffic Management Center (TMC) to the RSEs, which transmit them to passing vehicles. The vehicle system then alerts or informs the driver accordingly. These vehicles can also transmit operational data (e.g. speed, location, etc.) back to the RSE, which then forwards it over a backhaul link to the TMC or other data aggregator. This data can be used for dynamic control of the corridor, for general traffic information reports or for historical analysis. Operators at the TMC can also use the information for congestion management or traffic incident management.

The illustration in Figure 2 shows one example of DSRC communications for data collection on a freeway to gather vehicle data for use at the TMC as an input for ramp meter rates on entrance ramps.

**Cellular Concept**

Vehicles equipped with cellular data (for example, LTE) modems would send information requests to a server at periodic intervals (e.g., every 100 meters or three seconds) as they travel along the roadway. The request includes the current location and direction of travel. The server would then provide back a message including any roadway alerts, arterial management recommendation
messages and real time traffic data associated with segments or timeframes for which the driver would need actionable information. The vehicle system then alerts/informs the driver accordingly. The request could also include vehicle operational data (speed, location, etc.) so that the message transaction would implement both probe data collection and roadway messages simultaneously.

It is unclear if this system can support dynamic alerts such as traffic signal information because of latency issues, but this capability is expected to be tested in 2013 to determine what the latency and latency variation actually is.

Cellular implementations are more fully described in the Common Considerations section.

2.3.2.1 Field Infrastructure

The connected vehicle field equipment for an urban highway setting will be installed at highway access points and along highway segments. Fewer connected vehicle field equipment deployments will be required along segments with large distances between ramps, while more closely spaced placements will be necessary near urban and city centers to best serve TMC operators and to provide information to vehicle operators at critical locations. Locations expected to have a high density of connected vehicle field equipment may include roadway stretches with historically high congestion, on and off ramps, major interchanges, and other spot locations.

Typically the DSRC radio will be mounted to an existing elevated structure such as a sign gantry, light or camera pole, overpass, etc. DSRC ranges will vary by location and data collection purpose, but are anticipated to be around 400 meters (1300 feet) in this setting. For mainline detection locations, the DSRC radio will most likely be installed at the highest possible mounting height consistent with FCC regulations on the existing structure to obtain the greatest possible range. At ramp meters the range of the DSRC radio could be reduced to 100 meters (330 feet) or less to facilitate interaction only with vehicles likely to use the ramp metering application. Mounting of the DSRC radio might occur on the existing ramp meter pole for communication over distances less than 100 meters.

When identifying installation locations, utilizing existing communication infrastructure will reduce installation costs. The connected vehicle field equipment will ideally connect into an existing ITS cabinet that is equipped with an Ethernet switch and a backhaul communication connection to a management center. Power would be supplied through the existing cabinet,
solar, or nearby electrical service drop. Suitable locations could include existing data collection stations, dynamic message signs, traffic cameras, etc.

2.3.2.2 Backhaul Communications
Backhaul communications in an urban highway setting can be implemented in a wide variety of ways. These are described in the Common Considerations section. Roadside equipment could potentially communicate over the same backhaul network as existing ITS installations, provided that sufficient bandwidth is available for the various connected vehicle applications selected.

2.3.2.3 Management Centers and Information Services
Connected vehicle equipment deployments for the urban highway setting will provide two-way real-time communication between vehicles traveling on the freeway system and data acquisition and processing systems in a back-office facility. The systems at the back-office facility (or facilities) will process the data to support various applications and other ITS systems, and will archive the data for future use.

2.3.3 Applicability
Applications that may be supported by connected vehicle equipment deployments in the urban highway setting include, but are not limited to:

- Origin-Destination (with opt-in permissions or anonymization), Traffic Model Baselining & Predictive Traffic Studies
- Active Traffic Management (lane control, dynamic speed harmonization, cooperative adaptive cruise control)
- Advanced Traveler Information System (dynamic route guidance, travel time)
- Motorist Advisories and Warnings (emergencies, weather, variable speeds, queue, speed zone, work zone, oversize vehicle)
Urban Highway Deployment Concept

**CONCEPT**

- DSRC communications for data collection on a freeway to gather vehicle location, speed, and travel direction for applications at the Traffic Management Center.

**OTHER EXAMPLE APPLICATIONS**
- Origin-Destination Traffic Model
- Bottleneck & Predictive Traffic Studies
- Active Traffic Management
- Advanced Traveler Information System
- Motorist Advisories and Warnings

**TYPICAL SETTING FEATURES**

Urban highways are part of the principal arterial system and carry some of the highest user volumes.

**CONCEPT EXAMPLE**

**NOT FOR CONSTRUCTION**
2.4 **Urban Intersection**

2.4.1 **Current State**

An urban intersection is a junction of two or more roads within a city setting which typically includes features such as curbing, designated lane use markings, pedestrian crossings, and traffic control (traffic signals or stop signs). The simplest forms of urban intersections consist of 2-way or 4-way stop configurations. More complex settings may have a signalized intersection that is configured with a variety of lane usages, pedestrian and bicyclist facilities, and traffic signal equipment. At signalized intersections, controllers typically function on pre-timed, actuated, semi-actuated, and adaptive modes of operation with a dependence on current detector technology. The AASHTO *Connected Vehicle Infrastructure Deployment Analysis* included a description of traffic signal controllers and connected vehicle infrastructure needs.

Existing ITS infrastructure may include traffic signal and detection systems, red light cameras, transit signal priority (TSP), emergency vehicle preemption, CCTV cameras, and freight signal priority. Controller communication via Ethernet, optical fiber, or commercial wireless systems may be employed to relay backhaul communication to central servers, although use of 900 MHz radio systems or land-line telephone service is common.

In recent years, there have been an increasing number of adaptive signal control (ASC) system deployments that have proven to be an effective means of using ITS to improve operational efficiencies at an urban intersection and corridor in near real-time. An ASC system relies on vehicle detection and dynamically adjusts signal timing parameters to meet the roadway demands as necessary. Many adaptive signal systems rely on interconnected traffic signals which can be achieved through an Ethernet backbone. In the connected vehicle infrastructure deployments considered in this report, an Ethernet backbone would enable system-wide connectivity for multiple urban intersections.

2.4.2 **Concept Description**

The deployment of connected vehicle field equipment in an urban intersection setting may include a DSRC radio with associated communication equipment communicating with vehicles equipped with a DSRC OBE. Ideal mounting locations for a DSRC radio at an urban
intersection would include a signal mast arm, luminaire pole or arm, or utility pole.

Applications supported by the urban intersection setting typically engage in two-way (symmetric) communication with vehicles approaching the intersection. A reliable range to accommodate the required data transfer rates is approximately 200 to 500 feet. Roadway features and the urban environment (such as buildings) will need to be considered when identifying the mounting location for connected vehicle equipment. In the event of radio interference from geometry or trees, multiple radios may need to be deployed to support a single intersection.

The illustration in Figure 3 for this setting shows omnidirectional DSRC communications to all approaches of the intersection and also an additional DSRC antenna at a mid-block location.

2.4.2.1 Field Infrastructure

The field infrastructure for an urban intersection setting will comprise connected vehicle field equipment sharing communication with transportation field equipment installed in a traffic signal control cabinet. Power would also be provided by the traffic signal cabinet, solar, or a nearby electrical service drop. It is recommended that there is a connection from the connected vehicle equipment to an Ethernet switch that would be capable of communicating with the traffic signal controller. This connection can also provide a backhaul communication connection to a management center. At an urban intersection, the practical installation height of the DSRC radio would be up to 25 feet in order to achieve optimal line of sight to the vehicles. This is the approximate height typically provided by signal mast arms, luminaire poles or arms, or utility poles. This may need to be further adjusted depending on specific site characteristics.

2.4.2.2 Backhaul Communications

Backhaul communications at urban intersections could be implemented in a variety of ways depending on the applications being supported; these are discussed in the Common Considerations section. Actual bandwidth requirements will depend on the number and types of applications to be supported in a particular deployment.

2.4.2.3 Management Centers and Information Services

A connected vehicle equipment deployment at the urban intersection setting allows a back-office facility to gather vehicle-related data. Data could include intersection delays, collision data, transit reliability data, and congestion data.
Depending on the number of vehicles that the intersection services, a moderate level of data warehousing may be useful to analyze historical data and provide data for future use. Storage capacity for data backup is also recommended for redundancy.

2.4.3 Applicability

Applications that may be supported by a connected vehicle equipment deployment at the urban intersection setting include, but are not limited to:

- Red Light Violation Warning and Stop Sign Violation
- Driver Gap Assist at Signalized Intersections and Stop Signs
- Multimodal Intelligent Traffic Signal Systems (freight signal priority, intelligent traffic signal system, transit signal priority, pedestrian mobility, emergency vehicle pre-emption)
- Advanced Arterial Management and Operations
- Advanced Signal Operations
Figure 3 - Urban Intersection Deployment Concept
2.5 **Urban Corridor**

2.5.1 **Current State**

Urban corridors typically consist of multiple signalized intersections, spaced at regular intervals. These roadways have multiple types of roadway users, including pedestrians, bicyclists, transit vehicles, personal cars, and freight deliveries. Cross-sections and lane assignments vary and may include restricted lanes for transit-only vehicles, on-street parking, and center left turn lanes. The combination of modes and applications on an urban corridor make it a unique setting for incorporating traveler benefits across a range of transportation alternatives for a given corridor.

ITS infrastructure may include fixed time, semi-actuated or fully actuated signals, transit signal priority (TSP), emergency vehicle preemption, and freight signal priority to assist with the flow of traffic through the corridor. Controller communication over Ethernet, optic fiber, or wireless networks are typically employed for backhaul to central servers located at TMCs.

2.5.2 **Concept Description**

The urban corridor setting could include all of the applications described earlier for an urban intersection, but provides a richer context for discussion of modes, operations and technologies supporting integrated corridor management. In the example described in this section, applications could provide operators at a transportation management center with information to provide multimodal traveler information and improve the performance of transit routes. Figure 4 illustrates an example of DSRC communications for transit data on an urban corridor to transmit arrival times, passenger loadings, and other data to a Transit Control Center (TCC).

Connected vehicle mobile elements in transit vehicles could relay the location, passenger counts, and delay incurred at the signal to connected vehicle field equipment at intersections. The information from several DSRC RSEs located on an urban corridor could be sent to a communication hub, located at a transit center or other major transportation center, where data can be stored before it is sent to the control center for analysis.

The servers at the control center may contain preprogrammed bus schedules, time-points, and other route information that is compared to the field information gathered from the connected vehicle field equipment. Two-way communication could support changes to signal timings or phase operations to be updated at downstream intersections to anticipate the arrival of buses.
The time and location of buses on the urban corridor could also be compared to schedules to determine whether transit service is operating on schedule.

In addition to communicating on-time information to transit operators, the arrival time of buses to stops and transit centers could be relayed to passengers. Real-time updates for onboard and waiting passengers could be provided via message boards. Transit users could also find information through cellular communication via phone applications. Additionally, some applications may provide an interface between transit users and a transit center communication hub.

### 2.5.2.1 Field Infrastructure

Connected vehicle field equipment in this setting consists of DSRC antennas and associated communication equipment mounted to existing infrastructure and housed at intersections and transit centers. Major transit centers include communication hubs that store information in on-site servers. The communication hub collects information from DSRC equipment installed at the transit center, as well as corridor installation locations and sends data to control center where the data is processed.

When identifying installation locations, existing infrastructure will play an important role in reducing installation costs. Connected vehicle field equipment installed at intersections will ideally connect into an existing transportation system cabinet (such as a signal cabinet) that is equipped with an Ethernet switch and a backhaul communication connection to a control center. Power will be supplied by the existing cabinet.

### 2.5.2.2 Backhaul Communications

Backhaul communications at urban intersections could be implemented in a variety of ways depending on the applications being supported; these are discussed in the Common Considerations section.

### 2.5.2.3 Management Centers and Information Services

This concept will require transit agencies to have schedules, time points, and transit route information readily available for processing based upon data coming into the control center. Two-way communication between the connected vehicle field equipment along the corridor and the control center is vital for the urban corridor setting to be effective. This information may also need to be relayed to transit riders. Standard protocols for exchanging data about multiple intersection types and locations may need to be established for transit routes that operate in multiple jurisdictions.
2.5.3 Applicability

Applications that may be supported by connected vehicle equipment deployment in the urban corridor setting include those described in the urban intersection setting and others such as, but not limited to:

- Integrated Dynamic Transit Operations (Connection Protection, Dynamic Transit Operations, Dynamic Ridesharing)
- Eco-Signal Operations (approach and departure, traffic signal timing, transit signal priority, freight signal priority, connected eco-driving)
- Dynamic Eco-Routing
- Integrated Dynamic Multimodal Operations
Figure 4 - Urban Corridor Deployment Concept
2.6 **INTERNATIONAL LAND BORDER CROSSING**

### 2.6.1 Current State

Cross-border transportation is an important element of the nation’s transportation system. Because of increasing cross-border demand, limited infrastructure footprint at international border crossings (IBC) and staffing resources, wait times at IBCs continue to grow longer with negative impact on cross-border trade and travel.

Laws of the US, Canada, and Mexico require that every vehicle and passenger crossing the border must be screened and verified. Customs agencies stop and screen all incoming vehicles and verify proper documentation before letting them in their respective countries.

In both US-Canadian and US-Mexico international border crossings, once privately operated vehicles (POV’s) are released by respective customs agencies, they proceed to their destinations. On the US-Canadian border, vehicles entering Canada are screened and can be inspected by Canadian Border Services Administration (CBSA) and Canadian provincial motor vehicle enforcement agency. Commercially operated vehicles (COVs) entering US from Canada are screened and/or inspected by Customs and Border Protection (CBP) after which they may be screened and inspected by state agencies to enforce commercial vehicle safety regulations. On the US side of the US-Mexico border, there are permanent facilities adjacent to the custom’s facility and all COVs entering the US from Mexico are screened and/or inspected by the state agencies for safety. On the Mexican side, once COVs are released by Aduana (the custom’s agency in Mexico), they proceed to their destination.

Each IBC is different in terms of traffic patterns, geography, configuration, and physical characteristics. However, key functions performed by customs agencies (of all three countries) are similar as well as some of the truck safety related activities performed by provinces and states.

### 2.6.2 Concept Description

CBP and the CBSA are two agencies that provide Border Wait Times (BWT) information to motorists. CBP and CBSA’s method to estimate BWT rely on visual methods. They estimate BWT of vehicles inbound to the US and Canada using one of five methods depending on the point of entry (POE): unaided visual observation, cameras, driver surveys, time-stamped cards, and license plate readers. CAPUFE and Aduana which are Mexican federal agencies that operate border crossings, do not relay wait times.
USDOT, Transport Canada, provincial transport ministries (in Canada), and state departments of transportation (in the US) have implemented systems to measure, relay, and archive wait times of vehicles crossing the border. Some states have also implemented systems to measure crossing times for commercial vehicles. These systems use traditional vehicle detectors, Radio Frequency Identification (RFID, 915 MHz), and Bluetooth technology.

These systems currently deployed at select IBCs on both the US-Mexico and US-Canada borders rely on fixed-location detectors that identify transponders, mobile devices, or presence of vehicles, determine travel time between detectors, and estimate wait times. Detectors are isolated from each other and function independently. Data from individual detectors are sent to a central server using cellular communication. Servers then process the information and provide the wait and crossing times to users via Internet, dynamic message signs, 511 systems, etc.

In addition, vehicles on the roadway upstream of custom’s inspection booths are not well managed. Some IBCs do have static overhead signs to separate COVs from POVs. At most IBCs there are several roadways leading to the customs area and providing static signs to direct traffic can be difficult. Also, signs that separate vehicles types (and vehicles registered with various trusted shipper and traveler programs) are at fixed locations and messages are not dynamic to be coordinated with number of inspection lanes open at the custom facility.

One objective of applications in this setting is to deploy a next generation wait time and approach management system that automatically and accurately estimates wait and crossing times, provides information to motorists using OBE using DSRC technology, and migrates from currently used RFID and Bluetooth technologies. While doing so, the application will also direct motorists to appropriate approach lanes based on type of vehicles (i.e., COV or POV) or various types of trusted shipper and traveler programs using dynamic processes that coordinate in real-time with inspection lanes open and types of lanes open. The system will create a dynamic and close to optimal management of approach lanes and deliver traveler information to motorists in a more effective format resulting in more effective management of inspection lanes, reduced wait/crossing times, and better allocation of staffing resources.

In a connected vehicle environment, the application would use DSRC technology to gather information on identification of vehicles, lanes on which vehicles are traveling, and types of trusted shipper and traveler program
vehicles/motorists are registered to. With adequate density of OBEs, wait times for lane type will be predicted based on estimate of queue length, travel time between fixed points, and number of inspection lanes open.

RSEs strategically placed along the roadways approaching IBC will transmit messages to OBEs consisting of wait and crossing times, approach lane they should be on, lane changing suggestions to move to particular lanes. The concept diagram for this setting shows relative location of RSEs on approaches leading to IBCs on both the US-Canada and US-Mexico border. Number of RSEs and specific location of RSEs depend on the actual footprint of an IBC.

The system will however need to coordinate, in real-time with the number of inspection lanes open and which lanes are designated to process which trusted shipper and traveler programs. The customs agencies will also adjust their inspection process based on the wait and crossing times information they receive from the system, which in turn will influence the wait and crossing times of incoming vehicles.

IBCs include multiple lanes and types of credentials for vehicles passing through security checkpoints. The illustration in Concept 5 shows one example of DSRC communications to collect and disseminate traveler information, including border crossing wait times.

2.6.2.1 Field Infrastructure

The concept will be deployed on roadway approaches leading to primary inspection booths operated by customs agencies on both sides of the international border. Some RSEs will be inside the US State’s facility, especially on the US-Mexico border. The number of RSEs will depend on the actual footprint of individual IBC.

The concept can either be developed as a single multi-jurisdictional application or as multiple applications exchanging data in real-time. In a single multi-jurisdictional environment, a single entity will operate and manage all the RSEs on both sides of the border and operate the application as one system. The other option is to run separate applications in different countries and share data between applications.

Two configurations of RSEs may be needed in this concept—one that only collects vehicle information from the field, and another that both collects information from the field and sends information to OBEs. Mexican and Canadian vehicles should be able to communicate with RSEs deployed inside US and vice versa.
Power for RSEs would likely be provided by an existing cabinet or electrical service drop, as the border crossing typically already supports powered infrastructure equipment.

### 2.6.2.2 Backhaul Communications

RSEs, especially those close to the customs inspection booths, may communicate simultaneously with hundreds of vehicles and will require high bandwidth backhaul communication. Options for backhaul are described in the Section 3 Common Considerations.

Because the applications will require data sharing between multiple jurisdictions and agency systems (e.g., between a US state system and CBP), data transmission between the application’s central servers to servers of other jurisdictions can be done through a secured Internet connection. These agencies will have to agree on center to center data transfer protocols, communication security protocols, etc.

### 2.6.2.3 Management Centers and Information Services

The concept will require agencies responsible for deploying the IBC applications to provide a robust back-end system consisting of flexible database management, fault tolerance systems, standard operating protocols, fallback processes in case of RSE downtime etc. The server (or servers) will gather information from RSEs and archive the data for future reference, as well as use it to determine wait times. The server will also be responsible for sending wait time and approach lane guidance information to individual RSEs and on to OBEs. Standard operating procedures and guidelines on data archiving and processing will be required. Also, the server will require an interface to exchange data with other jurisdictions in the same country or a different one.

### 2.6.3 Applicability

The deployment concept is applicable at all IBCs on both the US-Canada and US-Mexico border, given there are justifiable needs in the form of perceivably long wait times, high vehicle demand, etc. Some IBCs have extremely low demand (i.e., few hundred vehicles a day). Even though the application can be implemented at these IBCs, the cost of doing so may outweigh the need.

IBCs can vary in their configurations, mainly in the number of lanes available for inspection and type of vehicles inspected. IBCs with a large number of inspection lanes will require more RSEs than IBCs with fewer inspection lanes. Some IBCs process both commercial and personal vehicles and some only process one type of vehicles.
RSEs deployed for this application can also be used for other border applications, such as toll collection, dynamic pricing, and COV safety pre-clearance. RSEs deployed for toll collection, which is becoming more and more prevalent at IBCs can also be used for collecting wait times information.
2.7 Freight Intermodal Facility

2.7.1 Current State

Freight intermodal facilities assist in long haul and drayage assignments where containers are transferred between rail and trucks. For the purpose of this report, freight trucks were the focus although there are likely multiple rail applications. Long haul and drayage activities that currently take place at an intermodal facility involve a complex interaction between facility personnel, trucking companies, end-customers, and rail lines. In order to coordinate freight activities, delays are often experienced and are commonly attributable to freight scheduling, dispatch activities, and congestion at the facility. Average in-gate to out-gate turnaround times at an intermodal facility are approximately 30-60 minutes per truck with about 20-30 minutes of this time spent in a queue. Efficiency is vital at intermodal facilities as most truck drivers involved in drayage activities are paid per move rather than by time. The typical process at an intermodal facility involves the following steps:

1. Rail arrives with manifest and goods containers.
2. Long haul or drayage firm is dispatched to pick-up container.
3. For long haul, container is loaded onto a chassis owned by the long haul company. For drayage, chassis is supplied at the facility.
4. Containers are shipped to their intended destination.
5. Drayage firm returns empty container to facility after delivery has been made to the end-customer.

A truck-to-rail process typically occurs in the opposite order as described above. Information that is shared between the intermodal facility and truck drivers include credential information, goods manifest, inspection information, and the availability and location of container for transport. This information is usually communicated in person at the processing in-gates and inspection gates at the facility entry. At some facilities, driver credential information is communicated through RFID technology established by the TSA. The National Cooperative Freight Research Program’s (NCFRP) Report 11 indicates that many gate delays are attributable to misinformation and miscommunication. Trouble tickets are assigned when a planned transaction cannot be processed and an escalated level of assistance is required from facility authorities. Due to the extensive amount of the information that needs to be communicated and complex procedures, there are often long delays which can often cause extensive inbound queuing. When the truck driver has
received their container load, they typically exit the site through an out gate processing area where facility personnel verify that the correct transaction and paperwork has taken place.

2.7.2 Concept Description

Within the freight intermodal facility setting, the connected vehicle field equipment would be installed at truck decision points and inspection points, such as in-gate stations, inspection stations, exit gates, and major truck decision points. The onboard equipment in the trucks would transmit and receive information to automate credentialing, inspection, customs, way finding, and traffic information at the facility. The two-way DSRC communication could help alleviate congestion and reduce turnaround times by automating the transaction process. Additional DSRC field equipment could also be installed on roadways leading to the intermodal facility to enable inbound trucks to report their arrival and receive notification of expected wait times (it is likely these units would also support the Urban Highway deployment concept). This information can be communicated to the facility’s control center through a local backhaul connection, or through the TMC of the adjacent community. The control center can utilize this information to coordinate scheduling, regulate and enforce inspection protocols, and direct traffic to and from the facility.

Figure 6 shows an example of DSRC communications at a freight facility to verify truck and rail entry at an intermodal facility. Upon entering the checkpoint lanes, driver credentials are checked for security purposes to pass through the entrance. Tracking shipments and destinations are also included in these messages to improve efficiency of facility operations once the vehicle has entered the drayage yard.

2.7.2.1 Field Infrastructure

Within the intermodal facility, connected vehicle field equipment could be installed at main gates and inspection checkpoints. These deployment locations are expected to have power available since the facility is generally equipped with lighting, inspection booths, and other monitoring and security equipment. The DSRC equipment should be mounted at a maximum height of 25 feet with adequate line-of-sight to communicate to vehicles within a 1000-foot radius. Where gates and inspection stations are separated by more than 1000 feet, an additional DSRC radio should be installed. All DSRC roadside units should be connected through a backhaul network to the control center where activity is monitored and a supervisory level of control is provided.
2.7.2.2 Backhaul Communications
These applications will require backhaul communications to the facility’s control center. The control center would be able to monitor and react to the information communicated by the trucks and issue response actions as necessary to ensure efficient and safe goods movement.

Backhaul communications at these facilities could be implemented in a variety of ways depending on the applications being supported; these are discussed in the Common Considerations section.

2.7.2.3 Management Centers and Information Services
Operations within an intermodal facility are often managed through an administrative center where freight activity is monitored from a control facility. Critical to the facility’s control center are the roles and responsibilities from various operating agencies which may include the Transportation Security Administration (TSA), the local department of transportation, the facility owner/operator and others. Each agency depends on different types of information distributed as part of the long haul and drayage operations to ensure that security is maintained, site logistics are efficient, and information is shared. The facility’s terminal operating system, which monitors container status, should be integrated with the connected vehicle environment in order to automate gate processing, resolve trouble tickets, and increase traffic throughput.

2.7.3 Applicability
Applications that may be supported by a connected vehicle equipment deployment in the freight facility setting include, but are not limited to:

- Freight Real-Time Traveler Information with Performance Monitoring
- Shipment (Trailer) Tamper Monitoring
- Information for Freight Carriers
Freight Intermodal Facility Deployment Concept

**Figure 6 - Freight Intermodal Facility Deployment Concept**
2.8 SMART ROADSIDE FREIGHT CORRIDOR

2.8.1 Current State

Freight movement is a pivotal part of the US economy and relies on the nation’s network of roadways, interstates, railways, waterways and airspace to transport goods. The National Highway System (NHS) identifies a strategic network of highways servicing major freight routes. Along these freight routes, various facilities exist to regulate commercial vehicle safety, security, and mobility. Some of these facilities include inspection checkpoints, border crossings, weigh stations, truck parking and rest facilities. The USDOT has developed a commercial vehicle information systems and networks (CVISN) nationwide initiative that focuses on the following functions:

- Safety Information Exchange
- Credentials Administration
- Electronic Screening

CVISN is currently used throughout the nation and falls under the National ITS Architecture, primarily leveraging DSRC, Weigh-in-Motion (WIM), Automatic Vehicle Identification (AVI), License Plate Readers (LPR) technology. The core goal of CVISN is to improve safety, simplify operations, improve efficiency, and improve security for freight movement.

Within the NHS, truck parking facilities are another major component of the existing freight infrastructure as they function as rest areas for truck drivers. Due to the large number of trucks on the roadway system, truck parking availability is often a concern at many public and privately-operated truck parking facilities. There are limited ways in which a truck driver ascertains information regarding truck parking availability. The Federal Motor Carrier Safety Administration (FMCSA) has commenced initiatives, such as Smart Park, to address these concerns. Smart Park provides real-time parking availability information to truckers by collecting space occupancy at a truck parking facility.

2.8.2 Concept Description

Within the connected vehicle environment, the freight corridor concept would further develop the applications established under the Smart Roadside Initiative using DSRC technology. The Smart Roadside Initiative is a joint program of the FHWA and FMCSA that identifies data sharing, e-screening, truck routing, inspection, data collection, and weight and dimension monitoring applications. Data is collected and shared between freight movers on a real time or near-real time basis and is used for multiple purposes.
The concepts illustrated in Figure 7 and Figure 8 would involve deploying DSRC radios on the roadside at key truck facilities such as truck parking facilities, weigh stations, truck fueling stops, and tolling facilities. Information that is shared at the key facilities would include truck parking availability, weight information, driver and truck credentials, and route information. In addition to the deployments at major truck facilities, the Smart Roadside application would also complement the Connected Vehicle field infrastructure within an urban interstate and rural roadway setting where available. Integration into the urban interstate and rural roadway setting would allow truck drivers to share and obtain useful information along their freight routes.

