

Estimated Benefits of Connected Vehicle Applications

Dynamic Mobility Applications, AERIS, V2I Safety, and Road Weather Management Applications

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16. Abstract <p>Connected vehicles have the potential to transform travel as we know it by combining leading edge technologies—advanced wireless communications, on-board computer processing, advanced vehicle-sensors, Global Positioning System (GPS) navigation, smart infrastructure, and others—to address safety, mobility, and environmental challenges. Over the last five years, application prototyping and assessment has been a focus of federal connected vehicle research and development activity, resulting in more than three dozen connected vehicle application concepts. This effort also included assessments to measure safety, mobility and environmental impacts from four USDOT connected vehicle Vehicle-to-Infrastructure (V2I) research programs (V2I Safety, Dynamic Mobility Applications (DMA), Applications for the Environment: Real-Time Information Synthesis (AERIS), and Road-Weather Management). Considering results to date from these assessment activities, there is a clear demonstrated potential for significant safety, mobility and environmental impacts from V2I connected vehicle applications:</p> <ul style="list-style-type: none"> • Combinations of V2I connected vehicle applications are effective in signalized networks, particularly in prioritizing signal timing and reducing overall delay (up to 27%), CO2 emissions and fuel consumption (up to 11%). Intersection-focused safety applications may potentially address up to 575,000 crashes and 5,100 fatalities per year. • V2I connected vehicle applications add a potentially new capability to flow management in congested freeway segments, particularly in the mitigation of potentially unsafe speed differentials in advance of bottleneck locations, reducing fuel consumption (up to 4.5%), or in the reduction of delay generated by major incidents (up to 14%). A curve speed warning safety application may potentially address up to 169,000 crashes and 5,000 fatal crashes per year. • The magnitude of benefits of many applications are highly dependent on the level of technology deployment at the roadside, in vehicles, or within mobile devices. However, applications targeting fleet vehicles may be early winners – as well as applications that serve to prioritize or facilitate facility access. 					
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Executive Summary

Connected vehicles have the potential to transform travel as we know it by combining leading edge technologies—advanced wireless communications, on-board computer processing, advanced vehicle-sensors, Global Positioning System (GPS) navigation, smart infrastructure, and others—to address safety, mobility, and environmental challenges.

Over the last five years, application prototyping and assessment has been a focus of federal connected vehicle research and development activity. As a result of these efforts, more than three dozen connected vehicle applications concepts have been developed, many through prototyping and demonstration. As a part of this process, the component application development programs have also conducted assessments to measure of safety, mobility, and environmental impacts. These field demonstrations have been supplemented by estimation of difficult to observe impacts and potential future impacts from broader application deployment using a range of analytical methods.

This document summarizes current findings and lessons learned from a collection of nearly 50 vehicle-to-infrastructure (V2I) applications developed in four United States Department of Transportation (USDOT) connected vehicle research programs: V2I Safety, Dynamic Mobility Applications (DMA), Applications for the Environment: Real-Time Information Synthesis (AERIS), and Road-Weather Management. The applications developed under these four programs have varied primary objectives (e.g., reducing crashes and fatalities; reducing travel times, increasing travel time reliability and throughput; reducing emissions and fuel consumption), but are collectively deemed V2I as they are predominantly enabled by V2I communications.

At this time, looking across multiple connected vehicle application development efforts, there is a demonstrated potential for significant safety, mobility, and environmental impacts from these applications. The magnitude of benefits of many applications are highly dependent on the level of technology deployment at the roadside, in vehicles, or within mobile devices. However, applications targeting fleet vehicles (e.g., transit, truck, and public safety vehicles) may be early winners – as well as applications that serve to prioritize or facilitate facility access. Table ES-1 shows the highlights of estimated impacts, gleaned through precursor safety analysis, field testing, simulation/analytical studies, or a combination of field testing and simulation/analytical studies.

The comprehensive role of Dedicated Short Range Communications (DSRC) in V2I connected vehicle applications is still emerging. Within the V2I Safety program, the DSRC use is a central tenet of the effort and DSRC is featured in all application concepts. However, application prototypes in this program are still in development and impacts have not yet been estimated. In the other three programs, DSRC is an optional technology to be applied where it is found to be advantageous. In the DMA program 7 of 16 applications successfully utilized DSRC technologies, primarily in and around signalized intersections and incident locations. In the AERIS program, potential opportunities for DSRC have been identified in the concept development efforts for several applications, but have not been directly applied. In the case of the Road Weather Program, a key project is in the process of developing, installing and operating a hybrid communication method which includes using DSRC in a test corridor in the next year.

Table ES-1: Estimated Impacts of Connected Vehicle Applications in Four V2I Research Programs

Impact Area	Estimated Impacts	Relevant Applications ¹	Program
Safety	Crash population targeted by V2I safety applications at intersections includes up to 575,000 crashes (involving more than 5,100 fatalities) annually ²	PCW, RLWW, SSGA, SSVW	V2I Safety
Safety	Crash population targeted by V2I safety applications at curves includes up to 169,000 crashes (including 5,000 fatal crashes) annually ²	CSW	V2I Safety
Safety	Reduction of crashes by up to 25% during winter weather due to weather traffic management applications on freeways ³	WRTM-VSL	RWM
Safety	Reduction in speed variations between freeway segments by 18%-58% and within freeway segments by 10%-47%, resulting in fewer rear-end crashes ⁴	SPD-HARM	DMA
Safety	Fewer instances of hard braking and up to 89% reduction in maximum deceleration in incident zones ³	INC-ZONE	DMA
Mobility	Reduction in travel time on arterial corridors by 6% to 27% when combined multimodal traffic signal system is implemented ³	I-SIG, FSP, TSP	DMA
Mobility	Reduction in travel time for transit vehicles by up to 10% with priority ³	TSP	DMA
Mobility	Reduction in travel time by up to 23% and number of stops by up to 15% for emergency vehicles ³	INC-ZONE	DMA
Mobility	Reduction in average network-wide delay of up to 14% due to alerts to incident zone workers ³	INC-ZONE	DMA
Mobility	Annual travel time reductions of 246,000-740,000 hours when an integrated corridor management decision support system with eco-capabilities is implemented ⁴	Eco-ICM	AERIS
Mobility	Reduction in travel time on freeways by 33% to 42% when cooperative adaptive cruise control, and speed harmonization are optimized for the environment ⁴	Eco-Lanes	AERIS
Environmental	Fuel savings of 2%-22% when signal operations and freeway lane management are optimized for the environment ⁴	Eco-Lanes, Eco-Signal Operations	AERIS
Environmental	Annual fuel savings of 323,000-981,000 gallons when an integrated corridor management decision support system with eco-capabilities is implemented ⁴	Eco-ICM	AERIS
Environmental	Annual mobile emissions savings of 3,100-9,400 tons when an integrated corridor management decision support system with eco-capabilities is implemented ⁴	Eco-ICM	AERIS

¹ CSW: Curve Speed Warning; ECO-ICM: Eco-Integrated Corridor Management; FSP: Freight Signal Priority; INC-ZONE: Incident Scene Work Zone Alerts for Drivers and Workers; I-SIG: Intelligent Traffic Signal System; ; PCW: Pedestrian in Signalized Crosswalk; RLWW: Red Light Violation Warning; SPD-HARM: Dynamic Speed Harmonization; SSGA: Stop Sign Gap Assist; SSVW: Stop Sign Violation Warning; TSP: Transit Signal Priority; WRTM-VSL: Weather Responsive Traffic Management - Variable Speed Limits

² Precursor safety analysis finding

³ Results based on field testing

⁴ Result based on simulation/analytical study

1 Introduction

Connected vehicles have the potential to transform travel as we know it by combining leading edge technologies—advanced wireless communications, vehicle-to-vehicle (V2V) broadcast, on-board computer processing, advanced vehicle-sensors, Global Positioning System (GPS) navigation, smart infrastructure, and others—to address safety, mobility, and environmental challenges. At its foundation connected vehicle technologies include a communications network that supports V2V two-way communications, vehicle-to-infrastructure (V2I) one- and two-way communications, and vehicle or infrastructure-to-device (X2D) one- and two-way communications to support cooperative system capability. The United States Department of Transportation’s (USDOT’s) connected vehicle research is establishing an information backbone for the surface transportation system that will support applications to enhance safety and mobility and, ultimately, an information-rich surface transportation system. Connected vehicle research also supports applications to enhance livable communities, environmental stewardship, and traveler convenience and choices.

The USDOT is engaged in assessing applications that realize the full potential of connected vehicles, travelers, and infrastructure to enhance current operational practices and transform future surface transportation systems management. This effort is a collaborative initiative spanning the Intelligent Transportation Systems Joint Program Office (ITS JPO), Federal Highway Administration (FHWA), Federal Transit Administration (FTA), Federal Motor Carrier Safety Administration (FMCSA) and National Highway Traffic Safety Administration (NHTSA). These agencies of the Federal Government work closely with American Association of State Highway and Transportation Officials (AASHTO), who represent state transportation agencies across the country, as well as the numerous private sector interests (car manufacturers, technology companies, etc.) to develop a nationwide system for ITS to be deployed in the future.

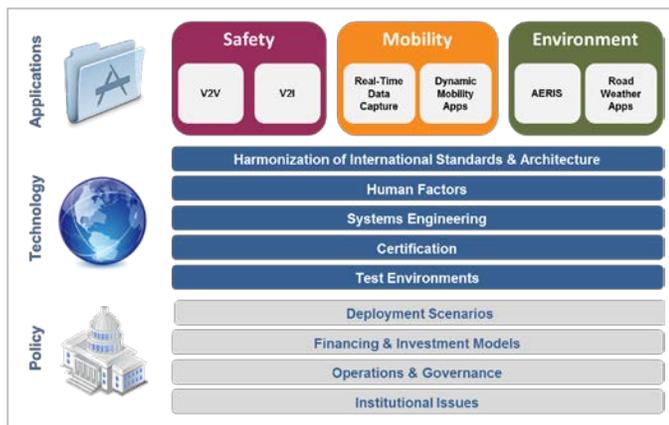


Figure 1-1: USDOT Connected Vehicle Research Program (Source: ITS JPO, 2015)

The USDOT’s connected vehicle research program is comprehensive and engages a wide range of stakeholders including the federal government, state agencies, the private sector, and vehicle manufacturers. As depicted in Figure 1-1, the federal research is focused in three areas: (1) applications, (2) technology, and (3) policy.

