Southwest Region University Transportation Center

Potential Connected Vehicle Applications to Enhance Mobility, Safety, and Environmental Security

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16. Abstract

The connected vehicle research initiative is the core of the U.S. Department of Transportation's intelligent transportation system research program. The initiative is beginning to gain momentum in the research community because of the development of a promising wireless communications technology—dedicated short-range communications. Connected vehicle technology has the potential to transform the transportation industry and significantly improve the quality of life of drivers. This study aims to explore the potential uses of connected vehicle technology in real-world settings.

Researchers first conducted a comprehensive review of the state-of-the-art connected-vehicle research and technologies. Once researchers had a thorough understanding of the technology, they focused on selecting and developing the near-term practical applications that use connected vehicle technology. The research team then sought expert opinions from the Texas Transportation Institute working group during two brainstorming sessions, which produced two lists of potential applications and prioritized the applications based on deployment feasibility. In particular, a total of five applications were selected for development of the full concept of operations, including two in safety, two in mobility, and one in environmental security. These applications address various problems, including wrong-way driving and unprotected-grade-crossing crashes (safety); work-zone merge efficiency and safety, and freeway speed harmonization (mobility); and slippery-pavement-related crashes (environmental security).

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Potential Connected Vehicle Applications to Enhance Mobility, Safety, and Environmental Security

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ABSTRACT

As the core of the US Department of Transportation's ITS research program, the Connected Vehicle initiative begins to gain momentums in the research communities due to the early development of a promising wireless communications technology. The technology, namely the Connected Vehicle technology, has the potential to transform the transportation industry and significantly improve the quality of life on the wheel. This study aims to explore the potential uses of the Connected Vehicle technology in the real-world settings. The researchers first conducted a comprehensive review on the states of the Connected Vehicle research and technologies. With thorough understanding of the current states, the researchers focused on selecting and developing the near-term practical applications that utilizes the Connected Vehicle technology. Expert opinions were then sought from the TTI working group in two brainstorming sessions, and two lists of potential applications were resulted and prioritized based on their applicability. In particular, a total of five applications have been selected for full concept of operations development, including two in safety, two in mobility and one in environmental protection. They have respectively addressed various problems, including wrong-way driving, unprotected grade-crossing crashes, work zone merge efficiency and safety, freeway speed harmonization, and slippery pavement-related crashes.

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EXECUTIVE SUMMARY

The Connected Vehicle research initiative is the latest U.S. Department of Transportation (USDOT) intelligent transportation system (ITS) research focus and is the core of the current ITS research program. The research on the Connected Vehicle concept is supported by the recent development and prototyping of a particular type of wireless communications technology, dedicated short-range communications (DSRC). Since the introduction of the technology more than a decade ago, the program has led a number of major ITS initiatives, including the Vehicle Infrastructure Initiative (VII), to test the potential of this communications technology to improve vehicular safety. Given the promising study results, USDOT then extended the scope of VII to a new initiative, the Connected Vehicle, in 2009. The Connected Vehicle initiative seeks broader applications of the technologies that address transportation problems related not only to safety but also to mobility and the environment.

This study aims to explore the potential uses of the Connected Vehicle technology in real-world settings. The researchers first conducted a comprehensive review of the state of art of DSRC technologies and of Connected Vehicle research. The technology review indicates that DSRC is a main contender for a communications method due to its technological advantages, such as fast, secure, two-way and broadband connections in a mobile environment. It is the only technology that meets the requirements for safety applications in high-speed conditions. Other communications methods could be used as low-cost alternatives for non-time-critical applications. The review of Connected Vehicle and other VII research has covered more than 100 documents on the topics of applications for safety, mobility, and environmental protection. The literature review suggests that most past efforts have focused on vehicle-to-vehicle safety applications. However, much less effort has been exerted on mobility and environmental improvements. Additionally, safety applications that were researched were mainly on individual vehicle scales. More consideration is needed to improve the traffic system as a whole.

After completing the state-of-the-art review, the researchers focused on developing various applications using DSRC. Two brainstorming sessions were conducted to seek expert opinions from the Texas Transportation Institute (TTI) working group about prominent transportation problems that can be addressed by this technology. Two lists of potential applications were produced and prioritized based on near-term feasibility.

In particular, a total of five applications have been selected for full Concepts of Operations (ConOps) development. In safety, the wrong-way warning system and the grade-crossing warning system both aim to enhance the detection and warning mechanisms for, respectively, wrong-way movements on high-speed roadways and the presence of trains at crossing areas. To improve mobility on freeway facilities, the smart work-zone management system enables in-vehicle delivery of critical work-zone merge advisories and end-of-queue warnings, while the freeway speed advisory system minimizes speed differentials and improves the flow of traffic. For environmental security, the slippery pavement warning system uses weather observations from Connected Vehicles to enable speed management measures for vehicles traveling on slippery pavements.

These ConOps have provided a high-level understanding of how particular issues can potentially be addressed by the Connected Vehicle technologies. Describing these concepts is the first step in the system engineering process of each application. Based on the developed concepts of the

applications presented in this report, practitioners may wish to design systems that fit their issues and needs.

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1. INTRODUCTION

1.1. THE CONNECTED VEHICLE PROGRAM

To propel intelligent transportation system (ITS) advancement in the United States, the U.S. Department of Transportation (USDOT) Research and Innovative Technology Administration (RITA) has laid out a five-year ITS strategic research plan, with the core of the plan being the Connected Vehicle research initiative. The Connected Vehicle represents USDOT's most recent ITS program initiative focusing on advancing connectivity among and within the roadway infrastructure to significantly improve the safety and mobility of the U.S. transportation system. The program is working toward a vision of the future where vehicles and infrastructure are connected to enable crashless vehicles and access to real-time data on the status of both vehicles and roadways.

To achieve these goals, the RITA ITS program is structured into three domains of research. Figure 1 shows these domains. At the highest level (i.e., bottom level in the figure), the research in policy and institutional issues addresses the limits and challenges of successfully deploying ITS applications that build on the foundation of wireless technologies. The research in technology issues aims to overcome the technical hurdles of building a human-behavior-based platform with architectural configurations and interfaces well defined; the platform provides a means for connecting all modes of transportation and all travelers smoothly and securely. At the application level, the program focus is on developing transformative applications that fall into the following three themes:

- Safety—includes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications for safety.
- Mobility—includes real-time data capture and management (DCM) and dynamic mobility applications (DMA).
- Environment—includes applications for environment: real-time information synthesis system (AERIS) and road weather applications (RWA).

This current project concentrates on the topic of applications and will briefly mention the technology used to support connectivity applications, but will not discuss policy issues at all. The following paragraphs present a short history and the planned future activities of application research and studies.

When the Federal Communications Commission (FCC) first licensed several communications channels (namely the Dedicated Short-Range Communications [DSRC]) for the sole purpose of vehicle communications, the era of automobile connectivity began (see Figure 2). DSRC was initially intended for transportation safety purposes. Around 2002, the Vehicle Infrastructure Initiative (VII) began to develop safety applications using V2V and V2I communications. A number of consortiums were created, including the Vehicle Safety Communications Consortium (VSCC) (*2*) and the VII Consortium (*3*). These consortiums represent cooperative efforts from the private (i.e., auto manufacture) and the public sectors (i.e., government and academic institutes). The collaborations help investigate the feasibility and applicability of DSRC to address transportation safety problems via a number of proof of concept (POC) tests. Many of these efforts successfully result in promising applications, including the Cooperative Intersection Collision Avoidance System (CICAS).

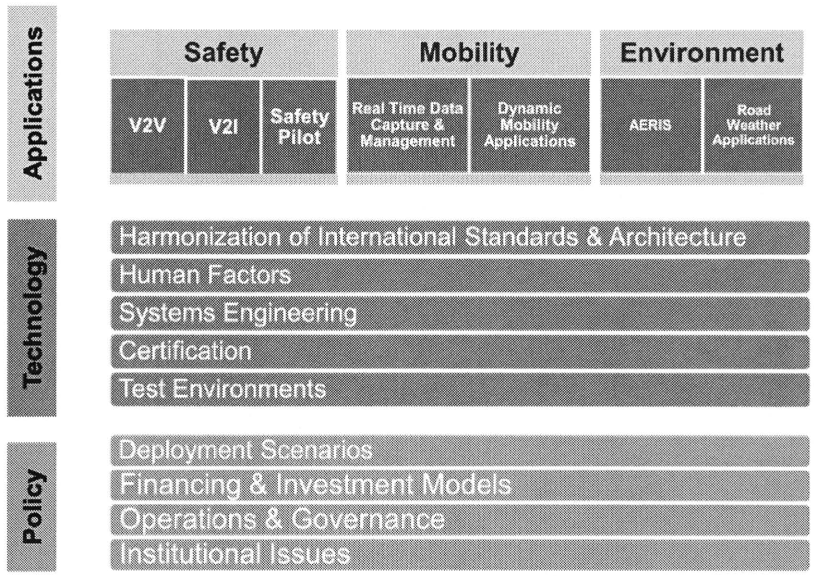


Figure 1: ITS Research Program Structure (*1*)

As DSRC technology matured in 2009, the VII was rebranded into the current Connected Vehicle initiative, the scope of which has been greatly expanded. Additional wireless communications technologies were considered and the range of application themes was widened. As of August 2011, the safety pilot as a national effort has been brought underway to testing Connected Vehicle technologies (e.g. mainly DSRC) in large-scale and real-world scenarios. The US Department of Transportation (US DOT) envisions a number of major milestones that each of the ITS research programs aims to achieve from 2010 to 2015(*1*). The DOT laid out detail roadmap of the expected efforts on testing Connected Vehicle framework. Five concurrent tracks of research activities on foundational analysis have been completed by early 2011. Individual safety, mobility, and environmental applications are to be developed and tested by the summer of 2013, and the benefits of these applications will be assessed by the end of 2013. If the Connected Vehicle framework is proven to generate significant benefits in all three application areas, more efforts for regional pilot implementation will be made.

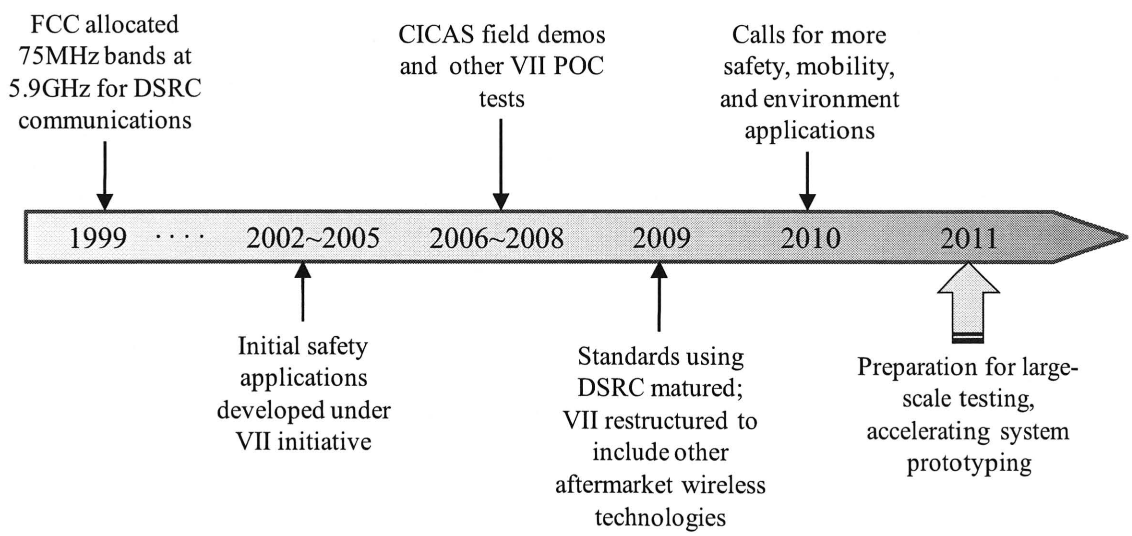


Figure 2: A Brief History of the Connected Vehicle Program

1.2. PROJECT PROBLEM STATEMENT AND OBJECTIVES

The surface transportation system has long been regarded as the lifeline of a nation's economy, security, and prosperity. As important as the transportation system is, it has also been responsible for more than 30,000 fatalities each year over the past decade (*4*), 4.2 billion wasted hours for travelers sitting in traffic congestion every year (equivalent to one full work week per person)(*5*), and around 20 percent of the carbon dioxide produced annually from tailpipe emissions around the globe (*6*). These severe problems in safety, mobility, and environmental security have cost the United States hundreds of billions of dollars every year.

Wireless communications is an emerging technology that has the potential to improve the transportation system as a whole. The presence of connectivity is ubiquitous, from individuals to corporate businesses, and the impacts of a fully connected, information-rich world are wide ranging and powerful. However, transportation communities have yet to reap the benefits of connectivity for highway safety, mobility, and environmental protection. The Connected Vehicle research initiative represents a national research effort that aims to support the development and deployment of transportation connectivity. The outcomes of the initiative will lead to a series of transformative benefits for individual travelers, transportation agencies, and private industrial sectors.

The goal of this research project is to identify opportunities for using Connected Vehicle technologies to improve safety, mobility, and environmental protection. Furthermore, the project will explore the potentials of a number of Connected Vehicle applications and develop brief concept of operations papers. The following specific objectives would help achieve this goal:

- Establish a comprehensive understanding of the current state of research and technologies, and identify gaps and opportunities in Connected Vehicle research.
- Conduct a series of brainstorming sessions with Texas Transportation Institute (TTI) researchers and others to identify transportation problems that can potentially be addressed by the use of wireless communications technologies, and to discuss the feasibility of these potential applications.
- Develop Concepts of Operations (ConOps) documents describing the potential applications using the Connected Vehicle technologies that help address a variety of transportation operations and management issues

1.3. RESEARCH PROCESS AND REPORT ORGANIZATION

To determine the list of applications for full concept development, the research team followed the process shown in Figure 3. Connected Vehicle research is still relatively new, and Connected Vehicle technologies are developing quickly. In order for this research project to identify gaps in research and practice, a compressive literature review was first conducted. The review was updated throughout the course of this project to reflect the most recent changes in research. The research team built upon the current state of research to create a preliminary list of applications for sparking brainstorming discussions. The brainstorming discussions in turn helped expand and prioritize the preliminary list of applications. The research team selected several high-priority applications for initial concept development. These initial concepts helped the team further understand whether the proposed concept was real-world practical or near-term feasible. Finally, the full ConOps were developed for a number of selected applications.

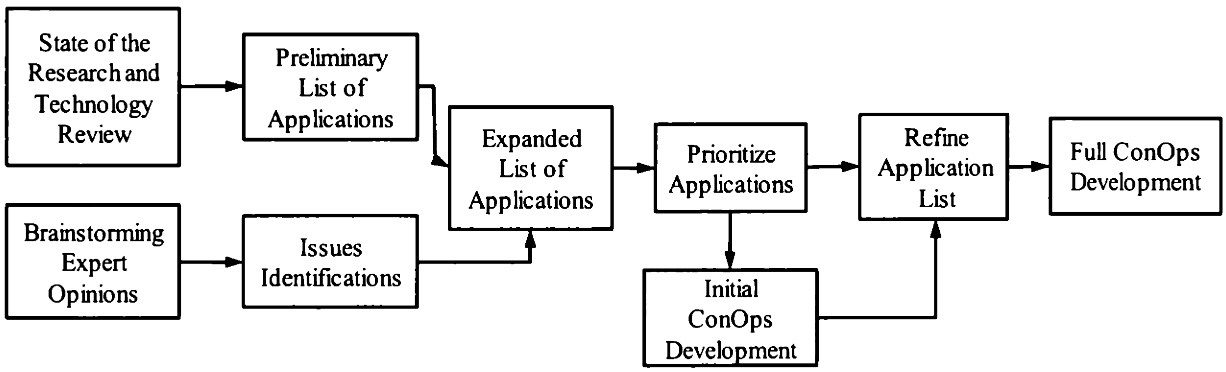


Figure 3: Flow Chart for the Research Procedure

Therefore, before developing any ConOps, the most important element is the selection of potential applications. This was done through the comprehensive review on the state of research and technology and the brainstorming workshop. Accordingly, the rest of the report is organized as follows:

- Chapter 2 provides a brief comparison of the currently available wireless technologies and summarizes the DSRC messages included in the Society of Automobile Engineers (SAE) J2735 standard.
- Chapter 3 describes past and ongoing research activities concerning the development of the related Connected Vehicle applications.
- Chapter 4 describes the research approach and the process of the brainstorming sessions.
- Chapters 5 through 7 report the results of the concept development within the three application themes.

2. CONNECTED VEHICLE COMMUNICATIONS STANDARDS

2.1. OVERVIEW OF WIRELESS COMMUNICATIONS

The application of wireless communications is what separates Connected Vehicle technology from traditional ITS technologies. The wired communications method cannot fit in a mobile environment because mobility is the main feature of a transportation network. Wireless telecommunications makes use of electromagnetic waves to transmit information between objects over the air. A wide variety of wireless communications technologies exist. Differing only in the use of electromagnetic spectrum, these technologies have different operating characteristics. Two main characteristics are range and latency, which are discussed below.

The communications range refers to the distance that a communications signal can travel. This range is governed by a number of factors and may vary greatly from design to use and from one location to another. In addition, some communications technologies have faster transmission speeds than others. This translates into communications latency, which is the time between when the transmission starts and when the transmission content is received.

Communications range and latency are the two most important criteria in selecting wireless technologies that meet the needs of various transportation applications. The range of a wireless communications technology greatly affects the degree of information connectivity. In a road network system, information coverage can be exponentially greater when using longer-range technologies. On the other hand, latency implies how fast information can propagate over a designated region. For applications carrying time-critical information, low-latency technologies are desired or required. Unfortunately, it is important to bear in mind that long range and low latency cannot coexist in practice; the user has to settle for one or the other or compromise somewhere in-between. Different wireless technologies are options to meet these different needs.

The following provides a brief description of some of the common wireless technologies used in transportation applications, highlighting the above two operating characteristics:

- Dedicated Short-Range Communications—DSRC uses the 75 MHz electromagnetic band around the 5.9 GHz spectrum to support location-based vehicle-to-vehicle and vehicle-to-infrastructure services. This type of technology has targeted the need for low-latency communications; thus, it has a relatively short communications range. The design range of DSRC is about 3,000 feet (1,000 meters), and the real-world range is less than 1,000 feet (300 meters) according to a recent study (*7*). Low latency is desirable in local vehicle-based applications. Example applications where DSRC is being used include the following:
    - Emergency earning system for vehicles.
    - Cooperative adaptive cruise control.
    - Cooperative forward collision warning.
    - Intersection collision avoidance.
    - Approaching emergency vehicle warning (blue waves).
    - Vehicle safety inspection.
    - Transit or emergency vehicle signal priority.
    - Electronic parking payments.

- Commercial vehicle clearance and safety inspections.
    - In-vehicle signing.
    - Rollover warning.
    - Probe data collection.
    - Highway-rail intersection warning.
    - Electronic toll collection.

- Cellular communications—The current 2.5- and third-generation cellular technologies are another means for wireless data exchange; however, the end-to-end cellular communications delay is likely to remain in the range of at least several seconds, and buffer-based delay may be encountered if the cellular networks are busy with higher-priority voice communications. In the near term, due to the high-latency characteristic, current cellular technologies are deemed suitable for only supplemental or non-time-critical applications, such as for non-safety purposes. Nonetheless, its constant evolution has been propelled by the cell-phone consumer market. The new generations of cellular technologies may in the future supersede DSRC because of a wider communications range, wider availability, and larger-packet data exchange capability.
- Bluetooth communications—Bluetooth may also establish two-way communications for data exchange, and is another widely accepted communications method available in the consumers' market. Different Bluetooth classes have different communication ranges, from 30 feet (10 meters) to 300 feet (100 meters). This type of communication also has significantly higher communication latency than DSRC (*8*). These characteristics make it only suitable for applications that allow both ends of the communication to be relatively stationary to each other, for instance, updating maps for the navigation system when the car is parked in the garage, or using in-vehicle hands-free telecommunications.
- Satellite communications—Ubiquitous coverage over the continental United States and long-range coverage provide a strong argument to consider two-way satellite services for wireless connectivity for vehicles. However, the data transmission capacity using satellite communications is rather limited, and the high communications latency is another reason that this communication type does not meet the requirements of safety-related applications. However, these operational parameters do not exclude it from some mobility applications such as probe vehicle monitoring.

Table 1 compares the capabilities of wireless technologies; the Crash Avoidance Metric Partnership (CAMP) (*8*) provides more comprehensive comparisons.

Table 1: Comparison of Wireless Technologies (*8*)

Capabilities	Wireless Technologies: 5.9 GHz DSRC	2.5-3G PCS and Digital Cellular	Bluetooth	Digital Television (DTV)	High Altitude Platforms	IEEE 802.11 Wireless LAN	Nationwide Differential Global Positioning System (NDGPS)	Radar	Remote Keyless Entry (RKE)	Satellite Digital Audio Radio Systems (SDARS)	Terrestrial Digital Radio	Two-way Satellite	Ultrawideband (UWB)
Range	1000 m	~4-6 km	10 m	~40 km	120 km	1000 m	300-400 km	2 km	30 m	US 48 states	30-50 km	NA	15-30 m ?
One-way to vehicle	X			X	?		X	X	X	X	X		
One-way from vehicle	X				?			X					?
Two-way	X	X	X		?	X						X	
Point-to-point	X	X	X		?	X			X			X	
Point-to-multipoint	X			X	?		X	X		X	X		?
Latency	200 micro sec	1.5-3.5 sec	3-4 sec	10-30 sec	?	3-5 sec	NA	NA	NA	10-20 sec	10-20 sec	60+ sec	?