2.8.2.1 Field Infrastructure
Within the smart roadside freight corridor setting, connected vehicle field equipment would be installed at major freight facilities including truck fuelling stops, weigh station facilities, truck parking facilities, highway rest stops and tolling facilities. These deployment locations are expected to have power available since these facilities are generally equipped with lighting, utilities and, often, retail establishments. The DSRC equipment should be mounted at a maximum height of 25 feet with adequate line-of-sight to communicate to vehicles within a 1000 feet radius. Depending on whether the freight corridor is situated in an urban or rural setting, backhaul communication to a management center could be provided through a fiber network or various other means.

For the WIM application presented in the concept schematic, a DSRC deployment would be consistent with the traditional approach for CVISN installations. DSRC radios are installed at the mainline WIM sensors location, dynamic message sign location, credentials verification location, and scale house facility. The spacing of these devices is typically dependent on state standards.

2.8.2.2 Backhaul Communications
Backhaul communications to the private business’s or agency’s central control facilities could be implemented in a variety of ways depending on the applications being supported. These are discussed in the Common Considerations section. The control center would be able to monitor and react to the information communicated by the trucks and issue response actions as necessary to ensure efficient and safe goods movement.
2.8.2.3 Management Centers and Information Services

Operations in the Smart Roadside initiative would involve various agencies that are involved in freight movement and have a need to communicate with trucks. Backhaul communications between the deployments at key truck facilities and agencies would include the USDOT FMCSA and state agencies that operate freight facilities such as weigh stations. A connected vehicle application would interface with management center systems that are already part of the CVISN program such as the ASPEN inspection reporting system, SAFER safety and fitness electronic records clearinghouse system, and CVIEW commercial vehicle information exchange window. In addition to these nationwide systems, each state agency will often have its own WIM systems, licensing databases, and law enforcement systems.

2.8.3 Applicability

Applications that may be supported by a connected vehicle equipment deployment in the freight corridor setting include, but are not limited to:

- E-Permitting Verification/Wireless Roadside Inspection
- E-Screening/Virtual Weigh Station
- Smart Truck Parking
Figure 7 - Smart Roadside Freight Corridor Deployment Concept - Weigh Station

Smart Roadside Freight Corridor Deployment Concept
NATIONAL CONNECTED VEHICLE FIELD INFRASTRUCTURE FOOTPRINT ANALYSIS

NOT FOR CONSTRUCTION

AASHTO

CONCEPT 7
PAGE 1 OF 2

LEGEND

• Existing Mast Arm
• Existing Pole
• Existing Cabinets
• DSRC Radio
• DSRC Comm

TYPICAL SETTING FEATURES
Truck weight station facilities for long-distance truck drivers are located close to major highway routes.

CONCEPT EXAMPLE
E-screening in this application notifies freight drivers about upcoming weigh stations.

OTHER EXAMPLE APPLICATIONS
• E-Permitting Verification / Wireless Roadside Inspection
• E-Screening / Virtual Weigh Station
• Smart Truck Parking
Figure 8 - Smart Roadside Freight Corridor Deployment Concept - Parking
2.9 DOT Operations and Maintenance

2.9.1 Current State

A Department of Transportation’s maintenance and operations divisions oversee the day-to-day needs of maintaining and operating their jurisdictional roadway network. These divisions typically focus specifically on the transportation network’s roadway conditions, drainage, roadside and vegetation, bridge and urban tunnels, road weather conditions, and traffic control. Of these functions, roadway conditions, weather, and traffic control tend to have the highest activity service level targets in a DOT’s accountability processes.

Maintenance and operations divisions require timely and accurate data to evaluate the condition of its roadways in order to provide the roadway user with a safe means of travel. Weather conditions greatly impact the roadway condition and users of the roadway. To monitor weather conditions, DOTs have installed Road Weather Information Systems (RWIS) that enable proactive winter maintenance practices and better-informed weather related travel decisions. RWIS includes an Environmental Sensor Station (ESS), a communication system for data backhaul, and a central system to manage and store this data. Atmospheric data (e.g. visibility, wind speed/direction), pavement data (e.g. temperature, condition), and water level data are typically collected by RWIS. Environmental data can also be collected from vehicle-based sensors on private vehicles or from specialized sensors that could be installed on snow plows by public agencies. With this data, maintenance control centers can allocate their fleet to desired locations while traffic management centers can alert roadway users via roadway warning systems (e.g. dynamic message signs), websites (e.g. traveler information map), and over land-line (e.g. 511).

Along with roadway conditions, work zone closures have a significant impact on the level of service of a roadway network. Full road closures, partial road closures, and lane closures all facilitate the completion of roadway construction projects. DOT maintenance and operations division as well as private construction contractors apply strategic plans that incorporate advanced warning notification which act as an effective way to manage safety and disruption to traffic along a roadway network.

2.9.2 Concept Description

The concept for the DOT operations and maintenance focuses on providing roadway condition and work zone data to regional maintenance engineers
and managers, maintenance personnel, the regional traffic management center personnel, and users of the roadway. Agency fleet vehicles would be equipped with connected vehicle mobile elements to transmit probe data that would include location, speed, heading, and vehicle-specific data such as air and pavement temperatures, snow plow position and spreader rates. The vehicle position data would supplement probe data that could be acquired from private vehicles, and the operational data could be used to feed decision support systems. Other related applications could gather information from and provide information about roadway and traffic conditions in work zones, or use accelerometry from the vehicle to monitor pavement defects.

**DSRC Concept**

Agency vehicles would be configured with DSRC OBEs with access to the vehicle data bus and any supplementary vehicle sensors or devices. The connected vehicle field equipment for DOT maintenance and operations setting would consist of a DSRC RSE for use by DOT maintenance and operations divisions as well as private construction contractors. Probe data would be cached on the vehicle until it could be transmitted to an RSE. The illustration in Figure 9 shows one example of DSRC communications at a DOT operations and maintenance facility that monitors roadway weather information.

**Cellular Concept**

Agency vehicles equipped with cellular data (for example, LTE) modems would send information to a server at periodic intervals (e.g., every 100 meters or three seconds) as they travel along the roadway. The message would include the current location, speed, and direction of travel as well as any vehicle operational data (plow position, accelerometry, etc.) that might be applicable to the vehicle and its sensors.

**2.9.2.1 Field Infrastructure**

The field infrastructure for DOT maintenance and operations using DSRC will consist of connected vehicle equipment permanently or temporarily installed at locations to best serve the maintenance personnel and work zone construction crews. These locations may include the regional maintenance facility, temporary construction staging sites, major interchanges, and spot locations, construction zones, or areas that may require special maintenance attention. For permanent installations, the equipment typically would be mounted to an existing elevated structure such as a sign gantry, light/camera pole, or overpass. To the greatest extent possible, field infrastructure
requirements for this setting should be accomplished through use of infrastructure deployed for other connected vehicle applications.

In order to provide the greatest range for a permanent DSRC deployment and minimize obstruction to line of sight, the equipment will most likely be installed at the highest possible mounting height on the existing structure while meeting FCC requirements.

When identifying permanent installation locations, utilizing existing communication infrastructure will play an important role in reducing installation costs. The connected vehicle field equipment will ideally share communication inside an existing Intelligent Transportation System (ITS) cabinet that is equipped with an Ethernet switch and a backhaul communication connection to the facility control center. Power would be supplied by the existing ITS cabinet (or service cabinet), solar, or nearby electrical service drop.

For temporary settings, such as for short term purposes (e.g. pot hole repair, guard rail repair) and moving operations (e.g. striping, paving), a trailer equipped with a 25 foot pole and cabinet could be utilized, subject to FCC licensing for DSRC operations in that particular location. Placement of the mobile unit should occur on the roadside in the clear zone to avoid a possible collision with construction and roadway vehicles.

2.9.2.2 Backhaul Communications

The recommended backhaul communications for DOT maintenance and operations setting would consist of an existing backhaul that is owned and maintained by the DOT or leased specifically for the DOT’s operational purposes. Backhaul communications for DOT O&M functions could be implemented in a variety of ways depending on the applications being supported; these are discussed in the Common Considerations section.

2.9.2.3 Management Centers and Information Services

Within the connected vehicle system, connected vehicle equipment deployment for the DOT maintenance and operations setting will typically provide real-time communication between fleet vehicles and the facility control center and also work zones and roadway users. Weather information such as snow and ice conditions will be communicated from RWIS back to the control center and relayed to connected vehicle field equipment at regional maintenance facilities and roadside installations. Connected vehicle mobile elements on fleet vehicles will receive this information and respond accordingly. Conversely, fleet vehicles and even general users of the road can
provide probe data (e.g., pot-hole detection, weather conditions, pavement traction) that can be sent back to the facility control center. The server system at the control center will gather and archive the data for future use. Potential control applications include DOT maintenance systems, DOT dispatch systems, and interfacing to a traffic management system.

2.9.3 Applicability

Applications that may be supported by a connected vehicle equipment deployment in the DOT operations and maintenance setting include, but are not limited to:

- Enhanced Maintenance Decision Support System
- Information for Maintenance and Fleet Management Systems
- Probe-based Pavement Maintenance
- Work Zone Traveler Information
Figure 9 - DOT Operations and Maintenance Deployment Concept

DOT Operations and Maintenance Deployment Concept
NATIONAL CONNECTED VEHICLE FIELD INFRASTRUCTURE FOOTPRINT ANALYSIS

LEGEND

- Existing Mast Arm
- Existing Pole
- Existing Cabinets
- DSRC Radio
- DSRC Comm.

TYPICAL SETTING FEATURES

DOT maintenance and operations typically provide communication between fleet vehicles, facility control center, and roadway users in work zones.

CONCEPT EXAMPLE

Application at a DOT Operations and Maintenance facility that monitors roadway weather information.

OTHER EXAMPLE APPLICATIONS

- Enhanced maintenance decision support systems
- Information for maintenance and fleet management systems
- Probe-based pavement maintenance
- Work zone traveler information
2.10 Fee Payment

2.10.1 Current State

User fees are an integral part in supporting transportation systems by means of collecting revenue to fund transportation projects, recuperate funds from a past project, as well as sustain maintenance and operations costs for roadway infrastructure. In the United States, user fees have been collected through traditional means such as toll booths and have been evolving towards electronic tolling collection (ETC) systems for improved operational efficiencies. ETC systems benefit from added efficiencies as vehicles typically do not stop while assessed a fee through tag readers and RFID technology. Roadway facilities that are commonly tolled include bridges, tunnels, express facilities (High Occupancy Tolling or HOT), freeway systems, and ferry systems. ETC systems typically require interaction with back-end systems to process monetary transactions, license plate database interrogation, and cooperation with enforcement agencies. With the added complexities of autonomously collecting a user fee, electronic tolling systems often require a substantial amount of added equipment to provide vehicle detection, pricing information dissemination, payment processing, enforcement, and auditing capabilities.

Toll facilities adopt pricing structures that are sometimes dependent on time-of-day and relative benefit to neighboring roadway facilities. Often times, user fees are also assessed as a flat-rate pricing structure. With ETC systems, the main form of public interaction is disseminating pricing information whether it is through dynamic message signs, traveler information resources, or other means. All other functions are processed by central system equipment.

2.10.2 Concept Description

The connected vehicle setting for a fee payment application using DSRC communications would generally involve deploying connected vehicle field equipment at facility entry and egress points with the primary objective of providing the driver, via a connected vehicle mobile element, with information regarding an upcoming fee payment facility, account balance, alternate non-tolled parallel routes, and any fees associated with using the system. In this context, the system would provide tolling presence detection similar to typical 915 MHz-based toll transponders, with additional bi-directional exchange of supporting account and traveler information. Although out of scope for this discussion, the DSRC-based system could
conceptually, with appropriate transactional safeguards, provide access to a payment transaction system.

2.10.2.1 Field Infrastructure

Field infrastructure that is available for mounting connected vehicle field equipment in a user fee setting includes sign or equipment gantries, bridge and tunnel structures, and ferry docks. Mountings will be elevated to avoid tampering and provide optimal line of sight and range. Preferred DSRC antenna mounting locations include locations in close proximity to roadside toll equipment where a communication source and power is readily available. While existing user fee collection technologies typically require one reader per lane, DSRC can use one radio that can cover an entire road.

2.10.2.2 Backhaul Communications

The preferred backhaul communications for a connected vehicle user fee system would consist of an existing network that is owned and maintained by the toll operator. The connected vehicle field equipment would communicate over the same backhaul network to a central management center where the payment can be processed. A high bandwidth network is recommended to provide capacity for potential sharing among connected vehicle applications. Most toll facilities in an urban setting would likely have backhaul communications to support the toll network. In a remote setting, a cellular form of communication may be required to support backhaul communication requirements.

For new deployments, backhaul communications at fee payment installations could be implemented in a variety of ways depending on the applications being supported. These options are discussed in the Common Considerations section.

2.10.2.3 Management Centers and Information Services

Regular and frequent communication with a central tolling system is critical for the operation of the user fee application. Depending on the user fee system utilized, the central system may be interrogated on a regular interval to obtain vehicle identification data, process payments, and update rate schedules. Two-way real-time communication is required between the management center and the connected vehicle field equipment to support the user fee application. Depending on the established user fee policies, other examples of communication requirements may include real-time toll facility usage to adjust pricing schemes and assessment of user fees based on distance travelled in a toll system.
Additionally, a national center-to-center communication may be required to universally process user fees for vehicles that travel out-of-state. Data that is shared between the state agencies will include vehicle/driver data and fee assessments. User fee back-end systems are typically state-specific and not interchangeable between states. A connected vehicle concept could unify different systems together to create a common platform for user fee assessment.

2.10.3 Applicability

Applications that may be supported by a connected vehicle equipment deployment in the user fee setting include, but are not limited to:

- Approach Lane Use Management
- Automated Toll/User Fee Collection and Administration
- Congestion Pricing
- High-occupancy Toll Lanes
Figure 10 - Fee Payment Deployment Concept
3 Considerations Common to All Concepts

3.1 Connected Vehicle System Architectures

The connected vehicle system architecture is, at a high level, a system for exchanging data bi-directionally between transportation system field equipment, mobile users, vehicle systems, and transportation system center users. Transportation Field Equipment is typically located at or near the roadway, and may include traffic signal controllers, access controls, or ITS field equipment such as dynamic message signs (DMS), count or vehicle detection (speed) stations, highway advisory radio (HAR) stations, surveillance stations (CCTV), and other related equipment. Vehicle Systems include sensors and various types of user interfaces such as displays, audio interfaces and such. Mobile Users interact directly with the transportation field equipment through the normal use of the transportation system—driving on a roadway, observing a traffic signal—and (if they are in a vehicle) interact with the vehicle systems through the vehicle’s user interface equipment. A Mobile User’s primary interests are to get through the transportation system safely and efficiently. Transportation Information System Users are any other users that may need information about the roadway or transportation system state or about vehicles on the roadway. These users are typically responsible for managing and maintaining the roads, or may be other users with an interest in information about the transportation system, such as users planning trips.

This overall system is illustrated in the figure below.

![Figure 11 - Top Level View of Connected Vehicle System](image-url)
This system is the same as the overall system described in the Core System architecture and the Connected Vehicle Reference Implementation Architecture (CVRIA) documentation, although here it is focused on the “Mobile”, Field” and “Center” elements of that architecture since these are the parts that actually carry out the steps of connected vehicle applications.

While it is included here for completeness, the Core System does not play a role in the applications discussed in this report. The Core System ConOps does not describe the applications treated in this report, and the Core System Requirements (SYRS) apply to elements within the core system (in support of the Core System functions described in the ConOps), but these do not apply to the Mobile, Field and Center elements described here since these elements are “outside” the Core System boundary.

Appendix A.1 provides a more detailed explanation of the system. It is important to note that the connected vehicle system sits within the existing transportation system. Thus the mobile, field and center elements of the system shown above actually include elements that are part of the connected vehicle system, and elements that lie outside the connected vehicle system. Vehicles (mobile), traffic signal controllers and signals (field), and traffic management centers (center) exist today without the connected vehicle system. As the connected vehicle system emerges, it will thus include new elements for each of these component areas. A key aspect of the system deployment will be the implementation of the interfaces between these new connected vehicle elements and the existing elements in the transportation system. Figure 12 below outlines this distinction, and illustrates the various internal elements of the connected vehicle system.

Figure 12 - Connected Vehicle System Diagram
To support this separation between existing elements and their connected vehicle counterparts, this analysis has adopted some slightly refined terminology, also described in more detail in Appendix A.1. For example, in a DSRC-based system, the Connected Vehicle Field Element is also known as an RSE (Roadside Equipment) and the Connected Vehicle Mobile Element is known as the OBE (On-Board Equipment). In general, the Connected Vehicle Mobile Element is located in a vehicle, and “connected vehicles” may therefore refer to a Connected Vehicle Mobile Element even if the mobile element were a user’s smartphone. There will always be a wireless connection to a mobile element.

As shown in the diagram above, the mobile element of the connected vehicle system may communicate with the field element using a wireless local area network (WLAN). The WLAN is so named because it supports communications over limited range in the area local to the field element. In most currently-envisioned implementations of the Connected Vehicle System, the WLAN element is implemented using DSRC. However many studies have examined other ways of implementing this element (for example, Wi-Fi, Bluetooth or LTE Direct), so it is referred to here by its more generic term. Through this connection the mobile element can receive information from the field element. This information may originate at a center element (e.g. a traffic management center) and be provided to the field element over the backhaul link, or it may originate from transportation field equipment co-located with the connected vehicle field equipment (for example, a signal controller providing signal information to a roadside DSRC unit). The mobile element may also provide data to the center element via the field elements (again over the backhaul link), or it may also exchange data (bi-directionally) directly with the center element using a wireless wide area network (WWAN) such as cellular/LTE network. The WWAN is so named because it facilitates communication over a long range, so the mobile element can communicate with the remotely located center element(s) over a large geographic region. Other technologies for implementing the WWAN element include satellite and WiMAX, although generally cellular/LTE is the dominant approach.

This system diagram above is general and technology-agnostic, but it also represents the two primary current connected vehicle approaches: local two-way communication using DSRC, and remote two-way communication using cellular/LTE. Other communication paths may be possible, but from a technical perspective these two approaches are representative and further discussion is generally limited to these concepts (see “Communications Elements” below for further discussion).
3.2 **Connected Vehicle Data Needs and Standards**

Connected vehicle data needs include data needed by connected vehicles from other nearby connected vehicles (V2V data), data needed by the center elements from connected vehicles (V2I data), and data needed by connected vehicles from the roadway (strictly speaking, I2V data, but commonly referred to as V2I data). “V2I” is used in this report for both directions of communication except where this direction is important to understanding the system (e.g., Table 1 below).

V2V data generally consists of kinematic data from nearby vehicles that will enable a receiving vehicle to understand the current state of the transmitting vehicle and to project its trajectory a few seconds into the future so as to assess potential conflicts.

V2I data includes data describing road and traffic conditions observed by the vehicle along sections of road traveled at some earlier time. These data are sent from a vehicle to an RSE using the local wireless link and are generally passed from the RSE to the center element over the backhaul communications link. These data may also be provided directly to the center element by the vehicle using the wide area link (e.g., via cellular). V2I data may also include V2V messages that may be received by an RSE (where the connected vehicle is transmitting V2V data in the vicinity of an RSE).

V2I data also includes data generally associated with the roadway on which the vehicle is or will likely be traveling. This data may be transmitted locally from RSEs to vehicles in the local vicinity of the RSE (i.e., in range of the wireless local link) or may be transmitted to the vehicle directly by the center element using the wide area wireless link. Some of this data may originate locally from transportation field equipment co-located with the RSE (for example, traffic signal data), and some may be provided to the RSE through its backhaul link by the center element. It is also important to note that data provided to the vehicle may be relevant at the current location or at a potential future location of the vehicle. For example, it is not necessary to deliver curve speed warning information to the vehicle at or near the curve in question. Since curve speed information is relatively static over time, it can be delivered at a remote location (for example, where it is convenient to locate an RSE) and then activated when/if the vehicle reaches the curve.² Information that has a higher time criticality must be delivered when the vehicle is closer to the

² This model presupposes that an application capable of caching and using the curve speed warning data at the appropriate location is deployed in the vehicle.
location to which the information relates. Traffic signal timing information, for example, generally needs to be delivered when the vehicle is relatively close to the intersection.

The data communications between vehicles and infrastructure are sent as discrete messages. These messages are typically structured as pre-defined sets of data corresponding to particular parameters. These sets may be fixed in size (i.e., a fixed number of data bits) or they may be variable in size, in which case they are preceded by an indication of the length of the subsequent data set. For current Connected Vehicle applications, the SAE J2735 standard defines messages for many of these types of information. These are listed in Table 1 below in relation to the type of communication (V2V, V2I or I2V) to which they relate.

<table>
<thead>
<tr>
<th>Table 1 - Representative SAE J2735 Messages and Communication Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Message Type</td>
</tr>
<tr>
<td>--------------------------------------</td>
</tr>
<tr>
<td>Basic Safety Message Part 1</td>
</tr>
<tr>
<td>Basic Safety Message Part 2</td>
</tr>
<tr>
<td>Emergency Vehicle Alert</td>
</tr>
<tr>
<td>Common Safety Request</td>
</tr>
<tr>
<td>Probe Vehicle Data</td>
</tr>
<tr>
<td>Signal Request Message</td>
</tr>
<tr>
<td>Roadside Alert</td>
</tr>
<tr>
<td>Traveler Information</td>
</tr>
<tr>
<td>MAP Data</td>
</tr>
<tr>
<td>Probe Data Management</td>
</tr>
<tr>
<td>Signal Phase and Timing</td>
</tr>
<tr>
<td>Signal State Message</td>
</tr>
<tr>
<td>NMEA Corrections</td>
</tr>
<tr>
<td>RTCM Corrections</td>
</tr>
</tbody>
</table>

* I2V here is commonly referred to as V2I data. It is denoted I2V here to illustrate the direction of transmission.
The messages defined in the current SAE J2735 standard partially meet the application needs, but there are issues beyond the scope of this analysis that are yet to be addressed.

A significant opportunity presented by the connected vehicle system is to obtain data from mobile (vehicle-based) sensors that would otherwise be provided by infrastructure sensors that are limited in coverage. A single infrastructure communications point can then gather information on what is happening at multiple points along miles of roadway, albeit with some delay. This provides a very cost effective means of creating a general situational awareness of the transportation system status. Some of the messages above, in particular the Probe Vehicle Data message, are intended for this purpose.

The J2735 standard provides a technical description of the potential messages and the data they may contain, but does not guarantee that data elements will actually be available or that messages would be delivered. The Basic Safety Message (BSM) Part 1 is currently the only message widely agreed to be transmitted. A more complete data needs discussion necessarily extends beyond what can be transmitted to what will be transmitted, but this is largely a policy issue outside the scope of this document. Nonetheless, many of the applications described in this document require data beyond the BSM Part 1, and the availability of those applications is linked to availability of data.

The collection of probe data poses significant privacy issues, especially where a mandate is considered. For data collected using wide area communications, the carrier knows who is sending the data, and so the data must be reliably separated from its source. In the case of local area communications, the data must be stored on the vehicle until the vehicle reaches a suitable RSE, and it must then be encrypted during transmission so that an eavesdropper cannot link the transferred data to a physically observed vehicle.

A potential solution to the privacy concern would be to enlist a third-party who does not know where the data is coming from (either via wide area or local area communications) to process the data packets. The carrier (WAN or LAN) may know the origin of packets, but cannot open the contents. Since this third-party would have access to the data, it is likely they could build a successful business model and help to finance the overall deployment, but many policy issues surround this concept.
3.3 Mobile Element Components

3.3.1 Embedded Vehicle Terminals

A typical embedded vehicle terminal is shown below in Figure 13. This implementation includes an interface that enables the collection of a variety of vehicle data that can then be sent over the local or wide area links. Depending on the implementation, this interface may be a bi-directional gateway allowing authorized input of data to the vehicle, or it may be a one-way data reporting gateway.\(^3\)

![Embedded Connected Vehicle Terminal Example](image)

Figure 13 - Embedded Connected Vehicle Terminal Example

The connected vehicle element is typically supported by a host processor that runs various connected vehicle applications and includes a location capability such as GPS. In general an embedded system will be implemented such that the connected vehicle functions are integral with other vehicle elements. They are shown here as separate to preserve the connected vehicle system boundary. In general, embedded vehicle implementations will be exclusively controlled by the vehicle OEM.

\(^3\)Note: Portions of this section were originally developed by this author, and delivered to the US DOT under contract numbers DTFH61-04-D-00002 and DTFH61-11-D-00019.
3.3.2 Aftermarket Vehicle Terminals

Aftermarket vehicle terminals are similar to embedded terminals except that they depend on post-production installation in the vehicle, and will typically include a dedicated user interface. Depending on the origin of the terminal, the vehicle interface may include extensive vehicle data (for example if the aftermarket device is OEM approved) or it may be limited to data available through the vehicle’s on-board diagnostics (OBD-II) connector. Systems without access to OEM data are likely to be limited in functionality due to the lack of access to sensors generally available within a vehicle.

A typical aftermarket implementation is illustrated in Figure 14.

![Figure 14 - Aftermarket Connected Vehicle Terminal Example](image)

In addition to variations in the vehicle interface, it is expected that some advanced implementations may also take advantage of specialized user interface technologies such as MirrorLink® or other systems that allow third party devices to access a user interface provided by the manufacturer embedded in the vehicle (shown notionally as a dashed line in the figure). This approach is attractive since it assures a high quality user interface that complies with OEM safety objectives but does not depend on the long vehicle product development cycle, so it can support a changing variety of
aftermarket terminal implementations. However, these systems have not yet been proven in the marketplace.

3.3.3 Portable Consumer Electronic Terminals

Portable or “nomadic” connected vehicle terminals are likely to be based on smartphones. The devices, shown in Figure 15 below, may connect to vehicle systems through a gateway using Bluetooth®, MirrorLink© or other serial protocols. Like aftermarket devices, they may use a dedicated device user interface, or may use a user interface embedded in the vehicle. Consumer electronic (CE) “Connected Vehicle” devices may also be used by pedestrians, wheelchairs, cyclists, motor cyclists, and other non-motor vehicle users. It is also likely that many CE based devices, especially initially, will not support a connected vehicle WLAN connection (i.e. DSRC). These devices will generally use a cellular data connection, and may support Wi-Fi, but these links will only provide access to and transactions with a connected vehicle center element, not connected to vehicle field equipment. It is possible that over time these devices may also support direct local connections to connected vehicle field equipment using DSRC, although no consumer electronics manufacturers have announced any such products.

![Figure 15 - Consumer Electronic Connected Vehicle Terminal Example](image-url)
3.4 V2I Communications

3.4.1 General Communication Elements

It is generally assumed in this report that connected vehicle communications between connected vehicle mobile elements and field elements are carried out using DSRC/WAVE technology, and that communications directly between connected vehicle mobile elements and center elements are carried out using cellular/LTE. These are discussed in more detail below. There are other communications systems that could also be used, but generally these are not seen as particularly viable for a variety of reasons; these alternatives are summarized in Appendix A.5.

3.4.2 DSRC WAVE Communications

DSRC is a form of 802.11 (Wi-Fi) that does not involve any association process between the terminals and the base station. (DSRC systems are not interoperable with other Wi-Fi systems, but they are based on most of the same underlying standards). It operates in a frequency band between 5.85 GHz and 5.925 GHz. Unlike Wi-Fi, in which the operating channel is selected at the time of association, DSRC also allows terminals to dynamically switch between channels, so the entire allocated frequency band can be used by any mobile terminal. The other two key differences between DSRC and Wi-Fi are in the upper layers of the protocol. For DSRC this is known as the Wireless Access in Vehicular Environments (WAVE) protocol. WAVE identifies two network layer protocols, the WAVE Short Message Protocol (WSMP) and IPv6, which are discussed below.