In the 2010-2015 Strategic Plan timeframe, application prototyping and assessment has been a focus of multiple programs in the top layer of Figure 1-1, including the V2V and V2I Safety Program, Dynamic Mobility Applications (DMA) Program, the Applications for the Environment: Real-Time Information Synthesis (AERIS) Program, and the Road-Weather Management Program. As a result of these efforts, more than three dozen connected vehicle applications concepts have been developed, many through prototyping and demonstration. As a part of this process, the component application development programs have also conducted assessments to measure of safety, mobility, and environmental impacts.

These field demonstrations have been supplemented by estimation of difficult to observe impacts and potential future impacts from broader application deployment using a range of analytical methods. While many of these prototype demonstrations and assessments have been completed or are nearly complete, across the complete portfolio of research and development activity there are several application development and assessment activities still underway in August 2015.

1.1 Purpose

The purpose of this document is to summarize current findings and lessons learned from the prototyping and assessment of mobility, environmental, V2I safety, and road-weather applications developed under the USDOT connected vehicle research effort. This interim summary is intended to give the current best information on connected vehicle applications development status, measured impacts, and potential impacts as a part of wider deployment of connected vehicle technologies.

1.2 Scope

The scope of this document regards connected vehicle applications and their impacts from four specific programs: DMA, AERIS, V2I Safety, and Road-Weather Management. This document does not address the potential benefits of applications from the V2V Safety Program which are summarized and documented elsewhere [1]. Benefits of applications considered in this report are limited to currently available documentation, in draft or final form.

1.3 Document Organization

This document covers applications from each of the four major programs in four separate sections (Sections 2-5). Within each of these sections, there is a brief overview of the program followed by a series of sub-sections covering individual applications or application groups developed a part of the program. Each of the sub-sections provides a short description of the applications themselves, the testing and development status, and a concise summary of impacts (measured or estimated) to date. These subsections also provide a summary of resources used as references. The document concludes with two summary sections. The first section summarizes the role of Dedicated Short Range Communications (DSRC) technologies utilized in the development of application prototypes, or potentially used in future application development. The final section summarizes findings and provides a synthesis of insights gained considering results to date from all four connected vehicle development programs.

2 Dynamic Mobility Applications (DMA) Program

2.1 Program Overview

The USDOT ITS JPO initiated the DMA Program as part of the Mobility program. The DMA Program seeks to create applications that fully leverage frequently collected and rapidly disseminated multi-source data gathered from connected travelers, vehicles and infrastructure to increase efficiency and improve individual mobility while reducing negative environmental impacts and safety risks. The objectives of the program are to:

- Create applications using frequently collected and rapidly disseminated multi-source data from connected travelers, vehicles (automobiles, transit, freight) and infrastructure
- Develop and assess applications showing potential to improve nature, accuracy, precision and/or speed of dynamic decision
- Demonstrate promising applications predicted to significantly improve capability of transportation system
- Determine required infrastructure for transformative applications implementation, along with associated costs and benefits

To address these objectives, the DMA Program is composed of three phases over eight years: Foundational Analysis (Phase 1); Research, Development, and Testing phase (Phase 2); and Pilot Deployments & Demonstrations (Phase 3). The DMA program has been characterized by strong participation and cooperation between both internal and external parties. There are two key challenges of developing and deploying mobility applications:

- **Technical Soundness** – Are the DMA bundles technically sound and deployment-ready?
- **Transformative Impact** – Are DMA bundle-related benefits big enough to warrant deployment?

To overcome these two challenges, a series of systems engineering documents, such as Concept of Operations (ConOps) and System Requirements (SyRs), were created during the development phase of each application, an open source portal was setup to share code from open source bundle prototype development, and demonstration and field test of the application prototypes were conducted both in isolation and in combination. Moreover, the DMA program developed projects to engage stakeholders to set transformative impact measures and goals, assess whether the prototype efforts show impacts when demonstrated, estimate benefits associated with broader deployment, and utilize analytic testbeds to identify synergistic bundle combinations.

2.2 DMA Application Bundles and Estimated Impacts

The DMA Program initiated the development of 17 mobility applications, grouped into six bundles. Table 2-1 lists each bundle and its applications. As a result of DMA research and development activity, 16 of the 17 applications have at least one prototype, demonstrated in at least one location. The exception is

the Cooperative Adaptive Cruise Control (CACC) application, where feasibility testing is now transitioning to prototyping and field testing. Figure 2-1 illustrates the locations of the DMA application prototype demonstrations. The following sections provide detailed descriptions of the DMA application bundles.

Table 2-1: DMA Bundles and Applications

Bundle Name		Applications	
Enable ATIS			
Enable Information Systems	Advanced Traveler	Traveler	EnableATIS (Advanced Traveler Information System 2.0)
FRATIS			
Freight Information Systems	Advanced Traveler	Traveler	Freight-Specific Dynamic Travel Planning Performance, Drayage Optimization (DR-OPT)
IDTO			
Integrated Operations	Dynamic	Transit	Connection Protection (T-CONNECT) Dynamic Transit Operations (T-DISP) Dynamic Ridesharing (D-RIDE)
INFLO			
Intelligent Optimization	Network	Flow	Dynamic Speed Harmonization (SPD-HARM) Queue Warning (Q-WARN) Cooperative Adaptive Cruise Control (CACC)
MMITSS			
Multimodal Traffic Signal System		Intelligent	Intelligent Traffic Signal System (I-SIG) Transit Signal Priority (TSP) Freight Signal Priority (FSP) Mobile Accessible Pedestrian Signal System (PED-SIG) Emergency Vehicle Preemption (PREEMPT)
R.E.S.C.U.M.E.			
Response, Emergency Management, and Evacuation	Staging and Communications, Uniform	Staging	Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG) Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE) Emergency Communications and Evacuation (EVAC)

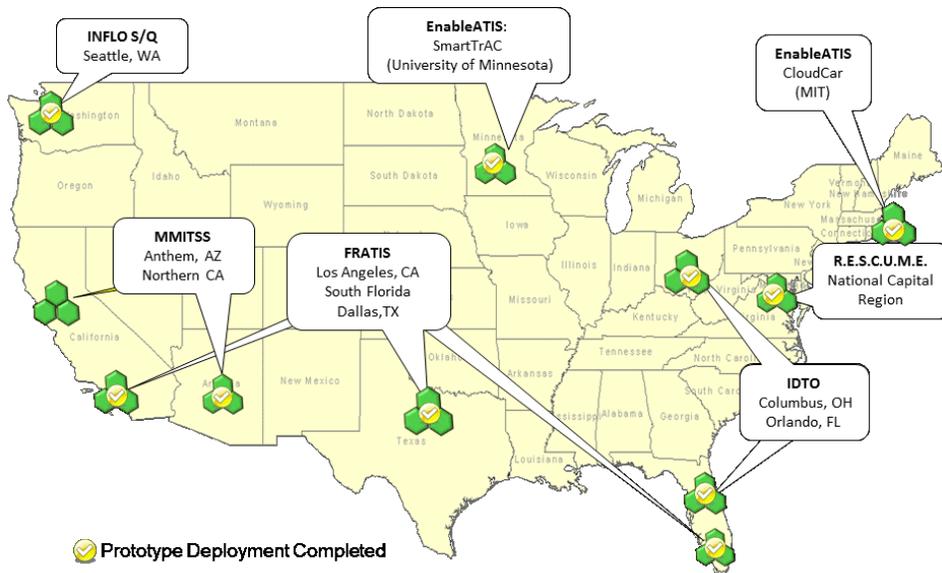


Figure 2-1: Locations of DMA Prototype Demonstrations (Source: ITS JPO, 2015)

2.2.1 Enabling Advanced Traveler Information Systems (EnableATIS)

EnableATIS is unique among the DMA applications as its focus is on providing support to the marketplace for application development, i.e., enabling development of Advanced Traveler Information Systems. EnableATIS is not developing a specific application or system, but is rather seeking to formalize a framework whereby multiple activities are envisioned to interact to support a diverse traveler information environment (see Figure 2-2). The Operational Concept describes two operational scenarios that define two different relationships between public sector agencies and the market [2]:

- The laissez-faire operational scenario entails an incremental build out and enhancement of traveler information services over time and with limited influence on the market from the USDOT.
- The robust operational scenario represents a desired end-state of a robust, multimodal, multisource traveler information environment that leverages new data sources and generates transformative uses of that information to benefit travelers as well as system operations and management by agencies.

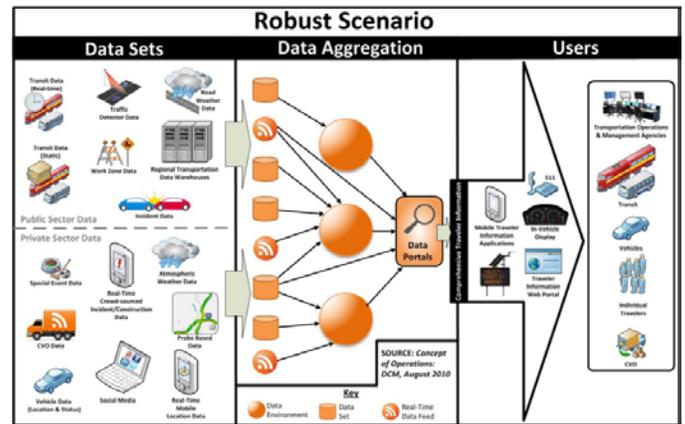


Figure 2-2: Robust Multimodal Integrated Traveler Information Data Environment
(Source: ITS JPO, 2012 [2])

Testing Summary and Status

There are three EnableATIS exploratory research efforts: SmarTrAC from University of Minnesota (UM), the CloudCar project developed by the Massachusetts Institute of Technology (MIT), and the ATIS 2.0 Precursor System. UM developed and prototyped SmarTrAC, a user-friendly, open-source Android smartphone application (see Figure 2-3) with two major functionalities: 1) it combines with advanced statistical and machine learning techniques to automatically detect, identify and summarize attributes of daily activity and travel episodes; and 2) it incorporates survey techniques to allow users to view and provide contextual information on the identified activity and travel episodes at their convenience on a daily basis [3]. The project demonstration concluded in December 2014 and the final report was submitted in February 2015. Similarly, MIT's CloudCar project consists of a Mobility-as-a-Service (MaaS) element that records user activity and can infer mode of travel through self-learning. The goal of the CloudCar effort is to evaluate mobile versus vehicle-based data collection and demonstrate alternative approaches for managing data rights [4]. The initial prototype testing began in June 2014 and the project concluded in June 2015. ATIS 2.0 effort is currently focused on the development of Version 2.0 of a precursor system. The project is in the preliminary stages. The research team completed the selection of use cases, and is currently at the planning stage of developing a Data Transformation and Cleansing plan.