2.2. DEDICATED SHORT-RANGE COMMUNICATIONS

For each wireless technology to be useable in the industry, standard specifications are necessary to guarantee devices produced by different manufactures can seamlessly communicate with each other. Thus, each wireless technology has its own industry standard. The DSRC technologies are specified by a suite of standards called the Dedicated Short Range Communications for Wireless Access in Vehicular Environment (DSRC/WAVE), or simply WAVE. This standard defines short- to medium-range communications services that use DSRC. The purpose of these services is to support both public safety and private operations in vehicle-to-vehicle and vehicle-to-roadside communication environments. WAVE is in fact a suite of Institute of Electrical and Electronics Engineers (IEEE) P1609.x standards, which are built over the IEEE 802.11p standards (i.e., an approved amendment of the Wi-Fi communications standards). Complete discussion of the DSRC/WAVE standards is outside the scope of this research, but Morgan (*9*) provides a comprehensive review of DSRC history and some technical aspects of DSRC.

Compared to other wireless communications methods, DSRC has unique technological advantages that better fit the needs of transportation applications. These advantages include designated licensed bandwidth, fast network acquisition, low communications latency, and high reliability, interoperability, and security. Licensed bandwidth prevents abuse of communication bandwidth resources; fast network acquisition quickly establishes two-way communications; low latency ensures minimum delay for message transmission; interoperability is guaranteed by building the DSRC standards with widely accepted standards (i.e., IEEE standard family); and security features authenticate connections and ensure data transfers are secure.

The DSRC architecture fully supports peer-to-peer two-way communications. In the transportation context, a "peer" can be a moving vehicle or a stationary roadside unit. To facilitate discussions in the remainder of this report, it is important to point out the two common peers that are frequently used in DSRC. The definitions used here follow those from the Federal Highway Administration (*10*):

- Onboard unit (OBU)—refers to equipment embedded in the mobile applications that allow information about the mobile user to be communicated to other applications. An

OBU generally consists of several components such as computer modules, display units, and a DSRC radio. The OBU interfaces with vehicular sensors and a wireless communication interface to other mobile users and the roadside.

- Roadside unit (RSU)—consists of equipment that has been installed at the roadside and communicates with mobile devices via DSRC radio communications. RSUs are the first point of contact between DSRC-enabled mobile devices and the transportation communications network. Data storage in an RSU is optional depending on the needs of a specific application.

2.3. COMPONENTS IN SAE J2735 STANDARD

SAE J2735—Dedicated Short Range Communications (DSRC) Message Set Dictionary is an industry-acknowledged standard that defines a set of data messages to facilitate various communications applications between any DSRC-enabled devices. As WAVE defines low-level communications, SAE J2735 defines high-level message contents. Each message is a collection of various data elements, which can be collected from the roadside or from within the vehicle and which are also defined in this standard.

The standard is written by the Society of Automobile Engineers (SAE) to ensure seamless interoperability among multiple ends of communications. Many of the messages within this standard are the results of almost a decade of research work on DSRC safety applications by a number of different projects, including the CAMP Vehicle Safety Communications (VSC) project, the CAMP VSC-Application (VSC-A) project, and the CAMP CICAS project series.

In the latest version (2009 revision), SAE J2735 includes 15 standardized messages. One is an all-inclusive message set, and two are related to local corrections for global positioning system (GPS) positioning. The remaining 12 message sets can support a variety of safety and mobility applications. The subsections below give a general overview of each of these messages.

2.3.1. Basic Safety Message (BSM)

The BSM is used for exchanging information related to the real-time operating statuses of the mobile device. Broadcast at a transmission frequency of 10 Hz, the BSM includes information about the position of the mobile device, the current motion of the mobile device, and other information. The BSM is also referred to as the "here I am" message since it can be broadcasted to make the surrounding vehicles and infrastructure aware of the vehicle's presence. Two parts of the contents can be included in each broadcast:

- Part I is required and contains the data elements that are used to outline the basic vehicle status. The data elements include vehicle dimensions, brake status, vehicle position (in terms of latitude, longitude, and altitude) and its accuracy, vehicle speed, heading, steering wheel angle, and accelerations.
- Part II is optional and contains the data elements that supplement part I data to give a full description of the vehicle status. The data elements include headlight status, brake system status, windshield wiper status, traction control status, anti-lock braking system (ABS), path history (namely "bread crumbs"), path prediction, acceleration sequence and its confidence, and weather reports (precipitation status, temperature, and air pressure).

2.3.2. Common Safety Request (CSR)

The CSR message allows a mobile device to broadcast requests to other DSRC receivers to acquire additional information that is not contained in a typical BSM broadcast. The purpose of this message is to minimize the data payload used by a typical BSM broadcast and reserve the communications bandwidth for application-specific broadcasts. The additional information, if available, can be attached to the next BSM broadcast or otherwise ignored. The data elements that can be requested are all the items supported by part II of the BSM.

2.3.3. Road Side Alert (RSA)

The RSA message is normally emitted from roadside infrastructure (e.g., RSU) to nearby mobile devices alerting them about roadway hazards. The actual content of the message is formatted in the International Traveler Information Standard (ITIS) code. Typical example messages would be "bridge icing ahead," "train coming," or "ambulances operating in the area." The ITIS standard (i.e., SAE J2540.1) contains the accepted phrases supported by the standard, which are all coded in standardized integer formats (*11*).

In addition, the RSA message contains optional fields used to determine the relevance of the RSA message. A position vector is sent along with the ITIS phrases, which can be used by the receiving device to filter out irrelevant messages. A priority level for the message is also sent and determines the order and type of message presentation to minimize driver distraction. A spatial extent message is used to provide a gross level of applicability for the message over a distance.

2.3.4. Map Data (MAP)

The MAP message is used to concisely define the geometries of a complex intersection, a highway curve, or a segment of roadway. This message is sometimes informally referred to as the "Geometric Intersection Description or GID layer." This digital map is typically broadcasted from an RSU. In SAE J2735 (*12*), only the data elements related to intersection geometries are fully specified.

To concisely digitize an intersection, the message contains a reference point in terms of three-dimensional coordinates. Based on the reference point, lanes on all approaches can be computed using coordinate offsets and orientation information. All the lanes are numbered, and each lane has its own lane properties such as lane width, movements allowed, downstream lanes, etc. Under this basic structure, different signal control zones, such as preemption and priority zones, can be specified in reference to the structure. In addition, dynamic intersection status (such as "preempt is active" or "intersection is in conflict flash") is also supported by this message.

Although the lane assignment to each intersection movement is static in one MAP broadcast, the lane assignments can be different from one broadcast to the next. In this sense, the MAP message can support dynamic lane assignment throughout the day.

2.3.5. Signal Phase and Timing (SPaT)

The SPaT message is designed to primarily convey the current states of all phases of a traffic signal. Phases currently in red are not transmitted. Other active phases are mapped with one or more traffic lanes. Along with the MAP message, the receiving devices can determine the signal status for each lane and for each movement. As an option, the expected time to the end of a particular phase and the confidence of this expectation are also supported and will be sent if available. In addition, a brief summary of any current priority or preemption events is sent through this message, but the full list of priority or preemption events is sent via another message (i.e., a signal status message). The SPaT message is deemed essential to a large number of applications involving traffic signal states.

2.3.6. Signal Request Message (SRM)

This message is one of the four messages that are used to support intersection signal-related applications. The SRM enables signal priority/preemption requests sent from public transit/safety vehicles to the RSU in a signalized intersection. The contents of an SRM request contain not only a specific request including the duration of service, but also the first part of the BSM that is used to identify the vehicle submitting the request.

To generate a signal request, the requesting vehicle needs first identify its current position in terms of the geometry of the intersection. The knowledge of intersection geometry is attained by decoding and examining the list of supported zones for that intersection. This list is contained in the MAP message that a vehicle receives prior to making a signal request. Optionally, the request can be further tailored by inputting the ingress and egress lanes on which the vehicle path is projected.

2.3.7. Signal Status Message (SSM)

This message is one of the four messages that are used to support intersection signal-related applications. The SSM is usually used to reply to a service request (sent via the SRM). To spare data transmission bandwidth, the generation of an SSM response is not always, but only when there are other active events or pending requests. In the case of no active request pending, the response to an SRM is reflected in the change of signal phasing (sent from SPaT). The SSM also contains the rankings of all the pending requests submitted so that each vehicle can determine its rank in the list. In addition, an SSM contains the general intersection signal state, all active priority states, and all active preemption states.

2.3.8. Probe Vehicle Data (PVD)

The PVD message is used for a vehicle to send vehicle attributes and recent history of the vehicle's running status to a roadside DSRC reader. The probe data are intended for learning the real-time conditions about road, weather, and traffic. In typical use, this message is a collection of one or more snapshots of a vehicle's current and past running statuses; each snapshot is also stamped with when and where the snapshot was taken. Each snapshot can support up to 42 vehicle data elements, including most of those in BSM part I and other data such as tire pressure. SAE J2735 (2009 revision) gives more details.

The probe data snapshots are generated in one of the three ways:

- Periodic snapshots—The period can be on a per-time or per-distance basis. The default method is to use time. Either way, the goal is to obtain a more uniform distribution of snapshots to minimize data collection frequency but also obtain ubiquitous coverage. As specified in the current standard, 20 seconds per snapshot for rural cases and 4 seconds per snapshot for urban cases are used as default values. However, these values can be easily changed by the probe data management message (discussed later).

- Event-triggered snapshots—Any changes or specific changes (e.g., change exceeding a threshold) in vehicle status elements can trigger a new snapshot of vehicle data. Comparing to the periodic method, it is useful to target specific purposes and save communication channel resources.
- Starts and stops snapshots—The collection of snapshots may also be triggered by vehicle starts or stops. The start and stop events are defined by vehicle speeds.

2.3.9. Probe Data Management (PDM)

The PDM message is typically sent from an RSU to a vehicle onboard unit. Its purpose is to instruct which OBUs should collect probe data, and how the data should be collected. It changes only the snapshot generation characteristics of the OBU but not the contents. When a vehicle equipped with an OBU comes in the range of an RSU, a new probe management process is started. This process is temporary and will live until a time duration expires, a distance is reached, or the vehicle is out of communications range. This instruction is specified in the PDM message.

By using the PDM, an RSU can sample only a portion of the OBU population in range for any of its applications. The OBU heading information is used by the RSU to filter out irrelevant OBUs. The PDM can also modify the threshold values for any of the three snapshot methods in the PVD message. The interval for snapshot generation and that for transmitting the PVD snapshots are separately defined to control different rates of data collection and communications. In general, the use of this message improves the flexibility of transportation agencies to dynamically manage the collection of probe vehicle data.

2.3.10. Traveler Information Message (TIM)

The TIM is used to send various types of lower-priority messages, currently supporting only road signs and advisories. It is a message very similar to the RSA message for its heavy use of the ITIS representations for various messages. Each message can be received earlier than the start time and/or prior to entering the specified region where the message becomes active. The nature of the message contents is usually informational. There are three parts of the message:

- Part I—specifies the type of message and the start time and duration of the message.
- Part II—specifies the geographic region and direction where the message is applicable.
- Part III—includes the actual content of the message. The current standard supports ITIS-encoded advisories, *Manual on Uniform Traffic Control Devices* (MUTCD) signs and directions, speed limit signs, and available roadside business services.

2.3.11. Emergency Vehicle Alert (EVA)

The EVA message is used to warn vehicles that a public safety vehicle is running in vicinity and that additional caution is required. The warning content is based on the ITIS phrase list. Additional information regarding the mass and overall type of vehicle and the status of the siren/light bar can also be appended. The message can be further customized to be applicable to a designated group of vehicles; thus, other groups of vehicles can simply ignore the message without processing the warning message. The standard currently supports 35 different groups of vehicles.

2.3.12. Intersection Collision Avoidance (ICA)

The ICA message is designed to support the intersection collision avoidance applications. This message is generated from the roadside unit, but the data are collected from the equipped vehicles. The data to collect from the vehicles include a set of vehicle path histories, the applicable lane number, and the violation flag. The vehicle path history is a series of vehicle positions (motion tracks) from a vehicle approaching the intersection. Combining the traffic signal states, the path history is used to infer the chance of the vehicle committing a stop-bar violation.

2.4. FURTHER REMARKS ON DSRC

The DSRC data messages described above represent only the most current version of the SAE J2735 standard at the time of writing this report. While the standard is undergone constant development, revisions of the current messages and inclusions of new messages are expected as the Connected Vehicle framework continues to evolve. The readers should revisit the latest version of the SAE J2735 for updates.

To avoid confusion, it should be noted that the SAE J2735 standard is sometimes referred to as the DSRC standard. This implies that the term DSRC can be used to refer to both the communications technology and the standardized set of messages. Therefore, this report uses DSRC to refer to either the SAE J2735 or the communications technologies without further distinction unless otherwise noted.

In this project, the researchers intend to develop connected vehicle applications built solely on the DSRC communications method. Other wireless communications methods may be mentioned, but they will be supplemental or replaceable. Therefore, the above data messages will serve as the building blocks for developing various applications in this research. For each application concept to be developed, the research team attempt to use the established DSRC messages as described above. Doing so helps to ensure the feasibility of the application. However, there are occasions where minor revision of the DSRC or a complete new DSRC messages might greatly facilitate the purpose of the application. In such cases, the research team will suggest new messages as appropriate.

3. STATE OF CONNECTED VEHICLE APPLICATION RESEARCH

The researchers have conducted a comprehensive review of the literature related to Vehicle Infrastructure Integration (VII), IntelliDrive^{SM}, and connected vehicle. The sources for the literature search include peer-reviewed journals, Federal Highway Administration (FHWA) and Research and Innovative Technology Administration (RITA) websites, relevant workshops and conference presentations, published project proposals, and technical reports. In total, more than 100 documents were collected and reviewed. The contents and topics of these documents vary greatly. Only about half are related to simulation studies, concept-of-operation developments, field testing, or demonstrations of potential connected vehicle applications.

This section summarizes the past, ongoing, and proposed research activities primarily related to connected vehicle application research. The review is intended to give an overall picture of the current state of research. Each of the three subsections presented below is dedicated to one application theme scoped by the ITS research program. In each subsection, relevant research activities are reported.

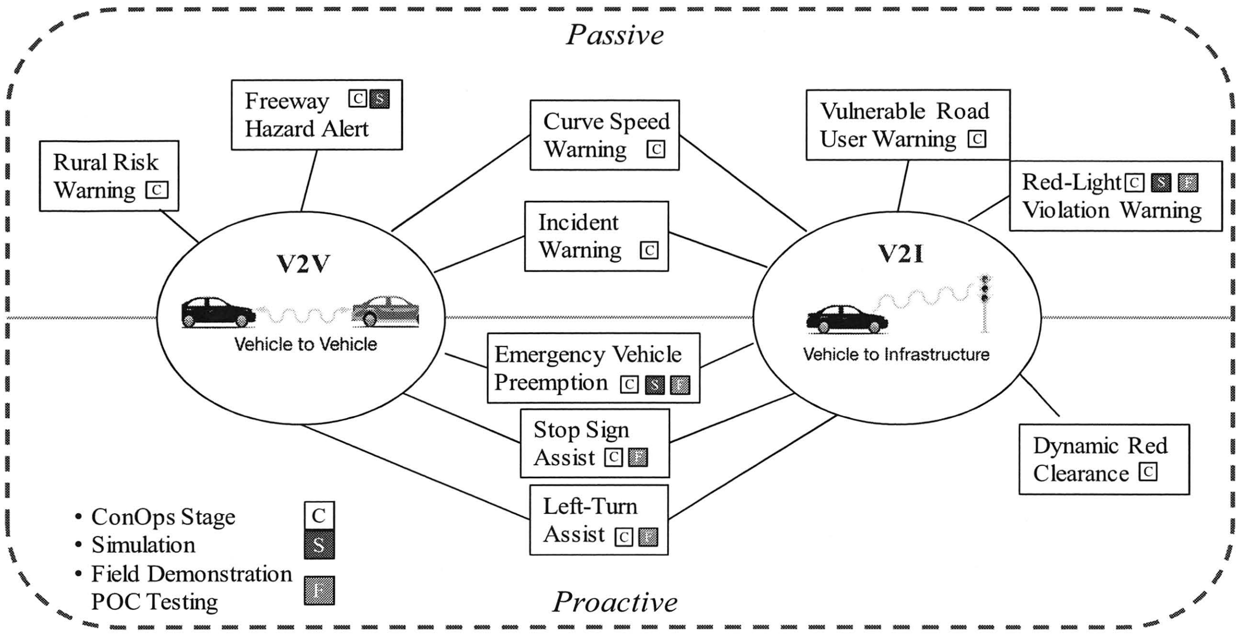
3.1. RESEARCH IN SAFETY APPLICATIONS

Safety applications are designed to increase situational awareness and reduce or eliminate crashes by communications via vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), or vehicle-to-any-device (V2X) data transmission that supports three kinds of applications:

- User advisories—suggestive messages that aid system users in taking a variety of preventive actions for potential dangers.
- User warnings—urgent messages that heighten users' circumstantial awareness for taking immediate actions to avert hazards.
- Vehicle and/or infrastructure controls—secondary actions taken by vehicular control systems that provide a fail-safe mechanism when users fail to comply with warnings or advisories.

According to a recent study by NHTSA (*13*), these applications could potentially address about 75 percent of all crashes involving all vehicle types, or 81 percent of all vehicle crashes involving unimpaired drivers. Given the promising benefits, a number of safety applications were conceived and became the subject of laboratory studies and field testing. In particular, there are two research segments under the RITA Connected Vehicle research initiative: the Vehicle-to-Vehicle Communications for Safety and the Vehicle-to-Infrastructure Communications for Safety.

Figure 4 summarizes the safety applications that can be found in major studies or testing that falls into these two research segments. The research activities associated with each segment are also shown. More details regarding each application study can be found in the subsections.



Note: only applications in active or recent studies/tests are shown

Figure 4: Summary of Safety Applications with Research Activities

Note that Figure 4 excludes the applications developed and field-tested by the Vehicle Safety Communications projects, for this series of projects emphasized more on the technical aspects of the communications technology. However, these efforts laid the foundation for continuous development of the connected vehicle research.

3.1.1. Vehicle Safety Communications Projects

The Vehicle Safety Communications (VSC) project series represents a significant segment of V2V and V2I communications research in the United States under the Crash Avoidance Metric Partnership. The Vehicle Safety Communications Consortium and the Vehicle Safety Communications Consortium 2 (VSCC-2) were formed to conduct the VSC and the VSC-Application (VSC-A) projects in 2002 through 2004 and 2006 through 2008, respectively (*8, 14*). Both VSC and VSC-A had similar goals, which were to develop and test DSRC-based vehicle safety systems and to determine the communications requirements, needs, real-world feasibility, and benefits of such communications for vehicle safety. Consequently, a total of 34 safety applications were identified, some of which were studied and tested. Table 2 is a list of the safety applications investigated in the projects.

Table 2: Summary of Vehicle Safety Communications Project Series

Type	Applications Studied/Tested	Project/Program Title	Performing Agency
Concept Development and Field Demonstrations	• V2I applications o Curve speed warning o Left-turn assistant o Stop sign movement assistance o Traffic signal violation warning • V2V applications o Cooperative forward collision warning o Emergency electronic brake lights o Lane change warning o Pre-crash sensing	Vehicle Safety Communications (*2*)	Crash Avoidance Metrics Partnership—Vehicle Safety Communications Consortium
Concept Development and Field Demonstrations	• V2I applications o Intersection movement assist • V2V applications o Cooperative forward collision warning o Emergency electronic brake lights o Lane change warning o Do not pass warning o Control loss warning	Vehicle Safety Communications Applications (*14*)	Crash Avoidance Metrics Partnership—Vehicle Safety Communications Consortium 2

These research efforts led to the development of the early versions of the SAE J2735 DSRC standard, highlighted the initial development of safety applications, and laid a technological foundation for current research directions. However significant these efforts were, however, the focus was on the communications engineering perspective instead of the traffic engineering perspective. Thus, details of these applications are not included in further discussions. Other sources (*2, 8, 14*) discuss application concepts and field test procedures and results.

3.1.2. Vehicle-to-Vehicle Communications for Safety

Research on V2V safety applications primarily focuses on how vehicle-based data (e.g., speed position and location) can and should be exchanged wirelessly in a fast, secure, and intelligent manner that maximizes drivers' situational awareness and reduces the risks of crashes. The "here I am" message is one of the basic V2V communications messages and is designed to promote vehicle safety by informing others of the vehicle's real-time location. Table 3 summarizes the current research and the performing agencies.

Table 3: Summary of Research Using V2V Communications

Type	Applications Studied/Tested	Project/Program Title	Performing Agency
Concept Development	• Incident warning	Arizona Emergency VII (*15*)	University of Arizona
Concept Development	• In-vehicle risk warnings (e.g., animal, electronic brake light, or road feature)	IntelliDrive[SM] Rural Risk Warning System (IRRWS) (*16*)	Western Transportation Institute and Montana State University
Simulations	• Freeway hazard alert	Microscopic Traffic Simulation of Vehicle-to-Vehicle Hazard Alerts on Freeway (*17*)	University of California at Berkeley

Since 2008, the University of Arizona (UA) has embarked on a VII initiative that focuses on supporting emergency responders and incident management activities. One of the applications being developed by UA uses V2V communications to establish an ad-hoc network that allows incident response vehicles to broadcast information from the incident site to approaching vehicles to alert them to lane blockage or road closures (*15*). The study is in the stage of ConOps development.