3.4.2.1 WAVE Short Message Protocol

The WAVE Short Message Protocol (WSMP) provides a simple means for sending a short (single packet) message (WAVE Short Message, or WSM) to other terminals in the local area. It is primarily intended for broadcast communication to any and all terminals in range, and as a result it uses a different type of addressing. Instead of addressing a message to a particular network element (i.e. a network address), WSMP “addresses” messages according to the type of service they are associated with. This enables a receiving terminal to deliver a received message to those applications that are associated with the referenced service. While it is also possible to send a message to a specific terminal (known as unicast), this requires that the target terminal has already sent a broadcast message (so that the transmitting terminal can learn its network address – known as a MAC address). In general, most WSM transmissions are broadcast since they relate to all terminals in the immediate proximity of the transmitter.
The WSM is limited in size because the entire message, including all of the headers and security information, must fit into the specified Maximum Transmission Unit (MTU). While the MTU size can be changed, this requires coordination and/or discovery by the communicating terminals, so typically the default value of 1500 bytes is used.

It is also important to note that WSMP is primarily a “local” protocol. That is, it is not routable using conventional network protocols, and thus it is intended to serve applications that are local to the transmitting radio.

### 3.4.2.2 Internet Protocol (IPv6)

For transactions involving larger amounts of data than can be supported by WSMP, or for transactions where the recipient is not local to the DSRC terminal (e.g. a remote service provider connected to the fixed provider terminal by a backhaul network) the DSRC system supports the well-known Internet Protocol (IP), specifically, the IPv6 protocol. IP transactions are only supported on the undesignated DSRC service channels, and are forbidden in the 802.11p Standard on the control channel. Unlike WSMP, IP enables the sender to send messages that are larger than a single packet. The IP protocol segments the original messages into smaller packets and sends these, and they are then reassembled at the receiving end to recover the original file.

In order to send an IP packet, a terminal must have an IP address. This is easily accomplished for fixed terminals where the IP address is established when the network is formed. For mobile terminals this is not so simple. Because the terminal is mobile, it is not likely to remain in contact with any given access point for very long, and as a result, if it were to have a fixed IP address, the routing information for each access point would be in constant flux, and would generally be hopelessly out of date all the time. In addition it would then be possible to geographically track any terminal by tracking the IP address. It is not practical to use Dynamic Host Configuration Protocol (DHCP) (which is typically used by Wi-Fi hot spots) to assign IP addresses because the vehicles are entering and leaving a given hot spot at a relatively fast rate, and servicing the high volume of DHCP requests would be overwhelming. IPv6 addresses this problem by using a different sort of IP address. In operation the mobile terminal can adopt a portion of the roadside unit’s IP address and thereby create an IP address that is valid while the vehicle is in the radio footprint of the RSE. This is described in more detail in Appendix A.2.
3.4.3 Cellular Communications

Cellular systems are widely available and, driven by various consumer devices (smartphones, tablet computers, etc.), the cellular industry has been substantially expanding cellular capacity and coverage over the past 20 years.

The most recent advancement in cellular technology is known as LTE (long term evolution). This technology effectively combines the benefits of Global System for Mobile Communications (GSM) and Code Division Multiple Access (CDMA) systems in a highly flexible and wideband IP-based system. While LTE is able to deliver very high data rates to fixed users, the highest achievable future LTE (LTE Advanced) data rate for moving users is 100 Mbps. In practice, however, because of user capacity limitations and interference, this is typically substantially lower. Still, LTE is a rapidly evolving technology that is specifically intended to provide high data rates to mobile users. LTE and the various previous versions of the cellular standard have been managed by the 3rd Generation Partnership Project (3GPP) since 1998. The 3GPP specification releases occur about every 2 years or so. Because the standard is so widely used, there is substantial attention paid to backward compatibility, so in most cases new features that extend performance can be used without rendering earlier systems obsolete. The current standard, known commonly as 4G, is expected to evolve as discussed briefly below (e.g., see LTE-Direct).

LTE is an all IP network. The cell areas are generally large, and each terminal is assigned an IP address when it joins the network. A variety of schemes have been developed to enable terminals to maintain IP connectivity with remote servers as they move from cell site to cell site. As a result LTE is very well suited to connecting mobile terminals to remote servers. Contacting mobile terminals over the IP network is somewhat more complex, although mechanisms for this have been developed.

Unlike DSRC, LTE currently provides no provision for one mobile terminal to communicate directly with another nearby mobile terminal or a local data source (e.g., a system that might be connected to an RSE to provide localized data). With LTE all communications currently must go through the cellular system carrier’s back haul network (a network that connects the cell site to the carrier’s back office systems, and generally, to the Internet) and must include an IP address. An emerging addition to the 3GPP specifications (Release 12) is a system known as LTE-Direct. This system will allow communication directly between LTE terminal devices. It uses a concept known as “Proximate Discovery” that allows LTE terminals to announce the services
they have to offer to other terminals in the local area. These announcements can then lead to one terminal providing information to other terminals in the area. The technology has not been widely used as yet, but it may provide an LTE-based mechanism for V2V and V2I communications. In this case, the WLAN of Figure 12 above would be an LTE-Direct link, and the WWAN would be a conventional LTE client terminal-to-cell site link.

Appendix A.4 provides a more detailed description of how the cellular implementation (including LTE Direct) might work.

### 3.5 Communications Security

The connected vehicle security system is aimed at ensuring three basic objectives: privacy, authenticity and robustness through certification. The basic structure of the security system is designed to provide assurance of the confidentiality of private message traffic, the authenticity of public message traffic, and the anonymity of private generators of public messages.

#### 3.5.1 Privacy

Because the connected vehicle system includes messages relating to location and speed of mobile users, it has been generally agreed that it is necessary to protect the privacy of the mobile user population (to avoid, for example, using the system to enforce traffic laws, and to prevent tracking of the movements of individuals based on their transmitted messages). Privacy is not necessarily needed or desired for public sector users and/or equipment, and generally both public and private field elements do not require anonymous certification since they are stationary.

For private sector mobile users, privacy is addressed in two ways: anonymity and confidentiality. Anonymity is achieved by excluding any sort of identifying information in publicly transmitted messages, and by assuring that there is no publicly available linkage between the user’s identity and any of the message content. In addition, when identifying information is passed through the system to trusted service providers (for example to execute a payment transaction, or to request services from a subscriber based service), the system provides mechanisms to encrypt this information so that only the intended recipient can access this information. This process uses conventional encryption techniques.

To assure anonymity, the connected vehicle system uses a special security credentialing process for private users. This process assures that the security credentials themselves do not provide a mechanism for tracking or
identifying the users. This system has some shortcomings outside the scope of this analysis that are yet to be addressed.

3.5.2 Authenticity

To provide assurance that received messages are authentic, the connected vehicle system employs a digital signing system based on conventional public key cryptography (PKI) systems. In this approach, each message includes a digital signature and a “certificate.” To generate a signature, a digest of the message is generated using some agreed-upon algorithm. This digest is essentially a small subset of the data that forms the message, generated by a hashing algorithm. The resulting digest is then encrypted using the sender’s private key. The certificate includes other information relating to the permissions of the sender. For example an RSE certificate might include the authorized location or jurisdiction for the RSE to avoid issues with the RSE being physically moved to a different location. The certificate also includes a digital signature which is provided by a trusted third party, known as a Certificate Authority (CA). This signature allows the receiving party to verify that the certificate is legitimate.

The signature and the sender’s certificate and, if appropriate, the certificate authority signature on the sender’s certificate are appended to the message; the sender’s certificate includes the sender’s public key so that the receiver can decrypt the signature. Once decrypted, the receiver can compare the decrypted signature to the same data generated from the received message (using the same agreed upon algorithm for generating the digest). If the two resulting files match, then the receiver can be assured that the message was sent by the holder of the certificate, the holder of the certificate is endorsed by the certificate authority, and the message was not somehow altered in transit.

This process is the same for both public and private users, except that the certificates used by public users are not necessarily anonymous, so, the certificate and/or the message itself may include information identifying, for example, the organization responsible for generating the message.

3.5.3 Certification

The originator must be certified by the certificate authority to send signed messages. In general the originator is assumed to be the transmitting terminal. For connected vehicle mobile equipment, the originator would be the WLAN or WWAN device; for connected vehicle field equipment, it would be the WLAN device (e.g. RSE); and for connected vehicle center elements it would be the server originating the message. It is generally assumed that
backhaul communication between the center elements and the field elements is secured using conventional network security methods, so a message provided by the center element to a field element for transmission would be provided through whatever secure backhaul system the agency had implemented, and the message transmitted over the WLAN (DSRC) link would be signed by the sending device.

There has been a great deal of industry attention applied to the process of certifying private mobile terminal equipment. This is primarily a result of the need for anonymity and the desire to prevent tracking of private mobile terminals through the security credentials. The process for certification of public sector mobile equipment and both public and private field equipment is much simpler since it can be based on conventional PKI certification processes. It is important to point out that field equipment is inherently trackable and non-anonymous (since it is generally licensed, and is located at a known place), so it does not require anonymous certification.

3.5.4 Other Security Elements

The entire security system and its management has been the topic of extensive development effort over the past few years. Currently the threats addressed by the security system focus primarily on false messages and resulting false positive application actions (generally false warnings). Issues associated with the number of certificates used in vehicles, the process of identifying bad actors (misbehavior detection), the process of removing those bad actors and the scope of this sort of problem (i.e. the size of the revocation list) are all key concerns to which interim approaches have been developed.

There are open questions about the ability of the system to withstand attacks and about the threat model that the system is designed to protect against. For example, the current assumptions about the scale of misbehavior and the resulting scale of certificate revocation are either so low as to suggest that the security system may not be all that necessary (i.e. the security system is imposing heavy overhead to avoid a problem that will almost never be seen), or are so large that the current design will be unable to cope with the load (i.e., creating a large number of misbehaving vehicles will cause the security system to fail). In addition the fact that a vehicle terminal has certificates does not by itself assure that the terminal has not been tampered with in some way. Recent studies have indicated that in addition to false messages, attacks where the terminal is injected with malware are feasible. Such an attack could find its way inside the existing security system (so malware messages would
be signed and appear legitimate), and could extensively subvert system operations.

Security is a moving target and will likely undergo extensive evolution over time.

3.6 Backhaul

The connected vehicle environment includes mobile terminals, field terminals and center terminals. Mobile terminals are typically vehicles, while field terminals, when they are used, are typically radio terminals located along the roadway (typically called “roadside equipment”, or RSE). Center facilities include traffic management centers and other road authority/agency back office facilities, and remote service providers.

Conventional connected vehicle architectures assume that field equipment and center facilities are connected by a communications link. This is typically called a “Backhaul Network”. In these systems the Center can send information to field terminals (e.g. messages to be transmitted by the field terminal) and the field equipment can send information back to the center facility. The information sent back to the center facility may be status information about the field terminal, or it may be local information relating to other field equipment such as signal controllers that are attached to the field terminal. It may also be information received from nearby mobile terminals and forwarded to the center by the field terminal.

Some connected vehicle architectures may not use field equipment. In this case communications between the mobile terminals and the center facilities would be over a wide area network. While this could be considered a backhaul link, for purposes of this project it is not included. Wireless wide area network connections to mobile terminals are discussed elsewhere in this report.

Numerous technologies can be used to provide backhaul communications. Table 2 below describes the available technologies and summarizes their key strengths and limitations for backhaul applications. The merits of these backhaul alternatives relative to specific CV application messaging requirements are described in Appendix A.7.
<table>
<thead>
<tr>
<th>Type</th>
<th>Technology</th>
<th>Description</th>
<th>Metrics</th>
<th>Strengths</th>
<th>Limitations</th>
</tr>
</thead>
</table>
| Wide Area  | Cellular (LTE)   | General purpose IP data oriented wide area wireless system. Generally available from a variety of commercial service providers. LTE is an evolution of the well-known European GSM system that provides increased capacity and data rates. Typical fixed service data rates of about 300 Mbps are available. | Data Rate: 300 Mbps (when stationary)  
Range: 10-20 Km  
Modem Cost: -$500 (industrial)  
Service Cost: ~$50/mo*  
BW Limit: 6 GB/Mo*  
* Pricing varies; rates shown were obtained 8/29/2013 | Widely available and generally low cost  
Generally high data rates  
Some limitations with IPv6  
Rural availability varies | Data volumes can be limited; excess data volume costs can rise rapidly  
Data rates and costs may be higher than required  
Substantial competition for data resources (may drive down stream costs)  
Requires external antenna |
|            | Cellular (GPRS)  | Low end cellular data link. Generally provided, at substantially lower cost than LTE, by the same providers. GPRS is commonly used for M2M data links that do not require significant data rates. | Data Rate: 80 kbps  
Range: 10-20 Km  
Modem Cost: -$300 (industrial)  
Service Cost: ~$50/mo*  
BW Limit: 6 GB/Mo* (25 kbps sustained 6 hours per day)  
* Pricing varies; rates shown were obtained 8/29/2013 | Widely available and generally low cost  
Generally usable data rates  
Cannot support IPv6  
Rural availability varies | May be being phased out in lieu of higher bandwidth higher priced services  
Requires external antenna |
|            | WiMAX            | WiMAX is a wide area Wi-Fi – like communications technology. It is simpler than cellular/LTE, and has a lower overall user capacity, but it is commonly used for relatively long range wireless backhaul networks. It is described by the IEEE 802.16 standard. | Data Rate: 1-70 Mbps  
Range: 30 Km (at lower data rates)  
Base Station Cost: ~$50K  
Modem Cost: -$200 (industrial)  
Service Cost: Typically none (custom network installation) | Very good performance in terms of range and data rates  
Costs are determinate; no data volume costs  
Easily extensible by adding inexpensive client modems  
Highly reliable | Somewhat high initial system cost  
Requires external antenna |
"Campus area" systems can be easily purchased and set up with minimal collateral complexity. Licenses are required for wide area implementations. Some service providers offer WiMAX commercially, but generally the technology is evolving toward self-contained purchased networks.

| Fixed Service Satellite (FSS) | Fixed Satellite Service (FSS) uses Very Small Aperture Satellite (VSAT) terminals to provide high data rate wide area two way communications nearly anywhere that has a clear sky view. This technology is used to deliver satellite television (e.g., DirecTV, DISH, etc.) although it can also be used to provide other types of data communication. When used in a two way system the terminals generally include a 1 meter (i.e. larger than a TV dish antenna) dish antenna. These systems may be useful in remote areas where RSEs are too far away to be services by conventional wide area radio links. | Data Rate: 5-15 Mbps Coverage: Nationwide Modem Cost: -$500 Service Cost: $40-$100/mo (<40GB) * HughesNet Gen4 pricing | Generally limited competition, and limited downstream cost risk | Generally limited competition, and limited downstream cost risk |
| Satellite SDARS | Satellite Digital Audio Radio Service (SDARS) is a system | Data Rate: 44 Kbps (single stream); | Low cost equipment and service | Very flexible in terms of geographic locations Generally high data rates | VSAT antennas are somewhat large for most physical installations (e.g., at a controller cabinet) May be subject to weather related performance issues May require periodic maintenance (snow/ice removal, etc.) |

Satellite SDARS

Satellite Digital Audio Radio Service (SDARS) is a system

Data Rate: 44 Kbps (single stream); Low cost equipment and service

Very flexible in terms of geographic locations Generally high data rates

VSAT antennas are somewhat large for most physical installations (e.g., at a controller cabinet) May be subject to weather related performance issues May require periodic maintenance (snow/ice removal, etc.)
<table>
<thead>
<tr>
<th>Local Area</th>
<th>Communication System</th>
<th>Data Rate</th>
<th>Range</th>
<th>Modem Cost</th>
<th>Service Cost</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>UWB</td>
<td>Ultra-wideband (UWB) is a short range communication system that uses very short pulses. The result is a very wide spectrum with low signal levels. It is used for short range high data rate communications. The technology has been in development for a long time and it has never gained any significant following. It could be used for local communications between an RSE and a handheld or truck mounted system that could link the RSE over a roaming cellular or other link on an intermittent basis.</td>
<td>675 Mbps</td>
<td>~5 meters</td>
<td>unknown</td>
<td>Typically none</td>
<td>High data rate, Low power</td>
<td>Limited commercial equipment availability, Uncertain regulator environment, Unstable standards environment, Only suitable for local manual RSE programming using a localized device. Not a true remote backhaul. Requires development of secure system access system to prevent unwanted RSE tampering. May require external antenna.</td>
</tr>
<tr>
<td>Wi-Fi</td>
<td>Wi-Fi is a relatively short range</td>
<td>~1-150 Mbps</td>
<td>May exist in RSE by default,</td>
<td></td>
<td></td>
<td>Only suitable for local manual</td>
<td></td>
</tr>
<tr>
<td>Technology</td>
<td>Description</td>
<td>Range</td>
<td>Modem Cost</td>
<td>Service Cost</td>
<td>Installation</td>
<td>Backhaul Wiring</td>
<td>RSE Programming</td>
</tr>
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<tr>
<td>Wireless Ethernet System</td>
<td>Provides relatively high data rate point to point communications between terminals. Defined by a set of standards under IEEE 802.11 which specifies numerous variants of the standard providing a range of ranges and data rates. Typical uses are for providing connectivity between mobile devices (e.g., PCs and consumer devices) and the internet. The system is very popular and is widely available and inexpensive.</td>
<td>~20-150 meters</td>
<td>~$20-$50</td>
<td>Typically none</td>
<td>zero added cost</td>
<td>No backhaul wiring installation</td>
<td>RSE programming using a localized device. Not a true remote backhaul. Requires development of secure system access system to prevent unwanted RSE tampering. May require external antenna.</td>
</tr>
<tr>
<td>DSRC</td>
<td>DSRC is a variant of Wi-Fi. As a result, and since the RSE already supports DSRC, the DSRC link could be used as described above to link the RSE to a mobile system (handheld or truck mounted) that would then provide a backhaul link to a center facility.</td>
<td>~20-400 meters</td>
<td>~$100-$500</td>
<td>Typically none</td>
<td>zero added cost</td>
<td>No backhaul wiring installation</td>
<td>Only suitable for local manual RSE programming using a localized device. Not a true remote backhaul. Requires development of secure system access system to prevent unwanted RSE tampering. May require external antenna.</td>
</tr>
<tr>
<td>ZigBee</td>
<td>ZigBee is a low power short range wireless networking system. Primarily used for smart metering and sensor network applications.</td>
<td>~10-100 meters</td>
<td>~$50</td>
<td>Typically none</td>
<td>Low cost, low power</td>
<td>Few commercially available general purpose components (most embedded in other products) Only suitable for local manual RSE programming using a localized device. Not a true remote backhaul. Requires development of secure system access system to prevent unwanted RSE tampering. May require external antenna.</td>
<td></td>
</tr>
</tbody>
</table>
| Point-to-Point | Fiber | High data rate long distance network that uses light traveling along a glass/plastic fiber. Communications is generally point to point. Numerous different types and capabilities. | Data Rate: > 10 Gbps  
Range: unlimited with relays  
Modem Cost: ~$100  
Service Cost: none for custom network installation; or as leased lines with variable cost depending on bandwidth | Very high data rates possible  
Non-conductive (simplifies installation with other power related equipment)  
Expensive to install  
Difficult to splice  
Expensive equipment and connectors, etc. | remote backhaul  
Requires development of secure system access system to prevent unwanted RSE tampering  
May require external antenna |
|---|---|---|---|---|---|
| Point-to-Point | DSL | Digital Subscriber Line (DSL) is a system for providing relatively high data rate communications over conventional phone lines. This is the technology that many homes and businesses use to access the internet. It is available in most urban areas, but is generally not available in rural locations. The service is offered by most wire-line phone companies. | Data Rate: 64 Kbps-8 Mbps  
Range: ~18K feet (3.4 miles from central station)  
Modem Cost: ~$50  
Service Cost: ~$60/mo | Reliable  
Low cost, low power equipment and service  
Relatively high data rate  
No antennas  
Secure | Requires wire-line connection  
Limited rural availability |
| Point-to-Point | Cable TV | Cable TV systems are well known for providing broadband internet access and VoIP phone service, as well as television services. These systems use standard 6 MHz cable TV channels, but | Data Rate: Up to about 500 Mbps  
Range: Limited only by cable provider facilities  
Modem Cost: ~$150  
Service Cost: ~$60/mo | Reliable  
Low cost, low power equipment and service  
High data rate  
No antennas  
Secure | Requires cable connection  
Cable connections not always available at or near roadside  
Uncertain rural availability |
because the link is well controlled (since it is over a cable) the systems can use very high order modulation schemes to provide very high digital data rates. In many cable systems one conventional TV channel can carry as many as 10 digital TV channels.

| Microwave | Microwave systems use a line of sight radio link to provide very high data rates between two fixed points. These systems are available in a variety of configurations and operating in a variety of radio bands. The systems are all generally configured to customized applications using off the shelf transmitter, receive modem and antenna components. | Data Rate: Up to about 1000 Mbps  
Range: Line of sight  
Equipment Cost: up to-$18K per link  
Service Cost: None | High data rate, Low operating cost | Expensive installation  
Requires licensing  
May require large exterior antennas |
| Power Line Carrier Communications (PLCC) | Power Line Carrier Communications is a system that overlays data communications signals on regular AC power line wires. Technically any system that has AC utility power can be connected for data purposes using PLCC. In practice the system is somewhat limited for applications outside a specific power distribution area since power pole transformers impose communications barriers, and to overcome this requires involvement of the power utility company | Data Rate: Up to about 30 Mbps, typically about 1Kbps Range: Depends on data rate Equipment Cost: unknown Service Cost: unknown | Simplified deployment (RSE installations typically all have AC power) Potentially high data rates | Uncertain feasibility for longer distances Uncertain deployment constraints due to power utility involvement |
3.7 Mapping Support

The term “map” is used very broadly in relation to connected vehicle applications. Connected vehicle maps are digital descriptions of the physical roadway environment in particular and of the transportation system environment in general. Maps in this context can range from road network descriptions that describe how different road segments connect together, all the way down to detailed geometric descriptions of roadway features such as curves, lanes, intersection limit lines, and other “road furniture”. In general maps use some form of geographic reference point (or points) so that a user application, knowing its current position, can orient itself relative to the road features described in the map. Depending on the function of the application, this orientation may be broad, as in “which road am I on,” narrow as in “which lane am I in,” or detailed, as in “where am I in the lane” or “how far am I from the intersection limit line.” Connected vehicle maps generally have little relation to conventional graphical maps simply because the connected vehicle applications relate their function to the relative position of the mobile unit to the roadway features of interest in strictly quantitative ways.

Road network level maps are widely available from commercial sources. These maps are generally used for routing and navigation, because they provide critical information about which road segments connect to which other road segments. They could also be used in a connected vehicle context for various types of roadway alerts and warnings. These maps generally have an accuracy of about 10 meters, since higher levels of accuracy are not really useful for routing, and few general road hazards require high location accuracy.

Vehicle safety warning and control applications generally require lane level or better maps. This enables them to correlate the vehicle path to hazards or movement states (e.g. signal states) associated with specific lanes, limit line locations and other position specific hazards. Depending on the application, these maps may require an accuracy of less than one meter. Nearly all control based applications will require map data at the higher end of the accuracy scale (i.e. finer resolution). Because of the higher level of resolution, these maps are very sensitive to local changes in the roadway, and since the roadway can change significantly at this scale (e.g. lane closures, construction, re-striping, etc.), they are much more difficult to maintain and validate.

Because they are used commercially in many navigation and internet related applications, road network map generation technology is generally highly refined. Higher level detail mapping is not as well established. Generally
these maps require relatively accurate and complete surveys of the region being mapped.

Connected vehicle deployments are likely to require at least two classes of maps. The first are those that are at road level and relatively stable and can be expected to be valid for some time. This class of map can support applications like curve speed warning and be broadcast to a vehicle at a remote location and used by the vehicle some time later when it reaches the curve. The second class of maps is more precise (supporting lane-level and geometry-specific applications) and dynamic (supporting time-dependent features in work zones and reversible lanes). These maps can then support applications that require the higher precision, but they need to be continually validated and cannot be stored indefinitely in a vehicle until use since they are subject to change.

In the simplest instantiation, a map distributed from an RSE would cover the communications area of that RSE. This greatly reduces the problem of building and maintaining the map. However, this greatly reduces the potential benefit of connected vehicle technology since the map would not support remote applications beyond the range of the RSE. If map coverage does extend beyond the RSE, problems of versioning and configuration control become much more significant, as well as priority of different databases that may represent the same spot, but don’t have the inherent authority of being the local source.

3.7.1 Consistency

Consistency of a connected vehicle map has several dimensions: spatial consistency with adjacent and possibly overlapping map regions for the same data (e.g., geometry between two adjacent RSEs); layer consistency among content from different sources, such as a navigation map and a geometric intersection description (GID) for an intersection; and source consistency, if the maps are derived from different master databases (e.g., a TomTom versus a Nokia database). Consistency across sources may be a significant problem since inaccuracies between maps may result in a location specified by latitude and longitude being on one lane (or road!) in one map database and on another lane in a second map.

3.8 SITING AND INSTALLATION

3.8.1 Siting Dependencies for DSRC

DSRC Services operate in a protected frequency band (i.e., 5.850 – 5.925 GHz), which means operators must obtain a license from the FCC in order to legally
operate DSRC-based devices. Typically, a FCC license is issued for a specific frequency range in a specific geographic area. This ensures that the license holder is the only operator allowed to deploy devices in the given area, guarding the system against interference. In the case of the RSE, the operating agency must apply for a DSRC license for their territory and each RSE must also be registered with the FCC such that other operators are aware of their existence.4

RSEs transmitting at the maximum licensed effective radiated power (ERP) have an antenna height limit of eight (8) meters above the roadway. RSE antennas that must be installed at heights greater than eight meters to meet coverage must operate at reduced ERP. RSE antennas cannot in any circumstance be located more than 15 meters above the roadway.5

A wireless spectrum analysis should be performed as part of the communications evaluation to identify relevant wireless communication systems in use in the area. The DSRC spectrum specifically should be evaluated as well as any spectrum intended for wireless backhaul. Specific factors governing the selection of a site and the particulars of the physical installation are:

- The expected applications served, and the traffic flow past the RSE. For example, if it is desired to collect probe data from freeways, then obviously the RSE must be located so that it has good RF coverage of the freeway.

- The environment around the site, especially in relation to the roadways served. For example, hills, buildings, signs, foliage and the roadway geometry all contribute to the overall RF performance. Since DSRC uses high frequency radio waves, these generally work best for line-of-sight communications. It is thus important to locate the RSE so that the messages it sends can be received sufficiently far from any hazards that stopping sight distance requirements of the MUTCD can be maintained.

- The impact of weather and seasonal variations in the local environment. For example, exposure to high snow or ice accumulations may have a very negative impact on RF performance. Heavy vegetation that blocks the line of sight in a particular direction may have a substantial seasonal impact on the range of the system in the affected direction.

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5 FCC regulations from 47 CFR Part 90.377 (10-1-10 Edition).
The antenna pattern selected also has a large impact on system performance.

The availability of power and backhaul communications may impact the site selection.

Physical security to prevent tampering with the equipment.

Traffic density and traffic flow behavior must be considered relative to the primary applications expected to be served by the RSE. In some cases this is obvious; an RSE providing intersection collision warning messages is best located so as to provide a clear line of sight along the approach(es) to the intersection for which it is providing messages. In other cases the location may be non-obvious. For example, many signage messages may be relatively static, so it might be more efficient to distribute these from “regional” RSEs that cover major traffic cross-points, thereby reaching as many vehicles as possible.