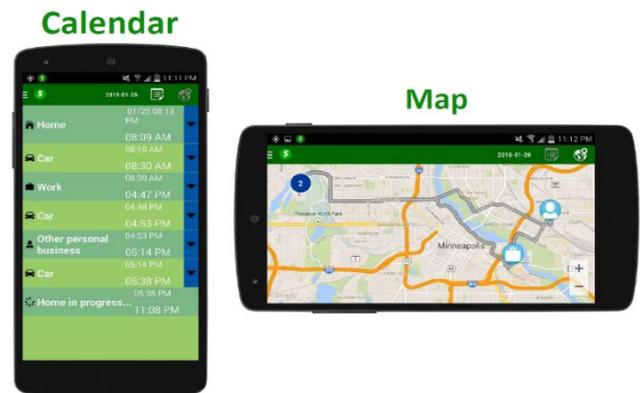


Figure 2-3: Daily detail views for displaying predicted daily activities and trips from SmarTrAC
(Source: University of Minnesota, 2015 [3])

Key Findings

- Test data indicates acceptable performance of SmarTrAC, with the project team observing a reasonable battery consumption rate, a moderate data storage/transmission requirement, a high accuracy in identifying activity vs. trip episodes, etc.
- The report from CloudCar project indicated that for the current scope of the CloudThink and Mobility as a Service project, MySQL is sufficient. For larger scale deployment of CloudThink and MaaS, a framework, such as Hadoop, which is better suited for large data sets should be used.

2.2.2 Freight Advanced Traveler Information Systems (FRATIS)

The FRATIS application bundle seeks to provide freight-specific route guidance and optimize drayage operations so that load movements are coordinated between freight facilities to reduce empty-load trips (see Figure 2-4). FRATIS is composed of the following applications [5]:

- *Freight Specific Dynamic Travel Planning and Performance* – This application contains a series of applications integrating freight traveler information, dynamic route guidance, and public sector performance monitoring to improve freight travel time and reduce fuel consumption and emissions.
- *Drayage Optimization (DR-OPT)* – This application integrates load matching and freight information exchange, including appointment scheduling and equipment availability at intermodal terminals.

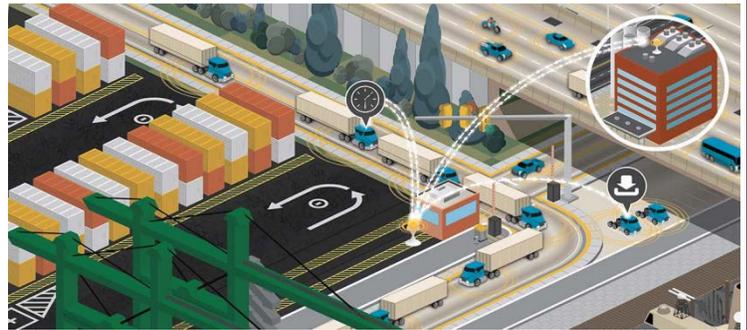


Figure 2-4: Concept of FRATIS System Core Functions
(Source: ITS JPO, 2015)

Testing Summary and Status

The USDOT selected multiple locations to test the FRATIS prototype under different environments that incorporated innovative, unique features of the FRATIS bundle: the Los Angeles Gateway Region, Dallas-Fort Worth (DFW), Texas, and South Florida. In addition, there is an Impacts Assessment (IA) activity to evaluate the three FRATIS prototypes. Figure 2-5

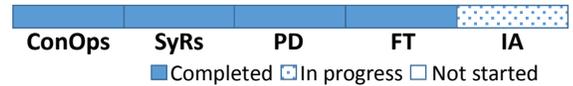


Figure 2-5: FRATIS Project Status
(Source: ITS JPO 2015)



Figure 2-6: FRATIS Demonstration at LA
(Source: ITS JPO, 2015)

shows the status of the FRATIS projects. All three projects have completed the ConOps, SyRS, prototype development (PD), and a field test (FT). The IA is still underway. In Los Angeles, a prototype demonstration was implemented in early 2014 around marine terminals (see Figure 2-6) to help move cargo out of the port more efficiently [6]. A Bluetooth (Wi-Fi) - based terminal queue management system was used to provide travel information. In early 2014, the DFW prototype demonstration was implemented with drayage operations coordinated among rail and local truck drayage companies [7]. The unique feature of the DFW FRATIS prototype was calculating terminal queue time using DSRC 5.9 GHz technology. The South Florida FRATIS demonstration was implemented after the previous two demonstrations with a focus on implementing a web-based drayage optimization tool that provided integrated load matching and freight information exchange to maximize the efficiency of daily load assignments [8]. The South Florida FRATIS

demonstration had a similar focus as the other two sites, but included an emergency response capacity. The final Impacts Assessment report is expected to be published in November 2015.

Key Findings

- FRATIS technologies demonstrate the potential for more efficient drayage operations, particularly avoiding traffic congestion, and reducing delay from better information about wait-time and status at intermodal container terminals, thus reducing overall travel time.
- Truck-mounted data collection devices provide useful truck operations data which can be analyzed to characterize drayage operations.
- The integration of new capabilities into existing systems is essential for a successful test. Within FRATIS, shipment orders were integrated successfully and without duplicated data entry, but full integration of the use of FRATIS would have required resources beyond those available for this project effort.

2.2.3 Integrated Dynamic Transit Operations (IDTO)

The IDTO application bundle aims to integrate passenger connection protection, dynamic scheduling, dispatching, routing of transit vehicles, and dynamic ridesharing into a single system that benefits both travelers and operators. IDTO is composed of the following applications [9]:

- *Connection Protection (T-CONNECT)* – This application enables coordination among public transportation providers and travelers to improve the probability of successful transit transfers (see Figure 2-7).
- *Dynamic Transit Operations (T-DISP)* – This application links available transportation service resources with travelers through dynamic transit vehicle scheduling, dispatching, and routing capabilities.
- *Dynamic Ridesharing (D-RIDE)* – This application uses dynamic ridesharing technology, personal mobile devices, and voice activated on-board equipment to match riders and drivers.



Figure 2-7: Concept of T-CONNECT Application
(Source: ITS JPO, 2015)

Testing Summary and Status

The IDTO project has completed the ConOps, SyRS [10], PD [11], and Field Test (FT) [12] efforts (see Figure 2-8). The IDTO Phase 1 demonstration

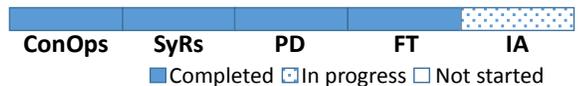


Figure 2-8: IDTO Project Status
(Source: ITS JPO, 2015)

was conducted in Columbus, Ohio in April 2014. This demonstration was the result of a cooperative arrangement with the Central Ohio Transit Agency (COTA) and the Ohio State University (OSU) Transportation and Traffic Management Department, which operates the Campus Area Bus System (CABS). A second site in Orlando, Florida, operated in partnership with the Central Florida Regional Transportation Authority (LYNX), which is the primary provider of public transit services in Orlando, was developed in a modular, scalable manner to allow for future use by other agencies. As such, the primary purpose of the second site was to develop the concept for the IDTO demonstration and identify new and unique system and user requirements for LYNX. A demonstration of this prototyping effort took place in November 2014. Lastly, project personnel provided a demonstration of an example D-RIDE application and interfacing capability (see Figure 2-9) to USDOT staff in March 2015. The IA team will collect vehicle and transaction data to evaluate travel time and reliability for IDTO users and non-users and conduct interviews with participating organizations to gauge effectiveness and inter-organizational cooperation/collaboration. The team will also project impacts across regions by scaling observations from the demonstration to hypothetical full-scale use of IDTO. The final impacts assessment report is expected in April 2016.

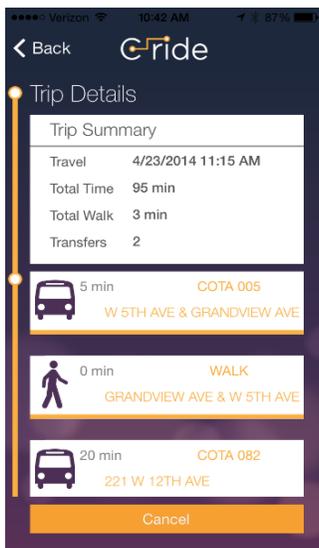


Figure 2-9: IDTO User Interface
(Source: ITS JPO, 2015)

Key Findings

- Analysis of interview returns indicate that the users placed a high value on the utility of the T-CONNECT application, which informed them when connecting vehicles would arrive and whether a connection would be feasible. The value of information on connections led to new travel patterns, repeat usage, and a limited number of protected connections.
- The team plans to develop an analytical tool to evaluate demand-response (D/R) impacts for the T-DISP application and scope of impacts for first-mile- and last-mile dynamic rideshare links to transit services for the D-RIDE application.

2.2.4 Intelligent Network Flow Optimization (INFLO)

The INFLO bundle is a collection of transformative applications capable of collecting and rapidly disseminating multi-source data drawn from connected vehicles, infrastructure, and travelers to increase roadway throughput, reduce primary and secondary crashes, and reduce emissions and fuel consumption. INFLO is composed of the following applications [13]:

- *Dynamic Speed Harmonization (SPD-HARM)* – This application recommends target speeds in response to congestion, incidents, and road conditions to maximize throughput and reduce crashes (Figure 2-11).
- *Queue Warning (Q-WARN)* - This application aims to provide drivers timely warnings of existing and impending queues.
- *Cooperative Adaptive Cruise Control (CACC)* – An application that aims to dynamically adjust and coordinate cruise control speeds among platooning vehicles to improve traffic flow stability and increase throughput.