Researchers at Western Transportation Institute have developed a ConOps for a risk warning system in rural areas (*16*). The purpose of the risk warning system is to give drivers crucial extra seconds before a risk event by means of ad-hoc communications and networking technologies. The details of estimating risks and mapping them to a categorical scale, however, have not been documented.

A simulation study was conducted by researchers at the University of California at Berkeley (*17*). The study proposed a methodology for modeling drivers' responses to lane-blocking incidents with and without the use of V2V hazard alerts. The results have shown that the proposed V2V alert system may help mitigate traffic congestion in areas with higher market penetration rates; additionally, driver messages should advise speed reduction but not gap increases when non-specific alert information is available; also, a larger communication range further reduces adverse traffic impacts caused by freeway hazards.

3.1.3. Vehicle-to-Infrastructure Communications for Safety

V2I communications enables interactions between vehicles and infrastructure. Infrastructure collects real-time information about traffic regulation (e.g., signal status and variable speed limits) and hazards (e.g., violations and incidents), and then disseminates this information to specific vehicles in the form of warnings or advisories.

Instead of broadcasting uniform warning messages to all drivers, the greatest advantage of the DSRC V2I system is that the infrastructure is able to customize communications to particular vehicles. The relevant research based upon V2I communications is summarized in Table 4 followed by brief descriptions of selected projects.

Table 4: Summary of Research Using V2I Communications

Type	Applications Studied/Tested	Project/Program Title	Performing Agency
Algorithm Development	• Intersection violation warning	CAMP VSC-2 Project: Subtask 3.2 (*18*)	Virginia Tech Transportation Institute
System Prototyping and Field Demonstrations	• Intersection violation warning	Cooperative Intersection Collision Avoidance System Limited to Stop Sign and Traffic Signal Violations (*19*)	Crash Avoidance Metrics Partnership
	• Left-turn gap assist	Cooperative Intersection Collision Avoidance System (CICAS): Signalized Left Turn Assist and Traffic Signal Adaptation (*20*)	University of California–Berkeley and California Partners for Transportation tecHnologies (PATH)
Concept Development	• Dynamic red clearance		
	• CICAS-violation • Dynamic all-red duration • Signal status display • Vulnerable road user warning • Truck signal change warning	Investigating the Potential Benefits of Broadcasted Signal Phase and Timing (SPAT) Data under IntelliDrive^{SM} (*21*)	
Concept Development and Field Demonstrations	• CICAS-stop sign gap assist	Cooperative Intersection Collision Avoidance System: Stop Sign Assist (*22, 23*)	University of Minnesota
Simulations and Field Demonstrations	• Preemptions at signals and on ramps	Arizona Emergency VII (*15, 24*)	University of Arizona
Algorithm Development	• Dilemma zone detection	Application of IntelliDrive^{SM} Information System to Enhance High-Speed Intersection Safety (*25*)	University of Akron

<u>CICAS-Violation</u>

CAMP was among the first partnerships that embarked on the development of the Cooperative Intersection Collision Avoidance System under the Vehicle Infrastructure Initiative. The research focus for CAMP was on prototyping a warning system that automatically predicts and warns drivers who are about to run red lights or stop signs (*19, 26-28*). And they coined the name of the system CACIS-violation (CACIS-V). Five original equipment manufacturers (OEMs) were involved in testing the system, including Daimler, Ford, General Motors, Honda, and Toyota. The system was tested on signalized/stop-controlled intersections in California, Michigan, and Virginia. Tests of the system included both on-road and test-track evaluations. The research team evaluated the technical subsystems (i.e., positioning and communications), the behavioral subsystems (i.e., driver interface), and the corresponding requirements and specifications for field deployments. System performance was excellent, and recommendations were made for continuing with a large field operational test (FOT).

In partnership with CAMP, the Virginia Tech Transportation Institute has developed and evaluated a large set of threat assessment algorithms for CICAS-V in a pseudo-real-time simulation environment (*18*). Signal detection theory was applied, which provided a statistical framework for developing the threat assessment algorithms. The most reliable algorithms for stop-controlled and signal-controlled intersections were both tested in an on-road test using 72 drivers (*29*). A driver-vehicle interface using a combination of visual, auditory, and brake pulse warning methods was also developed. The results suggested that the CICAS-V system and algorithms were mature for FOTs, and the system was favored by the drivers.

A University of California–Berkeley research team also developed a ConOps document for the CICAS-V warning system, which summarized high-level functionalities of the system (*21*). In the same document, the team developed the ConOps for another application that addressed the red-light-running (RLR) collision problem by actively adapting signal timing when RLR occurs. This ConOps served as the initial development of the system, which was evaluated in both a micro- and macro-simulation environment in another project performed by the same team (*30*). The results from the evaluation showed a reduction in the number of RLR while maintaining the level of service at the intersection.

CICAS-Gap Assist

In addition to reacting to intersection-crossing violations, other groups of researchers consider a more proactive approach – assisting drivers to cross intersections. This kind of system is generally called CICAS-Gap Assist (CICAS-GA). CICAS-GA addresses safety problems due to drivers' poor judgment of gaps in traffic (*26*). Currently, two applications by movement type are developed: left-turn assist and stop-sign assist.

The CICAS-Signalized Left-Turn Assist (CICAS-SLTA) was conducted by the California PATH program (*20*). The PATH research team tested the reactions of 20 drivers under three scenarios: no warnings presented, left-turn warnings displayed at infrastructure, and left-turn warnings displayed in vehicle. The study found that both the in-vehicle and the infrastructure warning interfaces provided assistance to drivers, while neither was proven superior. Also, the post-encroachment time was developed as a predictive metric to detect drivers' intentions in making left turns. However, the researchers suggested that fine-tuning of the metric was necessary. In addition, the concept of operations was briefly introduced for the CICAS-Traffic Signal Adaptation (CICAS-TSA). Although this project relied only upon traditional wired detection methods for vehicle conflicts, the results of studying the drivers' reactions to different warning interfaces are still valid when wireless communications are employed in the detection system.

Studied by the University of Minnesota, the CICAS-Stop Sign Assist (CICAS-SSA) targets the crash problems at rural thru-stop (i.e., two-way stop) intersections. The LIDAR sensors of the CICAS-SSA system first detects the speed and location of the oncoming vehicles on the mainline approaches; alerts and warnings are then issued to the drivers on the minor roads from the intersection infrastructure. The research team completed the development of a detail ConOps for this system (*23*) and then initiated a three-year field operational study at three two-way-stop-controlled intersections in April 2010 (*22*). The wireless-enabled CICAS-SSA system is now being designed.

Emergency Vehicle Preemptions

The University of Arizona has been conducting a three-year (2008 through 2011) VII initiative that focuses on improving the safety and performance of emergency responders and incident management teams. Two emergency VII applications that use DSRC capabilities to connect vehicles to infrastructure have been developed and demonstrated.

The first application addresses the safe preemption operation at traffic signals. This application allows the traffic signal to send signal status information to one or multiple emergency vehicles to ensure safe and undeterred passage of a signalized intersection. The research team has developed a priority control architecture (see Figure 5) and a specifically tailored priority control algorithm (*24*) to handle multiple priority requests at the same time. The second application extends the preemption concept to ramp meter operations. The use of VII/DSRC is similar to the traffic signal preemption request communications.

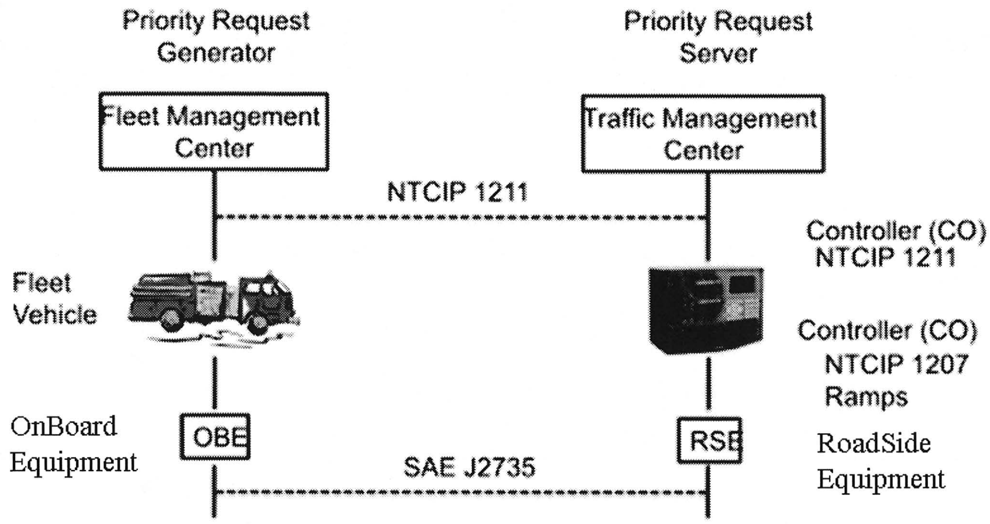


Figure 5: Priority Control Architecture (*31*)

The concept of operations for the preemption control has also been developed. In addition, the research team developed infrastructure and communications requirements for these applications. The field operations were demonstrated in two locations in Arizona, one inside a parking lot and the other on a signalized intersection. The following is a summary of the lessons learned from this deployment:

- Two-way DSRC is highly reliable and should be employed between infrastructure and emergency vehicles.
- The SAE J2735 and NTCIP communications standards are necessary to fulfill the operation needs of the preemption operations.

<u>Applications for Signal Phase and Timing</u>

California PATH is currently investigating how to integrate the broadcasting capability of the SPaT message in traffic controllers (*21*). The research team has conducted an extensive review of SPaT data to answer questions including what kinds of SPaT data are available and how often they are available in each time step. Secondly, the team is evaluating the potential applications of SPaT data; the ConOps has been developed for the following applications:

- CICAS red-light violation warning (CISAS-V)—This application would produce an auditory alert to a vehicle that, based on its estimated trajectory, will cross the stop line after the onset of the red phase.
- CICAS traffic signal adaption (CICAS-TSA)—This application would combine basic safety messages from vehicles with information from other vehicle detection systems to extend the red clearance interval to reduce the likelihood of a conflict with the start of green of the next phase.

- In-vehicle signal status display—This application would permit the status of the traffic signal to be displayed inside a vehicle approaching an intersection.
- Vulnerable road user warnings near intersections—This application is intended to provide drivers with warnings about vulnerable road users (pedestrians and bicyclists) who are in close proximity to the driver's vehicle and potentially in danger of being hit by a vehicle because it is violating the current traffic signal state.
- Truck signal change warning—This application would provide the driver of the truck with anticipatory information about an impending signal change by providing a countdown timer in the cab of the vehicle.

3.2. RESEARCH IN MOBILITY APPLICATIONS

The Connected Vehicle mobility applications promise to provide a data-rich travel environment. The transportation communications network captures real-time data from onboard units located inside vehicles (automobiles, trucks, and buses) and from roadside units. The captured data are transmitted wirelessly and are used by various transportation system users in a wide range of dynamic, multimodal applications to achieve system optimum performance (*32*).

Therefore, the immediate goal of research activities is to develop a set of data environments that encompass all modes of transportation on the freeways and arterial corridors. Not only will the sampling rate and coverage be dramatically increased by the connected vehicle technologies, but the types of data will also be greatly enriched. Examples of the newly available data include but are not limited to real-time speed, lane position, brake/throttle status, vehicle dimensions, the number of onboard passengers, the bus schedules to meet, etc. The abundant data captured from connected devices will provide a whole host of new applications for all road users and traffic managers.

Therefore, the segments under the connected vehicle mobility application research are real-time Data Capture and Management (DCM) and Dynamic Mobility Applications (DMA). Figure 6 lists a set of major applications for both data-capture and dynamic mobility purposes. Some of these applications are discussed in detail in the following subsections.

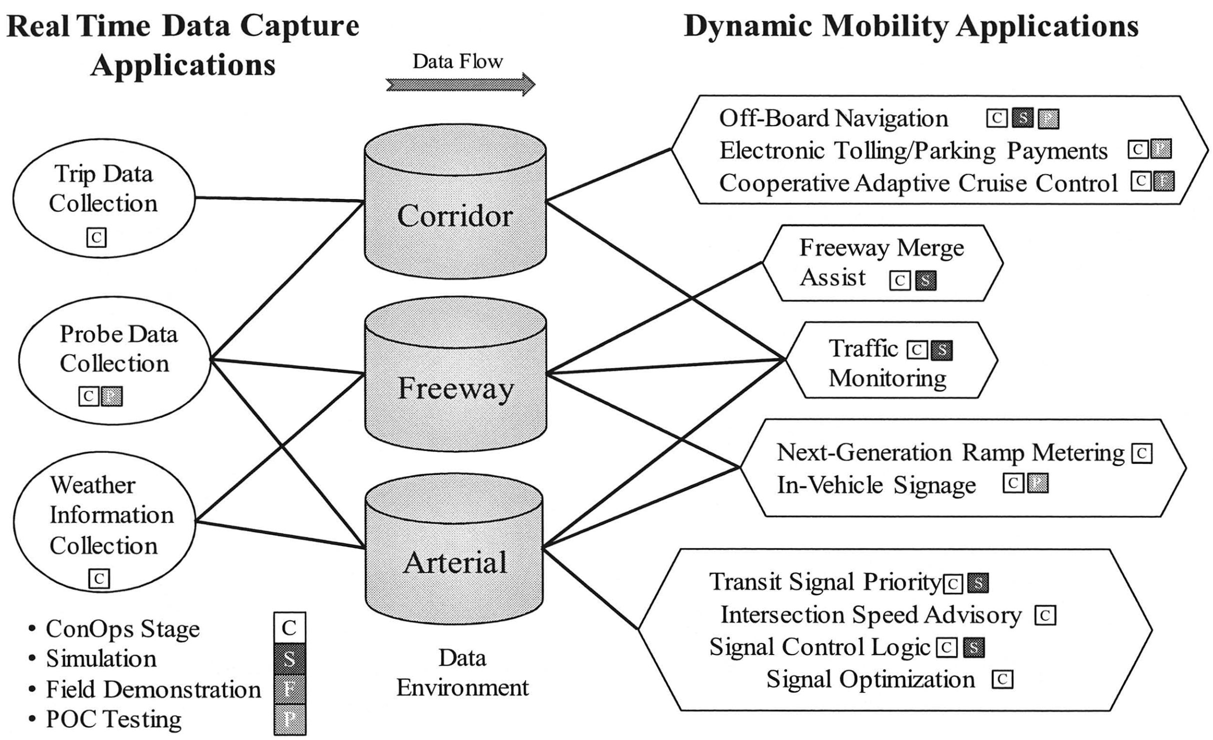


Figure 6: Summary of Mobility Applications with Research Activities

3.2.1. Real-Time Data Capture and Management

Currently, different traffic applications collect data for isolated purposes, and it is both technically and institutionally difficult to share data across different modes of transportation and across various agencies. The traditional paradigm of data capturing and management is not very cost-effective.

The vision for developing real-time data capture and management applications is to systematically capture real-time multimodal data from multiple sources for transportation management and performance measurement. That is to create a data center for most of the traffic applications. The captured data can be systematically formatted and integrated into well-defined data environments. There are currently four data environments supporting four specific geographic levels of system controls and decisions: arterial, freeway, corridor, and regional environments. These data environments should be able to work independently, to facilitate systematic data exchange between environments, and to improve data collection efficiency and quality. Detailed data environment concepts are described in McHale (*33*).

While few studies have been performed that are related to the development of real-time data capture and management systems, two initial efforts toward this direction were identified and are summarized in Table 5.

Table 5: Summary of Research Focusing on Real-Time Data Capture and Management

Type	Applications Studied/Tested	Project/Program Title	Performing Agency
Concept Development and System Prototyping	• Probe data collection • Trip data collection • Weather information collection	Vehicle Infrastructure Integration Proof of Concept — Vehicle/Infrastructure (*7, 34*)	VII Consortium
Concept Development	• Lane closure information to traffic management center (TMC)	Arizona Emergency VII (*15*)	University of Arizona
System Prototyping	• Online Data Center	Data Capture and Management Portal (*35*)	USDOT ITS Joint Program Office

The VII Consortium, in the Michigan test bed, carried out a series of field testing for data transmissions in the early phase of the VII initiative (*7, 34*). These studies demonstrate the ability of connected vehicles to capture new types of data (e.g., detailed probe data, origin-destination trip data, and real-time weather data) and test specifically the communications qualities under various line-of-sight obstructions. The consortium also developed a concise overall architecture/system framework and flow of events for a variety of applications.

In another effort, the University of Arizona is looking at enhancing the incident information on traditional legacy advanced traveler information system (ATIS) sources without operator inputs (*15*). Researchers are developing the ConOps and conducting field testing that leverages the current ATIS infrastructure to collect incident information from connected mobile devices using the V2I communications capabilities.

A noteworthy effort to capture connected vehicle data is the online data portal website https://datacapture.noblis.org. The effort represents a collaborative initiative spanning multiple USDOT agencies, which is to assess the potential of the multi-source, active-acquisition data paradigm. The current objective is to prototype and to refine the data environment concept. The website currently contains documented probe data samples and simulated data from the Michigan Connected Vehicle test bed (*33*). The website is open for researchers to upload or download research data.

3.2.2. Dynamic Mobility Applications

With the newly available data set from connected devices, dynamic mobility applications are designed to optimize traffic and transportation operations and to promote seamless connection across multiple modes. The improvement of system operations can reach a much higher level due to the possibility of collecting and sending real-time data from and to location-specific and context-relevant mobile devices.

More studies identified were focusing on the development and testing of dynamic mobility applications. However, this report presents only the literature that attempts to directly make use of real-time vehicular information to improve mobility since this information is unique to the connected vehicle applications. Table 6 summarizes the major research activities for dynamic mobility applications. Major activities include dynamic merge assistance, new signal logic development, signal optimization, bus transit priority, cooperative adaptive cruise control, etc.

Note that the effort promoted by the VII Consortium in Table 6 emphasized on communication capabilities and qualities as well as concept proofing purposes (*7, 34*). None of the listed applications under the VII Consortium effort helped identify mobility improvement using the Connected Vehicle technology. These studies are not discussed here, only noted for reference purposes.

Table 6: Summary of Research Focusing on Dynamic Mobility Applications

Type	**Applications Studied/Tested**	**Project/Program Title**	**Performing Agency**
Concept Development	• Signal timing optimization • Ramp metering	Vehicle Infrastructure Integration Proof of Concept —Infrastructure (*34*)	VII Consortium
Concept Development and POC Testing	• In-vehicle signage • Off-board navigation • Tolling and parking payments	Vehicle Infrastructure Integration Proof of Concept—Vehicle (*7*)	VII Consortium
	• Cooperative adaptive cruise control	Increasing Highway Throughput Communications and Control Technologies to Improve Traffic Flow (*36*)	California PATH
Concept Development	• Transit signal priority • Arterial truck driving support • Intersection speed advisory • Vehicle-only/all-user signal optimization	Investigating the Potential Benefits of Broadcasted Signal Phase and Timing (SPAT) Data under IntelliDrive^{SM} (*21*)	
Concept Development	• Signal control logic	Beyond Traffic Signals: A Paradigm Shift Intersection Control for Autonomous Vehicles (*37*)	University of Texas at Austin
Algorithm Development and Simulation Testing	• Signal control logic • Arterial performance measures	IntelliDrive^{SM} Traffic Signal Control Algorithms (*38, 39*)	University of Virginia
	• Freeway merge control • Gap-responsive metering	Advanced Freeway Merge Assistance: Harnessing the Potential of IntelliDrive^{SM} (*40*)	
	• Traffic monitoring • Signal control logic	Preparing to Use Vehicle Infrastructure Integration (VII) in Transportation Operation (*41*)	
	• Bus priority control logic	Simulation Study of a Bus Signal Priority Strategy Based on GPS/AVL and Wireless Communications (*42*)	University of Minnesota
	• Dynamic route guidance	Sweden/Michigan Naturalistic Field Operational Test (*43*)	University of Michigan Transportation Research Institute

Dynamic Merge Assistance

Similar to the studies in safety applications on intersection crossing gap assist, the freeway merge assistance provides advisories for drivers at heavy weaving areas. In addition to some safety improvements, such assistance also yields mobility benefits. The University of Virginia performed a simulation study in VISSIM that evaluated the merge algorithm, given vehicles are connected through V2V communications (*44*). The algorithm first collects gap information on the freeway main lanes and then calculates the acceleration rates needed and the resulting space headway. Once the space headway in target time step is greater than the minimum safety distance, the advisory is produced. In the study, the maximum operational improvement observed was 6.4 percent higher average speed in the freeway mainline within a merge area. However, it requires at least 90 percent compliance rate for the proposed algorithm to work.

New Signal Control Logics

The DSRC protocol has defined a set of standard messages to be communicated over the air. The basic data structure for signal-related applications is comprised of four of these messages, which are better known as SPaT messages. High-quality detailed data with respect to all cars at all times are not only beneficiary in signal optimization but also provide new opportunities to devise new signal control logics. The University of Virginia research team proposed a dynamic gap-out algorithm to enhance the current actuated signal controls (*41*). The concept predicts the end of the platoon based on gaps calculated from individual vehicle locations and speeds. The results from the simulation study indicate that for volume-to-capacity ratios of 0.25 or larger, the dynamic gap-out approach reduced delay consistently on the order of 12 percent.