One question that frequently arises relative to RSE placement is the issue of overlapping RSE coverage. Overlapping RSEs are generally not an issue in terms of technical performance. The access control schemes used in 802.11 assure that the RSEs will not interfere with each other as long as they are in range of each other (the system uses a scheme where each terminal listens to the channel before sending, and if another terminal is transmitting it waits). Problems may arise if RSEs are located near the limits of the radio range. In these situations each RSE becomes a “hidden terminal” for the other, and since they cannot hear each other they may transmit at the same time. A vehicle located between the two RSEs can hear both of them, and if they transmit at the same time, neither transmission will be intelligible. This may not be a problem if the region of potential interference is not a safety critical area, but the issue must be considered when placing multiple RSEs within about 500 meters of each other.

The other important issue when addressing overlapping RSEs is that they should operate on different service channels. This is not a necessity, since the CSMA scheme will generally assure that the service channel is shared properly. Using separate service channels will however provide substantially more system capacity, may avoid marginal hidden terminal effects, and can avoid the issues of duplicate messages being received by different RSEs.

Appendix A.3 provides substantial additional detail relating to specific issues for RSE siting.
### 3.8.2 Installation

Installation of Connected Vehicle field infrastructure is conceptually no different than installation of other Intelligent Transportation System (ITS) equipment. The same considerations of siting, foundations, mounting points, power, physical accessibility and security, backhaul networks and so forth that have become standardized and accepted in ITS practice will be considerations in connected vehicle infrastructure deployments. Connected vehicle infrastructure models and practices are still in development, however, and will continue to be so until applications have been deployed and operating for several years.

In the interim, guidance for installation of connected vehicle field infrastructure will be based on a combination of experiences.

- Substantial changes in DSRC radio hardware and software have been made over the last few years of development, particularly in anticipation of interoperability testing as part of the Safety Pilot Model Deployment. The equipment manufacturers’ guidance on installation of their equipment will continue to evolve and be the best first information on any new units.

- Siting of DSRC radios and antennas is a new factor to be considered in connected vehicle deployments relative to existing ITS, but is similar to other wireless communications models. Siting considerations are becoming well known and are discussed in the prior section of this document.

- Existing ITS installation practices can be followed for the majority of field infrastructure supporting connected vehicle application deployments. The structural, power, and physical security features are virtually identical between ITS and connected vehicle systems.

- The practice of configuring backhaul networks to support connected vehicle applications is developing rapidly in light of the Safety Pilot Model deployment. This will continue to develop as more diverse connected vehicle applications are deployed into other transportation system networks.

- Practical field experience with connected vehicle system and applications deployment will continue to accumulate as new prototypes and model deployments are brought into the field. The Safety Pilot Model Deployment has significantly scaled up the field deployment of both infrastructure equipment and back office systems.
relative to prior test beds and demonstrations. Lessons learned and best practices from Safety Pilot will be invaluable guides to future deployments.

3.9 **POWER CONSIDERATIONS**

3.9.1 **Power Consumption**

Power consumption calculations should be made to evaluate the demanded load of equipment utilized in the field. Power requirements will depend upon all of the ancillary equipment that may be considered to be installed in a roadside location. While some network switches or cabinet environment (temperature and humidity) control devices may require a few hundred watts of power each, a typical DSRC device consumes relatively low power. The evaluation of the demanded electrical load is needed to determine if existing field circuits could be utilized or if new sources need to be located.

3.9.2 **Power Type Considerations**

The type of power used will depend upon the load calculated and the location of available transformed power from the roadside location. For urban settings or in areas where 240/120 VAC utilization voltage is nearby, it is recommended that a permanent power connection is made to the roadside equipment. If 240/120 VAC is not nearby, transformation from higher (480 VAC) other types of distribution voltage may need to be made through the use of a nearby transformer.

If the roadside equipment is in a rural location and the equipment used consumes a relatively low amount of power, it may be more appropriate to use solar power as a permanent power source. The use of solar power should take into consideration the amount of available sunlight in a given locality for all seasons of use.
4 COSTING ELEMENTS

The deployment of Connected Vehicle field infrastructure is still in its infancy. There are still less than 200 deployed RSEs in the US. The design of RSEs has changed significantly from the original Proof of Concept test in 2007 to the current RSE 3.0 generation that has been deployed for the Safety Pilot Model Deployment, and new designs are being developed. As a result, the current manufacturers of RSEs are producing the devices in limited quantities, not as a mass produced item. Once RSEs are a mass produced commodity, the costs are expected to drop accordingly.

With the changes in the physical design of RSEs, their functional design has changed as well. In the original Proof of Concept testing, the RSEs were considered “thick” clients that had processing power built in to the RSEs to enable them to run applications at the local level. The current Generation 3.0 RSEs are considered thin clients, which have minimal internal processing power and are designed only as a pass through for messages, requiring additional processing power for local applications to be housed in a separate unit. Future designs of RSEs could include internal processing power or could be integrated into other traffic control devices, such as a traffic signal controller.

Finally, the design and architecture of backhaul network and central systems are a function of the applications being implemented, the security system for certificate management and bandwidth to support data transport across the network between the RSEs and central or back office services. As a result, the description of costing is focused more on the components associated with the successful deployment of a connected vehicle system than on specifics of particular applications.

4.1 FIELD INFRASTRUCTURE

The field infrastructure consists of those components that are deployed in the field at an RSE location. The following figure shows the components that are deployed to support SPAT in the City of Detroit at traffic signals where the RSE cannot be located in close proximity to the traffic signal controller. This figure provides one example of how the current Generation 3.0 RSEs are being deployed in the field in 2013.

Planning and design for installation of hardware and backhaul might be expected to cost $3000 to $5000 per site with an additional $500 for each radio frequency (RF) site survey. Construction oversight and integration costs might similarly run between $3000 and $5000 per site for basic deployments.
More complex deployments that require multiple radios or integration with other ITS devices would have higher integration costs.

The deployment in Detroit is fairly typical and costs between $15,000 and $20,000 per site for the RSE and required hardware, including installation and labor costs. Backhaul costs for the Detroit installation cost between $5,000 and $10,000 per site utilizing an unlicensed microwave radio system. These costs for Detroit do not include planning, design, integration, and installation oversight.

Figure 16 - Example RSE Deployment Supporting SPAT Broadcast

At present, the field infrastructure includes (communications devices are listed in the next section):

- **RSE Radio and antenna.** Current generation radios cost between $1500 and $6000 (depending on manufacturer) and typically include the mounting hardware.
- **Intelligent Power Module.** The current generation RSEs require Power over Ethernet (PoE). The Intelligent Power Module converts typical 120 VAC power into PoE to operate the RSE and provides power conditioning to protect the RSE from transient power surges and other

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6 The costs for the Detroit deployment are estimates. Actual bid prices will be available upon successful award in late 2013.
issues that could damage the RSE. Intelligent Power Modules typically cost approximately $750 per site.

- **NEMA Cabinet enclosure.** Most existing RSE deployments have required a separate, small NEMA enclosure, separate from any existing traffic signal controller cabinet to house connected vehicle equipment if there is not sufficient room in the existing cabinet. These small NEMA enclosures typically cost between $500 and $750 per site.

- **Cabling and mounting hardware.** Cabling is a function of the specific design of the RSE site as costs for cabling are typically paid by the foot. Likewise, mounting of the RSEs is determined by the specific design at the site to maximize antenna range. If the RSE can be mounted on an existing pole or mast arm, the costs are minimal—$50 to $250 per site. For the Proof of Concept test, short mast arms were added to existing traffic signal poles and cost were slightly more—$250 to $500 per site. If existing poles are not available on which to mount an RSE and antenna, new poles and foundations must be deployed. New poles and foundations can cost from $5000 to $25000 or more, depending on specific requirements at the local jurisdiction.

- **External processing.** As mentioned previously, the current generation of RSEs does not have sufficient processing power to run applications, even those as simple as converting NTCIP traffic signal controller information into an SAE J2735 format. As a result, an external processor is required if the applications being deployed require processing at the roadside. For the Safety Pilot Model deployment, the U.S. DOT supplied an environmentally-hardened Windows-based “black box” embedded computer for this purpose. For the deployment in California, PATH is developing a similar Linux device. These embedded computer systems are commercially available and cost approximately $1000 per device, not including the software application development or licensing.

- **Local communications.** Ethernet is limited without repeaters to a length of 100 meters. This becomes an issue if the antennas and RSE need to be mounted more than 100 meters from the source of the Ethernet traffic. For example, at a signalized intersection where the

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7 An embedded computer system is a PC designed for use in rugged environments, such as a traffic signal controller cabinet. For the FHWA SPAT program, a system using an Intel Atom N450 1.6 GHz processor with Ethernet ports and flash memory was used. Systems with similar specifications have been identified for use in California and Detroit.
controller cabinet is in a different intersection quadrant than where the radio is to be mounted. This typically requires local communications to transmit messages between the controller cabinet and the RSE using a media with longer range limits, such as fiber optics. The deployment designed for Detroit utilizes media converters to convert the range limited electrical Ethernet signal to “light” which has an extended range for this purpose at a cost of approximately $2000 per site. This cost included the fiber optic modems (media converters) and multimode cable pulled through existing conduit at a traffic signal between the traffic signal controller and the DSRC radio.

4.2 Backhaul Communications

The costs for communications between the field site (RSE) and the central system are a function of the existing communications systems in place within a jurisdiction. Each RSE has a maximum capacity of 6 megabits/second over the air. While it is not anticipated that a continuous 6 megabits/second of bandwidth will be required to be sent back to a central point, all current installations (Michigan Test Bed, Safety Pilot Model deployment, California) are designed to transmit all data received at the RSE back to a central point. For the Safety Pilot Model Deployment, this has resulted in daily data rate in excess of 500 GB per day being transmitted between the RSEs and central computer. For installations where there is an existing communications system with sufficient spare capacity to add additional devices and data, the costs to add RSEs the backhaul system are minimal and would likely only include minor hardware upgrades to attach the new devices.

For installations where there is not an existing communications system or where there is insufficient capacity to add new devices, the costs for communications backhaul infrastructure can be significant. There are three basic backhaul communications options: dedicated wireless, fiber optic line and leased line (as discussed in Section 3.6.5). Costs are dependent on the specific architecture and design at the local agency. For example, the City of Detroit installation is using unlicensed 5.8 GHz radio for local communications at a cost of approximately $3000 per site and all data is brought together at a single point and is transmitted to a TMC over either a fiber optic connection or higher bandwidth 5.8 GHz link.

4.3 Information Services and Software

Information services are the systems deployed at the back offices of the network for data processing, archiving and redistribution. Most DOTs with
an existing ITS deployment have some level of central information services, typically in a TMC. These systems, however, are designed for limited data from detection systems and for distributing video messages. The connected vehicle system can generate significant quantities of data that these ITS back-end information systems will likely not be capable of supporting.

Back end information services will need to be designed and implemented based on both the applications being implemented and on future architectural improvements to shift data processing towards the field, reducing the data storage and processing requirements in the back end.

Additionally, back end system design will be dependent on data storage and retention requirements associated with the local or state agency. If a typical seven-year data archival requirement is levied on connected vehicle data, storage systems that are capable of storing petabytes or more of data, including the data center requirements to house this type of equipment (power, cooling, etc.), will need to be implemented.

As a result, it is premature to develop cost estimates for the overall information systems deployment. Given the current implementations, the costs for a small installation could extend into the millions of dollars for a new TMC-type back office deployment.

An example system for data collection and warehousing was proposed for the Chicago metropolitan area in 2009. The initial costs to develop and deploy this regional data archiving system software were between $750,000 and $1,050,000 in 2008 dollars. The data volumes from a connected vehicle deployment and the complexity of operations would likely be significantly higher.

4.4 Communications Security

Connected vehicle system security has two elements: anonymous security for vehicles, and identified security for vehicles and roadside systems. The security credentials are defined in the IEEE 1609.2 standard. These credentials are similar to existing certificate-based credentials (known as X.509 certificates) used for secure digital transactions, but are tailored to DSRC wireless applications.

Supporting this security system will require the establishment and operation of a set of “Certificate Authorities”. These may be publicly funded and

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managed, or they may be private (today most X.509 certificate authorities are private). It is important to note that the certificate authority for identified certificates, which apply to vehicles for identified transactions such as payments and to identified terminals such as roadside equipment, are much simpler than the anonymous security support system. This is because the scale of the system is smaller (fewer certificates) and the issues associated with providing assurance and trust are much simpler when that trust can be based on identity.

The overall business model for the operations and management of the Certificate Authority for connected vehicles is still a work in progress. While it is not anticipated that the costs for obtaining security credentials for a roadside installation will be significant, there will likely still be a cost per roadside device to maintain the validity of the security system on those devices. The cost to develop, deploy, operate and maintain the overall Certificate Authority, however, is likely to be borne by a combination of the Federal Government through the USDOT and private enterprise and not AASHTO members.

However, the ability to capture secure roadway data from vehicles will rely on the anonymous security system. It is unclear how the business arrangements for this anonymous security apparatus will be managed. It is possible that the costs may be borne entirely by the vehicle manufacturers and passed on to the vehicle buyers. It is also possible that some portion of this cost may be recovered in the form of a data collection fee, or a system participation fee that could be levied against all system participants. The development of value chains and associated business models are still gaps in creating a realistic and sustainable system. The issue of data ownership, value exchange, and the motivation for vehicle manufacturers and vehicle users to provide data to roadside systems are also unresolved. Once these aspects have been addressed, it is expected that some scheme for distributing costs for these underlying support systems (e.g. security management) will be developed.

4.5 INSTALLATION, OPERATIONS AND MAINTENANCE

The installation, operations and maintenance costs for connected vehicle field infrastructure are anticipated to be consistent with the costs for operations and maintenance for traditional ITS components. An ITS installation typically costs approximately 1-2% of the installation cost per year for power and other basic operations. Routine maintenance for traditional ITS components costs
between 2% and 5% of the installation cost per year. Routine maintenance would include troubleshooting and diagnostics for a malfunctioning device, replacement of a device due to catastrophic events and regular cleaning and other related activities. Like other ITS devices, agencies will need to budget for the regular replacement of CV field infrastructure devices. There is not sufficient data available to determine the mean time between failures (MTBF) for an RSE, but like other IT components, they should be expected to last between 7 and 10 years before needing to be replaced. Finally, agencies will need to budget for updates to the RSEs based on emerging standards and changes required to permit applications to operate. While the costs for these upgrades are expected to be minimal as they should be able to be done remotely and not require a field visit, they must be done. Additionally, the field infrastructure must be maintained in an operational condition, especially for those locations that rely on field deployments to support V2I safety applications. RSE vendors on the US DOT Research Qualified Products List (QPL) are currently charging an annual cost for upgrades/maintenance to their RSEs, either per unit or per agency/organization. It is anticipated that these costs will continue and will help agencies ensure that they have the latest firmware available for their RSEs.

Staffing costs for operations of central connected vehicle systems must also be included. The previously referenced system for Chicago, for example, was assumed to require 1.5 full-time equivalent employees for day-to-day operations. These staff members can either be through direct labor or contracted out. The operations requirements in terms of FTEs for a connected vehicle deployment will depend on the applications being run and the ability of existing operations staff to monitor the newly deployed systems.

Agencies will also need to budget for backhaul communications costs. Backhaul costs for a dedicated connected vehicle communications system will be consistent with the O&M costs for an RSE – 1-2% per year for power and 2-5% per year for routine maintenance activities. If leased lines are used, those costs will need to be included as well. A 4G or LTE wireless service typically

9 Wyoming Department of Transportation Statewide TMC Weather Integration Plan, Wyoming Department of Transportation, December 15, 2010, Weather integration into TMC estimated at $6,270,000 with $833,000 in annual O&M Costs.

10 Cost data for Operations and Maintenance derived from a combination of the FHWA ITS Cost database and the 2011 Update to the Intelligent Transportation Systems Benefits, Costs, Deployment and Lessons Learned Desk Reference.
costs between $70 and $100 per site per month for an unlimited data plan\textsuperscript{11}. O&M costs for a shared backhaul system should not have a significant cost increase for O&M over costs that are already being borne for O&M unless a significant upgrade is required to increase bandwidth available.

There will be O&M costs for back end infrastructure, servers and storage. These costs, like those for the capital procurement of the back end systems discussed earlier in this report, are dependent on many variables, including the applications being run, data storage and retention requirements and current DOT arrangements with IT service providers who all have different costs for the operations and maintenance of data center hardware and services.

If an agency hosts and processes the raw data from connected vehicle applications, and purchases software from an outside vendor, there will likely be ongoing costs for software licenses and maintenance, similar to those paid for applications such as Microsoft Outlook or for Advanced Traffic Management Systems. These licenses cover the costs of ongoing maintenance and upgrades/updates, bug fixes and license costs for other software that is used in the prime software system. Software developed by the agency will also have ongoing costs for maintenance and upgrades.

4.6 Alternative Delivery Mechanisms

There are a number of probe data applications that have been identified that do not require additional field hardware. Rather these applications utilize data from smart phones to provide information regarding traffic speeds and travel times. The current business model for these smart phone based probe data systems is a “partnership” between the customer and the service provider. For example, when using Google Maps—a “free” application for directions on a smart phone—the user is providing real-time data to Google that is used to populate the traffic data within Google Maps. The cost for the data between the customer and Google is born by the customer—the owner of the cell, or smart, phone. Likewise a number of road roughness and pothole identification applications have been developed, including one in Michigan\textsuperscript{12} and one in Sweden\textsuperscript{13}, that used data from the accelerometer in a

\textsuperscript{11} \url{http://www.itscosts.its.dot.gov/its/benecost.nsf/Images/Reports/$File/CostElements%202010-10-30.pdf} The cost per month in the referenced table ranges between $100 and $150, however the data is from 2002 and cellular plans have changed significantly in that time.

smart phone to collect data on ride quality that was then sent to the DOT for processing and analysis. The cost of the data transmission for these systems was wholly the responsibility of the owner of the smart phone and not the DOT.

There is also the potential for a DOT to purchase data/information from a third party provider, as do the I-95 Corridor Coalition and the Michigan Department of Transportation, amongst others. The data, which typically consists of speeds and travel times along various links in the network, is gathered by a third party, processed and checked for errors and then delivered in near-real-time to the agency for use in a variety of applications, including incident detection and traveler information web sites.

13 Roadroid – Smartphone Road Quality Monitoring, Lars Forslöf, Inventor/CEO Roadroid AB, Sweden, Egnahemsgatan 5, 82735 Ljusdal, 
APPENDIX A. FURTHER TECHNICAL NOTES

A.1 ARCHITECTURE DETAILS

The connected vehicle system involves a wide variety of terms. These terms have evolved over the past 15 years or so, and in some cases the meanings of terms are somewhat ambiguous. For purposes of this report, we are proposing the following terminology:

- **Mobile Element**: This is the connected vehicle element that is equipment that is not fixed, that is it is part of a vehicle or a portable device. When the equipment is part of a vehicle it is generally referred to as On Board Equipment (OBE). The Mobile Station includes communications, data processing and data storage used to interact with other Mobile Stations and with the RSEs and the Transportation Information System (TIS) via the system communications link(s) (WLAN/DSRC and WWAN/Cellular/LTE). The Mobile Station supports the mobile user and, if it is an OBE, the vehicle system, both of which can be considered “users” of the system.

- **Field Element**: A stationary (temporary or permanent) platform that includes communications, data processing and data storage used to interact with Mobile stations (OBEs) over a short range communications link. When using DSRC the field element is typically called Roadside Equipment (RSE). The Field Element may also be connected to the Transportation Information Infrastructure. The field element of the system supports both Transportation Information Users (when passed through a center element) and Transportation Field Equipment, both of which are system users that are outside the system boundary.

- **Center Element**: The center element is the back office of the connected vehicle architecture. It is a distributed “cloud” that can collect information from the roadway, either directly from Mobile Stations or from Mobile Stations via Field Elements, or from other fixed transportation infrastructure such as signal controllers (the “Field” in the Core System Architecture). The Center Element generally supports Transportation Information users, who are outside the system boundary. In many instances, the Transportation Information users will be service providers, data aggregators or Traffic Management Centers (TMCs) and/or their personnel.

- **Transportation Field Equipment (TFE)**: Equipment that is associated with the roadway and is used to manage or control traffic. TFE is
typically located along the roadway. Examples include traffic signal controllers, access gates, etc. These are not part of the connected vehicle system, though they may be associated with a connected vehicle Field Element.

- **Cloud:** Refers to information that is stored in such a way as to be generally available via an internet connection with proper access. The physical storage medium may or may not be controlled by the owner of the data, and the access may or may not be controlled by passwords, VPNs, firewalls or other well understood techniques.

Each of the main elements of the system—the Center, Field and Mobile Elements—are able to exchange data with “co-located” or “proximate” users and/or equipment over a data interface. For example, a Field Element may have an interface to a local signal controller. The Mobile Element may have an interface to vehicle systems, and/or to vehicle users. The Center Element may have an interface to information users, such as third party data user or road authorities, as well as an interface to transportation field equipment (such as traffic signal controllers). Each of these elements may also be connected to the others via one or more communications links. For example, the Center Element(s) may be connected to the Mobile Elements over a wide area wireless communications link (for example a cellular implementation), and to the Field Elements through a backhaul communications link. The Mobile Elements may also communicate with Field Elements directly, and they may communicate with the Center Elements via the Field Elements. (In a conventional DSRC implementation the Field Element would be a DSRC RSE.) While a given implementation may not include all of these links, it must include enough links to enable each of the elements to communicate with the others, even if infrequently.

Each of the elements is capable of processing data either received by the communications link, or received locally over the data interface from their associated system (Vehicle System or Vehicle User, Transportation Field Equipment and Transportation Information User). The scope of processing may range from very limited (for example, a Field Element (RSE) that generates and sends a “canned” message), to a full-featured warning (e.g., a Mobile Station (OBE) that generates a message that the Vehicle System uses to issue a warning to the driver). These functions are included in a slightly more detailed system diagram provided below.
There generally will be very many Mobile Elements (e.g. OBEs), many Field Elements (e.g., RSEs), and a few (or one) Center Elements (e.g., TMCs or Service Providers) for a given region.

This architecture is very general, so it is useful to examine some concrete examples. Figure 18 below shows an implementation designed to collect probe data from Mobile Elements in vehicles using a wide area wireless (e.g. cellular) communications link and to distribute this data, with some level of post-processing to transportation information users.

Figure 19 shows this same application implemented using Field Elements (RSEs) and localized wireless communications (e.g., DSRC) to collect the
probe data. The Field Elements then forward the data to the Center Element which then processes it and makes it available to transportation information users.

The operation of these two implementations is described in Table 3 below. This table also provides an overview of key differences between these implementations.

Figure 20 below shows an implementation designed to collect signal phase and timing data from transportation field equipment (e.g., traffic signal controllers), and to distribute it, with some level of post processing, to mobile stations (e.g., vehicles) using a wide area (e.g., cellular) communications system, and Figure 21 shows the same application using DSRC RSEs. It is interesting to note that these two implementations are more or less mutually exclusive. The wide area implementation makes no use of RSEs and the RSE implementation makes no use of the Center Element (TMC). The operation of these two implementations is described in Table 4 below. This table also provides an overview of key differences between these implementations.
Figure 18 - Probe Data Collection Using Wide Area Communications

Figure 19 - Probe Data Collection Using RSEs
### Table 3 - Cellular and DSRC-based Probe Data Collection Systems Comparison

<table>
<thead>
<tr>
<th>Application</th>
<th>Comm. Technology</th>
<th>Operation</th>
<th>Differences Between Cellular and DSRC Implementations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe Data</td>
<td>Cellular</td>
<td>Vehicle collects and stores data as it travels along roadway. When a specific volume of data, or data for a specific distance has been collected, vehicle system sends data to infrastructure server (which may be public or private); Infrastructure server collects and stores data from numerous vehicles and makes data available to fixed infrastructure users in various forms.</td>
<td>Cellular systems can collect data over a large area because each cell is large (compared to the range of an RSE) and communication with vehicles is continuous from cell to cell. Cellular services are deployed by commercial providers to whom the senders’ identities are known but can be protected from exposure outside that service provision. Messages themselves may contain identifying information. Data collected over a wide area from many vehicles can be anonymized and processed into an abstract data service by the service provider or third parties. Depending on the reporting interval, data can be very timely.</td>
</tr>
<tr>
<td></td>
<td>DSRC</td>
<td>Vehicle collects and stores data as it travels along roadway and sends data when it encounters an RSE. RSE may either aggregate data from multiple vehicles and send it over backhaul to a server located at a Center Element (e.g., TMC), or it may simply forward the data to the server as it is received. The Center Element collects and stores data from numerous vehicles and makes data available to fixed infrastructure users in various forms.</td>
<td>DSRC systems can only communicate with vehicles where RSEs are located, and this means for probe data purposes that either they are sparse, or it requires a high density of RSEs. If sparse, then the data may not be timely, and the vehicle will need to store more data for deferred transmission. If dense, then deployment costs will be higher. RSEs are likely to be deployed by local and regional agencies, but could be deployed as a service by third parties. DSRC itself is designed to protect the privacy of communications, but messages may contain identifying information. Data collected over a wide area from many RSEs can be anonymized and processed into an abstract data service by the agencies, service provider or third parties. Timeliness of the data depends on the density of RSE deployment.</td>
</tr>
</tbody>
</table>
Figure 20 - SPAT Data Distribution Using Wide Area Communications

Figure 21 - SPAT Data Distribution Using RAPs
Table 4 - Cellular and DSRC SPAT Application Comparison

<table>
<thead>
<tr>
<th>Application</th>
<th>Comm. Technology</th>
<th>Operation</th>
<th>Differences Between Cellular and DSRC Implementations</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPAT (CICAS)</td>
<td>Cellular</td>
<td>Signal controllers provide real time SPAT data to the Center Element. The Mobile Element in a vehicle periodically requests roadway information for current and nearby road segments to a Center Element server. Server notes location and current IP address of vehicle, and sends data file with roadway hazard information (including SPAT data for nearby intersections) for specific bounded region. If SPAT (or other data) changes in that region during specified time interval server sends updated data to vehicle. Vehicle uses SPAT and other data as appropriate based on its location and direction of travel.</td>
<td>The Center Element server may need to support a large volume of requests. Updates must be provided on a user-by-user basis with sufficient timeliness relative to signal timing changes that vehicles and drivers can respond appropriately. If the Center Element server is publicly operated, then there may be privacy considerations that will need to be addressed since the vehicles will be sending their location as part of the request. Note that this system can also support other types of warnings and alerts with little change to the basic server system and modest changes to the messages.</td>
</tr>
<tr>
<td>DSRC</td>
<td>DSRC</td>
<td>Signal controller provides SPAT data to RSE located at or on approach to intersection. RSE periodically broadcasts SPAT data over DSRC channel. OBES in vicinity of RSE receive SPAT data and use it as appropriate based on their location and direction of travel.</td>
<td>Single message from RSE can be used by many vehicles, but RSE must send out messages regularly whether user vehicles are in the area or not. Messages need to be repeated often enough to enable vehicles in region between signal timing change and dilemma zone to receive changed signal timing data before they reach dilemma zone.</td>
</tr>
</tbody>
</table>
The tables above illustrate that the system can be implemented in a variety of ways. The technology choices may affect the specific details of the applications, but the basic architecture is not dependent on the choice of, in this case, communications technology. It is also possible to implement the system using, for example, both cellular and DSRC communications.