Figure 2-10: SPD-HARM Application
(Source: ITS JPO, 2015)

Testing Summary and Status

The INFLO project has concluded (see Figure 2-11) and the related documents have been published [13-17]. A prototype of the INFLO SPD-HARM and Q-WARN applications was developed and a small-scale demonstration was conducted with 20 vehicles on the I-5 corridor in Seattle, Washington (see Figure 2-12). Vehicle speed data from both the



Figure 2-11: INFLO Project Status
(Source: ITS JPO, 2015)



Figure 2-12: INFLO Demonstration at Seattle, WA
(Source: ITS JPO, 2015)

Washington State Department of Transportation (WSDOT) infrastructure-based speed detectors and the 20 connected vehicles were collected and processed in real time to deliver Q-WARN and SPD-HARM messages to drivers in advance of congestion. The demonstration revealed that the prototype resulted in fewer panic stops (due to accurate determination of back of queue) as indicated by longitudinal deceleration. Q-WARN and SPD-HARM messages were sent to the drivers at least a mile in advance of the congestion and within 5 seconds of detection of congestion. INFLO CACC was not prototyped as additional research was required. The Collision Avoidance Metrics Partners, LLC. (CAMP) has assessed the technical feasibility of prototyping CACC, and developed a

plan for prototyping and conducting a small-scale test of CACC. In the next phase of this effort, which will commence later in 2015, CAMP will incorporate both simulations and a prototype deployment effort. The impacts assessment team evaluated the SPD-HARM application using a simulation model for the US 101 freeway corridor in San Mateo, CA, as well as the small-scale demonstration of both SPD-HARM and Q-WARN applications that was conducted in Seattle, WA [18].

Key Findings

- Results from the simulation analysis found that the prototype significantly reduced the magnitudes of the speed drops (shockwaves) between vehicles, even at the 10% market penetration level. The prototype reduced average speeds on freeways by 10% to 20%. Biggest payoff in reducing shockwaves was seen for the first 20% of net response rate.
- The trade-off for the improved safety is that the prototype increases the geographic impact of existing bottlenecks on freeway speeds by expanding the upstream distance that is affected by congestion.
- Drivers who participated in the small-scale demonstration noted safety benefits from Q-WARN and SPD-HARM as it allowed them to take action in advance of congestion and reduce the need to slow down or stop suddenly.

2.2.5 Multimodal Intelligent Traffic Signal System (MMITSS)

The MMITSS application bundle seeks to develop a comprehensive traffic signal system that services all modes of transportation as shown in Figure 2-13. MMITSS is composed of the following applications:

- *Intelligent Traffic Signal System (I-SIG)* - Using connected data from vehicles, pedestrian and non-motorized travelers, this is an overarching system optimization application that accommodates transit or freight signal priority, preemption, and pedestrian movements to maximize overall network performance.
- *Transit Signal Priority (TSP) and Freight Signal Priority (FSP)* – These two applications provide signal priority to transit vehicles at intersections and along arterial corridors as well as signal priority to freight vehicles along an arterial corridor near a freight facility.
- *Mobile Accessible Pedestrian Signal System (PED-SIG)*– This application allows for an automated call from the smart phone of a visually impaired pedestrian to the traffic signal, as well as audio cues to safely navigate the crosswalk.
- *Emergency Vehicle Preemption (PREEMPT)* – This application provides signal preemption to emergency vehicles and accommodates multiple emergency requests.

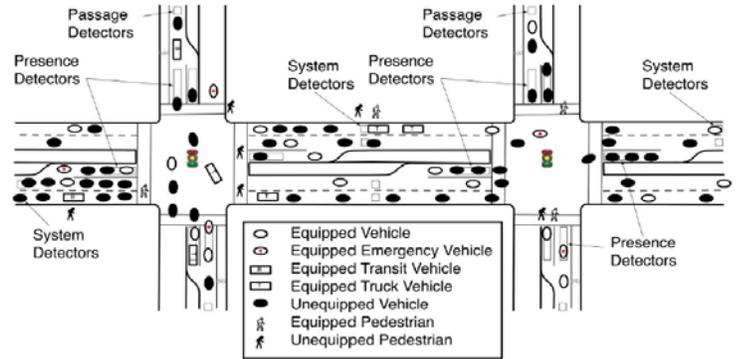


Figure 2-13: MMITSS Concept
(Source: University of Arizona, 2012 [19])

Testing Summary and Status

ConOps [19], SyRS [20] and PD efforts are completed (See Figure 2-14) and the related documentation has been published. There are two MMITSS test sites located in Anthem, Arizona and Northern California.



Figure 2-14: MMITSS Project Status
(Source: ITS JPO, 2015)

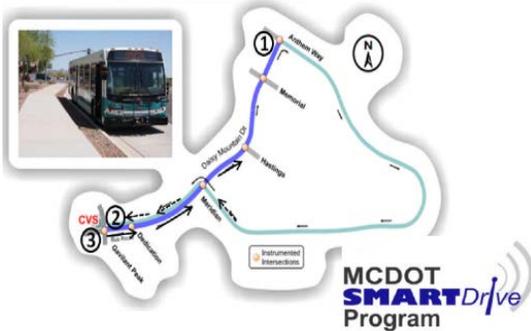


Figure 2-15: MMITSS Test Site at Anthem, AZ
(Source: University of Arizona)

The prototypes feature I-SIG, TSP and FSP applications and a pedestrian smartphone application (Savari SmartCross). The field test (FT) of the Arizona prototype occurred in March 2015 (see Figure 2-15). The field test of the California prototype will occur during summer 2015 and the project is expected to be completed by the end of 2015. The IA report was finalized in August and is under publication. The evaluation efforts include analyzing field test data from Anthem, AZ site and estimating impacts from simulation networks for the Anthem site and the US-50 corridor in Virginia. The IA effort will examine the impacts of I-SIG, TSP, FSP and a combination of TSP and FSP.

Key Findings

- *Anthem (AZ) Field Test*
 - I-SIG, FSP, and the combination of TSP and FSP effectively improved vehicle travel time, ranging from 6-27% improvement, and reduced the delay for equipped passenger car, trucks, and transit vehicles.
- *Anthem (AZ) and US-50 (VA) Network Simulations:*
 - TSP significantly reduced the travel time and delay of transit vehicles for all congestion levels by 10%. FSP can reduce the travel time and delay of trucks but might increase the system-wide delay when the demand level increases.
 - I-SIG performed efficiently when demand levels were near or below congested conditions under “medium” connected vehicle penetration rate. The combination of TSP and FSP applications successfully proved a hierarchical level of priority within MMITSS.

2.2.6 Response, Emergency Staging and Communications, Uniform Management, and Evacuation (R.E.S.C.U.M.E)

The R.E.S.C.U.M.E application bundle aims to advance vehicle to vehicle safety messaging over dedicated short-range communications (DSRC) to improve the safety of emergency responders and travelers (see Figure 2-16). R.E.S.C.U.M.E. is composed of the following applications [21]:

- *Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)* - This application provides input to responder vehicle routing, staging and secondary dispatch decisions.
- *Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)* – This application warns on-scene workers of vehicles with trajectories or speeds that pose a high risk to their safety. It also warns drivers passing an incident zone if they need to slow down, stop, or change lanes.
- *Emergency Communications and Evacuation (EVAC)* – This application addresses needs of evacuees who use their own transportation by providing information of routing, traffic and necessities, and evacuees who requires assistance by providing available evacuation resources.

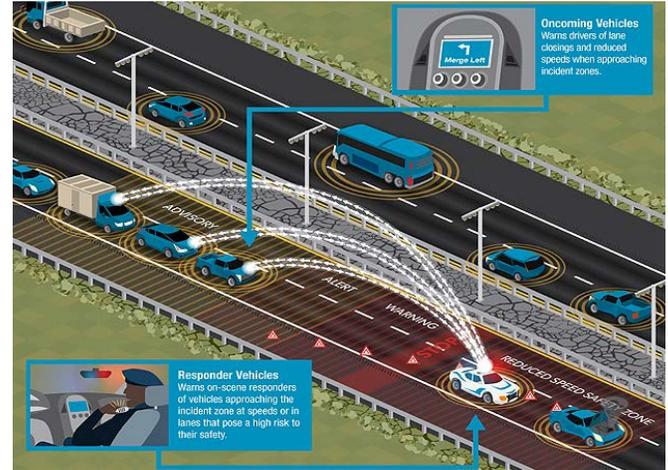


Figure 2-16: Concept of R.E.S.C.U.M.E. Applications (Source: ITS JPO, 2015)

Testing Summary and Status

The R.E.S.C.U.M.E. project has concluded (see Figure 2-18) and the related documentation has been published [21-25]. The R.E.S.C.U.M.E



Figure 2-18: R.E.S.C.U.M.E. Demonstration Test Track in Maryland (Source: Battelle)

prototype was developed and demonstrated at Columbus, Ohio and Sykesville, Maryland (see Figure 2-17). Twelve scenarios illustrated the functionality of the RESP-STG and INC-ZONE applications, which were viewed from the perspectives of the transportation center, the responder and the oncoming Vehicle. For INC-ZONE and RESP-STG, impacts assessment efforts included an evaluation of the prototype that was demonstrated in Maryland through interviews with test participants, and an evaluation applied to the US 101 San Mateo Corridor [26]. The EVAC application was evaluated through modeling and simulation using the Greater New Orleans evacuation model [27].

ConOps	SyRs	PD	FT	IA
<input checked="" type="checkbox"/>				

■ Completed □ In progress □ Not started

Figure 2-17. R.E.S.C.U.M.E. Project Status (Source: ITS JPO, 2015)

Key Findings

- *Interview:* The majority recognized the potential of the R.E.S.C.U.M.E. applications in reducing total response and clearance time, delays, and secondary incidents once these applications become widely adopted.
- *Network Simulations:*
 - Average network-wide delay was reduced by up to 14% when INC-ZONE was used in addition to an increase in average speeds by up to 8%. There were fewer instances of hard braking in the incident zone with up to 89% reduction in maximum deceleration. RESP-STG can potentially reduce the emergency vehicles' travel time by up to 23% and their number of stops by up to 15%.
 - EVAC functionalities such as route guidance, communications about transit services, and lodging and fueling assistance could be beneficial to evacuees in terms of reducing travel time and overall network congestion.