In a more recent study in the micro-simulation environment, the same team used vehicle locations, speeds, and headings to address many intersection congestion problems (*45*). Three algorithms were developed for this purpose (*38*). The first signal control algorithm developed is applicable to oversaturated intersections (*39*). The algorithm monitors queues in real time and then modifies the splits and offsets at intersections to more efficiently allocate green. The second algorithm, called the vehicle clustering algorithm, improves the signal progression by real-time monitoring of platoons on major streets. The third algorithm is called the predictive microscopic simulation algorithm and is based on the rolling horizon traffic control scheme. The algorithm uses the real-time data of vehicle speeds and positions to predict vehicle delays over the target time step for the signal phasing being used; then it determines the next phase to be displayed. These simulation studies were aimed at reducing delay, increasing throughput, or doing both.

The potential of V2I communications can only inspire even more investigations. Researchers at the University of Texas introduced a different intersection control paradigm built on the premise that all vehicles can communicate with the intersection infrastructure (*37*). The system eliminates the need for conventional traffic-light control altogether. The system allows a vehicle to request a reservation in space and time for traversing the intersection, via DSRC to the intersection manager, before entering the intersection; the intersection manager then transmits a confirmation, rejection, or alternative slot to the approaching vehicle. The concept has been demonstrated in a simulation environment, and dramatic reduction in waiting time results.

Signal Optimization

Due to the possibility of collecting real-time high-resolution speed, location, and heading information from individual vehicles approaching an intersection, signal timing and phasing can be optimized much more intelligently and adaptively. Currently, the new optimization paradigms based on the availability of new probe data are mostly explored at the concept development level. Both the California PATH program (*21*) and the VII Consortium (*34*) have sketched some elements in the architecture of the system and some flow of events with only a few details.

It should be noted that the adaptive traffic signal system is largely based on the concept of obtaining near-real-time information and adjusting the signal timing accordingly. In this sense, the existing adaptive signal paradigms may serve as the precursor for the next-generation traffic signal system.

Bus Transit Priority

The applications for bus transit priority have special appeal to large metropolitan areas since these applications may improve the competitiveness of bus travel, which in turn promotes more efficient use of urban public transportation. With real-time data about the passenger loadings and current schedule adherence, the priority can be set more intelligently. The California PATH program has embarked on the development of the ConOps for the bus signal priority application (*21*). Researchers at the University of Minnesota have recently conducted a simulation study to take advantage of the already equipped GPS/automatic vehicle location system on the buses (*42*). The priority algorithm developed could consider the bus schedule, number of passengers, location, and speed. The results showed up to 15 percent reduction in bus travel time during peak hours.

Cooperative Adaptive Cruise Control

The cooperative adaptive cruise control (CACC) system has been developed by adding a wireless vehicle-to-vehicle communication system and new control logic to an existing commercially available adaptive cruise control (ACC) system (*46*). Thus, instead of passively following and being followed by other vehicles, the CACC system can actively engage any acceleration and deceleration based upon the vehicle's longitudinal relationship with other vehicles in real time. Such a system may furnish tremendous potential for the reduction of headways while not compromising passenger safety. The California PATH program is actively developing and testing this vehicle-based mobility application in cooperation with car manufacturers in the federally funded Exploratory Advanced Research (EAR) program (*36*). They have designed and implemented the system on two passenger vehicles in a controlled test environment at Nissan's Arizona test track. The enhanced performance makes it possible to operate the CACC system at time gaps between 0.6 seconds and 1.1 seconds, compared to a range of 1.1 seconds to 2.2 seconds for the ACC system (*46*). Researchers reported that a test driver was less comfortable with the CACC system although he was willing to accept short gaps offered by the CACC system. These results were, however, based on a single participant.

3.3. RESEARCH IN ENVIRONMENTAL APPLICATIONS

The applications of environment protection offer to capture, synthesize, and deliver real-time, vehicle-based and infrastructure-based, environmentally relevant, as well as weather-related information. The right information supports travelers' "green" choices and advance environmental improvements within the transportation system. Segments under the connected vehicle environment application research support environmental applications: Applications for Environment: Real-Time Information Synthesis and Road Weather Applications.

3.3.1. Applications for Environment: Real-Time Information Synthesis

AERIS concerns real-time data capture and management for environmental purposes. The goals for AERIS are twofold (*47*):

- Integration—collects environmental data from vehicles and integrates the data with other sources for use in transportation management and performance improvement.

- Expansion—broadens the foundation of road weather data to include mobile sources and to focus the analysis on improving the ability to detect and forecast road weather and pavement conditions by specific roadway links.

Currently, there is less research on applications for environmental purposes that take advantage of Connected Vehicle technologies than on safety and mobility applications. Many of the evaluations and ConOps development for using vehicle-based probe data have only just begun. Table 7 summarizes a number of research projects, awarded only recently, concerning developing applications for AERIS (*48*).

These are the only documents researchers found publicly that describe each project in detail. According to the concepts of these proposed projects, the projects can be synthesized into the following applications:

- Capturing environmental performance data—These projects will determine the availability, relevance, and values of the real-time data sets from connected vehicles, and will develop environmental monitoring mechanisms to improve environmental performance.
- Eco-driving support system—Mathematical models will be enhanced to predict second-by-second fuel consumption and tailpipe emissions; the eco-cruise control algorithm will be developed and evaluated in a traffic simulation environment.
- Eco-adaptive signal control—By using traffic simulation tools, the concept of advising approaching vehicles about passage speed will be tested under different roadway configurations.

Table 7: Summary of Research Focusing on AERIS

Type	Applications Studied/Tested	Project/Program Title	Performing Agency
Simulation Testing	• Prediction of fuel consumption under eco-drive	ECO-ITS (*48*)	University of California at Riverside
Data Review	• Real-time environmental data capture	Research on ITS Applications to Improve Environmental Performance (*48*)	
Simulation Testing	• Signal control logic	Developing Eco-Adaptive Signalized Intersection Algorithms (*48*)	Virginia Tech
Algorithm Development and Field Testing	• Eco-cruise control logic	Developing and Evaluating Intelligent Eco-Drive Applications (*48*)	
Prototyping System	• Real-time environmental data capture management system	Research on ITS Applications to Improve Environmental Performance (*48*)	Mixon/Hill and Texas Transportation Institute
Simulation Testing	• Fuel-consumption-based route guidance system	An Evaluation of Likely Environmental Benefits of Lowest Fuel Consumption Route Guidance in the Buffalo-Niagara Metropolitan Area (*48*)	State University of New York at Buffalo

3.3.2. Road Weather Applications

Since inclement weather generally has adverse impacts on traffic mobility and safety, the collection and dissemination of weather-related information are particularly helpful to mitigate those impacts. With the possibility of collecting detailed information from Connected-Vehicle-equipped probe vehicles, the research focus for road weather applications is to build on the existing road weather systems to include mobile weather sources and to focus the analysis on improving the ability to detect and forecast road weather and pavement conditions by specific roadway links.

A plethora of past research efforts can be found in the literature related to the acquisition and dissemination of road weather information. Technologies have been deployed nationwide to enable active warning mechanisms to help inform travelers about adverse weather conditions. These technologies include environmental sensor stations, closed-circuit television cameras, local meteorological centers, and fixed vehicle detectors (*49*). Nonetheless, there have been relatively few efforts to study the ways of collecting weather data from vehicle-based sources.

The Clarus initiative (*50*) has explored ways to integrate a wide variety of systems observing and forecasting weather conditions. The Clarus system offered a one-stop, Internet-based portal for all surface transportation environmental observations. The system was integrated with robust and continuous data quality checking, assimilation, and dissemination procedures that could deliver timely, accurate, and reliable weather and road condition information. As successful as the Clarus initiative was, it did not include any vehicle-based observations.

Building upon the success of the Clarus initiative, the National Center for Atmospheric Research has looked at ways to collect weather-related data from not only meteorological stations but also day-to-day commute vehicles (*51, 52*). The center proposed methodologies to collect weather data, such as sun/rain information, windshield wiper status, headlight status, ambient air temperature, braking system status, and stability/traction control status. The center also developed an algorithm to parse and filter the weather data, and then produce and quality-check actionable information for data subscribers. In 2009, the research team prototyped a vehicle data translator (VDT) system and tested its accuracy and reliability in the Michigan test bed near Detroit. The VDT converts vehicle observations (e.g., ABS, stability control, traction control, and wiper statuses) into standardized formats of weather observations. Both studies confirmed that vehicle probe data have the potential to provide meteorological observations to the transportation community. The testing results from 11 equipped vehicles showed that temperatures were measured accurately but barometric pressures were too coarse to be useable. The findings further suggested that the data quality from vehicles was independent of ambient and vehicle conditions.

Another research team with the National Center for Atmospheric Research has conducted a feasibility and concept development study of road weather products enabled by the VII framework (*53*). The study examined the vehicle data elements that can be used to directly or indirectly sense weather and road conditions, and explored the possibility of predicting weather-related road hazards from these vehicle observations. A number of VII-enabled applications were envisioned and briefly discussed, as shown in Table 8.

Table 8: Summary of Road Weather Applications Discussed by Petty and Mahoney (*53*)

Category	Selected Applications
Weather Product	Diagnosis of Precipitation Type Identification of Foggy Regions Improved Air Quality Monitoring and Prediction
Pavement Condition Product	Improved Identification of Slippery Pavement Improved Knowledge of Pavement Temperature
Transportation System Management Decisions Support Product	Maintenance Decision Support System Summer Maintenance Traffic and Incident Management

4. DEVELOPMENT OF APPLICATION CONCEPTS

4.1. BRAINSTORMING SESSIONS

The research team carried out two brainstorming sessions in the Texas Transportation Institute. The first brainstorming session was conducted on June 17, 2011, and focused on potential safety issues and promising safety applications. The second brainstorming session was conducted on July 8, 2011, and focused on mobility-related issues and applications. Both brainstorming sessions lasted about 2 to 2.5 hours and resulted in a list of potential applications in respective themes.

To solicit expert opinions on the potential connected vehicle applications, TTI researchers were invited to participate in each of the brainstorming session. The roles of the participants were to identify current issues within their fields of expertise and to propose applications for discussion. Below is the list of the participants in the brainstorming sessions; parentheses denote which session(s) they attended:

- Christopher M. Poe, Ph.D., P.E. (safety, mobility).
- Yunlong Zhang, Ph.D., P.E. (safety).
- Gerald L. Ullman, Ph.D., P.E. (mobility).
- Beverly T. Kuhn, Ph.D., P.E. (safety).
- Nadeem A. Chaudhary, Ph.D., P.E. (safety, mobility).
- Srinivasa R. Sunkari, P.E. (safety).
- Geza Pesti, Ph.D., P.E. (safety).
- Gary B. Thomas, Ph.D., P.E. (mobility).
- Hassan Charara (safety, mobility).
- Bob Brydia (safety).
- Tony Voigt, P.E. (safety).

In each of the brainstorming workshops, a comprehensive review of the current state of connected vehicle research was given. Then a short overview of most of the DSRC messages contained in the SAE J2735 standard was presented. These reviews gave the attendees a general background of the research topic for this project. Additionally in the mobility session, an overview was given on high-priority mobility applications identified by RITA's Dynamic Mobility Application research program. Finally, the brainstorming discussions on application proposals were carried out by all the attendees in each of the sessions.

The discussions were directed to include two parts: the transportation issues in respective themes and the corresponding connected vehicle solutions. The research team solicited the expert opinions from each of the researchers in their respective fields of study for practical issues that could potentially be addressed using Connected Vehicle technology.

Both sessions resulted in a list of potential applications proposed by one or more of the attendees. The following lists include proposed applications with short descriptions:

- Safety:
  - Dilemma zone protection.
  - Rail preemption.
  - Unsignalized grade crossing.
  - School bus flashing operations.
  - Wrong-way warning.
  - Queue warning.
  - Warning for truck roll-over.
  - Merge warning.
- Mobility:
  - Dynamic work-zone speed limits.
  - Rail preemption.
  - Special event management (with smart park management).
  - Construction efficiency and productivity.
  - Speed harmonization.
  - Work-zone exits and entrances.
  - Dynamic freight routing.
  - Dynamic lane use for emergency dispatch.
  - Special needs (transit).
  - Responding to special-need evacuees.

In the list of proposed safety applications, the unsignalized grade-crossing and wrong-way warnings were selected for full ConOps development. In mobility, the researchers explored the concepts of speed harmonization, dynamic work-zone speed limits, rail preemption, and special event management. However, only the former two concepts were selected for full ConOps development.

4.2. OUTLINE OF CONCEPT OF OPERATIONS

A ConOps is a user-oriented document describing the functional characteristics of a to-be-delivered system from a user's point of view. In the FHWA ITS system engineering guidebook (*54*), a ConOps is the first document to be developed in the entire system engineering process. It outlines the basic components of the proposed system and their interactions as well as information flows. The ConOps also describes how the system concepts are applied under specific operational scenarios. In addition to the aforementioned components, more elements can be included in a ConOps to elaborate on the system concept. A ConOps document should describe the proposed system in plain language.

In this research project, the research team focused on developing the core concepts and operations of each application, which include the following aspects:

- Overview—describes the issues of the current practice or limitations of current ITS technologies.
- A system concept—outlines the goals and objectives as well as the basic components of the proposed system and their interactions in non-technical fashion.
- Operational scenarios—include the most likely scenario under which the proposed application is envisioned to operate, with descriptions of process flows.

It should be further noted that the development of the ConOps is based largely on the existing message sets available in the current version of the standard SAE J2735 (rev. 2009). This ensures the feasibility of these applications. However, there are times when new data messages need to be created to facilitate specific application development. Although new, these messages are built upon the existing data elements already defined in the current standard version. This effort may in turn help expand the collection of standardized messages in future revisions of the SAE J2735 standard.

In the following chapters, a total of five applications have been selected for ConOps development. Each section is dedicated to one application theme.

- Chapter 5 describes safety applications: the wrong-way warning system and the grade-crossing warning system are developed to enhance the detection and warning mechanisms for, respectively, wrong-way movements on high-speed roadways and the presence of trains at crossing areas.
- Chapter 6 describes freeway mobility applications: the smart work-zone management system enables in-vehicle delivery of critical work-zone merge advisories and the end of queue warning; the freeway speed advisory system is developed to minimize speed differentials and improve the flow of traffic.
- Chapter 7 describes an application for environmental security: the slippery pavement warning system uses the weather observations from connected vehicles to enable speed management measures for vehicles traveling on slippery pavements.

5. CONCEPT OF OPERATIONS FOR SAFETY APPLICATIONS

5.1. WRONG-WAY WARNING

5.1.1. Introduction

This application uses wireless communications technologies to enhance the detection and warning system for wrong-way movements on high-speed roadways.

Vision for the System

In the future, the wrong-way warning system will be able to detect if a driver is driving in a reverse direction. To detect a wrong-way violation, the warning system will use the real-time geographic coordinates of the vehicle to compare with digital drive lane configurations. Once a violation is detected, the system will generate visual or audible warnings to alert the driver about his own violation. Other motorists who are projected to have direct conflict with the violating vehicle will also be warned, and the urgencies of the warning will differ based upon the distances of these motorists from the violation. Additionally, the RSU infrastructure may send notifications to emergency responders for faster rescues. The wrong-way warning system can also be incorporated into other applications such as the reversible lane control system.

Current Practice and Problem

Wrong-way driving can typically be attributed to one of the following reasons: driver's lack of attention and lack of familiarity with local roadways, confusing or missing traffic control devices, poor weather or visibility conditions, and/or impaired driving. Although the number of wrong-way crashes is relatively limited, their consequences are much more severe than the consequences of other types of crashes, and they are usually fatal.

According to a survey of current practice conducted by TTI (*55*), the wrong-way countermeasures deployed by agencies nationwide rely solely on signing and pavement markings. The study also suggests that some innovative technologies, such as inductive loops and supplemental placards or flashers, be installed for warning a driver at the possible starting points of a violation. These countermeasures may be effective if the wrong-way driver is physically alert and sober. However, multiple studies reviewed by the TTI research team have suggested that approximately 50 to 75 percent of wrong-way crashes involve impaired drivers (*55*). Therefore, active warning mechanisms may be more effective if they warn the emergency responders and the motorists traveling in the correct direction in the vicinity of the impaired wrong-way driver. However, there is no active mechanism to warn other drivers; because of the rareness and uncertainty of wrong-way events, warning other drivers is not cost-effective. So once the warning to the violator fails at the entry point of a high-speed roadway, no backup warning mechanism is available to help other drivers avoid or mitigate head-on collisions.

The emerging connected vehicle technologies will be a low-cost enhancement to the current active warning system. Communications to deliver warnings to drivers inside the vehicle can eliminate the possibility of inattentiveness and minimize the level of distraction. Additionally, two-way communications can help the roadside infrastructure monitor violations and more intelligently broadcast warning messages to other drivers and emergency agencies.

5.1.2. System Concepts

Goal and Objectives

The goal for the system is to provide a cost-effective enhancement to the current wrong-way warning systems. Specific objectives of the system include:

- To enhance the detection of wrong-way movement by using the knowledge of a vehicle's real-time operational status.
- To intelligently warn the violating driver and other drivers who have direct conflicts with the violation.

Scope

Wrong-way movements may originate from a number of places, including interchanges, median crossings, exit ramps connecting with interstate roads, business establishments, and residential areas. Of the many possible places, freeway exit ramps have been identified as the most likely origination of severe wrong-way crashes, especially left-side exit ramps (*56*). The system concept developed here is limited to high-speed wrong-way crashes that originate from highway exit ramps.

System Components and Interactions

The system contains the following functional components:

- GPS receiver—The in-vehicle GPS receiver is an essential component of the wrong-way application. The receiver obtains the vehicle's location in real time. Lane-level accuracy for the GPS receiver is not required, but direction-level accuracy is necessary for the GPS receiver to be useful in this application.
- Onboard unit—In the wrong-way warning application, an OBU can retrieve the vehicle's heading and GPS location and the direction of the freeway. The required function of an OBU is to communicate a vehicle's real-time running status and receive any warning message broadcast over DSRC.
- Detection unit—To ensure 100 percent detection of the wrong-way movement, a set of detectors (e.g., loop detectors) is needed on to create a detection zone at an exit ramp where a wrong-way violation is likely to originate. This set of detectors is connected to a nearby RSU, so any detection signals are processed by the RSU.
- Roadside unit—Two RSUs are envisioned, with one used as a primary warning component and the other as a supplemental detection unit for an active violation. The function and requirements of these two RSUs are different:

    - The first RSU (RSU-1) is required and is installed at the exit ramp location. The placement of RSU-1 is at the gore area of the exit ramp such that half of its range covers a portion of the exit ramp and the other half covers a portion of the freeway main lane. This RSU is equipped with a computing unit that can process detection signals from two sources: the detection unit and the OBU in the violating vehicle. From the detection unit, simple algorithms can be devised to capture the wrong-way movement. From its OBU, the vehicle's real-time running status can be used as additional information to help generate more intelligent warning messages. Another

main function of this RSU is to relay the warning message upstream and to an emergency service agency.
  - The second RSU (RSU-2) is optional and installed at a location at least some duration (e.g., 30 seconds) upstream of the first RSU. The duration should be sufficient for a driver in the correct direction to react to the warning. The main purpose of RSU-2 is to broadcast any wrong-way warning messages received from RSU-1. In this discussion, RSU-2 is also installed. When other forms of communications are available, RSU-2 can be replaced.

- Emergency service center—A local emergency service center is an optional component but is useful to give a heads-up notification for emergency dispatches. There are various communications methods that can be used connecting the local RSUs with the emergency service center, such as fiber optics backbone networks or cellular networks.

Figure 7 illustrates the concept of the wrong-way warning system. Two RSUs are used in this illustration. Additionally, the violating vehicle is a vehicle equipped with an OBU device. In effect, the detection unit and the RSU-1 realize a double-checking mechanism that ensures the detection of wrong-way movement is not likely a false alarm. False alarms include instances of detection signal malfunctions. The warning message is delivered to equipped vehicles at locations upstream to the violation, and the level of urgency of the message may vary according to the real-time location of delivery. The diagram also includes the connection from RSU-1 to the emergency service center, to where the wrong-way event is reported as a traffic incident.