An important observation is that this architecture is somewhat independent of the locations of the transportation field equipment (e.g., traffic signal controllers) and the connected vehicle Field Elements (e.g., RSEs). Every RSE can support all applications, although certain applications may be more appropriate for a given RSE due to physical proximity. It is important to note, however, that the only factors binding an RSE to a specific location are:

1. To assure that data for a roadway segment is delivered to the OBEs in vehicles that will travel over that road segment. For example, one would deliver SPAT data or curve speed warning data at locations where the passing vehicles are likely to then travel over the road segment in question (as opposed to taking a different route).

2. If there is a requirement for a timely relationship between the data provided and the receipt of the data. If the time between when the data is received and when it will be relevant must be small, then the RSE must be located close to the location where the data is relevant.

Just as each OBE is connected to a vehicle network which may or may not have certain data elements, each RSE is a part of a larger infrastructure network connecting traffic signals, TMCs, weather stations and tolling stations. Not all RSEs have access to all of this data in real-time, but this is a deployment limitation rather than a system limitation.

One implication of this architecture model is that there is no system level association between a particular RSE and, for example, a traffic signal. Often in this document the two are associated since the controller cabinet is a handy place to put the communications equipment, but from an architectural perspective it is equally possible to have four RSEs midblock rather than one at the traffic signal. This is a deployment trade-off between cost and the certainty of coverage at specific locations. Within this document we have divided our deployments by roadway characteristics because this is the way deployments are often approached within the transportation community. This classification also tends to reflect equipment that can be already found in these locations, hence simplifying the deployment, but it is not a function of the connected vehicle system architecture.
At the initial phase of deployment there should be no limitation of bandwidth between RSEs and OBEs. If bandwidth becomes a problem, additional RSEs can be installed to offload some of the data (so long as their ranges do not overlap). Since all connected RSEs are within the same network, each additional RSE can share bandwidth as appropriate. Applications such as “spot safety” can be implemented by a single RSE located at the spot, which assures all approaching vehicles have the required information. They can equally well be implemented by remote RSEs, although this implies some probability that vehicles approaching the spot may not have appropriate information. There is a design trade-off between distance from a location of interest and likelihood the vehicle has the appropriate information, but this is not an architecture trade-off.
A.2 IPv6

Whereas fixed network terminals like a PC in an office LAN can be assigned persistent network addresses, mobile stations are constantly moving from one network location to another. To solve this problem, the mobile terminal in an IPv6 network creates a temporary address by appending its MAC address to the IP Prefix of the fixed routing terminal’s IP address. This is known as “stateless address auto-configuration”. For example, if the routing terminal prefix is 2001:0DB8:AC10:FE01, then the IP address of a mobile terminal with MAC address 1234:5678:1234:5678 would be 2001:0DB8:AC10:FE01:1234:5678:1234:5678 (i.e. prefix plus MAC address). This approach is very fast and very scalable since it does not require any form of request/response process on the part of the routing terminal or the access point. All it requires is a periodic broadcast from the access point so the mobile terminal can learn the IP address of the access point. This process is illustrated in Figure 22 below.

Once a mobile terminal has sent an IP packet to a remote server using this addressing scheme, the remote server then sends packets back to the fixed router terminal, which then simply broadcasts the packet. If the mobile terminal is still in the RF footprint, then it will receive the packet and pass it to the appropriate user application. If the mobile terminal is no longer in the access point footprint, it will fail to acknowledge receipt of the packet and eventually the sending server will give up.
In general, the DSRC/WAVE standards do not describe or support the use of IP between mobile terminals.

While IPv6 provides this useful stateless auto-configuration function, it creates other problems. In general, IPv6 is not widely used. The extension from IPv4 was originally intended to expand the IP address range because the industry was expecting a proliferation of devices, and they assumed that these devices would have fixed IP addresses. While this proliferation has occurred, most of these devices operate within sub-networks using systems like DHCP. As a result there is not a strong need for device-specific IP addresses, and today support for IPv6 in routing and communications equipment is inconsistent. This inconsistency raises significant compatibility issues if the IPv6 network is extended past the RSE into the backhaul. Many trial system implementations (e.g. Michigan Test Bed, Safety Pilot) have encountered issues arising from the fact that backhaul networks cannot support IPv6 traffic. To overcome this, various “tunneling” protocols are used, but these are somewhat difficult to set-up, and often produce unreliable communications. It is not clear how the industry will respond to this issue, but one possibility is to implement a proxy function within the RSE that effectively serves to bridge this disconnect between the DSRC air link, which benefits from IPv6, and the backhaul, which doesn’t. Another might be to
eliminate the use of IPv6 between the RSE and the mobile terminals and implement some other form of localized packet routing/addressing scheme.
A.3 RSE Siting

A.3.1 Multipath Effects

Using single antennas (i.e. non-diversity) multipath effects result in substantial signal fading at around 200-300 meters range. This is caused by the direct signal being cancelled by a reflected signal that is 180 degrees out of phase. The actual range of fading depends on the relative height of the transmitting and receiving antennas. The basic “two ray” multipath mechanism is illustrated in Figure 23 below. At any given range between the two communicating terminals there is a point where the transmitted signal reflects off the roadway and the reflected signal then arrives at the receiver together with the direct signal. Depending on the path length of this reflected ray, it may or may not cancel out the ray that propagated directly from the transmitting antenna to the receiving antenna.

![Figure 23 - Two Ray Multipath Model Geometry](image)

This effect is heavily dependent on the relative height of the two terminals. Figure 24 illustrates a typical analytically derived multipath behavior with a transmitter height of 5 meters and a receiver height of 1.5 meters.
Multipath can be mitigated by using two antennas (called “diversity”), but this can be physically complicated in a vehicle, since the antennas must be separated by some distance, and this is difficult to do within the vehicle styling constraints.

In addition increasing the height of the RSE antenna can improve range performance. This is due in part to changes in the multipath nulls that result from the increased height, and in part from generally lower incidence of blocking foliage, other vehicles, etc. On the other hand, the FCC limits the height of the RSE antenna to about 25 feet.

### A.3.2 Hidden Terminal Effects

A critically important element of RSE siting and configuration is to avoid hidden terminal effects as much as possible.

DSRC uses a scheme called Carrier Sense Multiple Access (CSMA) to determine which terminal is able to transmit when. While this approach is effective in enabling a large number of users to share an RF channel, it is not perfect. CSMA requires that each terminal desiring to transmit to first listen to the channel. If another terminal is transmitting (as determined by detecting RF energy in the channel) the terminal in question must wait a period of time and then listen again. This scheme effectively interleaves terminal transmissions on a given channel by spacing them out over time. However, it depends on all terminals being able to hear all other terminals (so they can
determine if any of them are transmitting). Figure 25 below illustrates a typical hidden terminal situation.

![Hidden Node Situation Diagram](image)

**Figure 25 - Hidden Node Situation (OBEs Approaching RSE)**

In this figure, OBEs A and B can hear the RSE. However, neither can hear the other. According to CSMA rules, each will listen to the channel, and, if the RSE is not transmitting, each will hear no channel activity, so they will send their messages. The RSE will hear both messages at the same time and will be unable to separate them, such that the transmissions will fail. Only when the OBEs are within the region identified as the “Safe Range of RSE” will they be able to hear each other. As a result, the range of the RSE should be limited to this range (ideally by a geographic boundary as described above). By doing this, the OBEs will not try to send messages to the RSE until they are also able to hear each other, and so the CSMA system will prevent the two OBEs from transmitting at the same time.

The complimentary situation can occur with two RSEs and a single OBE as shown in Figure 26 below. Here the RSEs cannot hear each other, and so they may send their messages at the same time. In the zone between the RSEs where an OBE can hear both RSEs, these overlapping messages will also fail. This situation may not be particularly problematic, since the OBE approaching any one of the RSEs will eventually be out of range of the other RSE, and thus messages from that RSE will be received without interference. To avoid this situation the RF power of the RSEs in this situation may either be limited so that there is a sufficient clear zone for the approaching OBE to interact with the RSE without interference, or the power levels should be high enough that the RSEs can hear each other, and the CSMA scheme will prevent...
them from transmitting at the same time. These two schemes are both illustrated in the figure.

![Diagram of Hidden Node Situation (OBE between RSEs)](image)

**Figure 26 - Hidden Node Situation (OBE between RSEs)**
A.4  **Cellular Implementation Description**

There has been a great deal of discussion about the use of other communications technologies for connected vehicles in addition to, or as an alternative to DSRC. While there are a variety of possible implementations of the connected vehicle system using cellular communications, they are all based on the same key characteristics of cellular systems. This section outlines those characteristics, and provides descriptions of how the system could be configured to provide the intended connected vehicle system services. As described in Section 3.1, a connected vehicle system is, in general, a means for:

- Communicating messages between mobile stations (e.g. vehicles);
- Communicating messages between field elements and mobile stations, and;
- Communicating messages between center elements and mobile stations either directly or via the field elements.

The discussion of connected vehicle applications using cellular communications is therefore built around implementations of these interactions rather than detailing specific applications.

A.4.1  **Cellular Network Technology and Performance Overview**

Cellular systems are widely available and, driven by various consumer devices (smartphones, tablet computers, etc.), the cellular industry has been substantially expanding cellular capacity and coverage.

The most recent advancement in cellular technology is known as Long Term Evolution (LTE). The system uses an Orthogonal Frequency Division Multiplexing (OFDM) downlink (Network to mobile, and a Single Carrier – Frequency Division Multiple Access (SC-FDMA) uplink. These links may employ a variety of high order modulation schemes to achieve very high data rates. The high data rates offered by LTE are based in part on a technology known as Multiple Input Multiple Output (MIMO). This approach effectively creates multiple parallel radio links, so the overall rate of the combined set of links is higher than any single link. The approach, however, requires significant processing to adapt the system to the current radio propagation characteristics. Since these are dependent on the physical environment, the technique does not work as effectively when the user is moving. For this reason, the highest achievable LTE data rate for moving users is only about 30% of the best stationary data rate. Theoretically, the best mobile data rate is 100 Mbps, but in practice this is typically substantially lower. Still, LTE is a
rapidly evolving technology that is specifically intended to provide high data rates to mobile users. Table 5 below summarizes the various network metrics for cellular systems. We have assumed that these systems are operating in a moving environment since they are always inside the cellular footprint (so there is no concern about leaving the footprint before a single transaction is completed. This assumption is not strictly valid across the entire geographic United States. Some rural areas may have limited coverage and so within these areas the system may provide inconsistent benefits. On the other hand, in these areas the user population is relatively limited, so the overall impact is expected to be small, certainly no larger than the impact of limited DSRC RSE deployment.

Table 5 - Cellular Network Metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Channel Data Rate</td>
<td>LTE supports a mobile data rate of 100 Mbps under ideal situations. Practical data rates appear to be about 7.3 Mbps.</td>
</tr>
<tr>
<td>Radio Footprint</td>
<td>LTE cells are generally about 2.2 Km in radius. It is unlikely that the terminal will leave cellular coverage before a transaction is complete.</td>
</tr>
<tr>
<td>User Demand</td>
<td>Because of the large cell radius, the maximum number of user vehicles within a cell is expected to range from 2,100 to 5,200.</td>
</tr>
<tr>
<td>User Capacity</td>
<td>LTE is designed to support 800 simultaneous active (sending and receiving data) users per cell sector. The system can support an essentially unlimited number of inactive users (assigned an IP address, but not sending or receiving data). There are generally three sectors within a cell, so LTE can theoretically support 2,400 active users within the 2.2 Km radius region of the cell (note this barely supports the maximum number of vehicles that can fit in the cell, but easily supports the likely number of active user vehicles within the cell (max 520, assuming 10% are active)</td>
</tr>
</tbody>
</table>
| User Data Rate          | Peak theoretical mobile data rate: 100 Mbps  
                          | Peak practical mobile data rate: 7 Mbps.  
                          | Typical LTE user data rate at max user capacity: 384 Kbps. |
| Network Attach Time     | 50 msec for new user (no IP address)  
                          | 5 msec for inactive user (time to transition from inactive to active)                                                                                 |

(References: LTE Networks: how far are the achievable capacities from the theoretical ones?  
ICUMT 2012, October 3-5, Sankt Petersburg, Russia; How to calculate peak data rate in LTE? - Hongyan -  
Expert Opinion - LTE University; LTE Advanced: Evolution of LTE | LteWorld)

Cellular coverage is generally available in all urban and suburban areas and across substantial portions of interurban corridors. Figure 27 depicts areas of the continental United States currently without 3G cellular coverage. Most urban areas and a large portion of the rural regions east of the Rocky Mountains have coverage, but there are also large regions without complete coverage, and random dead spots are not unusual. In addition, in areas with limited coverage, the range to the cell tower may be significant, and, this will significantly reduce the achievable data rates. In general the rapid growth of
LTE (4G) implies that it is reasonable to assume that this same level of coverage will prevail for LTE over the next decade.

![Cellular Non-coverage Map](Ref: FCC. For additional information, visit http://wireless.fcc.gov/auctions/901/)

The figure indicates that rural areas away from major urban centers may not have adequate network coverage. In general, these areas may have sparse populations and low-volume roadways.

LTE footprint size and capacity varies by installation. A typical value for cellular site range is 2.2 miles (3.5 km). Because of overlap and signal interference considerations, the area of the site, using an omnidirectional antenna is 12.3 mi² (31.86 km²). As a point of comparison, the Los Angeles metro region covers about 4,825 mi² (12,500 km²) and includes approximately 7 million cars and trucks (19,350 vehicles per square mile).

Using these figures the Los Angeles Metro region should have about 400 cell sites (per carrier). Based on private correspondence with Technocom, this number is closer to 1000 sites due to the population density. This results in a typical cell area of 4.8 mi² (12.5 km²), and a range of 1.4 mi (2.3 km).

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16 Los Angeles Almanac Website: [http://www.laalmanac.com/transport/tr02.htm](http://www.laalmanac.com/transport/tr02.htm).
The vehicle user density per site thus ranges between about 7,000 vehicles per site to about 17.5 K vehicles per site, with an average estimate of potential vehicle density of 12,250 per site. It is important to note that not all of these vehicles will be operational at the same time (see Data Load Concerns, below).

LTE is designed to support up to 800 active voice-over-IP (VoIP) users in any sector using 20 MHz channels (Note that at 384 Kbps per VoIP user this value is consistent with a total system bandwidth of about 300 Mbps). Thus, LTE can serve between 15% and 38% of the vehicles in an omnidirectional cell sector (i.e., multiple sub-sectors) at about 384 Kbps each.

The maximum theoretical data rate is currently about 325 Mbps using 4x4 MIMO and the highest order modulations. As described above, however, since MIMO is not feasible under highly dynamic (moving) situations, the maximum theoretical data rate for mobile terminals (moving at up to 217 mph [350 km/h]) is limited to 100 Mbps.

From a practical perspective, however, when channel interference and overhead effects are included, the maximum data rates drop significantly. One reference reports a practical sector data capacity of 23.7 Mbps in a channel that is advertised to support 325 Mbps. Based on the 325/100 data rate reduction when moving, a moving LTE terminal is likely to see a practical data rate of about 7.3 Mbps.

Given that LTE will need to serve many users (not just connected vehicles), 384 Kbps is probably a realistic average data rate, and in certain conditions, for brief periods, a connected vehicle terminal may see data rates up to about 7 Mbps (i.e. The entire practical sector data rate).

**A.4.2 Cellular/LTE System Characteristics**

The Cellular/LTE system is significantly different from DSRC. In the current cellular system, mobile cellular terminals (e.g. handsets) establish a connection with a cell site (typically the closest, and/or the one with the strongest signal). This connection includes a subnet IP address so that the cell site can route IP packets to and from the mobile terminal. The mobile

17 International Congress on Ultra Modern Telecommunications and Control Systems Workshops (ICUMT) 2012 (Conference). “LTE Networks: How Far are the Achievable Capacities from the Theoretical Ones?”

18 International Congress on Ultra Modern Telecommunications and Control Systems Workshops (ICUMT) 2012 (Conference). “LTE Networks: How Far are the Achievable Capacities from the Theoretical Ones?”

terminal can thus establish a phone call by sending VoIP packets to the phone network via the cell site, or it can send server requests to remote service providers over the Internet, by way of the cell site. It is important to note that while the cellular/LTE carrier maintains a directory of which mobile terminals are in which cell; this information is not publicly available. As a result, currently, the system can route incoming VoIP calls and SMS messages to the mobile terminal, but there is no equivalent mechanism for remote parties to send unrequested general data packets to the mobile terminal since, like the Internet, the server doesn’t generally know the IP address of the mobile terminal (and this address may change dynamically). The server can thus only pass packets back to the client if the client has made a request, and thereby established an address chain that can be used to route responses back to the client.

This characteristic has significant implications of the connected vehicle environment, since it requires that the mobile terminal actively request information as opposed to passively receiving it by virtue of being within radio range of an RSE. Since the mobile terminal doesn’t know if any given section of road includes potential hazards, it must regularly request this data, and most requests will typically result in a “no data” response. However, while somewhat inefficient, the requests and “no-data” responses are expected to be small (in terms of message size), so the data load imposed by these null transactions is expected to be well within the capability of the system.

A.4.3 Data Load Concerns

Because the LTE system uses IP addressing, it is very difficult and in some cases impossible to broadcast messages. The more typical architecture is for user terminals to request information, and for the system to then fulfill each request individually. This raises concerns about the cost and scalability of this approach. Table 6 below summarizes the data load characteristics for a typical single user. In this example we have assumed that every request includes a probe data “snapshot” so each vehicle provides a snapshot of its current road situation (speed, location, and any other parameters), and the system then sends back any data about roadway conditions, traffic congestion, etc. We have used typical message sizes from equivalent messages defined in SAE J2735. The request intervals, vehicle speeds and system usage are exemplary only.

| Table 6 - Cellular Data Load Characteristics |
| Parameter | Value |

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Thus for a given user, this approach does not appear to impose any significant load on the typical user’s data plan. It does assume that the user has a data plan, but other systems such as 511 transportation information services also assume this.

An additional concern is the overall scalability of this approach. While a single user’s data plan may not be overwhelmed, there is a concern that if all vehicles were executing this sort of transaction, that the server load and cellular system load could be overwhelming. To examine this, a usage model that distributes usage hours over a 24 hour period with morning and evening rush hours was developed. For a typical cell site density of 12,250 vehicles (the average of the max and min estimates discussed above), assuming each vehicle is operated for 2 hours each day, and distributing these usage hours as described above, the overall cell site active user density is provided in the figure below.
Using the data load per user from Table 6 above, the peak load will occur during rush hours and will be about 4.4 MB/sec (1.8 Kbps/user x 2450 users). Given that a cell site can support about 100 MB/sec of overall data load, this load represents a relatively minor impact. In addition, assuming a regional connected vehicle transportation information server that is supporting 1000 cell sites, the server transaction load corresponding to this level traffic would peak at 340K transactions per second. The aggregate volume on the server using this model would be about 3.6M transactions per day. While this is a heavy load, it could be distributed among more servers, and it is well within the capabilities of today’s cloud computing systems.

A.4.4 Subscription Concerns

Since cellular system services are commercial services, there has been a lingering concern about using this technology for connected vehicle applications. The concern seems to be that these applications should be public resources, and thus requiring road users to subscribe to a commercial service to receive public benefits is unacceptable. While this may be the case for safety applications mandated by regulation, it is less clear for applications that provide a mobility benefit based on voluntary road user participation. Applications that are not mandated can only supplement other operations and management systems used by drivers and transportation agencies. Connected vehicle mobility applications can improve both the road user
experience and transportation management, but would not obviate the ongoing need for existing infrastructure and services to support vehicles without those optional applications. Availability of opt-in connected vehicle traveler information services, for example, would not remove incentives to provide crash or construction messages on roadway dynamic message signs, 511 systems, or traditional traffic radio reports. In such circumstances it does not seem unreasonable that road users choosing to use connected vehicle applications can do so through commercial cellular subscriptions.

In addition, cellular data services are becoming increasingly common among users, and subscription plans are increasingly inexpensive. Most service plans today allow for additional devices on an account for modest additional monthly fees, and many plans allow the subscriber to share data usage between these devices.

As a result of these changes, there is an increasing assumption that vehicles will be equipped with some sort of cellular modem that can be activated and used should the vehicle owner choose. Examples of this include GM’s OnStar system, which is standard equipment on most GM models, and typically includes a one year free subscription. Similarly, many automakers include Sirius/XM radio equipment in their vehicles as standard equipment. The user is typically provided a one-month trial subscription after which they may extend the subscription by paying an annual fee.

Another model is the Ford Sync approach, where the vehicle is equipped with a Bluetooth interface to the user’s phone. Using this approach the user’s phone would provide the communications, while the vehicle would provide the data and user interface.

Further evidence of this trend is the AutoHere system recently announced by Nokia. This system provides a cloud-based navigation system embedded in the vehicle. It essentially provides all of the features and benefits of smartphone-based navigation systems (high quality voice recognition, up-to-date maps, web search on map locales, and traffic and incident data) on the map display. The system is based on the assumption that the vehicle will have a high bandwidth cellular connection.

As a result, it is unclear if the conventional view that one cannot rely on a private cellular subscription to provide connected vehicle services is realistic, at least in the long term.
A.4.5 Other Issues

Another characteristic of cellular communications is that it relies on the overall cellular network, including the backhaul between the cell site and the back office and the overall internet. These systems may not be functioning, for example, during a crisis or disaster, so the system may not be 100% reliable due to a combination of physical damage and/or excessive user demand. This risk is not necessarily greater for the cellular network than for any other communications technologies.

These basic characteristics may change over time. For example, 3GPP Release 12 (the latest cellular/LTE standard) includes LTE-Direct, which is a mechanism for implementing direct connections between mobile LTE terminals. This may make the system very distributed and mitigate the need for the mobile station to request data on a regular basis.

The following example deployment concepts describe how the connected vehicle services identified above might be implemented using an all-cellular/LTE implementation. In some cases the system performance may not be sufficient to provide useful capability, and these situations are noted.

A.4.6 4G LTE Implementation

The first concept is based on the existing 4G LTE implementation, as presently available. This is generally based on 3GPP Release 8 which was published in 2008, and which entered the market in 2011-2012.

A.4.6.1 Communicating Messages between Transportation Field Equipment and Mobile Stations

Communicating messages between transportation field equipment and mobile stations using today’s LTE system could be done over the backhaul and cellular networks. In this case there are no connected vehicle field elements (i.e. no RSEs used to transmit connected vehicle related messages), so the information from field equipment such as traffic signal controllers would be sent to a center element, at for example a TMC. The mobile stations would contact the center element periodically as they drive down the road, and obtain information relevant to their location. This approach could also be used to collect data about the roadway. For example, the mobile stations could send a probe snapshot providing speed, heading, location and any other unusual sensed information (e.g. vertical accelerations due to potholes, or traction control events due to oil or ice), and request road data for the next road segment. The server could use the provided snapshot data to identify road hazards, and data from field equipment such as signal controllers to
provide a snapshot of the road situation ahead back to the mobile station. It is unclear if this approach would support time sensitive applications such as traffic signal timing related applications, but to the extent that the timing plan does not change this information is not so time sensitive as to be affected by a few hundred milliseconds of delay. As described elsewhere in this report, to the extent that the signal timing data is referenced to absolute time, the only effect of latency in the messages is that if the signal timing changes, the change cycle must include an additional delay (for example in the all-red phase) to protect vehicles that are far enough from the dilemma zone that they will receive the (delayed) update after they cross the dilemma zone boundary. In general this latency will be less than about 100 milliseconds, so adding this additional protection time to the signal cycle may not be an issue. This approach is illustrated conceptually in Figure 29 below.

A.4.6.2 Communicating Messages between Center Elements and Mobile Stations

Communicating messages between center elements and mobile stations would be no different than as described above for communicating with field equipment, except that the data may not come from field equipment. The connection between the mobile station and the center equipment would be essentially the same as any other cellular based client-server connection.
A.4.6.3 Communicating Messages between Mobile Stations

Communicating data between mobile stations in the current 4G LTE system is complicated but not impossible. The issue here is that mobile stations do not necessarily know the network addresses of the other mobile stations around them. In this case the “all IP” nature of the LTE system is a disadvantage since there is no efficient way for a mobile station to send a message to all local LTE terminals. The LTE specifications do allow for “Multicast”, but this is typically not available to terminal devices for a variety of reasons. First, it is very difficult to monetize such a broadcast. Second, and more importantly, a multicast would be sent to every LTE terminal in the cell sub-net, which is a very large number of vehicles (potentially many thousands). This is hugely inefficient since the only mobile stations (vehicles) that are likely to benefit from a local message would be those in relatively close proximity to the broadcasting vehicle. Other network/server based approaches to local peer-to-peer communications have also been implemented. For example, the “Bump” application uses the built-in accelerometer and location capability of cellular smartphones to generate a message to a central server containing this information. The server correlates messages with similar locations and identifies those that have the same time stamp. It then provides the IP address of each phone to the other, thereby linking them through the network so they can then exchange contact information. A similar sort of proximity-based connection system could be implemented for vehicles, although the latency of this approach might not serve some time critical applications. This approach is illustrated conceptually in Figure 30 below.
A.4.7 LTE-Direct Implementation

The second deployment concept is based on a 3GPP Release 12, which includes proximity based services (e.g. LTE-Direct), this should be available in the market around 2016.

LTE-Direct uses what is referred to as “proximate discovery” to announce services to mobile stations located within proximity of the terminal making the announcement. The announcing terminal could be a fixed information outlet, or it could be another mobile station. In LTE-Direct, terminals broadcast what are called “expressions”. These are sent at a low power level so only those terminals in local proximity will receive them. Each expression describes the “services” being offered by that terminal. This is similar to the WAVE Service Announcement (WSA) used by RSEs in DSRC, although the “services” provided may be substantially different. Examples of this approach for the various connected vehicle services described above are provided below.

A.4.7.1 Communicating Messages between Field Elements and Mobile Stations

The mechanism for field elements communicating to mobile stations using LTE-Direct would be essentially the same as for communication between mobile stations described above. The key difference would be that the use of the expression would be more like the WAVE Service Announcement used in
DSRC. The field element would broadcast an expression identifying the sort of data and services it could offer, and mobile stations in the local area would then contact the field element to participate in the services. The field element would then send messages associated with the services to the mobile station. Of course, just as with a DSRC RSE, the field element could offer a variety of services and each mobile station could identify to the field element which services it chose to make use of. The field element would then send messages associated with those services to the IP address of the mobile station. This approach is illustrated conceptually in Figure 31 below.

Figure 31 - Field to Mobile Using LTE-Direct

A.4.7.2 Communicating Messages between Center Elements and Mobile Stations

Communicating messages between center elements and mobile stations with LTE-Direct would be no different than as described above for conventional LTE. The connection between the mobile station and the center equipment would be essentially the same as any other cellular-based client-server connection.
A.4.7.3 Communicating Messages between Mobile Stations

Using LTE-Direct, mobile stations on vehicles would emit expressions that might include, for example, their position and heading. Other vehicles in the local area would identify those expressions that represented useful additions to their situational map of the local area. For example, expressions from vehicles obviously on other roads or traveling on the other side of a crowded freeway would be ignored, while expressions from vehicles close by or traveling on potentially intersecting trajectories would be accessed. To access the expression, a mobile terminal would send a message to the terminal that had broadcast the expression and the two mobile stations would thus learn each other’s IP addresses. Using this method, the vehicles would form overlapping “networks” with the vehicles around them. As with DSRC, the mobile stations could then transmit a BSM type message to each of the other mobile stations in its local “network.” As vehicles left the local area (as evidenced by their BSM data, or from a lack of messages for a specific time interval), each mobile station could delete them from their “network” and add any new stations discovered by new expressions. In an alternative (and slightly degenerate) approach, the BSM itself, presumably modified to account for protocol needs, would be the expression.