3 Applications for the Environment: Real-Time Information Synthesis (AERIS) Program

3.1 Program Overview

The environmental component of the ITS JPO's connected vehicle research program includes a vision of *"Cleaner Air through Smarter Transportation"*. Employing a multimodal approach, the AERIS Research Program encourages the development of connected vehicle technologies and applications that support a more sustainable relationship between transportation and the environment chiefly through fuel use reductions and resulting emissions reductions. Within a connected vehicle environment, AERIS envisions a transportation system in which all transportation operators and users, regardless of mode, have the information they needed to make better and greener transportation choices, whenever and wherever they chose. AERIS research seeks to assist in addressing one of transportation's biggest challenges—the fact that according to the Environmental Protection Agency (EPA) transportation accounts for 28% of U.S. greenhouse gas emissions (GHG) [28]. GHGs from human activities are the most significant driver of observed climate change since the mid-20th century. The most prominent of these GHGs is carbon dioxide (CO₂) which is emitted primarily through the burning of fuels. Estimates indicate that 2.9 billion gallons of wasted fuel result from congestion in urban areas [29]. The AERIS Research Program began in 2009 and was a five-year research program. The program was established by the ITS JPO to investigate whether it was possible and feasible to:

- Identify connected vehicle applications that could provide environmental impact reduction benefits via reduced fuel use and efficiency impacts on emissions.
- Facilitate and incentivize "green choices" by transportation service consumers (i.e., system users, system operators, policy decision makers, etc.).
- Identify V2V, V2I, and vehicle-to-grid (V2G) data (and other) exchanges via wireless technologies of various types.
- Model and analyze connected vehicle applications to estimate the potential environmental impact reduction benefits.
- Develop a prototype for one of the applications to test its efficacy and usefulness.

Over the course of the program, AERIS sought to promote the highest levels of collaboration and cooperation in the research and development of transformative environmental applications using connected vehicle technologies. AERIS applications were designed to work in a connected vehicle environment where vehicles and infrastructure communicate among themselves and with each other to transmit information that can be used for various purposes. Dedicated Short-Range Communication (DSRC) along with other wireless communication means, such as cellular communications, facilitate the transmission of data.

3.2 AERIS Application Bundles and Estimated Impacts

AERIS research activities focused on five Operational Scenarios or strategic bundles of applications. As depicted in Figure 3-1, these Operational Scenarios include Eco-Signal Operations, Eco-Lanes, Low Emissions Zones, Eco-Traveler Information, and Eco-Integrated Corridor Management (Eco-ICM). Each Operational Scenario encompassed a set of applications which individually can provide environmental benefits. However, by strategically bundling the applications, the AERIS Program saw that the Operational Scenarios could achieve additional environment benefits above those of the individual applications.



Figure 3-1: AERIS Operational Scenarios and Applications
(Source: ITS JPO, 2015)

The AERIS Research Program consisted of a phased research approach. The first phase, *Concept Exploration*, examined the state-of-the-practice and explored ideas for AERIS research. Five state-of-the-practice reports were developed as part of this phase investigating (i) environmental applications, (ii) assessment of technologies to collect environmental data, (iii) environmental models, (iv) behavioral and activity-based models, and (v) evaluation of environmental deployments. Additionally, six Broad Agency Announcement (BAA) projects were conducted that leveraged cutting edge research activities from academia and private industry.

The next phase, *Development of Concepts of Operations for Operational Scenarios*, focused on the identification of environmental applications and the development of Concept of Operations for the Eco-Signal Operations, Eco-Lanes, Low Emissions Zones, Eco-Traveler Information, and Eco-ICM Operational Scenarios. Once the ConOps were developed, a preliminary benefit cost analysis was performed to identify high priority applications and refine/refocus the research. The high priority applications from the benefit cost analysis were then selected for more detailed *Modeling and Analysis*. Modeling and analysis consisted of algorithm development and integrated modeling using transportation simulation models (e.g., VISSIM) and environmental models (e.g., EPA's MOVES model) to estimate environmental benefits. The results of the modeling effort were detailed modeling reports that document the potential benefits that may be possible by implementing AERIS connected vehicle applications.

Finally, the AERIS Program selected one of the AERIS applications for *Prototyping*. The Eco-Approach and Departure at Signalized Intersections application was selected to test its efficacy and usefulness. A field experiment was conducted in 2012 at Turner Fairbank Highway Research Center (TFHRC) and more recently a more robust prototype was developed that integrates automated longitudinal control capabilities into the application.

3.2.1 Eco-Signal Operations

The Eco-Signal Operations applications use connected vehicle technologies to decrease fuel consumption and emissions on arterials by reducing idling, reducing unnecessary stops, and improving traffic flow at signalized intersections. This Operational Scenario is comprised of the following applications:

- *Eco-Approach and Departure at Signalized Intersections* – The application uses wireless data communications sent from a RSU to connected vehicles to encourage “green” approaches to signalized intersections.
- *Eco-Traffic Signal Timing* – This application optimizes the performance of traffic signals for the environment. The application collects data from vehicles, such as vehicle location, speed, and emissions data. It then processes these data to develop signal timing strategies focused on reducing fuel consumption and emissions.
- *Eco-Traffic Signal Priority* – This application allows either transit or freight vehicles approaching a signalized intersection to request signal priority. The application considers the vehicle’s location, speed, vehicle type, and associated emissions to determine whether priority should be granted.
- *Connected Eco-Driving* - This application provides customized real-time driving advice to drivers so that they can adjust their driving behavior to save fuel and reduce emissions. Eco-driving advice includes recommended driving speeds and optimal acceleration/decelerations based on prevailing traffic, interactions with nearby vehicles, and upcoming road grades.
- *Wireless Inductive/Resonance Charging* – This application enables wireless charging of electric vehicle batteries and supports static charging capable of transferring electric power to a vehicle stopped at a traffic signal or a stop sign.

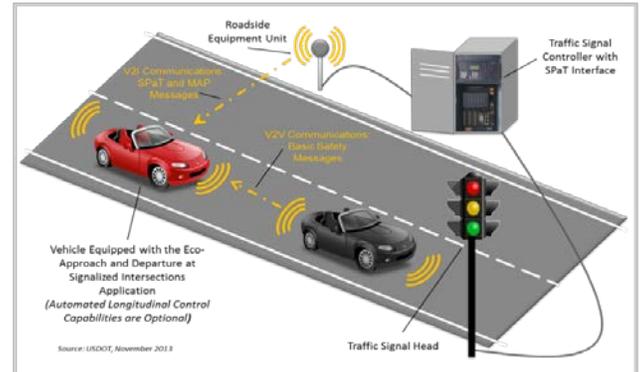


Figure 3-2: Eco-Signal Operations Visualization
(Source: ITS JPO, 2015)

Status

- A ConOps [30] was developed that describes the Eco-Signal Operations applications; communicates user needs and desired capabilities for and expectations of the applications; provides operational scenarios describing how the applications may operate; and identifies goals, objectives, and potential performance measures for the Operational Scenario. The ConOps is available at : http://ntl.bts.gov/lib/51000/51400/51429/FINAL_Eco-Signal_Operations_ConOps_01-2014.pdf
- The AERIS Program completed detailed analysis, modeling, and simulation (AMS) of the Eco-Signal Operations applications. Modeling of the applications was conducted using a microscopic traffic simulation model (VISSIM) and the Environmental Protection Agency’s (EPA’s) Motor Vehicle Emission Simulator (MOVES) emissions model. A twenty-seven intersection, 6.5 mile segment of El Camino Real in Northern was modeled. Simulations were conducted under different traffic conditions, network conditions, connected vehicle penetration rates, and other variables. The Eco-Signal Operations Modeling Report is currently in the USDOT publication process. [31]
- An initial field experiment of the Eco-Approach and departure at Signalized Intersections application was conducted at TFHRC with a single vehicle at a single intersection with no traffic. The field experiment resulted in up to 18% reductions in fuel consumption. Currently in development, the GlidePath Prototype Application sets out to test the efficacy and usefulness of automated longitudinal control capabilities with the Eco-Approach and Departure at Signalized Intersections application.

Key Findings

Key findings from modeling and simulation are summarized below:

- *Eco-Approach and Departure at Signalized Intersections* – The application provided 5-10% fuel reduction benefits for an uncoordinated corridor. For a coordinated corridor, the application provided up to 13% fuel reduction benefits; 8% of the benefits were attributable to signal coordination while 5% were attributable to the application.

- *Eco-Traffic Signal Timing* – When applied to a signalized corridor that was fairly well optimized, the application provided an additional 5% fuel reduction benefit at full connected vehicle penetration.
- *Eco-Traffic Signal Priority* – The Eco-Transit Signal Priority application provided up to 2% fuel reduction benefits for transit vehicles. The Eco-Freight Signal Priority application provided up to 4% fuel reduction benefits for freight vehicles.
- *Connected Eco-Driving* – When implemented along a signalized corridor, the application provided up to 2% fuel reduction benefits at full connected vehicle penetration.
- *Combined Modeling of the Eco-Signal Operations Applications* – Up to 11% improvement in CO2 and fuel consumption at full connected vehicle penetration. As with many ITS applications, the benefits decrease as volumes approach saturated, congested conditions, as there is little room for capacity improvement.

Key findings from prototyping are summarized below:

- *2012 Eco-Approach and Departure at Signalized Intersections Field Experiment* – The field experiment was conducted at TFHRC with a single vehicle at a single intersection with no traffic. Drivers were provided with speed recommendations using a driver-vehicle interface (DVI) incorporated into the speedometer (driver advisory feedback). The field experiment resulted in up to 18 percent reductions in fuel consumption. However, it was difficult for drivers to follow the recommended speed on the “speed advice speedometer”. Having drivers follow speed recommendations also created driver distraction.
- *GlidePath Prototype Application* – In 2014, FHWA began the GlidePath project that developed a working Eco-Approach and Departure application prototype application with automated longitudinal control. The project will evaluate the performance of the eco-approach and departure algorithm and automated prototype (specifically, the energy savings). Testing and demonstrations of the application will be conducted at TFHRC in the summer of 2015 with a final report released in early 2016. Initial results from August 2015 indicate that a driver with a DVI saw 7% fuel savings over un-informed drivers, while a driver with partial automation and the GlidePath application saw 22% fuel savings over the un-informed driver. These initial results indicate a 15% fuel improvement between a driver trying to follow a DVI speed recommendation and the partial automated GlidePath application. These improvements are due to minimizing the lag in speed changes to keep the optimal speed and approach for minimal environmental impact.