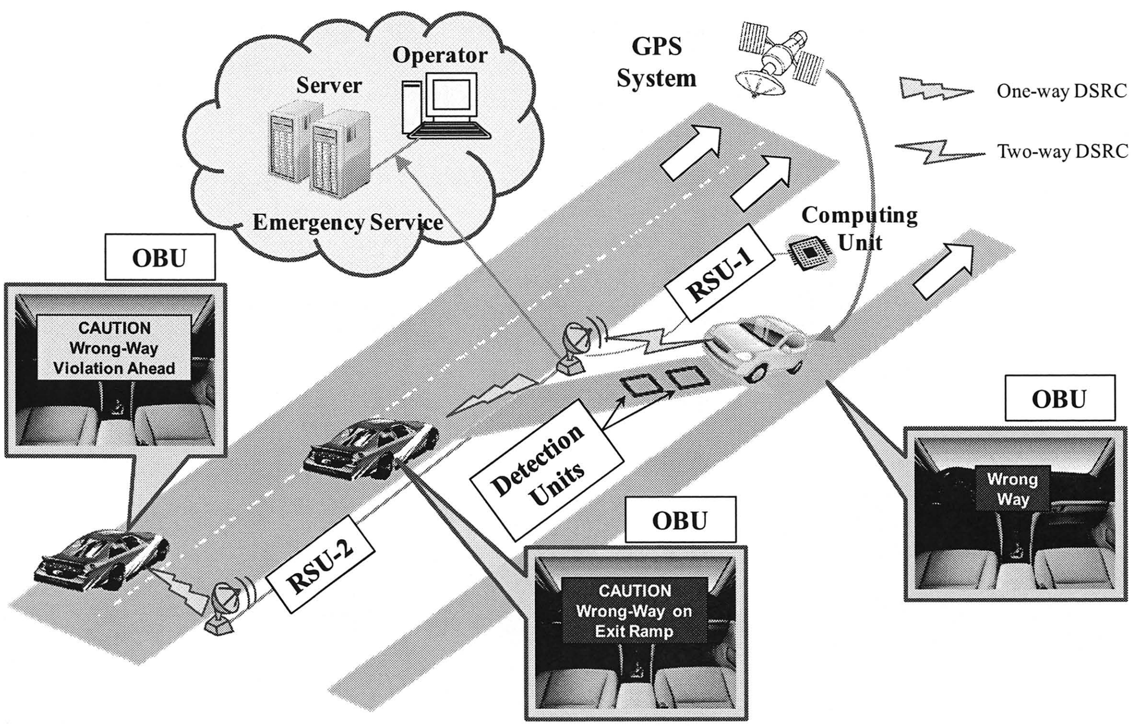


Figure 7: Concept of Wrong-Way Warning System

Supporting DSRC Messages

To support the operation of this application, the messages in the SAE J2735 standard (rev. 2009) are required:

- Basic Safety Message (BSM) – is used by the wrong-way OBU to broadcast its location, speed, acceleration and headings (see section 2.3.1).
- Common Safety Request (CSR) – is used by the RSU-1 to request the operational data from a wrong-way vehicle on the exit ramp (see section 2.3.2).
- Roadside Alert (RSA) – is used by both RSU-1 and RSU-2 to inform motorists about an active wrong-way event (see section 2.3.3).

Limitations

Until 100 percent market penetration, not all drivers will be notified. One of the side effects of this limitation is that when only some drivers are notified upstream, they may slow their vehicles while other unequipped driver will not. This may induce speed differentials. One remedy for this side effect is the speed harmonization strategy typically used in an active traffic management system (*57*) or the freeway speed advisory system proposed in section 6.2.

5.1.3. Operational Scenario

The detection of wrong-way driving sets off a series of events. Figure 8 is a flow chart illustrating the operations of the system. The roadside warning will be given to the violating driver, emergency agencies, and equipped vehicles in the immediate vicinity of RSU-1. Then, depending on whether the violating vehicle is equipped, the system will be operated slightly differently. If the wrong-way vehicle is equipped, a process where RSU-1 monitors the wrong-way OBU will be initiated as a smart warning mechanism. Such mechanisms provide a short time window in an attempt to warn the violating driver before warning further upstream drivers. Therefore, two operational scenarios are identified: violation by equipped vehicles and violation by non-equipped vehicles.

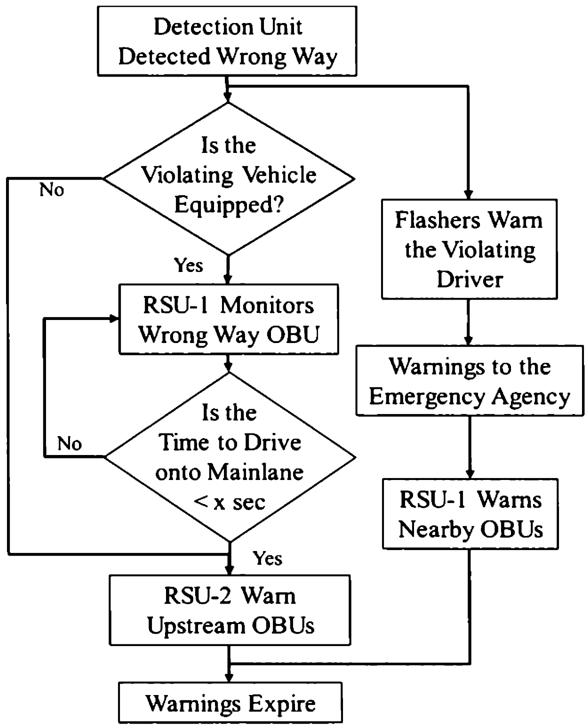


Figure 8: System Flow Chart for Wrong-Way Warning

Violation by Non-equipped Vehicle

In a case where the violating vehicle is not equipped with an OBU, the traditional active warning method is used to warn the violating driver. In addition, warnings to upstream drivers are provided through the use of infrastructure-to-vehicle communications. The following sequence of events describes the general process and data flows involved in this scenario, as shown in Figure 9:

1. The detection unit sends a sequence of detection signals to RSU-1, where a reverse sequence is detected, which indicates a wrong-way event.
2. RSU-1 triggers roadside warning devices (such as a flasher), sends the detection of the wrong-way event to the emergency agency, and broadcasts an RSA message to warn about the wrong-way driving.
3. Nearby OBUs pick up the RSA broadcast and warn their drivers about an active violation on the ramp.
4. Meanwhile, RSU-1 attempts to establish two-way communications with the violating vehicle but fails because the vehicle is not equipped.
5. RSU-1 then sends the RSA message to RSU-2, where the RSA message is broadcasted to upstream vehicles that are equipped.
6. The broadcast of the warning either expires after a long period of time or is switched off by a police officer on the scene.

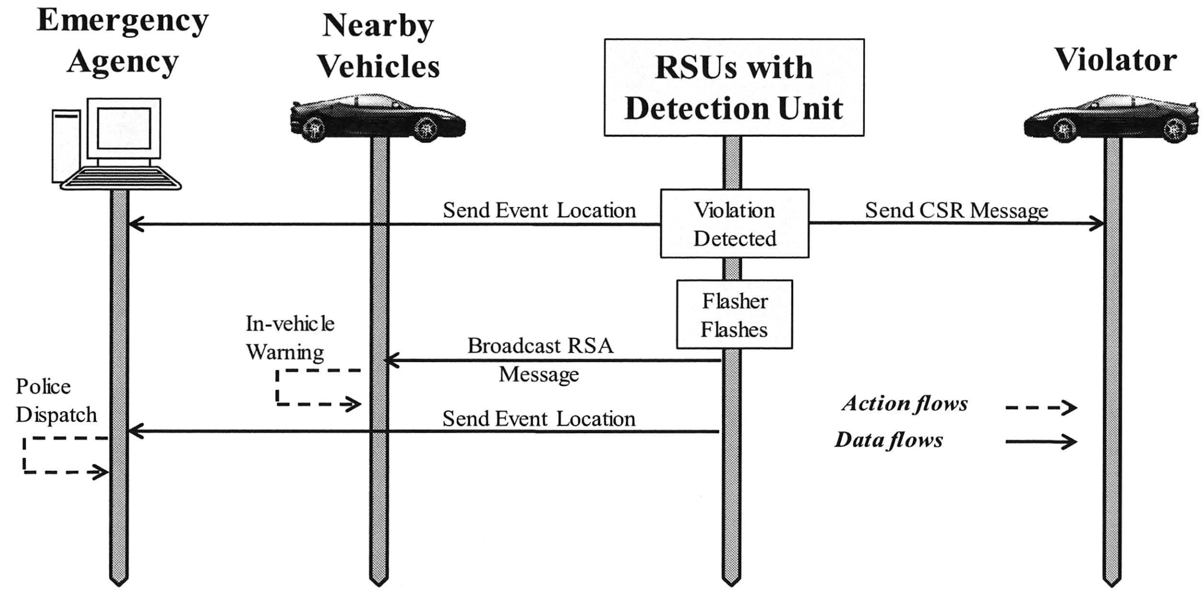


Figure 9: Data and Action Flows for Wrong-Way Warning (Non-equipped Vehicle)

Violation by Equipped Vehicle

When the violating vehicle is equipped with an OBU (as shown in Figure 7), the system will not only pick up the wrong-way movement from the detection units but will also be able to monitor the running status of the violation. By doing this, the system can have a better idea of whether the violation is likely to continue on the freeway main lane after the driver is warned. Therefore, the system can more intelligently determine whether to warn drivers further upstream. The following sequence of events describes the general process and data flows involved in this scenario, as illustrated in Figure 10:

1. The detection unit sends a sequence of detection signals to RSU-1, where the detection signals indicate a wrong-way event.
2. RSU-1 triggers roadside warning devices (such as a flasher) and sends the detection of the wrong-way event to the emergency agency to warn about the wrong-way driving.
3. Meanwhile, RSU-1 sends a CSR message to the vehicle in violation to ask for its current location, speed, and acceleration.
4. The OBU responds to the CSR message by periodically broadcasting its BSM.
5. On each receipt of the BSM, RSU-1 computes the time of the vehicle to entering the freeway main lane. If the time remaining is less than an agency-specified threshold (e.g., 5 seconds), both RSU-1 and RSU-2 broadcast an RSA message to warn other equipped vehicles on the main lane about the violation. The violation event is again sent to the emergency agency with a higher severity level.
6. The broadcast of warning either expires after a long period of time or is switched off by a police officer on the scene.

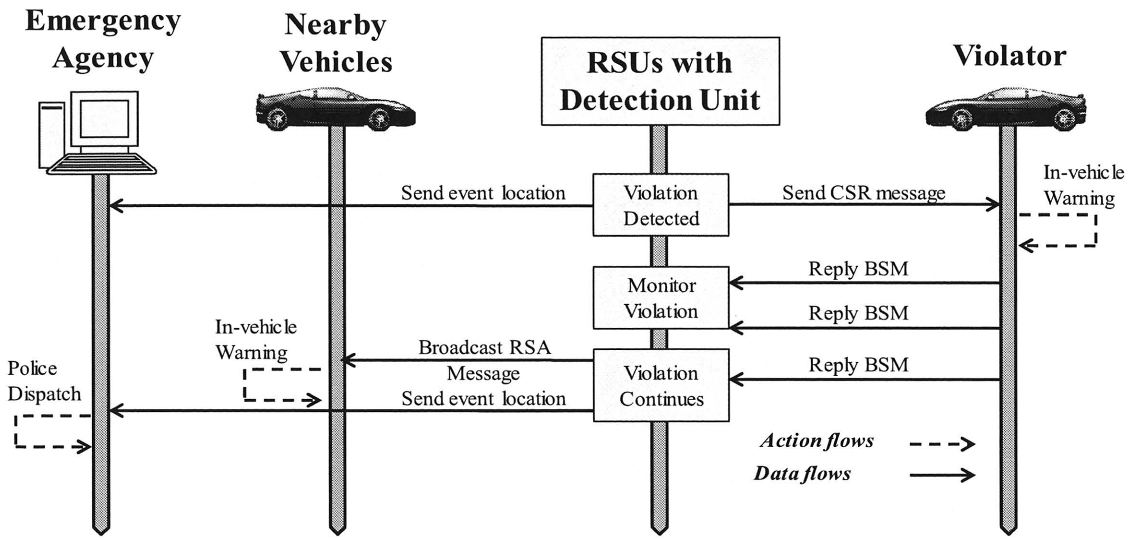


Figure 10: Data and Action Flows for Wrong-Way Warning (Equipped Vehicle)

5.2. GRADE-CROSSING WARNING

5.2.1. Introduction

This application uses wireless communications technologies to detect the presence of trains at any public grade crossing and thereafter to provide active warnings to approaching connected vehicles. The system is a low-cost supplement to the current grade-crossing warning system.

Vision for the System

In the future, highway-grade crossings where gating facilities are not required will be installed with the proposed system. In addition, such systems can serve as supplemental warning mechanisms at crossings where active warning systems currently exist. Public highway-rail grade crossings will be more protected with this low-cost detection and active warning system.

Current Practice and Problem

Highway-rail grade crossing protections are conventionally provided using a combination of signage, pavement markings, detection circuitries, gating facilities, and flashing warning signals. Whenever there are oncoming trains, grade-crossing traffic needs to yield the right of way for the passing trains. A number of warning devices are deployed in the United States, and they can be divided into two groups: active and passive. Active warning devices include gates, flashing lights, highway signals, wigwags, and bells. Passive devices include cross-buck signs, stop signs, and other signs.

The separation gating and the active warning infrastructures are not required at all grade-crossing areas. By 2005, about 55 percent of the public grade crossings in the United States were installed with either passive warning devices or no warning facilities at all (*58*). About 50 percent of vehicle-train crashes occur at public grade crossings where no active warning devices exist (*59*). Unprotected grade crossings at rural locations are particularly dangerous at night. When crossing drivers are distracted and do not see passing trains, they may easily run into the body of the train. About 20 percent of all accidents at grade crossings involve cars running into trains (*59*).

The major reason for not installing active warning devices at every grade crossing is the high costs of facilities and installation. It is estimated that the total cost of a traditional active warning system ranges from $100,000 to $200,000 (*60*), 25 to 30 percent of which is installation costs.

Connected Vehicle technologies are a low-cost supplement to traditional active warning systems at highway-rail grade crossings (i.e., protected and unprotected). Wireless communications provides a possibility of delivering in-vehicle warnings, which are envisioned to be a more cost-effective warning mechanism. Additionally, transmitting information wirelessly implies the installation costs (e.g., wiring and trenching) can be reduced and fewer materials are needed.

5.2.2. System Concepts

Goal and Objectives

This application attempts to enhance the safety of highway-rail crossings, particularly unprotected crossings, by providing a low-cost warning mechanism that uses vehicle-to-infrastructure wireless communications. Specific objectives of the system are:

- To reliably detect the presence of a passing train using low-cost devices.
- To warn the approaching traffic about the presence of a train in the crossing area.

System Components and Interactions

This system consists of:

- Detection unit—The sole purpose of a detection unit is to detect the presence of a train in the grade-crossing area. The detection unit should be able to differentiate trains from other moving objects (e.g., cars). The detection signal needs to be relayed to a nearby RSU. A battery-powered or solar-powered low-power consumption unit is preferred.
- Roadside unit—One RSU located at the grade-crossing point is needed for the application. The roadside unit can be wired or wirelessly connected to the detection unit, and it unconditionally broadcasts warnings about the presence of a train when a detection signal is received from the detection unit.
- Onboard unit—An OBU should be able to read the warning message sent from the RSU. The OBU can also generate an in-vehicle warning to the driver.
- GPS receiver—An in-vehicle GPS receiver is an optional component of this application and is used to identify a vehicle's real-time location. If there is a parallel highway in close proximity to the train track, non-crossing vehicles may pick up the warning message even though they are simply passing through the vicinity. In this case, the vehicle's real-time location and its heading can be useful to filter out the warning.

Figure 11 illustrates the concept of the grade-crossing warning system. The two equipped vehicles approaching the crossing area receive warning message sent from the RSU. A warning to stop for the train is delivered to the driver.

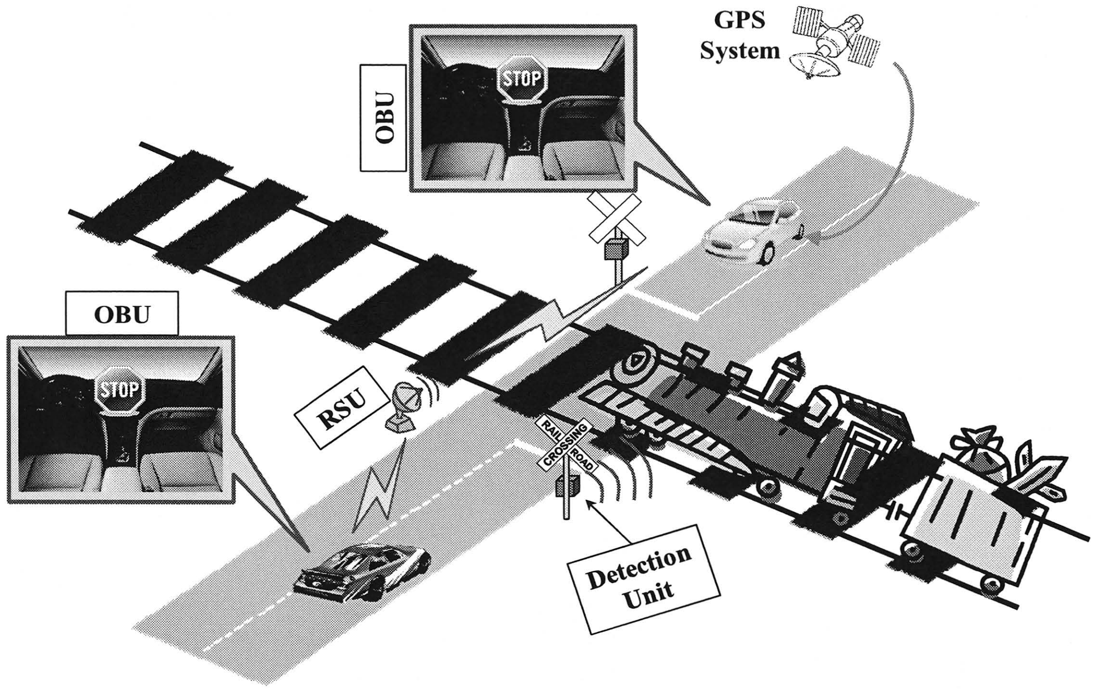


Figure 11: Concept of Grade-Crossing Warning System

Supporting DSRC Messages

To support the operation of this application, the messages in the SAE J2735 standard (rev. 2009) are required:

- Roadside alert message—The RSA message is used to tell a nearby OBU that a train at the grade-crossing area is detected (see section 2.3.3).
- MAP message—This message is used to provide the location of the grade-crossing area. Detailed lane configurations are not necessary (see section 2.3.4).

5.2.3. Operational Scenario

The proposed application will be used to warn motorists about the presence of a passing train. Thus, the system is only operational when a train is detected to have occupied the crossing. The following steps describe the process and interactions for this application scenario, as shown in Figure 12:

1. At the arrival of a train, the detection unit detects the presence of the train and sends a signal to an RSU located near the grade-crossing location.
2. The RSU receives the detection signal; it then generates an RSA message and broadcasts it along with a predefined MAP message to any equipped vehicles within range.
3. A nearby OBU extracts the crossing location and compares it to its own location and heading. If the OBU is driving toward the crossing area, the OBU sends a warning to the driver.
4. The RSU continues to broadcast the RSA and MAP messages every second as long as the detection signal from the detection unit persists. Once the train passes, no detection signal is sent. The RSU ceases broadcasting any messages.

5. Once the OBU receives no more RSA and MAP messages, the in-vehicle warning is lifted.

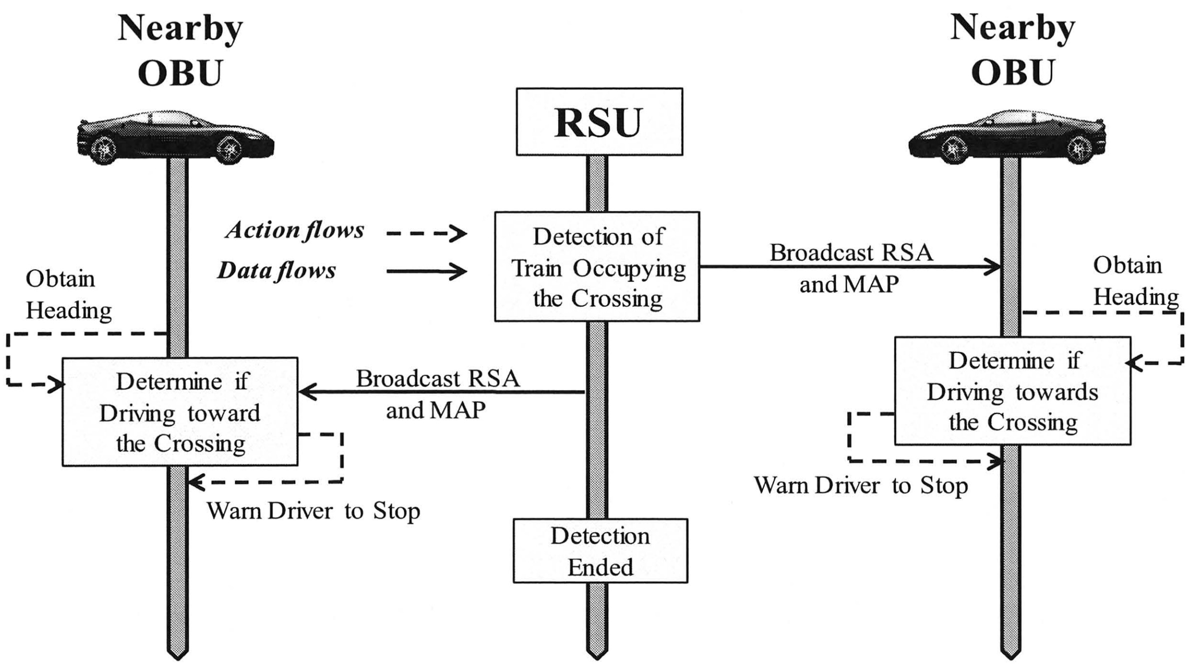


Figure 12: Action and Data Flows for Grade-Crossing Warning

6. CONCEPT OF OPERATIONS FOR MOBILITY APPLICATIONS

6.1. SMART WORK-ZONE MERGE MANAGEMENT

6.1.1. Introduction

This application uses vehicle-to-infrastructure DSRC to enable dynamic work-zone merge strategies. This application fully supports in-vehicle delivery of critical work-zone-related information, and also aims to intelligently provide merge advisories based on the vehicles' real-time locations, dynamic work-zone queue lengths, and, in the future, vehicle types.