This approach is illustrated conceptually in Figure 32 below.
A.4.8 Cellular Implementation Examples

There are a variety of existing cellular services implementations. Some of these are embedded connected vehicle systems, and others are currently based on portable/handheld terminals, but could just as easily be embedded in the vehicle.

A.4.8.1 Probe Data Collection

Probe data typically consists of operational data collected from moving vehicles. This data may be very simple, such as position and time, or it may
include a variety of vehicle operational parameters such as ABS events, speeds, accelerations, etc.

Several service providers collect time and position data from location aware cellular phones. These data are typically provided under a privacy agreement that essentially allows the consumer to receive location oriented services in exchange for providing their position at regular intervals. The collected data is generally aggregated and anonymized, and then reused for other purposes, for example as traffic congestion information described below.

Another common type of probe data is for usage-based insurance. This typically involves a GPS and cellular enabled device that plugs into the vehicle’s OBD-II port. The device monitors various data parameters associated with driving behavior and accident risk, and reports these via a cellular link to the insurer. The insurer then uses this data to determine insurance premiums for the user. Examples include the Progressive Snapshot device and similar services offered by other insurance companies.

In general these services are private, which facilitates overcoming the various potential privacy concerns of services based on public infrastructure.

In most cases the systems make use of various low priority and low quality of service cellular bandwidth. In the case of Google-type location services, the service is provided on a subscriber device, and the user is responsible for the cellular data fees. In other systems like the usage-based insurance systems, cellular services are generally offered by cellular carriers for high volume enterprise applications, where the user is not required to carry a cellular contract, but instead the service provider holds the service contract. A popular example of this approach is the Amazon.com Whispernet, which is provided by Sprint. When an Amazon Kindle user purchases a book, a portion of the cost of the book includes the cost of providing low-bandwidth 3G cellular data services to deliver the digital book to the Kindle device.

A.4.8.2 Traffic Information Distribution

A variety of other cellular-based “connected traveler” systems are available. As described above, Google and others provide traffic information services based on the collection of cell phone location data. These traffic services are unique in that they provide congestion (typically several color coded speed levels relative to free flow speed) on any streets where cellular data from phones has been collected. As a result these systems typically provide congestion data on surface streets as well as major arterials and freeways. An example of this “crowd-sourced” traffic data is provided in the figure below.
A.4.8.3  Speed Harmonization and Green Wave

Several companies have leveraged smartphones to provide information to drivers relating to traffic signals. One example is imagreendriver.com, headquartered in Portland, OR. This system uses real-time traffic signal data provided by the city to support routing and “green wave” applications on smartphones. Using the traffic signal data, one application will determine the optimal route that assures the shortest wait at traffic signals. Another application shows the driver the current state of an approaching traffic signal, and suggests an optimal speed to drive to assure that the light will be green when the vehicle arrives at the intersection. As such, this serves as an example of a time-sensitive V2I application based on cellular communications. A sample of the application interface is shown below.
A.4.9 Comparative Cellular and DSRC Examples

A key difference between DSRC and cellular implementations for V2I services is that cellular implementations generally initiate the transaction from the mobile device or vehicle, while DSRC is typically initiated by the RSE. This is illustrated in the Table 7 for a typical Data Collection application (e.g. probe data).

### Table 7 - Probe Data Collection DSRC vs. Cellular Comparison

<table>
<thead>
<tr>
<th>DSRC Sequence of Operations</th>
<th>Cellular Sequence of Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile Device collects and stores data</td>
<td>Mobile Device determines it has data to provide (e.g. after collecting some preset volume of data)</td>
</tr>
<tr>
<td>Mobile Device encounters DSRC RSE</td>
<td>Mobile Device contacts service provider over cellular link</td>
</tr>
<tr>
<td>RSE announces data collection service on Control Channel</td>
<td>Mobile Device initiates data transfer</td>
</tr>
<tr>
<td>Mobile Device (OBE) receives advertisement and switches to Service Channel associated with service</td>
<td></td>
</tr>
<tr>
<td>OBE initiates data transfer</td>
<td></td>
</tr>
<tr>
<td>RSE forwards received packets over backhaul network to service provider (data collector)</td>
<td></td>
</tr>
</tbody>
</table>
Note that data can be collected anywhere there is coverage for cellular or DSRC, although cellular coverage is generally much more continuous.

Table 8 below illustrates the sequence of events for a V2I data distribution application.

<table>
<thead>
<tr>
<th>DSRC Sequence of Operations</th>
<th>Cellular Sequence of Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile Device encounters DSRC RSE</td>
<td>Mobile Device generates a request for road data associated with its current location and sends request to service provider (e.g., every 100 m)</td>
</tr>
<tr>
<td>RSE broadcasts messages on Control Channel or “safety channel”</td>
<td>Service provider determines if there is any road data for the vehicle’s current area</td>
</tr>
<tr>
<td>Mobile Device (OBE) receives messages</td>
<td>If no data, it returns a null response. If data exists, it sends the data back to the Mobile Device.</td>
</tr>
<tr>
<td>OBE determines when vehicle is at location where message is active (it may receive the message in some other location)</td>
<td>OBE activates warning or other action as appropriate</td>
</tr>
<tr>
<td>OBE activates warning or other action as appropriate</td>
<td></td>
</tr>
</tbody>
</table>

It should be noted that the density of RSE placement will determine the efficiency of distribution for DSRC–based applications. The efficiency of a cellular-based application will be determined by the density of requests, many of which will return a null response (no data).

### A.4.10 Cellular Implementation Summary

This section has outlined the characteristics of cellular systems, and the typical architectures that could be used to implement the connected vehicle system given those characteristics. Based on the supporting top-level analyses, this approach would be feasible for many connected vehicle applications. Latency remains a concern for some applications (particularly V2V applications), although no direct tests have yet been performed to confirm that this is a severe limitation, and applications could presumably be designed to mitigate the impact of latency to some extent. For most V2I applications the cellular approach is feasible, and it may represent a faster adoption, lower cost and significantly lower risk option than DSRC.

- Faster adoption is a result of the existence of hundreds of millions of smartphones already in the field, many of which could access
connected vehicle services today with the simple installation of a (presumably free) application. This means connected vehicle services could be rolled out immediately rather than waiting decades for the equipped vehicle population to grow. In addition, the smart phone turnover rate is about 200 million units every 18 months, or 133 million per year – about 10 times the turnover of vehicles, so even if new hardware features were required the rollout speed would be substantially faster.

• Lower cost is partly a result of lower user terminal cost—most people use phones for other applications, so the incremental cost of connected vehicle applications is nearly zero—and substantially reduced infrastructure costs. The primary communications infrastructure is already in place and is funded by the user’s subscriptions. To support a cellular-based system the jurisdictional stakeholders (the presumed infrastructure deployers) would need only to implement appropriate back office systems.

• Lower risk arises from the fact that the cellular user base already exists. It is possible with DSRC that deployers could invest in infrastructure while automotive consumers could balk at the added cost of equipment in cars, rendering that investment worthless. This may be especially true if the infrastructure rollout lags, and/or if the limited number of equipped vehicles in the early years causes consumers to feel the system provides little real value. Lower cost solutions that provide benefits more quickly are also less likely to be subject to the uncertainty of political sensibilities.
A.5 Alternative Communications Technologies

Wi-Fi is a well-known communications system that is used for wireless Ethernet connections for PCs, phones and other personal computing devices. Wi-Fi is defined by a variety of sub-standards that specify the operating frequency bands and various details of the protocols. Common Wi-Fi standards include 802.11a, 802.11g and, more recently, 802.11n. These are not considered in this report for several reasons. First, all of these standards depend only on the IP protocol, and it is assumed that the communicating devices have an IP address. Second, as part of forming an IP-based network, these standards include a network association process. This process essentially enables a terminal to “join” (or associate with) the network. In that process the terminal tunes to the channel that the network is using, learns the addresses of all other nodes on the network, and has its address distributed to all other nodes on the network. This process is relatively slow because the networks are intended to support fixed or slow-moving terminals. The association process is too slow to enable a moving vehicle to reliably attach to the network (associate) and communicate data. In addition, vehicles in a roadway environment will be entering and leaving the radio footprint (the coverage area) of the network at a rapid rate. This means that the network is constantly changing, and the network management function (typically performed by the base station) would need to constantly change the network definition (which terminals and their addresses are part of the network). DSRC, discussed below, also uses the Wi-Fi protocol, but it has specifically eliminated this network association aspect. Wi-Fi systems generally operate with a maximum outdoor range between 140 and 250 meters, which is acceptable for V2I and I2V communications, but, in general, the systems actually achieve much shorter ranges than this.

Satellite radio, officially known as the Satellite Digital Audio Radio Service (SDARS), uses satellites to send CD-quality digital audio to terminals on the ground. This is used today by the Sirius/XM Radio service. While the system offers nationwide coverage and thus could be useful for some I2V applications, it is not capable of V2I communications since it has no user terminal uplink (e.g. vehicle to satellite). It is also relatively low bandwidth. The entire channel capacity of a typical SDARS satellite is 4 Mbps, and, because it is a subscription service, most of this data capacity is allocated to subscriber-based audio channels. Sirius/XM does provide subscription-based traffic information services using the system, and both Honda and General Motors (OnStar) lease capacity for their proprietary telematics services. The system is effective for these one-way services and it could be used for public
purposes, but it is one-way and using it on a large scale would quickly become very expensive. (The entire subscriber revenue is about $2.5 B per year, so this relates to about $0.16 per KB. This is roughly 10 times that of cellular.) In addition there are uncertain delays between when data is submitted to the SDARS system and when that data is actually broadcast. For some applications this latency and the uncertainty in the latency would not be acceptable.
A.6 COMMUNICATIONS LATENCY

Latency is often cited as a key differentiator between cellular and DSRC communications systems in connected vehicle applications. While latency may be important, the degree of importance appears to be somewhat overstated, as are the differences between DSRC and cellular technologies. Latency is generally defined as the time delay between when a message is sent and when it is received at its final destination. Latency includes any delays in the transmission processing, propagation delays through the medium (wireless, internet, etc.) and receiving processing. It is important to separate these components of latency from the network attach time, or association time. Network attach time is the time required to join the network, and be configured so that data can be sent or received. Latency estimates assume that the terminal is already part of the network.

A.6.1 Latency Requirements

Latency requirements have not been studied in great depth across all applications. Notional requirements are summarized briefly below for a variety of applications.

Roadside Hazard Warnings/Alerts: In general, roadside warnings and alerts persist on the roadway for some time, and it similarly takes some time to simply identify hazards and generate alert information. As a result, the maximum latency requirement for this sort of application presumably ranges between minutes and tens of minutes.

Probe Data Collection: Maximum latency requirements for probe data relate to how old the reported data can be. Since probe data may be collected in the vehicle and sent when the vehicle has travelled some distance, there will be some inherent latency in all probe data. As a lower bound, at an average speed of 30 mph, a vehicle reporting probe data every two miles will generate a data latency of four minutes from the time the first data element is stored to when the full set of data is transmitted. The subsequent communications latency in reporting the probe data to a center system could then reasonably be within 10-30 seconds.

Time Sensitive Applications: The most obvious time critical V2I application is intersection safety. This is because the signals are changing state over time. However, the criticality of latency for these applications is generally overstated. This is because the signal timing does not change arbitrarily. The key requirement for SPAT applications is that the SPAT data used by a vehicle at the time it reaches the dilemma zone must be valid until that vehicle passes through the intersection or stops. The current signal systems
use a yellow/all-red cycle of sufficient duration to assure that a vehicle at the edge of the dilemma zone when the signal changes from green to red can safely pass through the intersection before the conflicting signal turns green. If the message has any latency in this application, that latency must be accommodated in the duration of the all-red phase so that the user is protected against receiving a message that is out of date by the time it is received. This level of latency will not affect the performance of the application to the extent that the all-red phase can be extended by a moderate time intervals (on the order of 100-200 msec).

It should be noted that the current SAE J2735 SPAT and BSM messages are described as being transmitted every 100 msec. This repeat interval will be unaffected by transmission latency, but the messages received will be offset by the latency. It should also be noted that the requirement for a 100 msec repeat interval does not appear to be based on the needs of the application. This is especially so for SPAT applications. The tolerable latency for a BSM is actually the time interval in which the vehicle trajectory may change sufficiently that the projected position of the vehicle would be outside the tolerable position error for the application.

For locally-transmitted (e.g., DSRC) systems the latency will be driven by the message repeat interval and the communications latency. For request-based (e.g., cellular) systems the latency will be the server response and communication medium propagation time. For either of these cases the latency is non-zero, and this latency will need to be added to the yellow-all-red cycle to assure safety. Obviously lower latency systems will have lower impact on the signal timing.

**Vehicle-to-Vehicle Applications:** While the focus of this report is on V2I systems, latency is generally driven primarily by vehicle-to-vehicle (V2V) applications. In these systems the vehicle state is sent in a message, so the latency must be lower than a reasonable time in which the vehicle might change its trajectory significantly.

### A.6.2 Latency Comparisons

The latency of a DSRC system depends on the channel congestion. Channel access is generally based on a carrier sense multiple access (CSMA) collision avoidance process that results in a net average transmission time between 5

---

msec and about 50 msec. In addition, if the DSRC system uses channel switching, the system may see up to 50 msec of channel delay (time spent waiting for the proper channel interval to arrive). DSRC thus has an average latency of between 5 msec and about 50 msec for a non-switched system, and 55 msec to 100 msec for a switched system.

Cellular (LTE) specifies an inactive (attached to the network, but inactive) to active transition time of 5 msec. In addition, since the packets may pass through the internet to a server the propagation delay will typically average between 30 and 60 msec. Industry tests of the system indicate that these values are representative of the LTE system.21

So, under the best non-crowded conditions DSRC has lower latency, but cellular is reasonably close to the average DSRC latency, and cellular latency is improving. At the target LTE latency of 5 msec, it will significantly outperform DSRC.

These assessments are generally somewhat rough, and should be supported by more detailed testing.22

In general, however, the latencies for DSRC and cellular systems do not appear to be a limiting factor for V2I applications.


22 These tests are expected to be carried out later this year at the U.S. DOT Turner Fairbank Highway Research Center Saxton Transportation Operations Laboratory.
A.7 Application Backhaul Requirements Summary

While most field terminals (conventionally referred to as RSEs) support a variety of applications, there is no basic requirement that RSEs be connected to center equipment at all. As a result, the requirements on the backhaul, if any, depend on the applications the RSE is expected to support and the broadcast message management approach used. This section provides a summary of example backhaul requirements based on the different applications and message management approaches. In general the message sizes are based on the J2735 standard. These “requirements” are not intended to be normative but are instead provided to illustrate relative data loads for different backhaul approaches.

There are two basic approaches for managing broadcast messages. These have a significant impact on the need for and the data loads on the backhaul network. These are described below:

- **Store and Transmit:** This architecture includes provision in the RSE to store messages and to transmit them repeatedly according to a message transmission schedule (typically provided with the message). In this model the messages transmitted by the RSE reside in the RSE. The RSE may acquire these messages via several mechanisms. For example, they could be pre-programmed into the RSE during configuration, they could be provided by field equipment over a local network connection, they could be provided to the RSE from a mobile programmer (for example a service vehicle that establishes a wireless connection to the RSE and delivers messages for later transmission), or they could be provided by center facilities over a backhaul link. A store and transmit RSE can operate independently.

- **Pass-through:** In the pass-through architecture, the RSE has no ability to store any messages and no ability to transmit them according to a schedule. Instead every message to be transmitted is provided from a center facility over the backhaul link or by local field equipment over a local network and it is then immediately transmitted.

The applications supported by an RSE will determine the size of the messages that may need to be carried over the backhaul. This applies to messages to be broadcast by the RSE, and to messages sent by mobile terminals and collected by the RSE on behalf of the center facility. It should be noted that message collection at the RSE could also involve storing messages received over some time interval and periodically transmitting them as a bundle to the center, but this approach would mean that the collected data was not timely, and over
typical periods that the data might be bundled, the transmission over the back haul as a bundle would impose a higher backhaul load than transmitting the data as it was collected. For this reason we have not included this option in the analysis.

Table 9 shows the approximate message sizes for typical applications that an RSE might support, and the expected data load that each application would impose on the backhaul. Where appropriate the table also differentiates between the store-and-transmit and pass-through approaches for broadcast messages. As can be seen in the table, for most applications the overall backhaul load is not particularly high. Key exceptions are the distribution of certificate revocation lists (CRLs), the capture of Basic Safety Messages (BSMs) at an RSE, and high data load private services. The basis for derivation of these table values is provided in subsequent sections.
### Table 9 - Application Message Backhaul Analysis

<table>
<thead>
<tr>
<th>Broadcast Applications – Pass-through</th>
<th>Typical Message Size (Bytes)</th>
<th>Message Density (msg/sec)</th>
<th>Peak Backhaul Data Rate* (Kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roadway Hazard Alerts</td>
<td>300**</td>
<td>30</td>
<td>72.0</td>
</tr>
<tr>
<td>MAP/GID Distribution: 2 Lane/4-Way</td>
<td>1722</td>
<td>1</td>
<td>13.8</td>
</tr>
<tr>
<td>MAP/GID Distribution: 4-Lane/4-Way/Protected-Lefts</td>
<td>3143</td>
<td>1</td>
<td>25.1</td>
</tr>
<tr>
<td>Signal Phase and Timing (SPAT): 2-Lane/4-Way</td>
<td>283-603</td>
<td>10</td>
<td>22.6-48.2 (Local)</td>
</tr>
<tr>
<td>Signal Phase and Timing (SPAT): 4-Lane/4-Way/Protected-Lefts</td>
<td>461-1805</td>
<td>10</td>
<td>36.8-144.4 (Local)</td>
</tr>
<tr>
<td>Signal Status Message</td>
<td>300</td>
<td>0.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Broadcast Applications – Store &amp; Transmit</th>
<th>Typical Message Size (Bytes)</th>
<th>Message Density (msg/sec)</th>
<th>Peak Backhaul Data Rate* (Kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roadway Hazard Alerts</td>
<td>300</td>
<td>30</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>MAP/GID Distribution: 2 Lane/4-Way</td>
<td>1722</td>
<td>1</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>MAP/GID Distribution: 4-Lane/4-Way/Protected-Lefts</td>
<td>3143</td>
<td>1</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Signal Phase and Timing (SPAT): 2-Lane/4-Way</td>
<td>283-603</td>
<td>10</td>
<td>42.9-128.7 (Local)</td>
</tr>
<tr>
<td>Signal Phase and Timing (SPAT): 4-Lane/4-Way/Protected-Lefts</td>
<td>461-1805</td>
<td>10</td>
<td>42.9-128.7 (Local)</td>
</tr>
<tr>
<td>Signal Status Message</td>
<td>300</td>
<td>0.1</td>
<td>&lt;1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data Collection &amp; Transaction Applications</th>
<th>Typical Message Size (Bytes)</th>
<th>Message Density (msg/sec)</th>
<th>Peak Backhaul Data Rate* (Kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe Data Collection</td>
<td>9991</td>
<td>200</td>
<td>726.6</td>
</tr>
<tr>
<td>BSM Capture</td>
<td>300</td>
<td>2000</td>
<td>4,800.0</td>
</tr>
<tr>
<td>Certificate Distribution (3K certs)</td>
<td>780K</td>
<td>1</td>
<td>(Assume 1 update per RSE at any time)</td>
</tr>
<tr>
<td>CRL Distribution (1% Revocation)</td>
<td>100M</td>
<td>(Assume 1 update per RSE at any time)</td>
<td>36,363.6</td>
</tr>
<tr>
<td>Remote Private Services</td>
<td>100K</td>
<td>Assume 2 accesses per RSE at any time</td>
<td>72.7</td>
</tr>
<tr>
<td></td>
<td>500K</td>
<td></td>
<td>363.6</td>
</tr>
<tr>
<td></td>
<td>5M</td>
<td></td>
<td>3,636.4</td>
</tr>
</tbody>
</table>

* RSE Encounter time: 22 seconds at 60 mph (300 meter range)
** All messages assumed to include 200 byte signature. Small messages rounded to 100 byte payload.

#### A.7.1 Data Broadcast Load

The highest data load imposed from broadcast applications (e.g. safety messages being broadcast from the RSE) is imposed by roadway alert messages (72Kbps) using the pass-through message management architecture. This rate assumes three different alerts are being sent continuously at a 10 Hz rate. Obviously, if more alerts are broadcast there will be a corresponding increase in the backhaul data load. The 72 Kbps bandwidth is not significantly high, but it does illustrate the inefficiency of the pass-through message management architecture. In contrast, the same...
application implemented using the store and transmit architecture requires less than 1 Kbps. In fact, the store and transmit architecture only requires a backhaul connection when the messages are changed, so this system could be implemented with either a very slow backhaul, or an intermittent connection (as described in the Implementation Summary section).

The Signal Phase and Timing (SPAT) application also imposes a modestly high data rate requirement (42.8 Kbps). However, this assumes that the SPAT message is generated centrally and is then sent to the RSE over the backhaul. In most implementations, it is expected that the RSE will have a local network connection directly to the traffic signal controller, so this data load would not generally be imposed on the backhaul network.

The key backhaul driver for RSE broadcast messaging is thus the message management architecture. If the RSE is treated as a pass-through, then it must support a continuously connected backhaul capable of providing a minimum data rate of about 100 Kbps. If the store and transmit architecture is used, the backhaul data rate and connectivity requirements are very low, and numerous non-backhaul alternatives may be used.

A.7.2  Data Collection/Transaction Load

The highest backhaul loads are imposed by the collection of data from vehicles and the distribution of specific types of data to the vehicles.

The distribution of the certificate revocation list imposes the highest load (36 Mbps). The level in the table is presumably the highest that this load could be expected to be, and it may be much lower. In addition the DOT and the automakers are working on alternative designs to limit this load. However, if CRLs are to be distributed by RSEs, those RSEs that provide this service will require a relatively high data rate backhaul.

The capture of BSMs at RSE also represents a significant load (4.8Mbps). This function/application has been implemented as part of the Safety Pilot project as a way to test the system and evaluate the effective density of DSRC messages at a given density of equipped vehicles, but in general this approach would not be used in a practical implementation. Specifically, the BSM is sent ten times per second, which means that the vehicle will have moved only about 4.4 to 8.8 feet between messages (depending on speed - e.g. 30 to 60 mph). This is generally too short of a sample interval for most road state/measurement applications. In contrast, probe data messages include snapshots (which are similar in content to the BSM) that relate to other sections of the roadway, for example between RSEs, and these snapshots are
generally spaced much farther apart. A typical probe data message can include up to 32 snapshots, which, if “taken” every 100 meters represents a sample of the road state over 3.2 Km. In contrast, the capture of BSMs at an RSE provides an ultra dense (thousands of samples per second in heavy traffic) measure of the state of the road in an area approximately 200 meters on either side of an RSE. BSM capture thus represents a very inefficient approach to the collection of roadway data. It imposes a very heavy data load on the backhaul and provides too much data about too little of the road network.

In addition, some private services could generate significant backhaul loads. These loads, however, can be managed by simply not offering private services at RSEs, or by limiting the private service data rate. We have included these loads in the table above at three different data transfer volumes.

A.7.3 Application Message Backhaul Analysis Basis

This section provides the basis for example backhaul messages summarized in Table 9 based on the different applications and message management approaches. In general the message sizes are based on the J2735 standard. These estimates are not intended to be normative, but are instead provided to illustrate relative data loads for different backhaul approaches.

The structure and size of the SPAT and GID/MAP messages depend on the type of intersection and the number of lanes. These messages in this analysis are developed in accordance with the fields and field sizes described in the SAE J2735 standard for two different intersections: a conventional two-lane crossing road (a “2x2” intersection), and a four-lane crossing with protected left turn lanes. These are shown in the figures below. The number of lanes, and the connections between the lanes for these two intersection types are different, and the resulting SPAT and GID messages will have substantial differences.

The SAE standard also defines a large number of optional fields which will also change the overall size of the messages substantially. As a result, the analysis includes a range of sizes, the smaller messages assuming no optional fields, and the larger sizes representing a presumed typical size. Potentially very large messages in which all optional fields are used are not included since this seemed unrealistic.

Lastly, the impact of message encoding has been estimated by assuming that all independently defined fields in any message will require 2 bytes for encoding. In cases where the SAE standard has identified non-independently
encoded fields (e.g., the BSM Blob), the encoding overhead has been adjusted accordingly.

The size of the Probe Data message depends on the number of snapshots included in the messages. A minimum of one and a maximum of 32 snapshots, per the SAE standard, have been assumed.

All message sizes include a digital signature and certificate per IEEE 1609.2.

In general these messages sizes are representative of the typical messages expected to be sent in the connected vehicle system.

![Two-lane Intersection Model for Message Analysis](image-url)
Figure 36 - Four-lane Intersection Model for Message Analysis
A.7.4 Backhaul Implementation Summary

Table 10 below rates the performance of various backhaul communications technologies against the application-based requirements.

It is important to note that the pass-through message management architecture cannot be supported by low data rate backhaul systems, or systems that exhibit significant latency. This means that none of the intermittent connections are suitable, and neither of the satellite systems can support this approach. In contrast, the store and transmit architecture does not suffer under this constraint. For example, while unorthodox, it would be possible to deliver travel advisory data to RSEs using XM/Sirius. The data would be downloaded to the RSE over some time period, and stored at the RSE. It would then retransmit the data in messages until the data was updated.

RSEs that are required to transfer large volumes of data (e.g. CRL distribution, and data collection applications) may not be served well by intermittent connections because the intermittent connection will require on-site storage of collected data (until it is offloaded). This not only drives up RSE cost and power usage, but it also introduced delays in the availability of the collected data, thereby limiting its use for any dynamic applications.

In general all of the non-satellite WAN technologies are able to support all applications. The use of commercial cellular services to deliver CRLs may, however prove to be rather expensive since the data volume is so high for this application.
### Table 10 - Backhaul Application Summary

<table>
<thead>
<tr>
<th></th>
<th>Wide Area (WAN)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cellular (LTE)</td>
<td>Cellular (GPRS)</td>
<td>WiMAX</td>
<td>FSS</td>
<td>SDARS</td>
<td>UWB</td>
<td>Wi-Fi</td>
<td>DSRC</td>
<td>ZigBee</td>
<td>Fiber</td>
<td>DSL</td>
<td>Cable TV</td>
</tr>
<tr>
<td><strong>Broadcast (Pass-Through)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roadway Hazard Alerts</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>MAP/GID Distribution</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Signal Phase and Timing (SPAT)</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>●</td>
<td>O</td>
<td>O</td>
<td>●</td>
</tr>
<tr>
<td>Signal Status Message</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>●</td>
<td>O</td>
<td>O</td>
<td>●</td>
</tr>
<tr>
<td><strong>Broadcast (Store &amp; Transmit)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roadway Hazard Alerts</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>MAP/GID Distribution</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Signal Phase and Timing (SPAT)</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>●</td>
<td>O</td>
<td>O</td>
<td>●</td>
</tr>
<tr>
<td>Signal Status Message</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>●</td>
<td>O</td>
<td>O</td>
<td>●</td>
</tr>
<tr>
<td><strong>Data Collection &amp; Transactions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probe Data Collection</td>
<td>●</td>
<td>O</td>
<td>●</td>
<td>●</td>
<td>X*</td>
<td>X*</td>
<td>X*</td>
<td>X*</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>BSM Capture</td>
<td>O</td>
<td>O</td>
<td>●</td>
<td>X</td>
<td>X*</td>
<td>X*</td>
<td>X*</td>
<td>X*</td>
<td>X</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Certificate Distribution (3K certs)</td>
<td>O</td>
<td>O</td>
<td>●</td>
<td>●</td>
<td>X*</td>
<td>X*</td>
<td>X*</td>
<td>X*</td>
<td>X</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>CRL Distribution (1% Revocation)</td>
<td>O</td>
<td>X</td>
<td>●</td>
<td>O</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td>●</td>
<td>O</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Remote Private Services</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

Key: ● = Good  ○ = Marginal  X = Unacceptable  * Intermittent WLAN connections could be used for these applications, but this would require extensive on-site data storage for each RSE, and would produce data with a substantial time delay.
APPENDIX B. APPLICATIONS

This appendix provides brief descriptions of connected vehicle applications mentioned in the deployment scenarios. The applications listed in Table 11 are drawn from earlier work performed as part of this National Connected Vehicle Field Infrastructure Footprint Analysis and documented in the Application Analysis.