3.2.2 Eco-Lanes

Eco-Lanes are similar to managed lanes; however these lanes are optimized for the environment using connected vehicle data and can be responsive to real-time traffic and environmental conditions. Lanes would be targeted toward low emission, high occupancy, transit, and alternative fuel vehicles. The Eco-Lanes Operational Scenario comprises the following applications:

- *Eco-Lanes Management* – The Eco-Lanes Management application is used to manage the eco-lanes. Eco-lanes parameters may include the types of vehicles allowed in the eco-lanes, emissions parameters for entering the eco-lanes, the number of lanes, and the start and end of the eco-lanes.
- *Eco-Speed Harmonization* – The application adjusts speed limits on links that approach areas of traffic congestion, bottlenecks, and incidents. Speed harmonization assists in maintaining flow, reducing unnecessary stops and starts, and maintaining consistent speeds, thus reducing fuel consumption and emissions.
- *Eco-Cooperative Adaptive Cruise Control (ECACC)* – Expanding on existing ACC systems, connected vehicle technologies can be used to collect the preceding vehicle's speed, acceleration, and location and feed these data into the vehicle's ACC. These data are transmitted from the lead vehicle to the following vehicle to support vehicle platooning. The ECACC application also considers information, such as road grade, roadway geometry, and road weather information.
- *Eco-Ramp Metering* – The application determines the most environmentally efficient operation of traffic signals at freeway on-ramps to manage the rate of entering vehicles.
- *Connected Eco-Driving* – The application provides customized real-time driving advice to drivers so that they can adjust their driving behavior to save fuel and reduce emissions. Eco-driving includes recommended driving speeds and optimal accelerations/decelerations based on prevailing traffic, interactions with nearby vehicles, and upcoming road grades.
- *Wireless Inductive/Resonance Charging* – This application enables wireless charging of electric vehicle batteries. Eco-Lanes Operational Scenario supports dynamic charging of electric vehicle batteries when the vehicle is in motion.

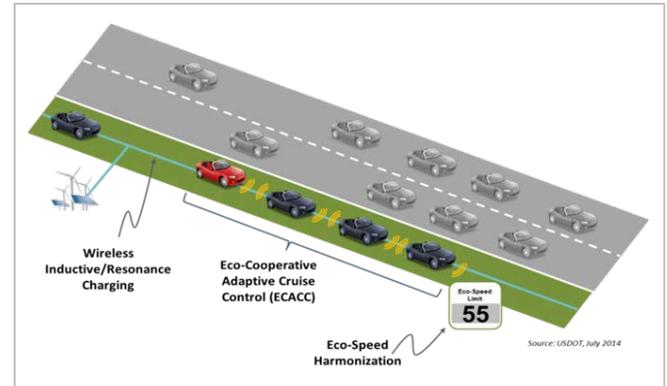


Figure 3-3: Eco-Lanes Visualization (Source: ITS JPO, 2015)

Status

- A ConOps [32] was developed that describes the Eco-Lanes applications; communicates user needs and desired capabilities for and expectations of the applications; provides operational scenarios describing how the applications may operate; and identifies goals, objectives, and potential performance measures for the bundle. The ConOps is available at: <http://ntl.bts.gov/lib/51000/51700/51774/114.pdf>
- The Eco-Speed Harmonization and ECACC applications were modeled for a segment of roadway on State Route 91 Eastbound in Southern California using VISSIM and MOVES. An ECACC-reserved “Eco-Lane” was developed, while the remaining lanes were used for Eco-Speed Harmonization. The Eco-Lanes Modeling Report is currently in the USDOT publication process. [33]

Key Findings

Key findings from modeling and simulation are summarized below:

- *Eco-Speed Harmonization* – The application provides up to 4.5% fuel reduction benefits for a freeway corridor. It assists in maintaining the flow of traffic, reducing unnecessary stops and starts, and maintaining consistent speeds near bottlenecks and other disturbance areas.
- *Eco-Cooperative Adaptive Cruise Control* – CACC provides up to 19% fuel savings on a real-world freeway. Vehicles using a dedicated “eco-lane” experience 7% more fuel savings when compared to vehicles in the general lanes. CACC has the potential to provide up to 42% travel time savings on a real-world freeway corridor for all vehicles.

- *Combined Modeling of the Eco-Lanes Applications* – Together the applications provide up to 22% fuel savings on a real-world freeway corridor for all vehicles. Vehicles using the dedicated “eco-lane” experience 2% more fuel savings when compared to vehicles in the general traffic lanes. The scenario provides up to 33% travel time savings for all vehicles.

3.2.3 Low Emissions Zones

The Low Emissions Zones Operational Scenario envisions entities responsible for the operations of the transportation network to have the ability to define geographic areas that seeks to restrict or deter access by specific categories of high-polluting vehicles into the area for the purpose of improving the air quality within the geographic area. Alternatively, the Operational Scenario may incentivize traveler decisions that are determined to be environmentally friendly such as the use of alternative fuel vehicles or transit. Low Emissions Zones in a connected vehicle environment would be similar to existing low emissions zones; however they would leverage connected vehicle technologies allowing the systems to be more responsive to real-time traffic and environmental conditions. The Low Emissions Zones Operational Scenario is comprised of the following applications:

- *Low Emissions Zone Management* – This application supports the operation of a Low Emissions Zone that is responsive to real-time traffic and environmental conditions. The application would establish parameters including the types of vehicles permitted to enter the zone, exemptions for transit vehicles, emissions criteria for entering the zone, fees or incentives for vehicles based on emissions data collected from the vehicle, and geographic boundaries for the low emissions zones.
- *Eco-Traveler Information Applications* –Eco-Traveler Information Applications provide pre-trip and en-route traveler information about the low emissions zones including information about the geographic boundaries of the low emissions zones, criteria for vehicles to enter the zones, expected fees and incentives for their trip, and current and predicted traffic and environmental conditions within and adjacent to the zones.

Status

- A ConOps [34] was developed that describes the applications; communicates user needs and desired capabilities for and expectations of the applications; provides operational scenarios describing how the applications may operate; and identifies goals, objectives, and potential performance measures for the bundle. The ConOps is available on the National Transportation Library: http://ntl.bts.gov/lib/52000/52700/52755/FINAL_Low_Emissions_Zones_ConOps_01-2014.pdf
- Analysis, modeling, and simulation were conducted for a low emissions zone in the Phoenix, AZ metropolitan area using the SimTRAVEL (Simulator of Transport, Routes, Activities, Vehicles, Emissions, and Land) integrated model system. [35]

Key Findings

Key findings from modeling and simulation are summarized below:

- A Low Emissions Zone modeled in the Phoenix Metropolitan Area resulted in up to 4.5% reduction in fuel consumption when both eco-vehicle incentives and transit incentives were offered.
- The modeling indicated that the Low Emissions Zone has the potential to reduce vehicle miles traveled by up to 2.5% and increase transit use by up to 20% in to the Low Emissions Zones.
- An effective Low Emissions Zone includes a combination of incentives to eco-vehicles as well as enhanced transit services to attract non-eco travelers



Figure 3-4: Low Emissions Zones Modeling for Phoenix (Source: ITS JPO, 2015)

3.2.4 Eco-Traveler Information

This Operational Scenario seeks to provide the traveling public with information regarding available modes, optimal routes, and departure times in real-time either pre-trip or en-route. Research has shown that successful traveler information services can impact fuel consumption and vehicular emissions in various forms. Significant environmental benefits also exist from mode shifts (e.g., from a single occupancy vehicle to transit, bicycle, carpool, etc.).

- **Connected Vehicle-Enabled Environmental Probe Data Collection** – This application supports the collection of fuel consumption and emissions data from vehicles. Using these data, real-time air quality maps may be created for roadway segments.
- **Multimodal Traveler Information** – This application provides pre-trip and en-route traveler information to travelers encouraging a more sustainable travel. The application collects multimodal data to support trip planning tools that provide travelers with information about multimodal travel options. The application also provides travelers with real-time traffic conditions so they can adjust departure time and mode choices or select an alternate.
- **Eco-Smart Parking** – This application provide users with real-time location, availability, type (e.g., street, garage), and price of parking. Eco-Smart Parking applications also supports dynamic pricing or incentives for parking based on vehicle type. Pricing and incentives may serve a traffic demand management strategy helping to reduce vehicle miles traveled in an area, or incentivize travel by eco-vehicles. The application also allows travelers to reserve parking spaces in advance, as well as pay for parking, using mobile devices and connected vehicle technologies.
- **AFV Charging/Fueling Information, Reservations, and Payment** – This application informs travelers of the range of their AFV and provides locations and the availability of AFV charging and fueling stations. The application allows drivers to make reservations to use charging/fueling stations before they start their trip or while en-route. Additionally, the application supports electronic payment for fuel/energy using connected vehicle technologies. The vehicle would also learn from the driver's behavior providing accurate estimates of the vehicle's range, reducing the driver's fear of being stranded.
- **Dynamic Eco-Routing** – This application determines the most eco-friendly route for individual travelers. The application leverages connected vehicle data to determine the eco-routes based on historical, real-time, predicted traffic and environmental data as well as road type (e.g., arterial or freeway) and road grade. The Dynamic Eco-Routing application takes into account a variety of different data, including: real-time traffic information, road type, and road grade.
- **Connected Eco-Driving – Gamified / Incentives-Based Applications** – This application use advanced sensors, software, and telematics allowing vehicular systems to communicate information about the vehicle's performance directly to the driver— via the dashboard or wirelessly to a smartphone. Drivers receive eco-driving recommendations and post-trip feedback on their behavior adapted to them and to their vehicle's characteristics. Eco-driving information applications provide recommendations via an onboard unit (OBU) to promote energy efficient driving techniques. These applications also leverage a social media component, where people can compete on leaderboards.
- **Gamified / Incentives-Based Multimodal Traveler Information Applications** – This application allows travelers to opt-in to smartphone apps to earn points for based on their travel choices. Travelers would earn points for green transportation choices including travel during off-peak hours, transit usage, bike usage, etc. These applications would allow system operators to collect data from travelers on their traveling behavior, would allow app users to receive customized traveler information, and would leverage a social media component where people would compete on leaderboards on how much fuel and emissions they save from making green transportation choices.