Vision for the System

The smart work-zone merge system will eventually be a low-cost solution to harmonize the work-zone merge traffic flows that in turn minimize traffic incidents and maximize operational efficiencies in the work-zone merge area. The system can potentially replace the current dynamic work-zone lane merge systems for advisory purposes. Work-zone motorists will receive optimized instructions to merge based upon primarily the work-zone traffic conditions and secondarily the vehicle's operating characteristics.

In the near-term, the system still relies on dynamic message signs (DMSs) to broadcast optimized merge advisories, but it has the added capability to warn drivers about upcoming queues. Thus, the system is expected to be either a standalone solution to work-zone queue warning (without the use of DMSs) or a low-cost enhancement to the current work-zone dynamic lane merge systems (with the use of DMSs). As the number of connected vehicles increases and GPS accuracy improves, more work-zone motorists can be advised with better merge instructions. Eventually, this application is envisioned to completely replace the current dynamic lane merge systems to deliver safe and efficient work-zone merge traffic flows. However, this application is not envisioned to replace the static road signs and markings mandated by the MUTCD.

Current Practice and Problem

As the U.S. infrastructure ages (*61*), maintenance works are much needed, and the number of work zones is expected to rise. To help inform work-zone motorists, essentially two mechanisms are in place; one is mandatory, and the other is supplemental. Static signs are mandated by the MUTCD to warn travelers about the existence of the work zone and its configurations. The goal of these static signs is safety with little consideration of impacted mobility in the work-zone area. On the other hand, the dynamic work-zone merge systems are optional and can be seen in some work-zone areas where traffic flow patterns fluctuate greatly. These systems are attempts to further improve the mobility and safety of work-zone traffic.

However, current dynamic work-zone merging strategies are relatively infrastructure intensive (*62*). Intensive infrastructure not only equals higher costs but sometimes introduces added confusions to drivers. Additionally, current merge strategies are designed mainly for general traffic flows because of the lack of methods to provide individualized messages to work-zone motorists. Uniform messages do not account for different operating characteristics of vehicles and their real-time locations. For example, trucks have more difficulty merging than passenger cars; thus, they need to be advised to merge further upstream so that they are more likely to find a gap before coming to a forced merge maneuver. Also, travelers might want to know if they can drive straight or have to merge into an open lane to achieve the fastest travel time. Deploying more signs to accommodate the various vehicle types and dynamics in a traffic stream is not always an option since it will surely need more infrastructure placements and add more irrelevant information for drivers to filter through.

Connected Vehicle technologies make it entirely possible to identify the needs of each motorist and provide individualized merge messages to the right vehicle at the right time. The wireless and computing technologies maximize the flexibilities of a work-zone merge system and thus further improve the safety and mobility of such systems.

6.1.2. System Concepts

<u>Assumptions</u>

This application assumes some low percentage (say 10 percent, for example) of the work-zone traffic is equipped with DSRC OBUs that can communicate with the RSU placed in the work-zone area. The percentage of market penetration is to ensure a reasonable estimate of the work-zone traffic conditions, and a higher percentage results in higher confidence in the estimate. In another case, when the market penetration is lower than required, additional radar sensors could be added as remedies for estimation. With added radar sensors, the DSRC OBUs will be used only for receiving queue warning from RSUs. However, this research focuses on the first case only.

Another assumption is that the work-zone queues can never build up beyond the first work-zone signage upstream (i.e., WORK ZONE AHEAD). Because this is a rare occurrence, this application does not consider the situation. To account for the aforementioned case, modifications to this application would be needed.

<u>Goal and Objectives</u>

The goal for the system is to build a new paradigm of work-zone merge advisory systems that makes use of connected vehicle technologies. In the near term, the system is expected to be either a standalone solution to work-zone queue warnings or a low-cost enhancement to the current work-zone dynamic lane merge systems. Specific near-term objectives of the system include:

- To estimate at least two measures of traffic conditions: speed and the end of the work-zone queue.
- To intelligently deploy lane merge strategies that account for real-time traffic conditions.
- To efficiently communicate to any connected vehicles about the location of a work zone in their path, critical work-zone configurations (e.g., which lane is closed), and the real-time work-zone queue conditions.

<u>Scope</u>

The concept developed here is limited to any type of work zone on a multi-lane highway or an interstate freeway. Work zones at signalized arterial and local streets are not applicable since the placements of RSUs need to consider the impacts of the side street and driveway traffic. However, the concept may be extended to include arterial work zones as well.

System Components and Interactions

The system contains the following functional components:

- GPS receiver—A GPS receiver is an essential component of this application and is used to identify a vehicle's real-time location. Different levels of GPS accuracy apply to different levels of message details to be sent to travelers, but the accuracy levels are not expected to significantly alter the general concepts of this application. At the coarsest level, this application will provide only cross-section-based positioning and messages; at the finest level, this application will additionally provide lane-based positioning and messages.
- Onboard unit—In this application, an OBU is necessary to communicate with RSUs and the vehicle-driver interface. The OBU obtains a digital MAP message from the very first upstream work-zone RSU (or RSU-n in Figure 13). The MAP message has to be updated every time the work-zone configuration is changed. The OBU needs to obtain a vehicle real-time speed and send it to a nearby RSU when needed. In the early deployment of this application, to avoid confusing drivers, an OBU does not display any merge instructions but only the status of the work-zone queue. As the connected vehicle market penetration increases to a high percentage, an OBU can display both the merge instructions and queue status.
- Roadside unit—The placement of the RSUs is in accordance with that of the MUTCD-mandated signs for the distance to the work zone(*63*). Depending on the speed of the highway, these signs are placed at an interval of about 0.25 to 0.5 miles from the work-zone location. For example, each RSU can be mounted on the top of a work-zone sign post. Based upon the practical range of 1000 feet for a DSRC RSU, placing these RSUs at the sign post locations can maximize the coverage of DSRC signals. The first RSU is installed at the location of the first work-zone sign post. Its sole functionality is to broadcast work-zone descriptions and merge management messages that are similar to typical implementations. All the RSUs downstream should be able to collect vehicle passing speeds and broadcast merge management messages. The last downstream RSU should also be equipped with computing powers so that management algorithms and MAP messages can be implemented and updated.
- Dynamic message signs—A DMS is necessary in the early deployment of this application. The merge instructions are exclusively displayed on these DMSs to ensure every driver receives the same merge instructions. DMSs are placed at or close to the location of the RSUs.
- Communication network—The backbone network connects all the RSUs and DMSs to facilitate information flow. The back office network is an additional module and is needed to support real-time monitoring of work-zone traffic conditions at local management centers.

Figure 13 illustrates the concept of the smart work-zone merge management system in near-term deployment. All the aforementioned system components are included. The colored vehicles in the figure represent vehicles equipped with DSRC OBUs. The example diagram shows the system is working when the dynamic late merge strategy is activated in high-volume conditions.

However, the system does not directly detect the number of vehicles in the merge area, but uses speed measurement from a sample of equipped vehicles to activate the merge strategy and to estimate the end of the work-zone queue.

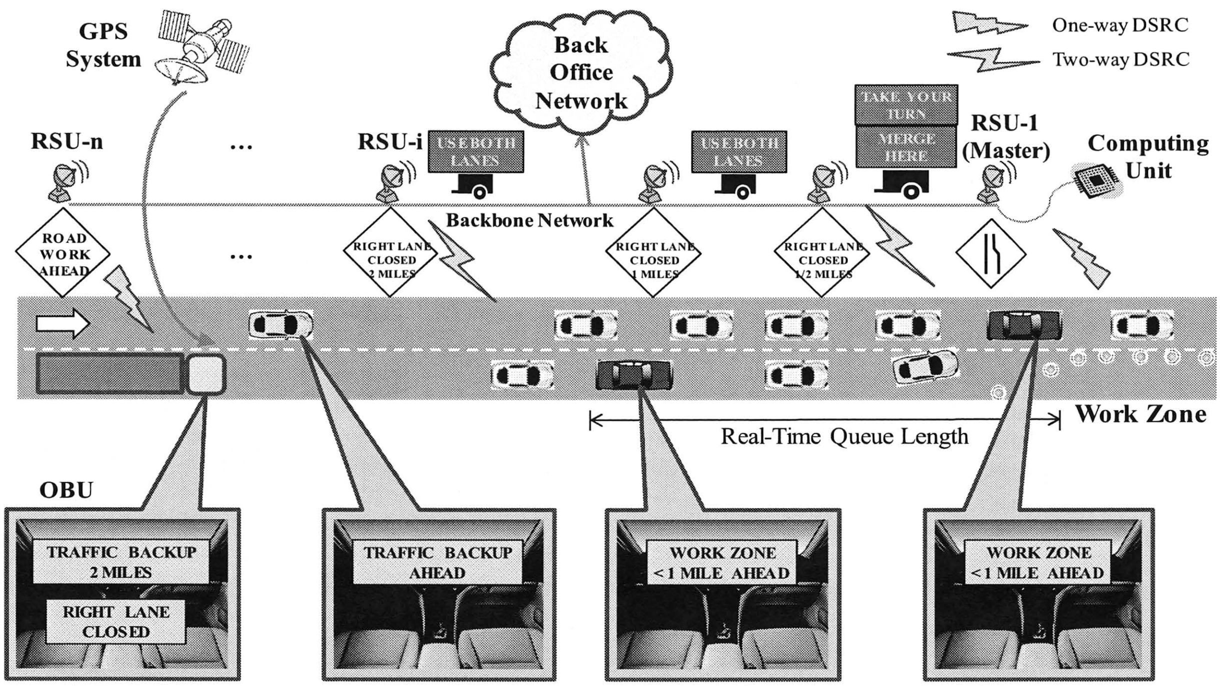


Figure 13: Concept of Smart Work-Zone Merge System (Early Form)

Figure 14 illustrates the concept of this system in its final form when more than 90 percent of the vehicles are equipped with some forms of OBUs. As compared to its early form (shown in Figure 13), the DMS infrastructure is removed, and the OBUs display not only queue status but merge instructions as well. In addition, given better GPS systems which have more accurate lane positioning, the system can more intelligently customize the merge instructions and deliver them to the right car, at the right lanes/locations and at the right time. Thirdly, a work-zone merge message needs to be added to the current version of SAE J2375 to support the communication of merge instructions to OBUs (see the next subsection for details). Other than these three modifications to the system, other aspects of the system remain the same as those being developed in this ConOps. However, in order to focus on near-term feasibility of this system, the final form of the work-zone merge system is not further discussed in this report.

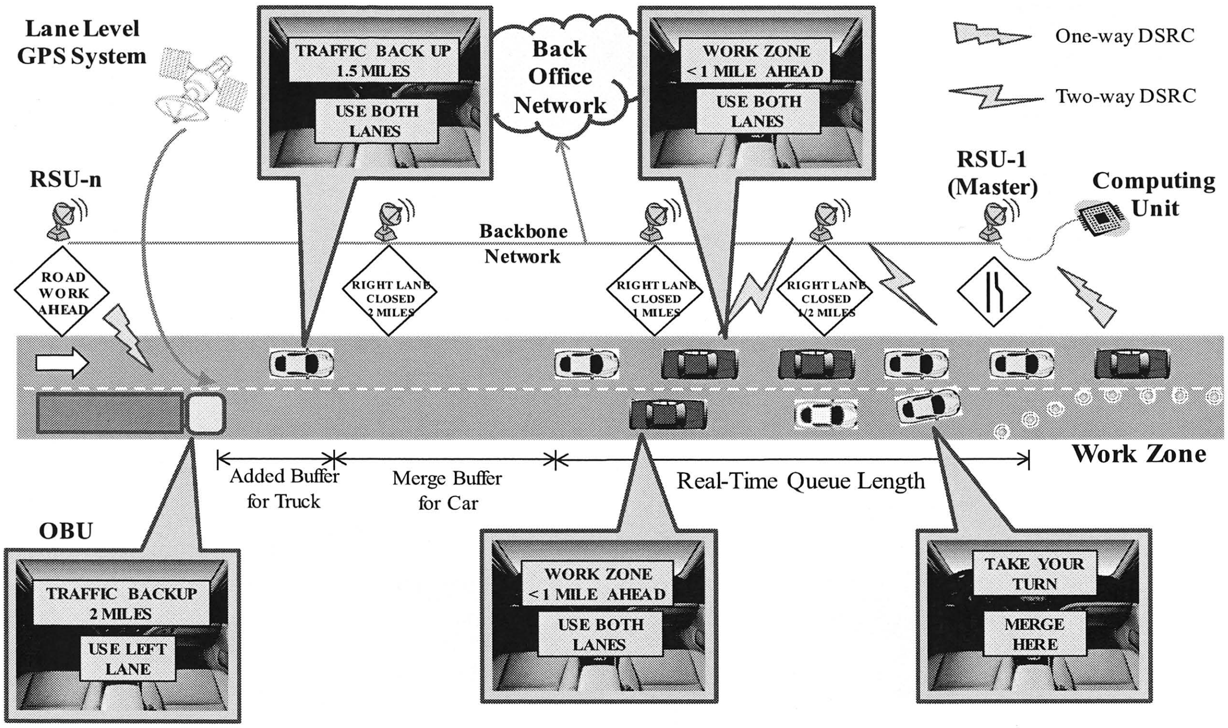


Figure 14: Concept of Smart Work-Zone Merge System (Final Form)

Supporting DSRC Messages

To support the operation of this application, the messages in the SAE J2735 standard (rev. 2009) are required:

- Probe vehicle data—used to generate traffic conditions in the work-zone merge area (see section 2.3.8).
- Probe data management—used to instruct OBUs to collect speed data on a per-time-interval basis (see section 2.3.9).
- MAP message—used to provide a digital reference of the lane configurations in the work-zone merge areas (see section 2.3.4).
- Traveler information messages—used to convey queue conditions to work-zone travelers (see section 2.3.10).

In addition to the currently available messages in the standard, an additional message is required to be transmitted over the DSRC channels in the final form of the system.

- Work-zone merge (WZM) message—The message is used to inform drivers of where and how to merge and is generated by a central computing unit. It is essentially a lookup table populated with merge instructions. Each merge instruction is time stamped and location stamped. Therefore, an OBU can easily look up the merge instructions to be displayed based on its current time and location.

6.1.3. Operational Scenario

The system brings the best aspects of the early and late merge methods. Under different traffic conditions measured mainly by speed, different merge strategies will be activated to achieve their respective goals. Thus, the system operates under two merge scenarios: early merge and late merge. Figure 15 is a flow chart illustrating the operations of the system. Early merge is the default scenario of the system, while late merge is a scenario that is activated by any RSUs having observed a low range of speed from passing OBUs.

Early Merge

The early merge is the default scenario for the system. In this scenario, the system monitors the work-zone traffic conditions and optionally displays the speed estimates to the driver (if this information is not readily available from other applications). Under this scenario, the OBU will not automatically warn the driver about a work zone in the path. The driver will normally rely on reading the work-zone signs. However, the driver can request work-zone information (such as lane configurations, distance before lane drop, and current traffic conditions) whenever the driver is in the work-zone merge area.

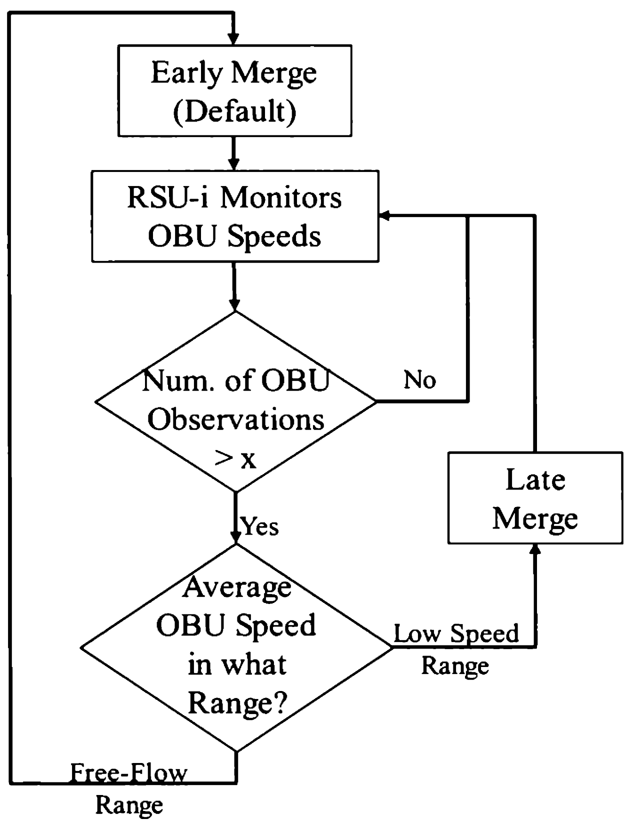


Figure 15: System Flow Chart for Work-Zone Merge

The following sequence of events describes the general process and data flows that are involved in this scenario, as illustrated in Figure 16:

1. The RSU-*i* (where *i* is from 2 to n) broadcasts two messages to passing OBUs: an instructional message for probe data collection (i.e., PDM) and work-zone configurations (i.e., MAP).
2. Upon receiving the two messages, the OBUs collect their speeds according to the PDM and format the speed data into PVD messages. The OBUs send the PVD messages back to RSU-*i* and the master RSU (i.e., RSU-1).
3. When RSU-*i* receives a PVD message from an OBU, it directly relays the PVD message to the master RSU.
4. The computing unit at the master RSU estimates, at fixed time intervals, the traffic speed and queue conditions in the work-zone merge area.

If a back office network is connected to the master RSU, then this operation mode can be used for the transportation management center to monitor work-zone traffic conditions.

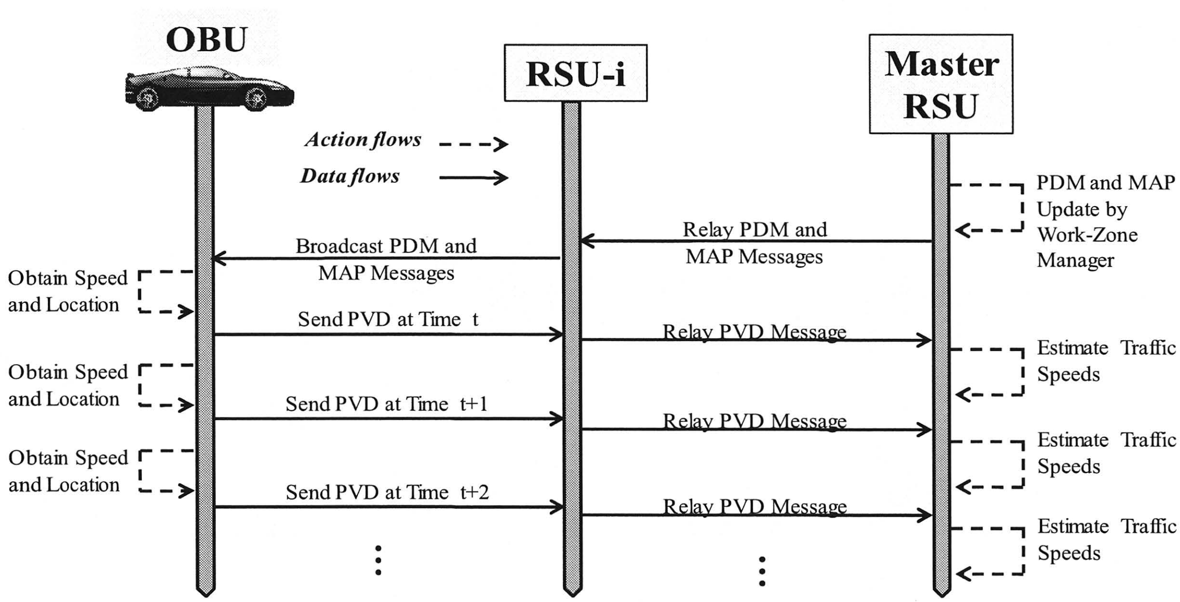


Figure 16: Action and Data Flows for Work-Zone Merge (Early Merge)

Late Merge

The late merge strategy is used when the traffic volume is too heavy, to the point where the bottleneck capacity is exceeded. The late merge strategy allows drivers to use both lanes up to the location of lane drop. This strategy maximizes the queue storage capacity by using all lanes.

The following sequence of events describes the general process and data flows that are involved in this mode, as illustrated in Figure 17:

1. The system runs in early merge mode, as described previously.
2. The traffic slows down below the threshold speed, and a queue forms by the RSU-I, so the system activates the dynamic mode. The threshold speed needs to be established prior

use of the system. There should also be a minimum time before activation to prevent false alarms.

3. The master RSU estimates the queue length by employing some speed-based queue estimation algorithms. For example, speed differentials at two or more RSUs can be used to interpolate the queue length. Then the RSU generates queue status messages in the format of TIMs.
4. The master RSU generates merge instructions. In the early form of the system, simple merge advisory messages, such as "TAKE TURN/MERGE HERE" and "USE BOTH LANE/MERGE AHEAD," can be used. In the final form of the system, customized merge advisory messages can be generated using the WZM format.
5. The TIM is packaged with PDM and MAP messages. The data package is then communicated to all RSUs and relayed to OBUs in the work-zone merge area. Simple merge advisory messages are sent to the DMSs to be displayed to all work-zone motorists.
6. The OBUs warn their drivers about an upcoming queue by reading the TIM. Example warning messages may include "TRAFFIC BACKUP IN X MILES."