Table 11 - Potential Connected Vehicle Applications

<table>
<thead>
<tr>
<th>Application Group</th>
<th>Application Bundle</th>
<th>Application</th>
<th>Brief Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2I Safety</td>
<td>Intersection Safety</td>
<td>Driver Gap Assist at Signalized Intersections</td>
<td>Equipment at signalized intersection determines the locations and speeds of oncoming vehicles (e.g. using Radar/Lidar). This information plus SPAT data is broadcast in vicinity of intersection. Vehicle OBU receives oncoming vehicle information (or gap info) and SPAT info, and determines if a warning is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Intersection Safety</td>
<td>Railroad Crossing Violation Warning</td>
<td>RSU in vicinity of intersection and connected to RR crossing guard controller sends out Signal Phase and Timing Messages (or RRX equivalent). Vehicle OBU receives SPAT/RRX info and determines if a warning is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Intersection Safety</td>
<td>Red Light Violation Warning (Cellular)</td>
<td>Signal controller sends Signal Phase and Timing information to server. Vehicle contacts server and requests road warning/alert info based on its location and direction. Vehicle OBU receives SPAT info and determines if a warning is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Intersection Safety</td>
<td>Red Light Violation Warning (DSRC)</td>
<td>RSU in vicinity of intersection and connected to signal controller sends out Signal Phase and Timing Messages. Vehicle OBU receives SPAT info and determines if a warning is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Intersection Safety</td>
<td>Stop Sign Gap Assist (V2I Only)</td>
<td>Equipment at stop sign controlled intersection determines the locations and speeds of oncoming vehicles (e.g. using Radar/Lidar). This information plus stop sign info and intersection map is broadcast in vicinity of intersection. Vehicle OBU receives oncoming vehicle information (or gap info), and stop sign info and determines if a warning is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Intersection Safety</td>
<td>Stop Sign Violation (Cellular)</td>
<td>Server has locations and directions of stop signs for a region. Vehicle contacts server and requests road warning/alert info based on its location and direction. Vehicle OBU receives stop sign info and determines if a warning is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Intersection Safety</td>
<td>Stop Sign Violation (DSRC)</td>
<td>RSU in vicinity of stop sign sends out stop sign locations and directions. Vehicle OBU receives stop sign info and determines if a warning is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Other Safety</td>
<td>Oversize Vehicle Warning (Cellular)</td>
<td>Server has locations and directions of overhead restrictions for a region. Vehicle contacts server and requests road warning/alert info based on its type, location and direction. Vehicle OBU receives restriction info and determines if a warning is appropriate. Ideally, an alert would be given so that the oversize vehicle can be rerouted before a warning to stop is required.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Other Safety</td>
<td>Oversize Vehicle Warning (DSRC)</td>
<td>RSU in vicinity of (i.e. on approach to) overhead restriction sends out overhead limit locations and directions. Vehicle OBU receives overhead limit info and determines if a warning is appropriate. Ideally, an alert would be given so that the oversize vehicle can be rerouted before a warning to stop is required.</td>
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<td>Application Group</td>
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<tr>
<td>V2I Safety</td>
<td>Speed Safety</td>
<td>Curve Speed Warning (Cellular)</td>
<td>Rerouted before a warning to stop is required. Server has info for road curves (locations, directions and speeds) for a region. Vehicle contacts server and requests road warning/alert info based on its location and direction. Vehicle OBU receives curve info and determines if a warning is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Speed Safety</td>
<td>Curve Speed Warning (DSRC)</td>
<td>RSU in vicinity of (e.g. on approach to) curve sends out curve information (location and recommended speed and directions). Vehicle OBU receives info and determines if a warning is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Speed Safety</td>
<td>Reduced Speed Work Zone Warning (Cellular)</td>
<td>Workers provide info on work zone to server. Vehicle contacts server and requests road warning/alert info based on its location and direction. Vehicle OBU receives work zone info and determines if a warning/alert is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Speed Safety</td>
<td>Reduced Speed Work Zone Warning (DSRC)</td>
<td>Fixed RSU in vicinity of (e.g. on approach to) work zone, or portable RSU at work zone sends out alert information (e.g. location and recommended speed(s) and directions). Vehicle OBU receives info and determines if a warning/alert is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Speed Safety</td>
<td>Speed Zone Warning (Cellular)</td>
<td>Server has info for speed zones (locations, directions and speeds) for a region. Vehicle contacts server and requests road warning/alert info based on its location and direction. Vehicle OBU receives speed zone info and determines if a warning/alert is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Speed Safety</td>
<td>Speed Zone Warning (DSRC)</td>
<td>Fixed RSU in vicinity of (e.g. on approach to) speed zone, or portable RSU at temporary speed zone sends out alert information (e.g. location and recommended speed(s) and directions). Vehicle OBU receives info and determines if a warning/alert is appropriate.</td>
</tr>
<tr>
<td>V2I Safety</td>
<td>Transit Safety</td>
<td>Pedestrian in Signalized Crosswalk Warning</td>
<td>RSU in vicinity of intersection and connected to pedestrian detection system sends out pedestrian info (presence and crosswalk) as part of Signal Phase and Timing Messages. Vehicle OBU receives info and determines if a warning/alert is appropriate.</td>
</tr>
<tr>
<td>Mobility</td>
<td>Enable ATIS</td>
<td>ATIS (Cellular)</td>
<td>Vehicle contacts server and provides speed and location data. Back office app (server) determines travel times and other traveler information. Server provides this information to vehicle in same transaction, or vehicle subsequently contacts server and requests road info based on its location and direction. Vehicle OBU receives info and plans accordingly, informs driver.</td>
</tr>
<tr>
<td>Mobility</td>
<td>Enable ATIS</td>
<td>ATIS (DSRC)</td>
<td>Vehicles broadcast location (possibly via BSM); RSU receives messages and sends info to back office. Local or back office app determines travel times and other traveler information and sends this to the RSUs in the area. RSUs broadcast information to vehicles. Data likely used by vehicle for routing and/or energy management.</td>
</tr>
<tr>
<td>Mobility</td>
<td>Enable ATIS</td>
<td>Motorist Advisories and Warnings (Cellular)</td>
<td>Information is obtained from external sources and used to determine the locations of hazards and other localized warning/advisory content. Vehicles call server to obtain information on the road ahead.</td>
</tr>
<tr>
<td>Mobility</td>
<td>Enable ATIS</td>
<td>Motorist Advisories and Warnings (DSRC)</td>
<td>Information is obtained from external sources and used to determine the locations of hazards and other localized warning/advisory content. CV system used to inform vehicles appropriately based on their location.</td>
</tr>
<tr>
<td>Mobility</td>
<td>Enable ATIS</td>
<td>WX-INFO (Cellular)</td>
<td>Provides real-time route-specific weather information for</td>
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<tr>
<td>Mobility</td>
<td>Enable ATIS</td>
<td>WX-INFO (DSRC)</td>
<td>Provides real-time route-specific weather information for motorized and non-motorized vehicles; part of the Enable ATIS bundle.</td>
</tr>
<tr>
<td>Mobility</td>
<td>FRATIS</td>
<td>Dynamic Route Guidance (F-DRG) (DSRC)</td>
<td>Vehicle passes an RSU and provides speed, location and destination information. RSU relays information to central server where data is compounded with other data to derive the optimum route. Route is passed back to RSU and on to vehicle.</td>
</tr>
<tr>
<td>Mobility</td>
<td>FRATIS</td>
<td>Dynamic Route Guidance (F-DRG) (Cellular)</td>
<td>Vehicle provides speed, location and destination information over wireless connection to central server where data is compounded with other data to derive the optimum route. Route is passed back to vehicle.</td>
</tr>
<tr>
<td>Mobility</td>
<td>FRATIS</td>
<td>Freight Real-Time Traveler Information with Performance Monitoring (F-ATIS) (Cellular)</td>
<td>FRATIS shall provide a specialized output interface to public sector agencies that will provide open-source data collected in the FRATIS system, such as sanitized route, speed, congestion, and alternative route selection information. This information shall support public sector freight planners and other public agencies in assessing both the needs and impacts of truck traffic in a metropolitan region (e.g., air quality reductions due to FRATIS applications, assessment of the best alternative routes, and information on where to potentially plan new connectors to support better dynamic routing). The format of the public sector output data shall be determined during the FRATIS System Development and Limited Testing phase.</td>
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<td>Mobility</td>
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</tr>
<tr>
<td>Mobility</td>
<td>IDTO</td>
<td>Connection Protection (T-CONNECT)</td>
<td>The proposed transit multi-modal and multi-agency application will enable public transportation providers and travelers to communicate to improve the probability of successful transit transfers. Travelers can initiate a request for connection protection anytime during the trip using a personal mobile device, or potentially via transit vehicle or personal automobile on-board equipment/interface, and receive a confirmation based on a set of criteria indicating whether the request is accepted.</td>
</tr>
<tr>
<td>Mobility</td>
<td>IDTO</td>
<td>Dynamic Ridesharing (D-RIDE)</td>
<td>This proposed application will make use of personal information gathering systems (such as in-vehicle and hand-held devices) to allow ride-matching, thereby reducing congestion, pollution, and travel costs to the individual with a low initial investment. Under one implementation scenario, it is proposed that the D-RIDE application will integrate carpooling functions into a vehicle computer so voice activated ridesharing technology can be built into the vehicle’s interface enabling the driver to find and accept</td>
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<tr>
<td>Mobility</td>
<td>IDTO</td>
<td>Dynamic Transit Operations (T-DISP)</td>
<td>This application will allow travelers to request trips using a variety of media and seeks to enhance existing on-board and central systems to provide public transportation and shared-ride services. A central system, such as a Travel Management Coordination Center, or decentralized system would dynamically schedule and dispatch or modify the route of an in-service vehicle by matching compatible trips together. The application may consider both public and private (e.g., taxi) transportation providers and may include paratransit, fixed-route bus, flex-route bus, and rail transit services.</td>
</tr>
<tr>
<td>Mobility</td>
<td>INFLO</td>
<td>Cooperative Adaptive Cruise Control</td>
<td>Cooperative adaptive cruise control can significantly increase traffic throughput by tightly coordinating in-platoon vehicle movements to reduce headways between vehicles. The lead vehicle broadcasts location, heading and speed. CACC-enabled following vehicles automatically adjust speed, acceleration and following distance. A traffic management center observes traffic flow and adjusts the gap policy to manage road capacity. This is primarily a V2V application and the assessment here describes only the V2I component addressing the gap policy.</td>
</tr>
<tr>
<td>Mobility</td>
<td>INFLO</td>
<td>Queue Warning (Q-WARN) (Cellular)</td>
<td>Vehicle contacts server and provides speed and location data. Back office app (server) correlates data from this and other vehicles and determines that a queue is forming. Server provides this information to vehicle in same transaction, or vehicle subsequently contacts server and requests road warning/alert info based on its location and direction. OBU receives queue warning info and determines if a warning is appropriate.</td>
</tr>
<tr>
<td>Mobility</td>
<td>INFLO</td>
<td>Queue Warning (Q-WARN) (DSRC)</td>
<td>DSRC equipped vehicles transmit Basic Safety Messages. RSUs along the corridor receive these messages and a server determines, from them, that a queue is forming at some location on the corridor. RSUs along the corridor broadcast queue warning messages (location and direction). OBUs along corridor receive queue warning messages and determine if a warning/alert is appropriate.</td>
</tr>
<tr>
<td>Mobility</td>
<td>INFLO</td>
<td>Speed Harmonization SPD-HARM (Cellular)</td>
<td>The INFLO SPD-HARM application concept aims to utilize connected vehicle [V2V and V2I] communication to detect the precipitating roadway or congestion conditions that might necessitate speed harmonization, to generate the appropriate response plans and speed recommendation strategies for upstream traffic, and to broadcast such recommendations to the affected vehicles.</td>
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</tr>
<tr>
<td>Mobility</td>
<td>MMITSS</td>
<td>Emergency Vehicle</td>
<td>Emergency vehicle approaching signalized intersection</td>
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<td>Preemption</td>
<td>broadcasts signal preemption/priority request. RSU in vicinity of intersection receives request and, based on state of signal, other preemptions/extensions in progress, and authority of emergency vehicle, determines if the request will be honored. RSU sends response message, and may change the signal timing to support the request.</td>
</tr>
<tr>
<td>Mobility</td>
<td>MMITSS</td>
<td>Freight Signal Priority (FSP)</td>
<td>Freight vehicle approaching signalized intersection broadcasts signal priority request. RSU in vicinity of intersection receives request and, based on state of signal, other preemptions/extensions in progress, and authority of freight vehicle, determines if the request will be honored. RSU sends response message, and may change the signal timing to support the priority request</td>
</tr>
<tr>
<td>Mobility</td>
<td>MMITSS</td>
<td>Intelligent Traffic Signal System (I-SIG)</td>
<td>The use of high-fidelity data collected from vehicles through wireless communications will facilitate accurate measurements and predictions of lane-specific platoon flow, platoon size, and other driving characteristics. Real-time data availability has the potential to transform how traffic signal systems are designed, implemented and monitored. Developing new systems that use data via V2V and V2I wireless communications to control signals in order to maximize flows in real-time can improve traffic conditions significantly. The ISIG plays the role of an over-arching system optimization application, accommodating transit or freight signal priority, preemption, and pedestrian movements to maximize overall arterial network performance. In addition, the interface (or data flow) between arterial signals and ramp meters (essentially traffic signals installed on freeway onramps) must be considered also. Note, however, that the development of ramp metering algorithms — the metering rates to optimize freeway flow — is not included in the scope of this application.</td>
</tr>
<tr>
<td>Mobility</td>
<td>MMITSS</td>
<td>Pedestrian Mobility</td>
<td>MMITSS will facilitate pedestrian mobility at intersections for meeting pedestrians’ special needs or for balanced utilization of the intersection by vehicles and pedestrians. This application will integrate traffic and pedestrian information from roadside or intersection detectors and new forms of data from wirelessly connected pedestrian-carried mobile devices (nomadic devices) to activate dynamic pedestrian signals or to inform pedestrians when to cross and how to remain aligned with the crosswalk based on real-time Signal Phase and Timing (SPAT) information. In some cases, priority will be given to pedestrians, such as handicapped pedestrians that need additional crossing time, or in special conditions (e.g. weather) where pedestrians may warrant priority. This application will enable a “pedestrian call” to be sent to the traffic controller from a nomadic device of registered handicapped pedestrian after confirming the direction and orientation of the roadway that the pedestrian is intending to cross. The MMITSS will be able to manage pedestrian crosswalks when certain predetermined conditions occur in order to improve efficiency of the intersection utilization or to avoid overcrowding pedestrian at intersections.</td>
</tr>
<tr>
<td>Mobility</td>
<td>MMITSS</td>
<td>Transit Signal Priority (TSP)</td>
<td>Transit vehicle approaching signalized intersection broadcasts signal priority request. RSU in vicinity of intersection receives request and, based on state of signal, other</td>
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<tr>
<td>Mobility</td>
<td>R.E.S.C.U.M.E.</td>
<td>Emergency Communications and Evacuation (EVAC) (Cellular)</td>
<td>The purpose of the EVAC application is to facilitate coordination for evacuees. During an incident, the EMA would have the ability to push information such as evacuation orders by evacuation zone to registered users of the system (either those that have pre-registered, or real-time registration during the event) through the EVAC application. The TMC working with the EOC will use the EVAC application to coordinate the listing of available transportation resources to assist with special needs evacuation. The EVAC application will dispatch and route the transportation resources to the appropriate location, while providing communications updates to those individuals in need of assistance. For non-special needs evacuees, the EVAC application will provide evacuation route guidance that accounts for road conditions, traffic conditions, and final destination. If the evacuee intends to go to a shelter or hotel, the EVAC application will provide a shelter matching function to help the evacuee determine where he should go based upon shelter availability and capability (e.g., does the shelter accept pets?). Should the evacuee need a resource such as food or fuel along the evacuation route, the EVAC application can provide recommended stops and will incorporate user input feedback to provide information (though not necessarily validated information) on the availability of the needed resource.</td>
</tr>
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<td>Additionally, the EVAC application will provide a Return of Evacuees Function to provide evacuees with information regarding when they can return to their area of the jurisdiction and provide recommended routes taking into consideration road conditions (i.e., roadway infrastructure and traffic lights).</td>
</tr>
<tr>
<td>AERIS</td>
<td>AERIS</td>
<td>Dynamic Eco-Routing (Cellular)</td>
<td>The Dynamic Eco-Routing application determines the most eco-friendly route, in terms of minimum fuel consumption or emissions, for individual travelers. This application is similar to current navigation systems, which determine the route based on the shortest path or minimum time. This application also recommends routes that produce the fewest emissions or reduce fuel consumption based on historical, real-time, and predicted traffic and environmental data (e.g., prevailing weather conditions).</td>
</tr>
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</tr>
<tr>
<td>AERIS</td>
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<td>Eco-Approach and Departure at a Signalized Intersection</td>
<td>The Eco-Approach and Departure at Signalized Intersections application uses wireless data communications sent from roadside equipment (RSU) to vehicles and encourages green approaches to signalized intersections, including broadcasting signal phase and timing (SPAT) and geographic information description (GID). The application also considers vehicle status messages, sent from nearby vehicles using V2V communications. Upon receiving this information, onboard equipment (OBU) units perform calculations to provide speed advice to the vehicle driver, allowing the driver to adapt the vehicle’s speed to pass the next traffic signal on green or to decelerate to a stop in the most eco-friendly manner. This application also considers a vehicle’s acceleration as it departs from a signalized intersection.</td>
</tr>
<tr>
<td>AERIS</td>
<td>AERIS</td>
<td>Eco-Freight Signal Priority</td>
<td>Freight vehicle approaching signalized intersection broadcasts signal priority request. RSU in vicinity of intersection receives request and, based on state of signal, other preemptions/extensions in progress, environmental factors, and authority of freight vehicle, determines if the request will be honored. RSU sends response message, and may change the signal timing to support the priority request.</td>
</tr>
<tr>
<td>AERIS</td>
<td>AERIS</td>
<td>Eco-Integrated Corridor Management Decision Support System (Cellular)</td>
<td>The Eco-Integrated Corridor Management Decision Support System application involves using historical, real-time, and predictive traffic and environmental data on arterials, freeways, and transit systems to determine operational decisions that are environmentally beneficial to the corridor. The Eco-Integrated Corridor Management (Eco-ICM) Decision Support System is a data-fusion system that collects information from various multimodal systems. Data from these systems is then used to determine operational strategies for arterials, freeways, and transit that minimize the environmental impact of the corridor. For example, on a code red air quality day, the Eco-ICM Decision Support System may recommend eco-signal timing plans, eco-</td>
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<td>Eco-Integrated Corridor Management Decision Support System (DSRC)</td>
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</tr>
<tr>
<td>AERIS</td>
<td>AERIS</td>
<td>Eco-Speed Harmonization (Cellular)</td>
<td>Vehicle contacts server and provides speed and location data. Back office app (server) determines optimal speed for traffic flow to minimize environmental impact. Server provides this information to vehicle in same transaction, or vehicle subsequently contacts server and requests road info based on its location and direction. Vehicle OBU receives speed info and informs driver about optimal speed.</td>
</tr>
<tr>
<td>AERIS</td>
<td>AERIS</td>
<td>Eco-Speed Harmonization (DSRC)</td>
<td>Vehicles broadcast speed and location data (BSM) RSU receives BSMs and either determines optimal speed locally (at RSU) or sends info to back office. Local or back office app determines optimal speed for traffic to minimize environmental impact, and sends this to the RSUs in the area. RSUs broadcast speed advisories to vehicles. Vehicles inform drivers about optimal speed.</td>
</tr>
<tr>
<td>AERIS</td>
<td>AERIS</td>
<td>Eco-Traffic Signal Timing</td>
<td>Vehicles Broadcast data such as vehicle location, speed, GHG and other emissions data to RSUs. RSU application (or remote app at TMC) determines the optimal operation of the traffic signal system based on the data, and adjusts the signal system timing.</td>
</tr>
<tr>
<td>AERIS</td>
<td>AERIS</td>
<td>Eco-Transit Signal Priority</td>
<td>Transit vehicle approaching signalized intersection broadcasts signal priority request. RSU in vicinity of intersection receives request and, based on state of signal, other preemptions/extensions in progress, environmental factors, and authority/schedule of transit vehicle, determines if the request will be honored. RSU sends response message, and may change the signal timing to support the priority request.</td>
</tr>
<tr>
<td>Smart Roadside</td>
<td>Smart Roadside</td>
<td>E-Screening / Virtual Weigh Station (Cellular)</td>
<td>E-Screening is a key component of the information collection systems and communications networks that support commercial vehicle operation – referred to as the Commercial Vehicle Information Systems and Networks (CVISN). E-Screening defined at the highest-level is when a commercial vehicle is identified automatically and assessed for safety while the vehicle is in motion. With E-Screening, safe and legal vehicles are allowed to continue on their route. Enforcement resources can be used to target unsafe vehicles and carriers. Currently, E-Screening occurs at fixed stations and on-demand verification sites. Truck Size and Weight researchers conducted an Enforcement Study in 2008 and 2009 to develop the foundation for roadside technologies that can</td>
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</tr>
<tr>
<td><strong>Smart Roadside</strong></td>
<td><strong>Smart Roadside</strong></td>
<td>Smart Truck Parking (Cellular)</td>
<td>Truck Parking research currently includes two projects, which will provide commercial vehicle parking information so that commercial drivers can make advanced route planning decisions based on hour-of-service constraints, location and supply of parking, travel conditions, and loading/unloading.</td>
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<td><strong>Smart Roadside</strong></td>
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<td>Wireless Roadside Inspection (Cellular)</td>
<td>WRI research is being done to increase the number and frequency of safety inspections at the roadside and obtain data about the commercial vehicle and its driver. This safety data is termed the Safety Data Message Set (SDMS) and can be transmitted directly from the vehicle to the roadside and from a carrier system to a government system. The initial SDMS will contain basic identification data (for driver, vehicle, and carrier), the driver’s log, a small set of vehicle measurement data, and selected vehicle status information. Enforcement systems and staff will use the SDMS to support E-Screening and inspections at locations such as staffed roadside sites, virtual weigh stations, and on-demand verification sites.</td>
</tr>
<tr>
<td><strong>Smart Roadside</strong></td>
<td><strong>Smart Roadside</strong></td>
<td>Wireless Roadside Inspection (DSRC)</td>
<td>WRI research is being done to increase the number and frequency of safety inspections at the roadside and obtain data about the commercial vehicle and its driver. This safety data is termed the Safety Data Message Set (SDMS) and can be transmitted directly from the vehicle to the roadside and from a carrier system to a government system. The initial SDMS will contain basic identification data (for driver, vehicle, and carrier), the driver’s log, a small set of vehicle measurement data, and selected vehicle status information. Enforcement systems and staff will use the SDMS to support E-Screening and inspections at locations such as staffed roadside sites, virtual weigh stations, and on-demand verification sites.</td>
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<td>carrier system to a government system. The initial SDMS will contain basic identification data (for driver, vehicle, and carrier), the driver’s log, a small set of vehicle measurement data, and selected vehicle status information. Enforcement systems and staff will use the SDMS to support E-Screening and inspections at locations such as staffed roadside sites, virtual weigh stations, and on-demand verification sites.</td>
</tr>
<tr>
<td>IBC</td>
<td>IBC</td>
<td>Approach Lane Use Management</td>
<td>One of the contributing factors to long wait times at international border crossings is improper management of approach lanes where different types of vehicles (e.g., trucks, cars, NEXUS, FAST, non-SENTRI) merge and cross paths. Lanes are segregated close to the inspection facilities, but not further inland. This situation is especially true in MX. With adequate density of OBUs, wait times of different lane types can be estimated and subsequently directed to appropriate lanes. RSUs to identify OBUs could be fixed or portable, but backhaul to central location is optional since approach management can be done locally. Lane level mapping support will be required to identify different approach lanes. Siting dependencies of RSUs are not critical if OBUs can be read in any direction. Management of data collected by RSUs is not required and so is the back office service since a central server connected to all RSUs can evaluate approach lane management strategies and send messages to overhead signs and OBUs inside vehicles. Data connection between vehicle and OBU is not required. Larger deployment of OBUs more effective would be lane approach management strategies because they would require accurate estimation of vehicular volume on different approach lanes.</td>
</tr>
<tr>
<td>IBC</td>
<td>IBC</td>
<td>Automated Toll/User Fee Collection and Administration</td>
<td>Majority of border crossings are tolled in different ways (e.g., cash, electronic) by local government agencies. Commercial vehicles to enter US also have to purchase user fees from CBP, which in turn provides RFID transponder (sticker) to identify these vehicles. Similar to highway tolling operation, physical location of RSUs are fixed with backhaul communication to a central location to credit toll usage. Latency is critical since toll collections are typically done close to Federal facility and faster toll collection means less chance of longer queue to the Federal facility. Vehicle to OBU is not required. However, larger deployments of OBUs, toll collection agencies will find it to be more cost effective.</td>
</tr>
<tr>
<td>IBC</td>
<td>IBC</td>
<td>Automated Toll/User Fee Collection and Administration (DSRC)</td>
<td>Vehicle encounters RSU at or prior to tolled facility (bridge, roadway entrance, etc.); RSU announces toll requirement. Vehicle sends request for toll payment (possibly indicating type of vehicle) to RSU. RSU executes payment (either directly or via back office account transaction). RSU provides receipt (generally including occupancy data) to vehicle. During subsequent RSU encounters on tolled facility, RSU requests validation of paid toll; vehicle sends receipt to RSU to avoid enforcement actions.</td>
</tr>
<tr>
<td>IBC</td>
<td>IBC</td>
<td>Border Crossing Performance Monitoring</td>
<td>Border crossing performance monitoring is primarily based on wait and crossing times experienced by vehicles crossing the border. This application is directly tied to Wait Time and Traveler Information application. The same RSUs and OBUs can be used for both applications. Backhaul communication is required to send the identification information to a central database. Lane level</td>
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<td>mapping support will be required since different types of lanes are designated based on various programs implemented by Federal agencies (e.g., FAST, NEXUS/SENTRI, READY). Location of RSUs or siting dependency is not critical if OBUs as long as a good sample of OBUs can be identified. Management of collected is required, however back office services are not critical since database can be maintained with significant downtime because performance measurement does not have a real-time need. The same latency that applies to Wait Time application applies here as well. OBU does not communicate with the vehicle. Because statistically significant sample is required, benefits require minimum threshold of deployment.</td>
</tr>
<tr>
<td>IBC</td>
<td>IBC</td>
<td>Excess Emission Identification from Trucks and Cars [Emissions Analysis]</td>
<td>Goal is to identify vehicles with unacceptable emissions levels at border crossings. Data from the vehicle’s engine management system is sent to infrastructure. Emissions are rated and a message sent to locals to hold or pass vehicle as appropriate. Very likely interface to local external sensors.</td>
</tr>
<tr>
<td>IBC</td>
<td>IBC</td>
<td>Excess Emission Reduction from Trucks and Cars [Emissions Analysis]</td>
<td>Long wait times at international border crossings have contributed to proliferation of greenhouse gas and particle matter emissions for communities close to the border. This situation is especially true in MX. Idling and emissions data from properly designed CAN bus and OBUs can be read by RSUs to estimate environmental performance of border crossings. RSUs would send the data collected from OBUs to a central location. Siting dependencies of RSUs are not critical if OBUs can be read in any direction. Management of data collected by RSUs is not required and so is the back office service since a central server connected to all RSUs can determine environmental performance parameters using a pre-designed algorithms and data warehouse. Data connection between vehicle and OBU is required to send CAN bus data and other emissions data. The larger the deployment of OBUs the more samples would be available for more precise estimation of emissions.</td>
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<tr>
<td>IBC</td>
<td>IBC</td>
<td>HAZMAT Monitoring and Response</td>
<td>Millions of tons of HAZMAT cross the international border daily, which has created HAZMAT corridors going through border towns and cities. Responding to HAZMAT related incidents typically fall under the jurisdictions of local governments (and some state/province). However, they have no clue as to where, how, what kind of HAZMAT will be passing through their jurisdictions. On the one hand Federal agencies (CBP, CBSA, Aduanas) know before HAZMAT arrives at the border. The information can be easily shared with local agencies, but they would also want to know the fidelity of the HAZMAT being transported so that they can prepare necessary resources to respond to HAZMAT incidents. Companies have developed OBUs that monitor vital stats of the HAZMAT content, which can be easily transmitted through RSUs and on to local agencies. These RSUs can be fixed or portable with backhaul communication to inform first responders. Road network level mapping support would be required with non-critical siting dependencies. At this time, there is no critical need to manage data collected by RSUs and have a back office service. Latency to read OBUs in milliseconds is not critical. HAZMAT content sensors would be connected to other</td>
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<tr>
<td>IBC</td>
<td>IBC</td>
<td>Pre-Clearance, Expedited Screening of Cars and Trucks</td>
<td>The purpose of this application is electronically screen carriers, shippers, motorists, and vehicles while they enter US, CA, MX border with a goal of reducing long wait times at border and for enforcement agencies to focus resources on high value targets. Pre-clearance of vehicles can only be performed at certain fixed locations e.g., CBP, CBSA, Aduana, FMCSA inspection facilities. Backhaul communication is required to query identified vehicles and bring up security and safety related information back to terminals to inspection officers. Mapping support is not required since proximity between RSU and vehicles with OBU would be enough. Location of RSUs or siting dependency is critical since OBUs should be read at close to 100% rate. Management and back office services and applications are required to secure and maintain databases and also integrate with other security related databases shared between international, federal and state agencies. Latency does not have to be in milliseconds, but should not be in minutes either. OBU does not have to communicate with the vehicle.</td>
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<tr>
<td>IBC</td>
<td>IBC</td>
<td>Shipment (Trailer) Tamper Monitoring [Cargo Security]</td>
<td>One of the biggest concerns of Federal enforcement agencies in all three countries is the fidelity of trailers or containers crossing the border. The big question is &quot;are they carrying what they had reported to the agencies that they would be carrying?&quot; Trailers can be easily tampered without the knowledge of shippers en-route. To reduce tampering, fidelity of trailers can be read at fixed locations or preferably portable locations and information sent to a central location to verify that the trailer has not deviated from its original route or opened by unauthorized personnel. Tamper seals constantly communicate with OBUs, which will alert carrier/shipper and enforcement agencies through RSUs. Backhaul could happen through cellular network or through wireline communication depending on where RSUs are placed and how they are connected to a central repository. Road level mapping support is sufficient, and RSUs do not have siting dependencies unless they can receive data from OBUs even with some latency.</td>
</tr>
<tr>
<td>IBC</td>
<td>IBC</td>
<td>Truck Safety Condition Monitoring and Reporting</td>
<td>Millions of trucks cross the border every day and enter local/state/provincial roadways. Their safety is important to rest of the traveling public. Millions of labor hours are spent on random inspections of trucks by agencies in all three countries. If OBU can be integrated with a vehicle CAN bus, then some vehicle diagnostic information (e.g., brake conditions, engine conditions) can be relayed back to carriers/drivers and enforcement officers to remove unfit vehicles from crossing the border. Information on truck's diagnostics and physical condition along with its identification information will be read at fixed locations e.g., FMCSA and state/provincial inspection facilities and provided to enforcement officers for review. Backhaul communication is required to query historical safety records of carriers, drivers. Mapping support is not required since proximity between RSU and vehicles with OBU would be enough. Location of RSUs or siting dependency is critical since OBUs should be read at close to 100% rate. Management of collected data is required to update archive of safety related databases and citation records. Latency</td>
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<tr>
<td>IBC</td>
<td>IBC</td>
<td>Wait Time and Other Traveler Information</td>
<td>Wait times for vehicles crossing the border are measured by identifying a sample of vehicles at several fixed locations while they are waiting to cross the border. Backhaul communication is required to send the identification information to a central database. Lane level mapping support will be required since different types of approach lanes are designated based on various programs implemented by Federal agencies (e.g., FAST, NEXUS/SENTRI, READY). Location of RSUs or siting dependency is not critical for OBUs as long as a good sample of OBUs can be identified. Management and back office services and applications are required to secure and maintain databases and provide expected wait and crossing times of vehicles to motorists, and other users. Latency does not have to be in milliseconds, but should not be in minutes either. OBU does not have to communicate with the vehicle. Because statistically significant sample is required, benefits require minimum threshold of deployment.</td>
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</table>