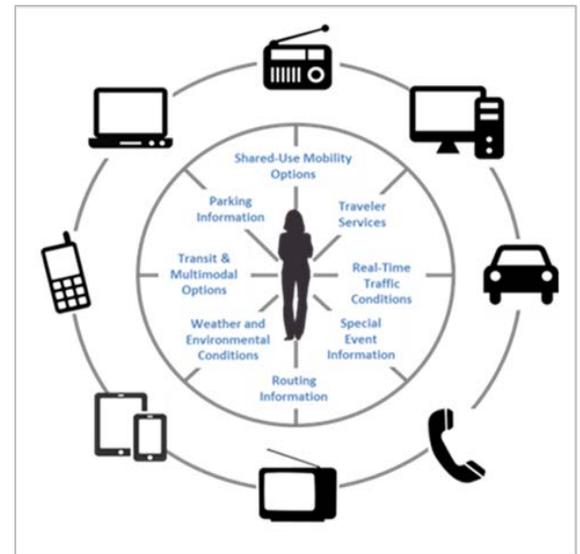


Figure 3-5: Eco-Traveler Information (Source: ITS JPO, 2015)

Status

- The AERIS Program recently completed a ConOps for the Eco-Traveler Information Operational Scenario. The ConOps is expected to be finalized in late 2015. This Operational Scenario did not undergo detailed modeling or prototyping activities.

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3.2.5 Eco-Integrated Corridor Management (Eco-ICM)

The objective of Eco-Integrated Corridor Management (Eco-ICM) is to “realize significant environmental improvements in the efficient movement of people and goods through integrated and proactive management of major multimodal transportation corridors. The Eco-ICM Operational Scenario seeks to build on the successes of previous ICM initiatives by considering how connected vehicle and other future technologies may support the integrated operation of a major travel corridor to reduce transportation-related emissions on arterials and freeways. Eco-ICM should be thought of as an extension to the existing ICM concept – with the difference being that Eco-ICM seeks to ensure that environmental data and performance measures are considered in making operational decisions including the implementation of environmentally-oriented operational strategies.

- Eco-Integrated Corridor Management Decision Support System –**
 The Eco-Integrated Corridor Management Decision Support System (DSS) seeks to assist managers in the process of collaboratively managing a multimodal transportation network. The ICM DSS would support eco-capabilities to ensure that environmental objectives are considered when managing the transportation network for the purpose of reducing transportation's negative impact on the environment. In general, the ICM DSS and associated eco-capabilities support multimodal, transportation operational decision-making in real-time including reducing delay as well as reducing emissions and fuel consumption. The DSS would integrate multiple real-time data sources from a variety of systems – including arterial, freeway, transit, and other management systems. Expanding on existing ICM DSSs, the Eco-ICM DSS would also collect environmental, connected vehicle, and shared use mobility data. These data would be processed, modeled, and analyzed to support decisions for specific actions, strategies, and recommendations. Those strategies would support environmental (and other) objectives such as reducing emissions, reducing fuel consumption, and improving air quality.



Figure 3-6: Eco-ICM
(Source: ITS JPO, 2015)

Status

- The AERIS Program recently completed a ConOps for the Eco-ICM Operational Scenario. The ConOps is expected to be finalized in late 2015. This Operational Scenario did not undergo detailed modeling or prototyping activities.

Key Findings

The AERIS Research Program did not conduct modeling of the Eco-ICM Operational Scenario. Analysis, simulation, and modeling were however conducted by ICM Pioneer sites in San Diego, CA and Dallas, TX to measure the potential benefits of implementing ICM. Those modeling results identified potential environmental benefits. Modeling results from the San Diego, CA ICM Pioneer Site indicate the following benefits:

- 246,000 hours of annual travel time savings
- 323,000 gallons of fuel saved annually
- 3,100 tons of mobile emissions saved
- Benefit-Cost Ratio of 10:1

Modeling results from the Dallas, TX ICM Pioneer Site indicate the following benefits:

- 740,000 hours of annual travel time savings
- 981,000 gallons of fuel saved annually
- 9,400 tons of mobile emissions saved
- Benefit-Cost Ratio of 20:1

4 Vehicle-to-Infrastructure (V2I) Safety Program

4.1 Program Overview

The V2I safety research program has been focused on crash prevention through low-latency DSRC safety applications, building off V2V and Vehicle-Infrastructure Integration (VII) proof of concept (POC) research previously conducted by the USDOT. The V2I safety research plan is structured with several interrelated “tracks” that include crash analyses to help identify applications that will be selected for development, test, and evaluation. The research plan is also addressing research on the foundational V2I technologies to enable interoperable safety applications nationally and across jurisdictional lines – communications, mapping, and positioning; and developing materials to support V2I deployment planning.

V2I safety research for crash avoidance focused initially on four areas - intersections, speed management, run off road and lane departure, and enforcement and operational safety for commercial vehicles and transit. Analyses was done in the area of crash factors to help identify high priority crash types that prove to be technically feasible and cost-effective for research investment. Several studies have been conducted to estimate the benefits of V2I safety applications: CICAS-V Research on Comprehensive Costs of Intersection Crashes [36] estimated the potential benefits of Cooperative Intersection Collision Avoidance Systems (CICAS) in terms of comprehensive crash costs; and Crash Data Analyses for Vehicle-to-Infrastructure Communications for Safety Applications [37] documented the results of crash data analyses to assess the potential safety benefits of a broad set of vehicle-to-infrastructure (V2I) communication applications to improve highway safety.

From these efforts, FHWA and other modal partners were able to select potential applications for further research. Eight V2I safety applications were identified by FHWA for further research: Red Light Violation Warning (RLVW), Stop Sign Gap Assist (SSGA), Curve Speed Warning (CSW), Stop Sign Violation Warning (SSVW), Railroad Crossing Violation Warning (RCVW), Spot Weather Information Warning (SWIW), Oversize Vehicle Warning (OVW), and Reduced Speed Zone Warning (RSZW). Concepts of operations (ConOps) and selected application system requirements (SyRS) were developed for these applications. These documents identify expected benefits for V2I safety applications (e.g., reductions in the number of roadway fatalities, reductions in the number and severity of roadway injuries). FRA has built upon the initial work for RCVW and is pursuing further development for an application prototype. FTA has developed a prototype transit V2I safety application as part of the Transit Retrofit Package, Pedestrian in Signalized Crosswalk Warning (PCW). CSW and PCW applications were tested during the Safety Pilot Model Deployment in Ann Arbor, Michigan. Also, FTA is conducting additional development on a V2I Pedestrian / Cyclist Crossing Safety Application that builds upon the PCW prototype, and intends to pursue a V2I application to improve safety for pedestrians at bus stops.

In late 2013/early 2014, FHWA entered into a cooperative agreement with the Crash Avoidance Metrics Partners, LLC. (CAMP) to develop, test, and evaluate a number of V2I safety applications. CAMP formed the V2I Consortium, comprising 10 light vehicle and one heavy vehicle manufacturers, which selected three safety applications for prototype development: RLVW, CSW and RSZW. Application development is in progress with testing to begin late summer 2015. FHWA anticipates that one or more of the CV Pilots will include V2I safety applications.

Under the FHWA's V2I Deployment Guidance effort, several tools and products will be developed to assist state and local agencies deploy V2I applications. The V2I Benefit Cost Analysis Tool (Desk Reference and Tools for Estimating the Local, Regional, and State-Wide Economic Development Benefits of Connected Vehicle to Infrastructure Deployments) is one tool. The primary outcomes will be a desk reference and tools for estimating the full range of potential local, regional and State economic benefits, costs and economic development associated with implementation of connected vehicle technologies. Another product is being developed under the Guide to Initial Deployments (AASHTO Near-Term V2I Transition and Phasing Analysis) project. The scope of the project is to include development of three tools – Application Prioritization Tool, Infrastructure Planning and Phasing Tool, and Lifecycle Cost Model Tool (note that an examination of benefits is not included).

Research under NCHRP 03-101, Costs and Benefits of Public-Sector Deployment of Vehicle to Infrastructure Technologies, began in 2011 and was recently completed. The objective of this research was to evaluate and document agency benefits and costs of connected vehicles in order to assist with deployment decisions by state and local DOTs. The project report is not yet available; however, a December 2014 [38] briefing contains cost benefits analysis (net Benefit/Cost) results for three deployments: Virginia DOT Test Bed (Year 6), Michigan (Year 10), and Maricopa County region (year 6).

Additional mode-specific applications are being developed in partnership with ITS JPO, FHWA, Federal Motor Carrier Safety Administration (FMCSA), Federal Transit Administration (FTA), and the Federal Railroad Administration (FRA). Under a collaborative effort, FHWA, FMCSA, and the ITS JPO are developing a Smart Roadside Initiative (SRI) prototype that is focused on achieving V2I communication between commercial vehicles and the roadside, specifically at weigh and inspection stations to improve motor carrier safety, security, operational efficiency, and freight mobility. The SRI prototype development team has completed concept definition, system requirements, system architecture and high-level design. The prototype development will conclude with working application(s) that are suitable to include in a field operational test. The USDOT has contracted for an independent assessment of the SRI prototype to estimate the effectiveness and impacts at weigh stations). Results of the impact assessment are expected in the first quarter of 2016.

The FTA and the ITS JPO developed research prototypes of selected V2V and V2I safety applications (referred to as the Transit Retrofit Package or TRP) on transit vehicles. The TRP was tested in the Safety Pilot Model Deployment in Ann Arbor, Michigan where data were collected for analysis by Volpe (independent evaluator). Subsequently, the TRP system and two applications were modified, demonstrated in Ann Arbor, and additional data collected. Volpe completed a full analysis of system performance, driver assistance, and safety impacts and published the results [39]. FTA also intends to conduct additional research to develop, test, and evaluate a prototype Transit V2I Bus Stop Pedestrian Safety Application. The FTA Transit Bus Stop Pedestrian Safety targets cases where buses collide with pedestrians at or near bus stops. FTA plans for Volpe to conduct an independent evaluation of this prototype transit V2I safety application.