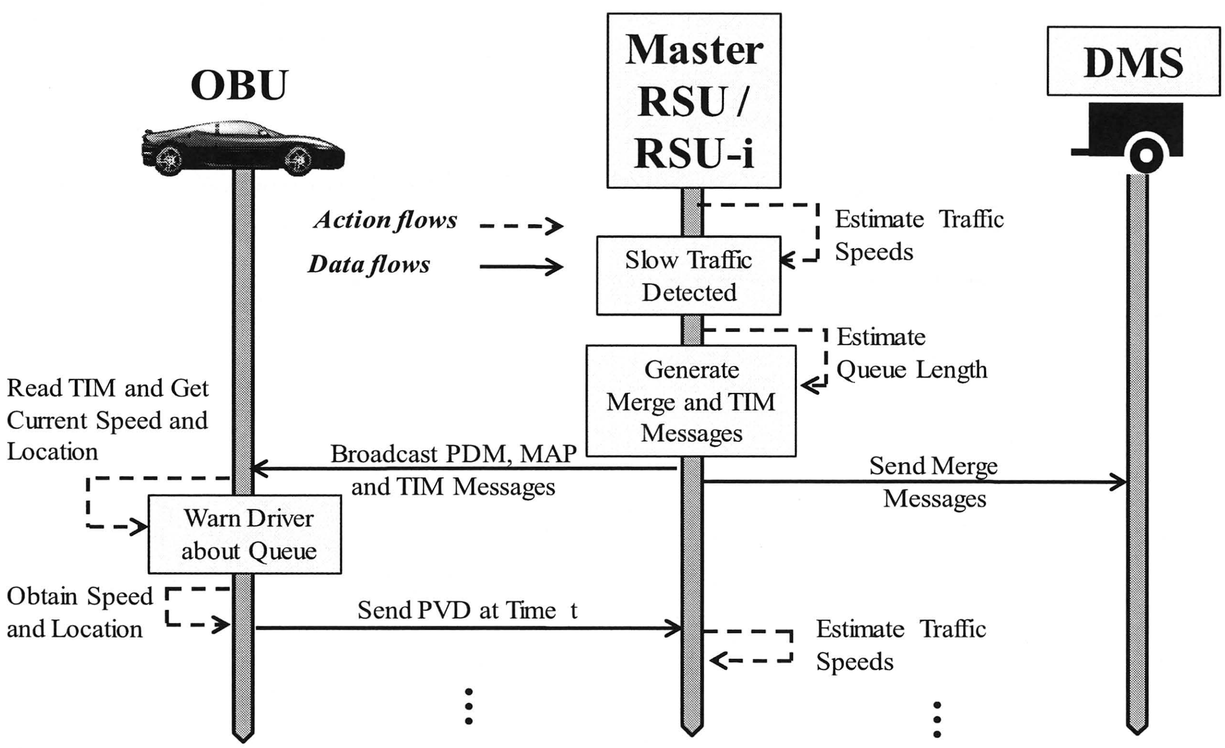


Figure 17: Action and Data Flows for Work-Zone Merge (Late Merge)

6.2. DYNAMIC FREEWAY SPEED ADVISORY

6.2.1. Introduction

This application uses V2V communications to observe freeway speed variations and then interpolate the optimal speed between areas with significant speed differentials. The optimal speed is then used to advise drivers.

Vision for the System

The dynamic speed advisory system is envisioned to be able to collect detailed speed data and generate real-time speed maps. Speed maps are not necessarily displayed to drivers directly, but the information contained in the map can be intelligently used to better inform motorists. A real-time speed map helps motorists better anticipate speed differentials ahead. Based on this information, the application provides advisories that suggest what speeds to take. In effect, this application harmonizes the traffic flow and minimizes the shockwave effect. In the near term, the application is used mainly for speed observations so that travelers can better adapt their speeds to the observed traffic conditions. As the number of connected vehicles increases, the speed advisories can become more detailed. Additionally, vehicles equipped with a cooperative adaptive cruise control system can automatically adjust traveling speeds by incorporating the advised speeds.

Additionally, since this application uses mostly V2V communications, OBUs in vehicles are purchased and maintained by users (drivers); thus, it is less costly on the traffic management side, which has only to manage software and policy updates. Therefore, it could be a possible business model to accelerate the deployment of connected vehicle technologies.

Current Practice and Problem

Speed differentials on uninterrupted flow facilities are undesired but are usually created by daily fluctuations of traffic demands and by nonrecurrent traffic incidents. These variations in speed create shockwaves in the traffic stream, causing frequent decelerations and accelerations, and sometimes stop-and-go situations. Traffic management strategies try to harmonize speed differentials by informing drivers of the potential or observed differentials in the form of different speed limits.

Traditional static speed limit signs on an uninterrupted flow facility mostly address the speed differentials generated by roadway geometries. Current active traffic management strategies combine sensing, communications technologies, and dynamic message signs to proactively address the speed differential problem. However, initial investments and ongoing maintenance costs are relatively high that traffic engineers have to implement these strategies at a selected few locations. The limitation of deploying the current system at discrete locations restricts the full potential of the speed harmonization concept.

Connected Vehicle technologies make use of DSRC, which allows information propagations through the traffic stream wirelessly. Based upon this technology, data collection and disseminations can be done dynamically and continuously instead of discretely. The speed data collected and displayed to the driver can be more relevant to the particular driver.

6.2.2. System Concepts

Assumptions

This application assumes some low percentage (say 10 percent, for example) of the freeway traffic is equipped with DSRC OBUs that can communicate with each other. The percentage of market penetration is to ensure the possibility of continuous propagation of speed information along a freeway segment. A higher percentage will improve the information propagation.

Goal and Objectives

The goal of this system is to proactively harmonize the speeds in a traffic stream and limit the generation of traffic flow shockwaves, which helps maximize freeway throughput and minimize the risks of collisions. Specific objectives of this application include:

- To collect detailed data that can characterize spatial traffic dynamics in real time.
- To enable effective advisories that help motorists adjust speeds based on the observed and projected traffic conditions.

Scope

The application is only limited to any uninterrupted flow facilities, such as freeways and expressways.

System Components and Interactions

The system contains the following functional components:

- GPS receiver—A GPS receiver is an essential component of this application as it is used to identify vehicles' real-time locations for speed map generation.
- Onboard unit on the subject vehicle (dubbed subject OBU)—In this application, an OBU is necessary to communicate with other OBUs and the driver-vehicle interface. The OBU on the subject vehicle is the only OBU that needs to have this proposed application installed. This OBU specifies the downstream OBUs and how they collect speed data. The OBU in the subject vehicle projects a length of freeway segment downstream of the current vehicle location. This virtual segment is a moving segment that begins from the vehicle's location and covers a distance that is long enough to allow the driver to react to any speed advisories. A minimum distance requirement can be set by the traffic engineers/managers when the system is deployed or maintained.
- Onboard unit on downstream vehicles (dubbed downstream OBU)—All other OBUs downstream of the subject OBU are responsible for sending out speed advisory status (SAS) messages and relaying speed advisory request (SAR) messages (see section *Supporting DSRC Messages* for details). In effect, the speed information propagates upstream to the subject vehicle, while the request for speed data propagates downstream.
- Roadside unit—RSUs are not necessary in this application but can be quite useful in the following ways:
    - To allow traffic managers to implement algorithms to dynamically update the distance requirements mentioned above.
    - To help, to some extent, speed data propagation to downstream OBUs.

- To provide portals for the speed maps to be disseminated to a wider public, other than just those connected users in the traffic stream.
- RSUs installed at strategic locations (where the bottleneck phenomenon occurs often, incident-prone locations, or work-zone areas) can be a cost-effective alternative to collect real-time traffic conditions.

Figure 18 illustrates the concept of the dynamic freeway speed advisory system. The color-coded speed map overlaying the freeway segment shows the observed speed variations along the segment. In general, the speed data can be collected only at discrete locations, and proper interpolations among these observations represent likely speeds at any given downstream locations. Note that the color-coded speed map is not fixed but is moving with the subject vehicle. Thus, a look-ahead zone is dynamically created and populated via continuous speed data collection. In this application, the speed map is not directly displayed to the driver but is used to determine speed differentials at locations with reference to the subject vehicle. At about the 0.5- to 1-mile downstream segment (this threshold can be changed), the application looks for large speed differences and posts the observed segment speed to the driver. The driver slows down or speeds up accordingly. The RSU checkpoint is optional, which may most likely serve as a portal for the speed data to be sent back to a central data hub.

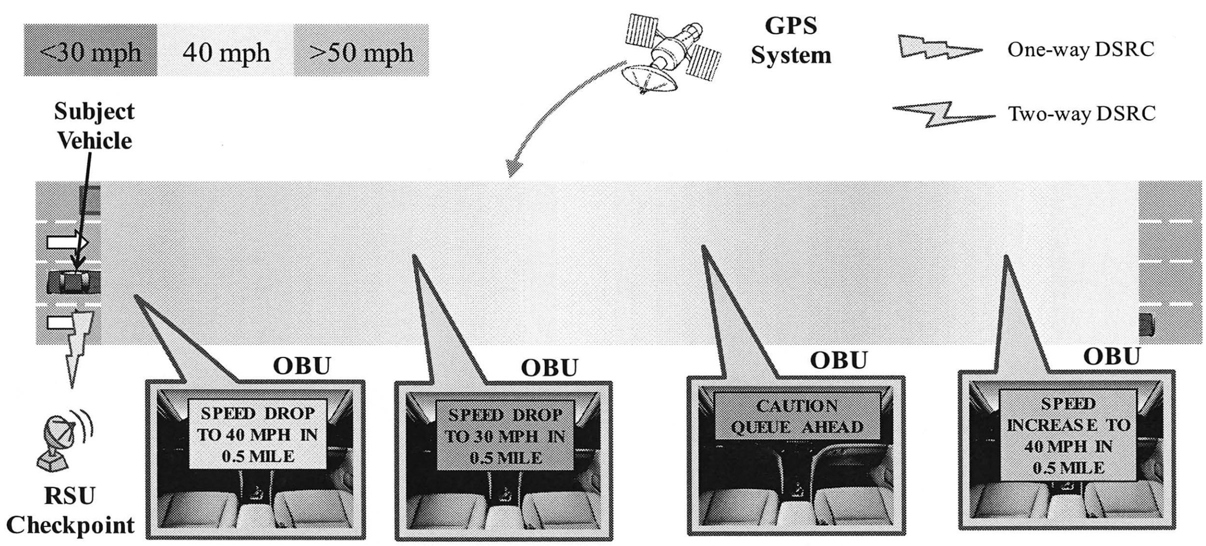


Figure 18: Concept of Dynamic Freeway Speed Advisory

<u>Supporting DSRC Messages</u>

The researchers do not expect that any currently available DSRC messages (in SAE J2735 [rev. 2009]) can be directly applied to this application. However, a new set of messages is required to be transmitted over the DSRC channels to support the operations of this application:

- Speed advisory request message—The SAR message is used to specify a geographic region downstream of the OBU that emits the message. This message contains the geographic boundary and the heading information of interest. These two pieces of information are used to construct a virtual speed segment, with which other OBUs can determine their relevance to this the request.

- Speed advisory status message—The SAS message is used to reply to the request made by the SAR message. This message contains the current speed and location of the responding OBU.

Limitation

Since the law does not require every vehicle to have an OBU in good operating condition, this application is limited to only advisories for those equipped vehicles. Before the market penetration of DSRC OBU devices reaches 100 percent, no speed limits can be enforced on any vehicles. In other words, traffic managers cannot replace current static or dynamic speed limits with this system. Nonetheless, the speed advisory concept developed here can be easily extended to the in-vehicle dynamic speed limits.

Possible Variation of the Proposed System

One variation of this application is envisioned for the time when lane-level GPS positioning services become commonly available. Note that the discussion here only provides a general concept; a separate ConOps will need to be developed for design purposes. The discussion of this concept is limited to this subsection.

With improved positioning accuracy, lane-based speed conditions can be observed. The added information can be directly delivered to the driver or be used to improve the section-based speed advisory. Figure 19 illustrates three speed advisories (for example) under the assumption of lane-level positioning. Drivers will have the option to choose which type of speed advisory to have delivered to them.

In addition to the enhanced onboard speed advisory, two RSUs are added to ensure the lane configurations are available to all OBUs passing by. The downstream RSU is equipped with computational power to aggregate the collected speed data and provide speed summaries (the lane-based speed map). The upstream RSU serves as a communications relay point that broadcasts the speed map (see the next section for general specifications) and the lane configurations (as the MAP message format). This message will allow OBUs to position themselves in reference to a common digital lane map. The upstream RSU also broadcasts the PDM to instruct OBUs to collect speed summaries.

The lane-based functionality can be regarded as a mode of the proposed application, which is activated under the scenario that the number of lane-level speed observations is sufficient. This implies that this functionality can be added incrementally and at locations historically known to have high lane-by-lane speed variations (e.g., greater than 5 mph). For example, strategic locations may include exit ramps immediately leading to traffic signals and entrance ramps without ramping strategies.

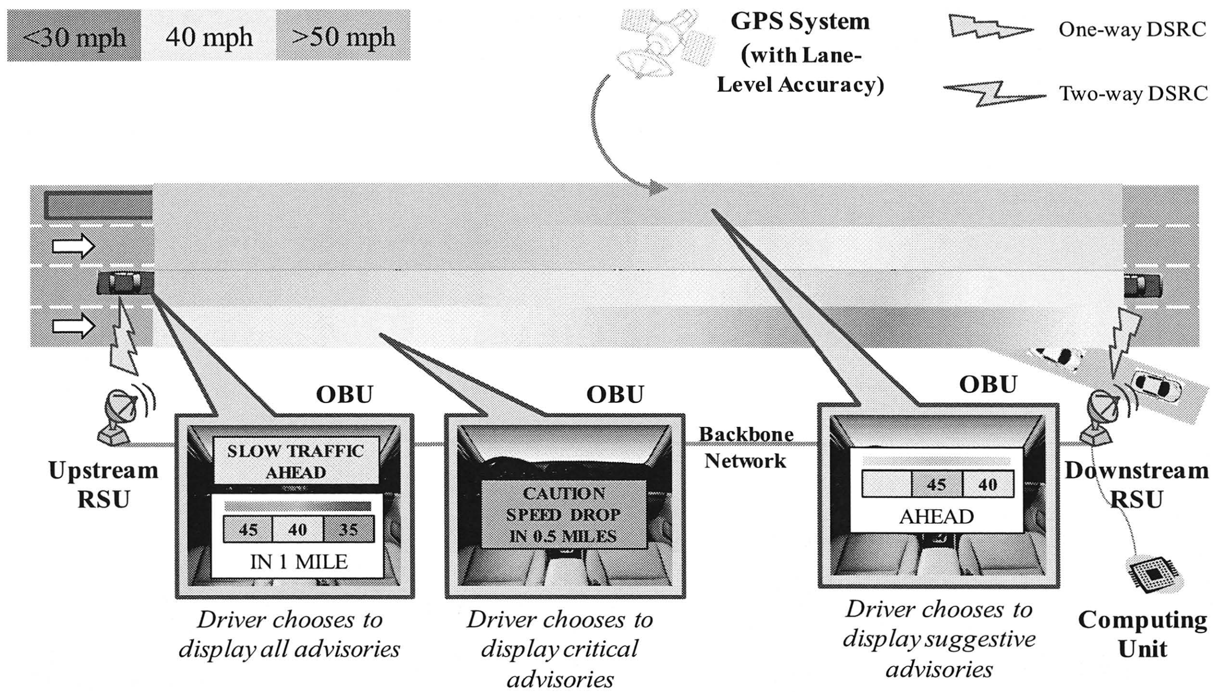


Figure 19: Concept of Dynamic Freeway Speed Advisory (at Congested Ramps)

6.2.3. Operational Scenario

This application is expected to using V2V DSRC to generate a speed map that supports speed advisories. One operational scenario is identified. The following sequence of events describes the action and data flows that are involved in this application, as shown in Figure 21:

1. At the initiation of the application, the subject OBU reads the current location from the GPS receiver. The OBU defines a spatial boundary and a heading in terms of any digitized geographic information system road map. The information is used to generate a virtual segment and is broadcasted in the format of an SAR message.
2. A nearby OBU receives the SAR message. The OBU immediately obtains its current speed, heading, and location. Based on this information, the OBU determines whether the vehicle falls within the virtual segment of the requesting vehicle.
3. If the nearby OBU falls outside the boundary of the downstream virtual segment (e.g., nearby vehicles immediately upstream of the subject vehicle), then the SAR message is ignored; that is, only the downstream OBUs will take the following actions:

    - The downstream OBU broadcasts the SAR message it initially received without any changes. As a result, all downstream OBUs within the virtual segment will be emitting the SAR message.
    - The downstream OBU formats its speed and location information into a SAS message and sends the message back to the subject OBU. The result of this action is that all downstream OBUs within the virtual segment will also be emitting the SAS message (i.e., their speeds and locations).

4. The subject OBU aggregates all the SAS messages and generates a speed map. Based on this information, speed advisories are generated and delivered to the driver. Essentially, the subject OBU monitors the speed difference between the subject vehicle and the vehicles at a downstream segment about 0.5 to 1 mile away; then the OBU posts the observed segment speed and the location of the segment to the driver as a speed advisory. See Figure 18 for examples of advisories.
5. The driver adapts to the speed advisory at his or her discretion accordingly.

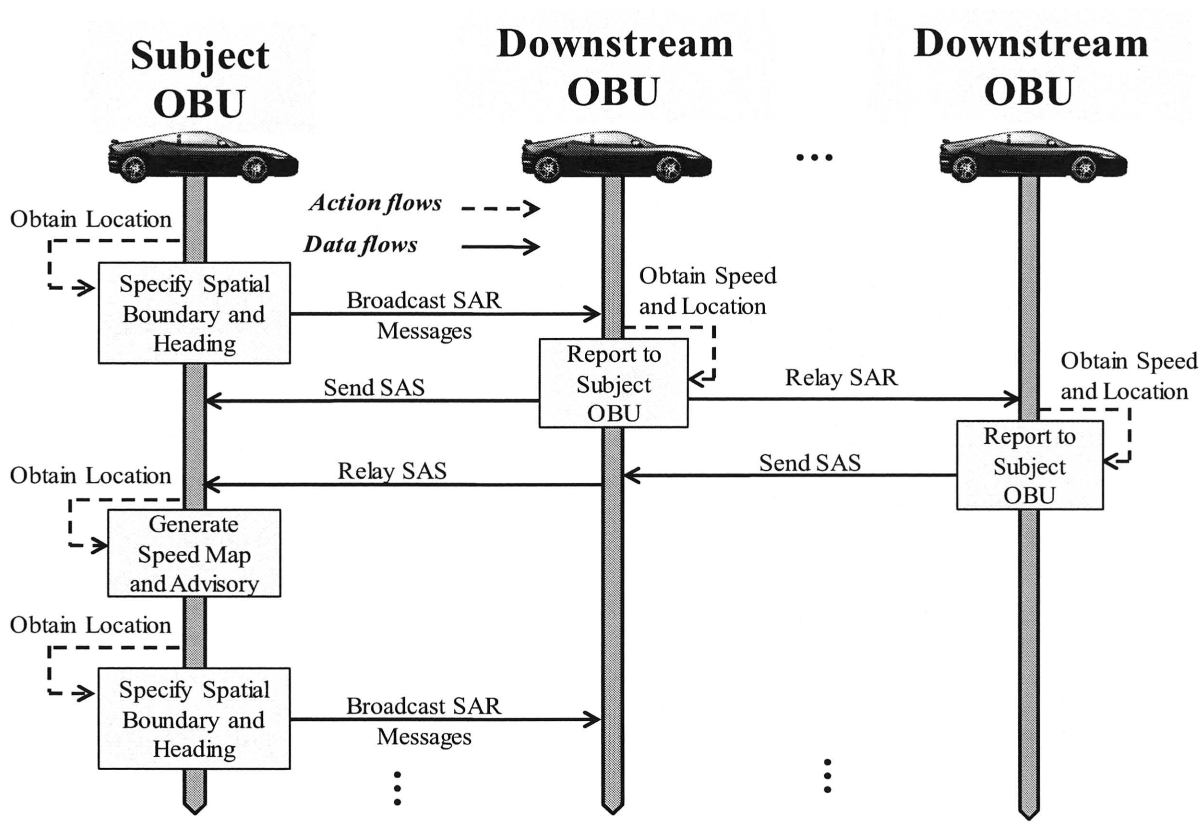


Figure 20: Action and Data Flows for Speed Advisory

It should be noted that this chain of events implies that all vehicles within the virtual segment will be emitting two messages: a common SAR message and a SAS messages. Computationally, this may cause information redundancy, especially when the OBU density gets higher, although it guarantees the subject OBU receives all the speed and location information from all other downstream equipped vehicles. Alternatively, a more efficient sequence of events is to first establish an ad hoc mobile network among the vehicles inside the virtual segment, and then to initiate SAS message collection according to efficient routings within the ad hoc network. This alternative approach requires further research to ensure technical feasibility.

7. CONCEPT OF OPERATIONS FOR ENVIRONMENTAL APPLICATIONS

7.1. ADVISORY AND WARNING FOR WEATHER-INDUCED SLIPPERY PAVEMENTS

7.1.1. Introduction

This application uses weather observations from vehicle-based sources to identify locations with slippery pavement conditions. These identified locations are then used to enable speed management measures to prevent vehicle loss of control and crashes.