| Road Weather | Road Weather | [Weather] Information for Freight Carriers (Cellular) | This application can be considered a special case of the Road-Weather Motorist Advisory and Warning System. Truck drivers have similar access to the variety of traveler information systems that are available to all road users. However, the available traveler information options are almost always intended for use by passenger car drivers. The limitations of the existing systems with respect to the type and quality of information provided have particular impacts on motor carriers. |

| Road Weather | Road Weather | [Weather] Information for Freight Carriers (DSRC) | This application can be considered a special case of the Road-Weather Motorist Advisory and Warning System. Truck drivers have similar access to the variety of traveler information systems that are available to all road users. However, the available traveler information options are almost always intended for use by passenger car drivers. The limitations of the existing systems with respect to the type and quality of information provided have particular impacts on motor carriers. |

| Road Weather | Road Weather | Enhanced Maintenance Decision Support System (Cellular) | Enhanced Maintenance Decision Support System will provide the existing federal prototype MDSS with expanded data acquisition from connected vehicles. Snow plows, other agency fleet vehicles, and other vehicles operated by the general public will provide road-weather connected vehicle data to the Enhanced-MDSS, which will use this data to generate improved plans and recommendations to maintenance personnel. In turn, enhanced treatment plans and recommendations will be provided back to the snow plow operators and drivers of agency maintenance vehicles. |

<p>| Road Weather | Road Weather | Enhanced Maintenance Decision Support System (DSRC) | Enhanced Maintenance Decision Support System will provide the existing federal prototype MDSS with expanded data acquisition from connected vehicles. Snow plows, other agency fleet vehicles, and other vehicles operated by the general public will provide road-weather connected vehicle data to the Enhanced-MDSS, which will use this data to generate improved plans and recommendations to maintenance personnel. In turn, enhanced treatment plans and recommendations will be provided back to the |</p>
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<tr>
<td>Road Weather</td>
<td>Road Weather</td>
<td>Information and Routing Support for Emergency Responders (Cellular)</td>
<td>Emergency responders, including ambulance operators, paramedics, and fire and rescue companies, have a compelling need for the short, medium, and long time horizon road-weather alerts and warnings. This information can help drivers safely operate their vehicles during severe weather events and under deteriorating road conditions. Emergency responders also have a particular need for information that affects their dispatching and routing decisions. Information on weather-impacted travel routes, especially road or lane closures due to snow, flooding, and wind-blow debris, is particularly important. Low latency road-weather information from connected vehicles for specific roadway segments, together with information from other surface weather observation systems, such as flooding and high winds, will be used to determine response routes, calculate response times, and influence decisions to hand-off an emergency call from one responder to another responder in a different location.</td>
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<tr>
<td>Road Weather</td>
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<td>Information and Routing Support for Emergency Responders (DSRC)</td>
<td>Emergency responders, including ambulance operators, paramedics, and fire and rescue companies, have a compelling need for the short, medium, and long time horizon road-weather alerts and warnings. This information can help drivers safely operate their vehicles during severe weather events and under deteriorating road conditions. Emergency responders also have a particular need for information that affects their dispatching and routing decisions. Information on weather-impacted travel routes, especially road or lane closures due to snow, flooding, and wind-blow debris, is particularly important. Low latency road-weather information from connected vehicles for specific roadway segments, together with information from other surface weather observation systems, such as flooding and high winds, will be used to determine response routes, calculate response times, and influence decisions to hand-off an emergency call from one responder to another responder in a different location.</td>
</tr>
<tr>
<td>Road Weather</td>
<td>Road Weather</td>
<td>Information for Maintenance and Fleet Management Systems (Cellular)</td>
<td>In this concept, connected vehicle information is more concerned with non-road-weather data. The data collected may include powertrain diagnostic information from maintenance and specialty vehicles; the status of vehicle components; the current location of maintenance vehicles and other equipment; and the types and amounts of materials onboard maintenance vehicles, and will be used to automate the inputs to Maintenance and Fleet Management Systems on year-round basis. In addition, desirable synergies can be achieved if selected data relating to winter maintenance activities, such as the location and status of snow plows or the location and availability of deicing chemicals, can be passed to an Enhanced-MDSS to refine the recommended winter weather response plans and treatment strategies.</td>
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<tr>
<td>Road Weather</td>
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<td>Information for Maintenance and Fleet Management Systems (DSRC)</td>
<td>In this concept, connected vehicle information is more concerned with non-road-weather data. The data collected may include powertrain diagnostic information from maintenance and specialty vehicles; the status of vehicle components; the current location of maintenance vehicles and other equipment; and the types and amounts of materials onboard maintenance vehicles, and will be used to automate the inputs to Maintenance and Fleet</td>
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<tr>
<td>Road Weather</td>
<td>Road Weather</td>
<td>Motorist Advisories and Warnings (Cellular)</td>
<td>Information on segment-specific weather and road conditions is not broadly available, even though surveys suggest that this information is considered to be of significant importance to travelers. The ability to gather road-weather information from connected vehicles will dramatically change this situation. Information on deteriorating road and weather conditions on specific roadway segments can be pushed to travelers through a variety of means as alerts and advisories within a few minutes. In combination with observations and forecasts from other sources and with additional processing, medium-term advisories of the next two to twelve hours to long-term advisories for more than twelve hours into the future can also be provided to motorists.</td>
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<tr>
<td>Road Weather</td>
<td>Road Weather</td>
<td>Motorist Advisories and Warnings (DSRC)</td>
<td>Information on segment-specific weather and road conditions is not broadly available, even though surveys suggest that this information is considered to be of significant importance to travelers. The ability to gather road-weather information from connected vehicles will dramatically change this situation. Information on deteriorating road and weather conditions on specific roadway segments can be pushed to travelers through a variety of means as alerts and advisories within a few minutes. In combination with observations and forecasts from other sources and with additional processing, medium-term advisories of the next two to twelve hours to long-term advisories for more than twelve hours into the future can also be provided to motorists.</td>
</tr>
<tr>
<td>Road Weather</td>
<td>Road Weather</td>
<td>Variable Speed Limits for Weather-Responsive Traffic Management (Cellular)</td>
<td>Connected vehicle systems provide opportunities to enhance the operation of VSL systems and dramatically improve work zone safety during severe weather events. Additional road-weather information can be gathered from connected vehicles and used in algorithms to refine the posted speed limits to reflect prevailing weather and road conditions.</td>
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<td>Road Weather</td>
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<td>Variable Speed Limits for Weather-Responsive Traffic Management (DSRC)</td>
<td>Connected vehicle systems provide opportunities to enhance the operation of VSL systems and dramatically improve work zone safety during severe weather events. Additional road-weather information can be gathered from connected vehicles and used in algorithms to refine the posted speed limits to reflect prevailing weather and road conditions.</td>
</tr>
<tr>
<td>Agency Data Applications</td>
<td>CV-enabled Traffic Studies</td>
<td>CV-enabled Origin-Destination Studies (Cellular)</td>
<td>Obtain a general location near a vehicle's start and end of trip, provides path in between.</td>
</tr>
<tr>
<td>Agency Data Applications</td>
<td>CV-enabled Traffic Studies</td>
<td>CV-enabled Origin-Destination Studies (DSRC)</td>
<td>Obtain a general location near a vehicle's start and end of trip, or when the vehicle passes certain locations (freeway on ramps and off ramps).</td>
</tr>
<tr>
<td>Agency Data Applications</td>
<td>CV-enabled Traffic Studies</td>
<td>CV-enabled Traffic Model Baselining &amp; Predictive Traffic Studies (DSRC)</td>
<td>Vehicles provide speed information as a function of location and time in order to build a baseline model for analysis, optimized timing plans and predictive studies. Does not require real time connection for the model, real time traffic necessary to capture perturbations to the model.</td>
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<td>Application Group</td>
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<tr>
<td>Agency Data</td>
<td>CV-enabled Traffic</td>
<td>CV-enabled Turning Movement &amp; Intersection Analysis (DSRC)</td>
<td>Use self-reported paths of vehicles to determine turning ratios, delays by maneuver and other characterizations of an intersection. Not intended for real time optimization of traffic flows. No data provided to vehicles.</td>
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<tr>
<td>Applications</td>
<td>Traffic Studies</td>
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<tr>
<td>Agency Data</td>
<td>CV-enabled Traffic</td>
<td>Vehicle classification-based Traffic Studies (DSRC)</td>
<td>Ability to associate vehicle type with vehicle behaviors.</td>
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<tr>
<td>Applications</td>
<td>Studies</td>
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<tr>
<td>Agency Data</td>
<td>Probe Data</td>
<td>Probe-based Pavement Maintenance (Cellular)</td>
<td>Vehicles report the location (and size) of potholes or gross surface roughness. Detection based on vertical wheel movement or body acceleration. Provides quantitative measurement of road quality. Would require additional data for normalization.</td>
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<tr>
<td>Applications</td>
<td>Probe Data</td>
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<tr>
<td>Agency Data</td>
<td>Probe Data</td>
<td>Probe-enabled Traffic Monitoring (Cellular)</td>
<td>Real Time traffic data supplied by connected vehicles.</td>
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<td>Applications</td>
<td>Probe Data</td>
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<tr>
<td>Agency Data</td>
<td>Probe Data</td>
<td>Probe-enabled Traffic Monitoring (DSRC)</td>
<td>Real Time traffic data supplied by connected vehicles.</td>
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<tr>
<td>Applications</td>
<td>Probe Data</td>
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<tr>
<td>Fee Payment</td>
<td>Fee Payment</td>
<td>Congestion Pricing</td>
<td>RSU at boundary of congestion management area sends out announcement that vehicles entering the area will be charged a specified toll/fee. Vehicles send request for fee payment to RSU, and RSU communicates with Back office system to execute payment transaction. Back office provides payment receipt to RSU, and RSU forwards receipt to vehicle. During subsequent RSU encounters, RSU requests validation of paid toll; vehicle sends receipt to RSU to avoid enforcement actions.</td>
</tr>
<tr>
<td>Fee Payment</td>
<td>Fee Payment</td>
<td>High-occupancy Toll Lanes (DSRC)</td>
<td>Vehicle encounters RSU at or prior to entry to HOT lane; Vehicle sends request for entry to HOT Lane to RSU. Request may include statement of vehicle occupancy. RSU executes payment (either directly or via back office account transaction). RSU provides receipt (generally including occupancy data) to vehicle. During subsequent RSU encounters RSU requests validation of paid toll; vehicle sends receipt to RSU to avoid enforcement actions.</td>
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## APPENDIX C. ACRONYMS

<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ABS</td>
<td>Antilock Braking System</td>
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<tr>
<td>AACN</td>
<td>Advanced Automatic Crash Notification</td>
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<tr>
<td>AASHTO</td>
<td>American Association of State Highway and Transportation Officials</td>
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<tr>
<td>AERIS</td>
<td>Applications for the Environment: Real-Time Information Synthesis</td>
</tr>
<tr>
<td>ASC</td>
<td>Adaptive signal control</td>
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<tr>
<td>ATIS</td>
<td>Advanced Traveler Information Systems</td>
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<tr>
<td>AVI</td>
<td>Automatic Vehicle Identification</td>
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<tr>
<td>BLOB</td>
<td>Binary Large OBject</td>
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<tr>
<td>BMM</td>
<td>Basic Mobility Message</td>
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<tr>
<td>BSM</td>
<td>Basic Safety Message</td>
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<tr>
<td>BWT</td>
<td>Border wait time</td>
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<tr>
<td>CACC</td>
<td>Cooperative Adaptive Cruise Control</td>
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<tr>
<td>CBP</td>
<td>Customs and Border Protection</td>
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<tr>
<td>CBSA</td>
<td>Canadian Border Services Administration</td>
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<tr>
<td>CCTV</td>
<td>Closed caption television</td>
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<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
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<tr>
<td>CE</td>
<td>Consumer electronic</td>
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<tr>
<td>CFR</td>
<td>Code of Federal Regulations</td>
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<tr>
<td>CICAS</td>
<td>Cooperative Intersection Collision Avoidance System</td>
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<td>COV</td>
<td>Commercially-operated vehicle</td>
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<td>Acronym</td>
<td>Description</td>
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<tr>
<td>CRL</td>
<td>Certificate Revocation List</td>
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<td>CSMA</td>
<td>Carrier sense multiple access</td>
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<td>CVISN</td>
<td>Commercial Vehicle Information Systems and Networks</td>
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<tr>
<td>CVRIA</td>
<td>Connected Vehicle Reference Implementation Architecture</td>
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<tr>
<td>DHCP</td>
<td>Dynamic Host Configuration Protocol</td>
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<tr>
<td>DMA</td>
<td>Dynamic Mobility Applications</td>
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<tr>
<td>DMS</td>
<td>Dynamic message sign</td>
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<tr>
<td>DOT</td>
<td>Department of Transportation</td>
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<tr>
<td>DRG</td>
<td>Dynamic Route Guidance</td>
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<tr>
<td>D-RIDE</td>
<td>Dynamic Ridesharing</td>
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<tr>
<td>DR-OPT</td>
<td>Drayage Optimization</td>
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<tr>
<td>DSL</td>
<td>Digital subscriber line</td>
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<tr>
<td>DSRC</td>
<td>Dedicated Short Range Communications</td>
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<tr>
<td>ERP</td>
<td>Effective radiated power</td>
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<tr>
<td>ESS</td>
<td>Environmental sensor station</td>
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<tr>
<td>ETC</td>
<td>Electronic toll collection</td>
</tr>
<tr>
<td>[EV] DRG</td>
<td>Dynamic Routing of Emergency Vehicles</td>
</tr>
<tr>
<td>EVAC</td>
<td>Emergency Communications and Evacuation</td>
</tr>
<tr>
<td>F-ATIS</td>
<td>Freight Real-time Traveler Information with Performance Monitoring</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>F-DRG</td>
<td>Freight Dynamic Route Guidance</td>
</tr>
<tr>
<td>FHWA</td>
<td>Federal Highway Administration</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
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</tr>
<tr>
<td>FMCSA</td>
<td>Federal Motor Carrier Safety Administration</td>
</tr>
<tr>
<td>FRATIS</td>
<td>Freight Advanced Traveler Information Systems</td>
</tr>
<tr>
<td>FSP</td>
<td>Freight Signal Priority</td>
</tr>
<tr>
<td>FTA</td>
<td>Federal Transit Administration</td>
</tr>
<tr>
<td>FTE</td>
<td>Full-Time Equivalent (labor allocation)</td>
</tr>
<tr>
<td>GID</td>
<td>Geometric intersection description</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite Systems</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>HAR</td>
<td>Highway advisory radio</td>
</tr>
<tr>
<td>HAZMAT</td>
<td>Hazardous Material</td>
</tr>
<tr>
<td>HOT</td>
<td>High Occupancy Tolling</td>
</tr>
<tr>
<td>I2V</td>
<td>Infrastructure-to-vehicle</td>
</tr>
<tr>
<td>IBC</td>
<td>International Border Crossing</td>
</tr>
<tr>
<td>IDTO</td>
<td>Integrated Dynamic Transit Operations</td>
</tr>
<tr>
<td>INC-ZONE</td>
<td>Incident Scene Workzone Alerts for Drivers and Workers</td>
</tr>
<tr>
<td>INFLO</td>
<td>Integrated Network Flow Optimization</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>IPv4</td>
<td>Internet Protocol version 4</td>
</tr>
<tr>
<td>IPv6</td>
<td>Internet Protocol version 6</td>
</tr>
<tr>
<td>I-SIG</td>
<td>Intelligent Traffic Signal System</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
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</tr>
<tr>
<td>ITIS</td>
<td>International Traveler Information Systems</td>
</tr>
<tr>
<td>ITS</td>
<td>Intelligent Transportation Systems</td>
</tr>
<tr>
<td>ITS JPO</td>
<td>Intelligent Transportation Systems Joint Program Office</td>
</tr>
<tr>
<td>LAN</td>
<td>Local area network</td>
</tr>
<tr>
<td>LPR</td>
<td>License Plate Reader</td>
</tr>
<tr>
<td>LTE</td>
<td>Long-term Evolution; a type of 4G cellular network</td>
</tr>
<tr>
<td>MAC</td>
<td>Media Access Control</td>
</tr>
<tr>
<td>M-ISIG</td>
<td>Multi-Modal Intelligent Traffic Signal System</td>
</tr>
<tr>
<td>MDSS</td>
<td>Maintenance Decision Support System</td>
</tr>
<tr>
<td>MHz</td>
<td>Megahertz</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
</tr>
<tr>
<td>MMITSS</td>
<td>Multi-Modal Intelligent Traffic Signal System</td>
</tr>
<tr>
<td>MS</td>
<td>Mobile station</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean time between failures</td>
</tr>
<tr>
<td>MTU</td>
<td>Maximum Transmission Unit</td>
</tr>
<tr>
<td>MUTCD</td>
<td>Manual on Uniform Traffic Control Devices</td>
</tr>
<tr>
<td>NCFRP</td>
<td>National Cooperative Freight Research Program</td>
</tr>
<tr>
<td>NHS</td>
<td>National Highway System</td>
</tr>
<tr>
<td>NHTSA</td>
<td>National Highway Traffic Safety Administration</td>
</tr>
<tr>
<td>NTCIP</td>
<td>National Transportation Communications for ITS Protocol</td>
</tr>
<tr>
<td>OBD</td>
<td>On-board diagnostics</td>
</tr>
<tr>
<td>OBE</td>
<td>On-board Equipment</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>PED-SIG</td>
<td>Mobile Accessible Pedestrian Signal System</td>
</tr>
<tr>
<td>PKI</td>
<td>Public key infrastructure</td>
</tr>
<tr>
<td>POE</td>
<td>Point/Port of Entry</td>
</tr>
<tr>
<td>PoE</td>
<td>Power over Ethernet</td>
</tr>
<tr>
<td>POV</td>
<td>Privately-operated vehicle</td>
</tr>
<tr>
<td>PREEMPT</td>
<td>Emergency Vehicle Preemption with Proximity Warning</td>
</tr>
<tr>
<td>QPL</td>
<td>Qualified Products List</td>
</tr>
<tr>
<td>Q-WARN</td>
<td>Queue Warning</td>
</tr>
<tr>
<td>RAMP</td>
<td>Next Generation Ramp Metering System</td>
</tr>
<tr>
<td>RAP</td>
<td>Roadside access point</td>
</tr>
<tr>
<td>RDE</td>
<td>Research Data Exchange</td>
</tr>
<tr>
<td>RESP-STG</td>
<td>Incident Scene Pre-Arrival Staging and Guidance for Emergency Responders</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio frequency identification</td>
</tr>
<tr>
<td>RITA</td>
<td>Research and Innovative Technology Administration</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received Signal Strength Indication</td>
</tr>
<tr>
<td>RSE</td>
<td>Roadside Equipment</td>
</tr>
<tr>
<td>RTCM</td>
<td>Radio Technical Commission for Maritime Services</td>
</tr>
<tr>
<td>RWIS</td>
<td>Road Weather Information System</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single Carrier – Frequency Division Multiple Access</td>
</tr>
<tr>
<td>SDARS</td>
<td>Satellite Digital Audio Radio Service</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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</tr>
<tr>
<td>S-PARK</td>
<td>Smart Park and Ride</td>
</tr>
<tr>
<td>SPAT</td>
<td>Signal phase and timing</td>
</tr>
<tr>
<td>SPD-HARM</td>
<td>Dynamic Speed Harmonization</td>
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<tr>
<td>T-CONNECT</td>
<td>Connection Protection</td>
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<tr>
<td>T-DISP</td>
<td>Dynamic Transit Operations</td>
</tr>
<tr>
<td>TFE</td>
<td>Transportation field equipment</td>
</tr>
<tr>
<td>TIS</td>
<td>Transportation information system</td>
</tr>
<tr>
<td>T-MAP</td>
<td>Universal Map Application</td>
</tr>
<tr>
<td>TBD</td>
<td>To Be Determined</td>
</tr>
<tr>
<td>TMC</td>
<td>Traffic Management Center</td>
</tr>
<tr>
<td>TSA</td>
<td>Transportation Security Administration</td>
</tr>
<tr>
<td>TSP</td>
<td>Transit Signal Priority</td>
</tr>
<tr>
<td>USDOT</td>
<td>United States Department of Transportation</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra-wideband</td>
</tr>
<tr>
<td>V2I</td>
<td>Vehicle-to-infrastructure</td>
</tr>
<tr>
<td>V2V</td>
<td>Vehicle-to-vehicle</td>
</tr>
<tr>
<td>VII</td>
<td>Vehicle Infrastructure Integration</td>
</tr>
<tr>
<td>VIN</td>
<td>Vehicle Identification Number</td>
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<tr>
<td>VoIP</td>
<td>Voice over IP</td>
</tr>
<tr>
<td>WAN</td>
<td>Wide area network</td>
</tr>
<tr>
<td>WAVE</td>
<td>Wireless Access in Vehicular Environments</td>
</tr>
<tr>
<td>Wi-Fi</td>
<td>Wireless Fidelity</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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</tr>
<tr>
<td>WIM</td>
<td>Weigh-in-Motion</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless local area network</td>
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<tr>
<td>WSA</td>
<td>WAVE Service Announcement</td>
</tr>
<tr>
<td>WSM</td>
<td>WAVE Short Message</td>
</tr>
<tr>
<td>WSMP</td>
<td>WAVE Short Message Protocol</td>
</tr>
<tr>
<td>WWAN</td>
<td>Wireless wide area network</td>
</tr>
<tr>
<td>WX</td>
<td>Weather</td>
</tr>
<tr>
<td>WX-INFO</td>
<td>Real-Time Route Specific Weather Information for Motorized and Non-Motorized Vehicles</td>
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</tbody>
</table>