Vision for the System

The application is envisioned to address the highway safety hazards caused by slippery pavement conditions. The real-time estimates of pavement conditions are collected from sampled vehicles. Such conditions are inferred from common vehicle safety systems, such as ABS and traction control systems. The collected estimates are used to generate a map of road segments with a reduced level of road surface friction. The system then provides either a "heads-up" or speed advisories to aid drivers' speed selection before coming to a slippery road segment. The initial deployment emphasis will focus on strategic locations, such as bridges, where one roadside DSRC unit can be installed to monitor pavement conditions over a large area. In the mid-term to long term, as the number of connected vehicles increases, the need for roadside infrastructure will be minimized, and the detection and notification of slick pavement conditions can be done mostly through vehicle-to-vehicle communications.

Current Practice and Problem

Weather presents considerable challenges to highway safety. First, weather degrades the vehicle's operating performance. Precipitation (in particular rain, snow, and ice) and wind-blown sand and grit reduce pavement friction, increasing the potential for losing control of the vehicle, running off the road, and having a rear-ended crash. Secondly, adverse weather conditions may obscure motorists' vision and intensify their stress levels. Passive warning signs installed at locations with possible weather-related slick pavements might lose effectiveness over time because drivers might drive through these locations and more frequently encounter non-slick pavement than slick pavement conditions. New technologies have been deployed nationwide to enable active warning mechanisms to help inform travelers about pavement conditions when the pavement is slippery. These technologies include environmental sensor stations, closed-circuit television cameras, local meteorological centers, and fixed vehicle detectors (*49*). The costs and the stationary natures of these technologies, however, become the major constraints to large coverage of an active traveler information system broadcasting road weather conditions.

The connected vehicle framework provides an architecture that improves the quality and quantity of weather observations from vehicle-based probe sources. Using mobile sources can largely extend the coverage of the detection of weather-induced road hazards. According to previous studies (*64, 65*), many types of road weather data are expected under the connected vehicle vision, including precipitation status, fog densities, pavement conditions, and wind intensities. A standardized weather data translator (WDT) will translate vehicle events into useful weather observations. Based on these observations, this application can help travelers and managing agencies better identify locations or road segments with reduced levels of surface friction.

7.1.2. System Concepts

Assumptions

The Road Weather Application segment in the Connected Vehicle research initiative is currently undergoing the development of WDT, which converts vehicle observations (e.g., ABS, stability control, traction control, and wiper statuses) into standardized formats of weather observations. The availability and quality of these estimates directly affect the effectiveness of the application being developed here.

Goal and Objectives

The goal of the system is to minimize the impacts of slippery pavements on highway traffic safety by detecting pavements with reduced surface friction due to weather events. The following are the specific objectives:

- To detect or infer locations of roadways with a reduced level of surface friction.
- To enable reliable speed advisories at locations or road segments wherever slippery pavement conditions are detected.

Scope

Slippery pavements can have different forms, such as pavements with water puddles, ice, and snow. These conditions may be observed on any type of roadway surface. Thus, this application applies to all types of surfaces.

System Components and Interactions

The system contains the following functional components:

- GPS receiver—A GPS receiver is necessary to provide approximate readings of the locations with slick pavement conditions. In this application, lane-level GPS accuracy is not necessary, and cross-section-level accuracy of GPS readings is sufficient. The GPS readings, combined with vehicle heading information, can be used to infer whether the slick pavement conditions are in both or either direction of the road segment.
- Weather data translator—In this application, the WDT translates readings of a combination of vehicle statuses (including but not limited to ABS status, traction control system status, wiper status, and temperature reading) to infer current road pavement friction status (i.e., normal or reduced). Example conversion algorithms can be found in Drobot et al. (*65*).
- Onboard unit—An OBU takes the outputs of pavement friction status from the WDT and the location reading from the GPS receiver to generate a DSRC-compatible message. The message is then broadcasted to nearby RSUs. The temporary storage capability of an OBU is required in this application. The storage unit can ensure that the observation of slick pavement conditions is not lost until an authorized RSU has received the message. Alternatively, the OBU can have a USB port interface and supporting software to allow connections from common handheld devices (e.g., mobile phone or tablet computers);

thus, once connected, the friction status can be communicated directly to a local TMC via other forms of communications (e.g., cellular or satellite) instead of merely DSRC.

- Roadside unit—An RSU, in this application, serves only as a communication means to relay the friction status message to the local TMC. Thus, it is not needed if other forms of communications from an OBU to the TMC are available. As soon as an RSU receives such a message from the OBU, it replies to confirm the receipt and retains the message until it successfully relays the message to the local TMC.
- Traffic management center—A TMC is required in this application to synthesize the weather observations to provide reliable speed advisories. The TMC fuses the pavement observations collected from a number of OBUs. Fusing as many samples as possible improves the reliability of the estimate of pavement conditions. A reduced pavement friction level is entered into the incident management database as an active incident and can be made accessible to motorists through the Internet or the cellular networks.

Figure 21 illustrates the concepts of the slippery pavement warning system. The colored vehicles are equipped with OBUs and installed with the proposed system; the gray vehicles are not. Two communication methods are envisioned in this concept. The V2V DSRC method allows the detection of slick pavement to propagate upstream without a central management system. The V2I DSRC plus cellular communications can enable speed advisories to go to equipped vehicles and also the general public.

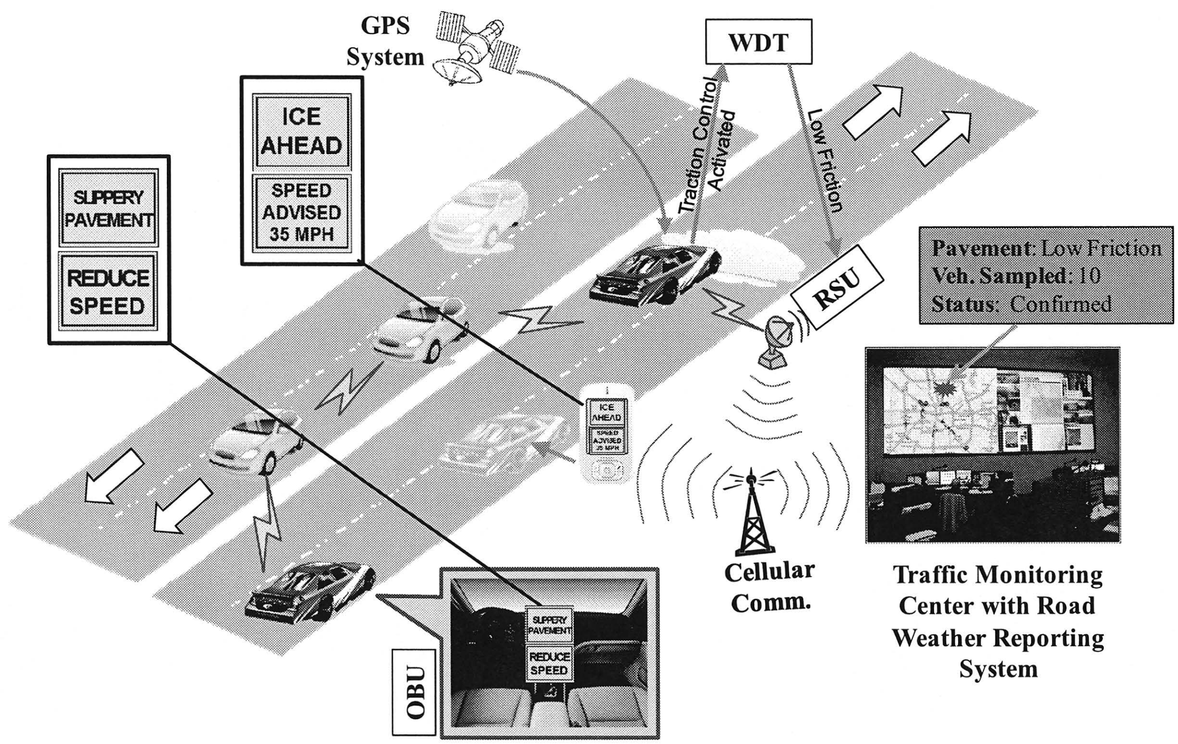


Figure 21: Concept of Slippery Pavement Information System

Supporting DSRC Messages

The researchers do not expect that any currently available DSRC messages (in SAE J2735 [rev. 2009]) can be directly applied to this application. However, new collections of data elements already in the current standard version will facilitate the operations of this application.

- The slick pavement information (SPI) message is used to convey the detection of slick pavement from one OBU to other DSRC-enabled units. At a minimum, the data contents needed include the type of event (i.e., ABS or traction control system activation), GPS readings, time stamp, vehicle heading, and speed).

Notice that this message contains data elements that are partially in the BSM and TIM (see sections 2.3.1 and 2.3.10, respectively). Therefore, the BSM and TIM can be broadcasted in support of this application.

Near-Term Limitations

The speed advisories have to be used with dynamic message signs so that all drivers can adjust their speeds accordingly. Speed advisories cannot be delivered to only those equipped because accelerations and decelerations cause more vehicles to lose control than speed itself does. Suggesting speed reduction to only a portion of the travelers on the slippery road segments will create speed differentials on these segments, which makes the slippery locations even more dangerous. Therefore, all travelers have to be informed of any potential need for speed reduction at locations with slick pavements. Until the connected vehicle technology has 100 percent market penetration, the dynamic speed limit sign is one of a few ways to disseminate speed advisory or enforcement.

7.1.3. Operational Scenario

The goal of the application is to minimize the impacts of slippery pavements on highway traffic. One effective measure is to notify motorists about the locations of slick pavement conditions and advise an appropriate traveling speed whenever possible. Once a slick pavement condition is detected by an equipped vehicle, the vehicle broadcasts the location and the vehicle speed at the time of the detection. Depending on the receiving end of the broadcast, one of the two operational scenarios are triggered: warning or speed advisory. Figure 22 illustrates the chain of events for these two scenarios. The vehicle detecting the pavement conditions is the subject vehicle.

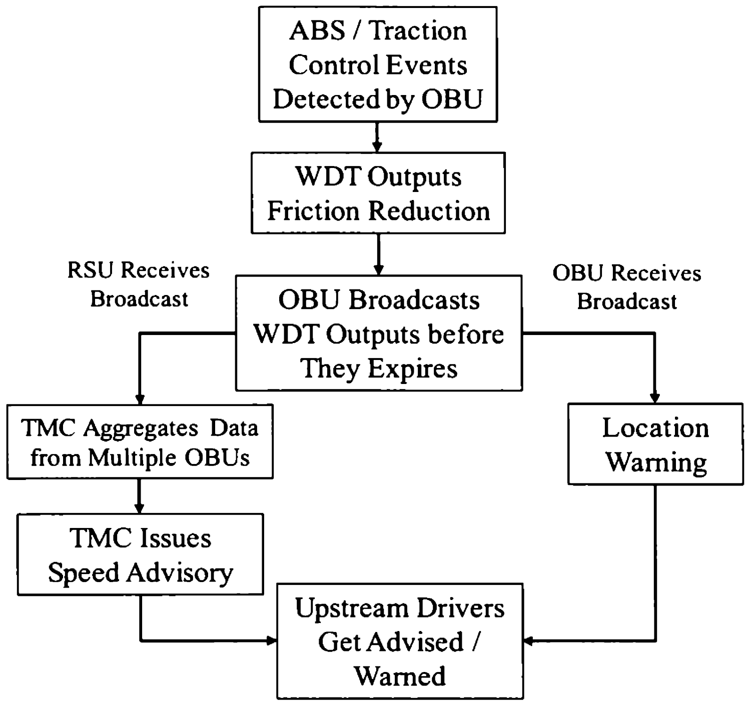


Figure 22: System Flow Chart for Slippery Pavement Information

Warning of Slippery Locations for Connected Vehicles

Sending the detection of a slippery surface to the local TMC may not always be possible. In rural highways outside the coverage of any TMCs, some forms of warnings may help prevent vehicle control losses due to slick pavements. In this scenario, warnings of merely slippery locations are sufficient to heighten drivers' circumstantial awareness. In this case, the application can enhance roadway safety via general warning messages.

The following sequence of events describes the general process and data flows involved in this application, as shown in Figure 23:

1. The subject vehicle's WDT detects slippery pavement conditions by observing activation from the ABS or traction control systems. The WDT sends the detection to the vehicle's OBU.
2. The OBU immediately retrieves current GPS readings, the vehicle heading, and the time it receives the WDT output. The information is formatted into an SPI message and is broadcasted at fixed time intervals.
3. Another OBU nearby picks up the SPI message. The OBU then compares its current location with the location of slick pavement and compares its current heading with the heading stored in the SPI message. If the vehicle is traveling toward the slippery pavement location, the OBU warns the driver with "SLIPERY PAVEMENT AHEAD." If otherwise, the OBU simply retains the message in its temporary cache and broadcasts the original message at fixed time intervals. The message is carried over to other OBUs traveling toward the slick location in the original direction (see Figure 21.)
4. OBUs upstream of the slippery location warn their drivers regardless of their speeds and vehicle types. The warning is dropped after the vehicles pass through the slippery location.

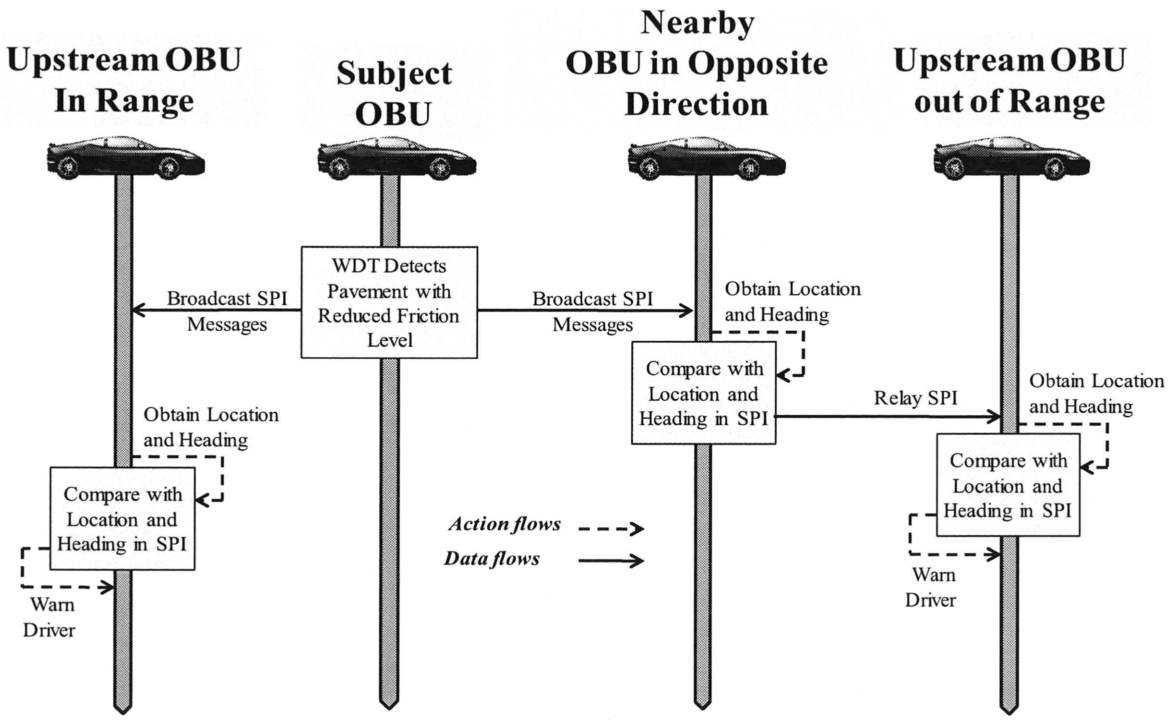


Figure 23: Action and Data Flows for Slippery Pavement Location Warning

<u>Speed Advisory</u>

In the scenario that the subject vehicle can get into the range of an RSU before the weather data expires (e.g., 10 minutes after detection), the detection data can be relayed to a local TMC. Based on these data, it is possible for the TMC to issue speed advisories.

The following sequence of events describes the general process and data flows involved in this application, as shown in Figure 24:

1. A vehicle's WDT detects slippery pavement conditions by observing activation events from the ABS or traction control systems. The WDT sends the detection to the vehicle's OBU.
2. The OBU immediately retrieves current GPS readings, the vehicle heading, and the time it receives the WDT output. The information is formatted into an SPI message and gets broadcasted at fixed time intervals.
3. A nearby RSU picks up the SPI message and relays the message to the local TMC.
4. The TMC fuses the SPI messages from multiple OBUs at various locations or the same location. Based on the location information, the TMC infers the spatial extent of the roadway with slick pavements; based on the speed information, the TMC infers a safe driving speed.
5. The TMC issues speed advisories through various channels, such as its official website, RSUs in the vicinity of the area, and related smart-phone application service providers (see Figure 21).
6. Any connected vehicles are given speed advisories by the in-vehicle OBU-enabled interfaces when their OBUs project their paths through the slippery area.

7. Any smart-phone application service subscribers are notified about the speed advisory as long as the mobile application is turned on and the advisory is active.

One example algorithm to generate a speed advisory given slick pavement conditions uses the information from the related vehicle safety systems, including ABS and traction control systems. Current ABS and traction control systems cannot directly measure pavement friction (*64*), but whether or not the systems are activated at a given time can be captured. Thus, to infer a more appropriate driving speed on slick pavements is to assign a speed reduction (e.g., 10 mph) to the lowest speed observed from the vehicles whose ABS or traction control systems have been activated. Such a speed is likely to be a reasonable speed to advise incoming motorists. For example, the TMC receives 10 ABS events at a particular location, one of which has the lowest traveling speed of 50 mph. By applying a 10 mph speed reduction, the speed advisory is set at 40 mph.

When the appropriate speed advisory cannot be confidently calculated, a "speed reduction ahead" warning message can be used to replace the advisory.

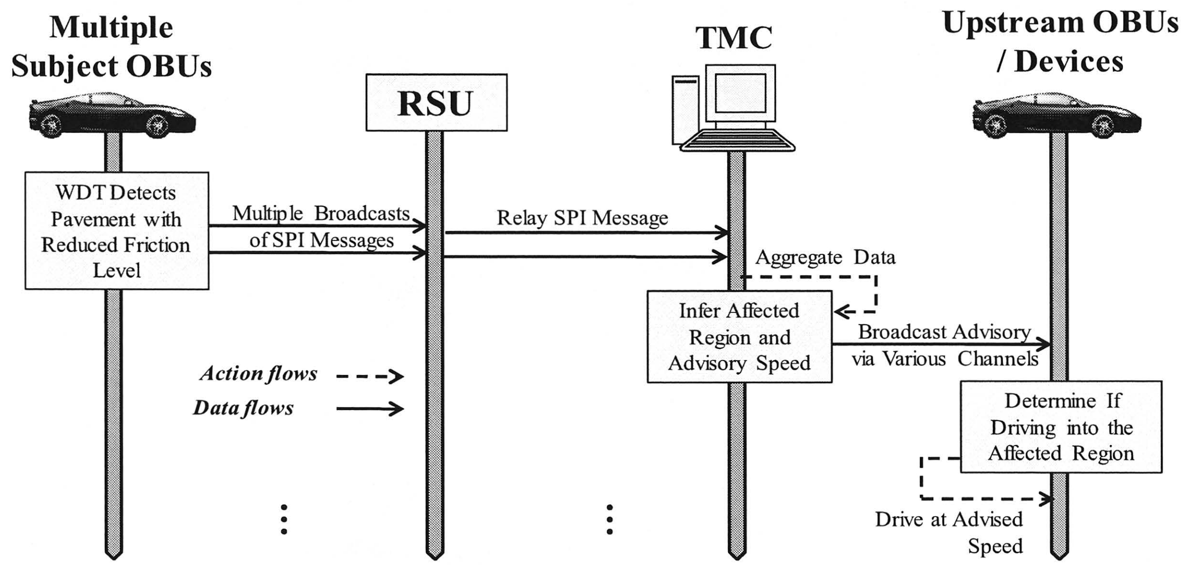


Figure 24: Action and Data Flows for Slippery Pavement Speed Advisory

8. FINAL REMARKS

The researchers first conducted a comprehensive review of the state of art of DSRC technologies and of Connected Vehicle research. The technology review indicates that DSRC is a main contender for a communications method due to its technological advantages, such as fast, secure, two-way and broadband connections in a mobile environment. It is the only technology that meets the requirements for safety applications in high-speed conditions. Other communications methods could be used as low-cost alternatives for non-time-critical applications.

The researchers have developed full ConOps for a total of five applications spanning safety, mobility and environmental protection. These applications include: the wrong-way warning system and the grade-crossing warning system (in safety); the smart work-zone management system and the freeway speed advisory system (in mobility); the slippery pavement warning system (in environmental security). For each of these applications, the researchers have developed concept diagram, and pointed out potential benefits, applicability and possible limitations. Supporting DSRC messages have also been proposed. Typical operational scenarios were given.

These ConOps have only provided a high-level understanding of how traffic managers can harness the Connected Vehicle technologies to address certain transportation problems. Nonetheless, the potential of the Connected Vehicle framework is not limited to all the systems mentioned in this report. On the contrary, this research serves as an initial effort that helps transportation professionals and researchers understand how the Connected Vehicle technologies have the potential to transform the transportation industry.

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