The FRA in collaboration with the ITS JPO and FHWA, intends to develop a Grade Crossing Violation Warning application for proof of concept and testing. The application aims at reducing crashes between vehicles and trains at active railroad grade crossings. ConOps and SyRS documents have been developed and will serve as a basis for application development. Both FTA and FRA projects help to build multimodal capability for V2I Safety.

4.2 V2I Safety Applications and Estimated Impacts

The V2I safety applications which have been demonstrated in the field and tested or evaluated or are currently the focus of V2I safety program are presented in this section. The primary advisory or warning alerts for these applications are determined by vehicle-based components, using a combination of vehicle data and data (e.g., signal phase and timing) received from the infrastructure. In some cases, a driver-infrastructure interface (e.g., dynamic signage) with advisory information is also supported. These applications and a concise description follow:

- *Red Light Violation Warning (RLVW)* – An application that broadcasts signal phase and timing (SPaT) and other data to the in-vehicle device, allowing the vehicle to compute warnings for impending red light violations.
- *Stop Sign Violation Warning (SSVW)* – An application that broadcasts the presence and position of a stop sign to the in-vehicle device, allowing the vehicle to determine, and provide alerts and warnings, if the driver is at risk of violating the stop sign.
- *Stop Sign Gap Assist (SSGA)* – An application that utilizes traffic information broadcasting from roadside equipment to warn drivers of potential collisions at two-way stop controlled intersections.
- *Pedestrian in Signalized Crosswalk Warning* – An application that warns drivers when pedestrians, within the crosswalk of a signalized intersection, are in the intended path of the vehicle.
- *Curve Speed Warning (CSW)* – An application that broadcasts precise geometric information and road surface friction to the in-vehicle device, allowing the vehicle to provide alerts and warnings to the driver who is approaching the curve at an unsafe speed.
- *Spot Weather Impact Warning (SWIW)* – An application that warns drivers of local hazardous weather conditions by relaying management center and other weather data to roadside equipment, which then re-broadcasts to nearby vehicles.
- *Reduced Speed/Work Zone Warning (RSZW)* – An application that utilizes roadside equipment to broadcast alerts to drivers warning them to reduce speed, change lanes, or watch for stopped traffic ahead within work zones.

Before discussing each application and the available benefits information, we present the considerations in an overall V2I safety benefits framework. This information is useful in understanding what factors drive the quantification of benefits for V2I safety applications. For the most part, the information presented in this section are from the perspective of an equipped roadside and an equipped vehicle. Of course, the market penetration of equipped vehicles and equipped infrastructure will be low in the early stages of a rollout, as consumers start buying cars equipped with onboard equipment and DSRC communications and DOT's similarly begin to equip the infrastructure. While initial low market penetration may limit the overall safety benefit of any of these applications, factors such as strategic placement of infrastructure deployments based on high expected benefits can maximize cost-effectiveness. In fact, the expected national safety benefits of each application depends on several factors, including the:

- Size of the target crash population, (how many and what type of crashes correspond to the scenarios being targeted by this application?)
- Effectiveness of that application in preventing that type of crash, (what is the probability that the crash will be avoided given an equipped infrastructure and equipped vehicle?)
- Expected market penetration of infrastructure equipment in covering the geographic locations pertinent to targeted crash impacts (crash frequency & severity), and
- Expected market penetration of vehicles equipped with the V2I application that addresses that crash type. This factor may be modified to accommodate varying retrofit or aftermarket

capabilities in vehicles, and the potential impact of advisories provided by a driver-infrastructure interface for non-equipped vehicles.

A simplistic relationship would be one of direct proportionality; see equation 1 for an illustration.

Equation 1. Simplified Estimation of National Safety Benefits

$$\text{National safety benefits (V2I app}^i\text{)(annual crashes avoided)}$$

$$= \# \text{ annual target crashes (V2I app}^i\text{)} \times \text{effectivenesses (V2I app}^i\text{)}$$

- × proportion of target crashe impacts covered by infrastructure RSUs supporting(V2I appⁱ)
- × percentage of vehicle fleet equipped with(V2I appⁱ).

It is important to note that the target crash population for a given V2I application alone does not represent the estimated benefits for the application, but rather a potential benefit. Only applications with 100% effectiveness, and deployed across 100% of the infrastructure and vehicle markets would be able to eliminate all of the crashes (in theory). In reality, crashes are not uniformly distributed across networks. In fact, crashes more frequently occur at intersections with various risk factors, such as poor visibility or sight distance. See Figure 4-1 for an illustration of this. This figure highlights the relationship between cumulative number of signalized intersections and the cumulative target crashes in Minnesota (for Running Red Light crashes). The figure illustrates that by selectively placing roadside equipment at just 10% of the intersections in the network, there is the potential to address up to 30% of the target crashes, while increasing deployments to cover 20% of intersections has the potential to address up to 45% of target crashes. In addition, the geographic distribution of crash severities and associated costs also affects the expected benefits achieved by infrastructure deployments. Agencies will thus need to deploy roadside equipment wisely to maximize the benefit to cost ratio.

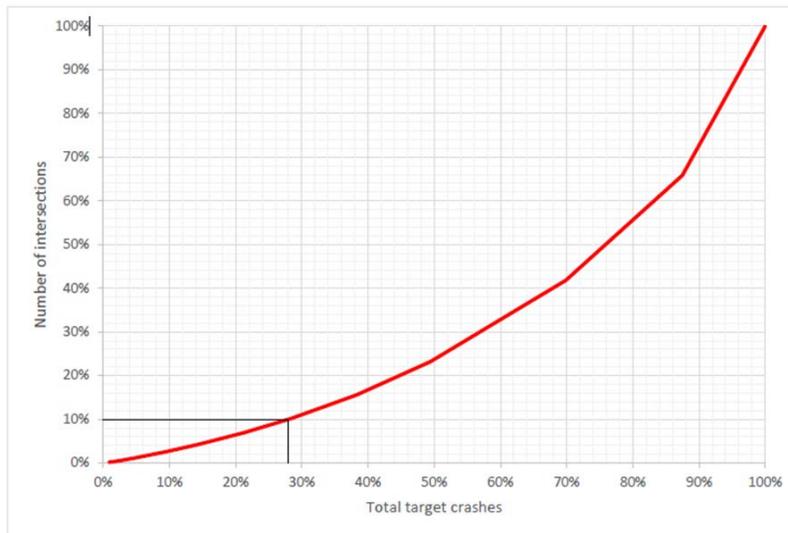


Figure 4-1: Relationship between Cumulative Number of Signalized Intersections and Cumulative Target Crashes in Minnesota (for Running Red Light crashes) (Source: [40])

The remainder of this section describes the V2I applications, focusing on any projects that implemented or prototyped these applications, and discusses evaluation activities and findings related to system performance, user acceptance, and safety impacts.

4.2.1 Traffic Control Device Violation Warning Applications

- *Red Light Violation Warning (RLVW)* application is a cooperative vehicle and infrastructure system that assists drivers in avoiding crashes at signalized intersections by providing a warning to the vehicle driver that, based on their speeds and distance to the intersection, they may violate an upcoming red light. (see Figure 4-2)
- *Stop Sign Violation Warning (SSVW)* application is a cooperative vehicle and infrastructure system that assists drivers in avoiding crashes at stop sign - controlled intersections by providing a warning to the vehicle driver that, based on their speeds and distance to the intersection, they may violate an upcoming stop sign.

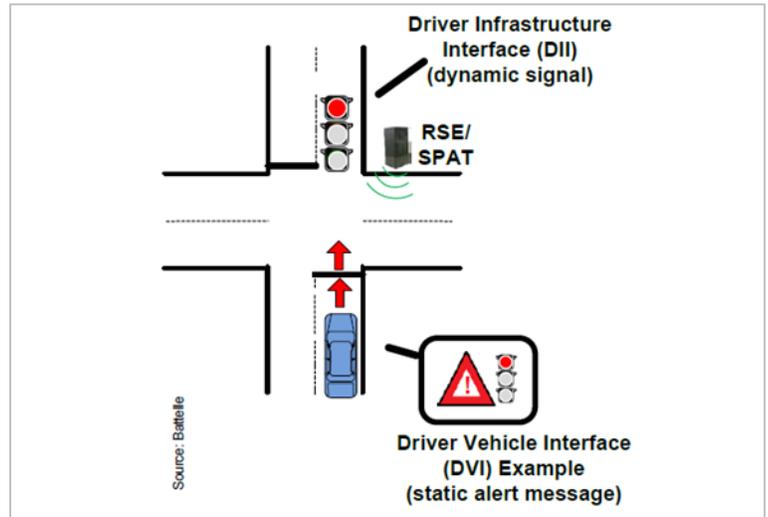


Figure 4-2: Violation Warning Illustration (Source: Battelle)

- *Target annual crashes* [37]
 - running red light – may potentially address up to 235,000 crashes per year
 - running stop signs – may potentially address up to 44,400 crashes per year
- *Associated annual fatalities* [36]
 - running red light – may potentially address up to 1,300 fatalities per year
 - running stop signs – may potentially address up to 1,500 fatalities per year

Testing Summary

Concept of Operation (ConOps) [41], System Requirements Specification (SyRS) [42] and CICAS-V Pilot FOT Report [43] efforts are completed and the related documentation has been published.

As part of CICAS-V, a prototype system was installed in the vehicles of five Original Equipment Manufacturers (OEMs): Daimler, Ford, General Motors, Honda, and Toyota. Intersections were equipped in California, Michigan, and Virginia for both on-road and test-track evaluations. The system was tested with 87 naïve drivers in a Pilot FOT. If a violation is predicted, the driver was warned via a visual/auditory/haptic brake pulse DVI.

Key Findings [47]

Benefits expected: Reduced violation-related crossing path crashes and near misses at signalized or stop-controlled intersections

- System reacted properly in the vast majority of 2168 stop-controlled crossings and 1455 signal controlled intersection crossings recorded during the test.
- Different algorithms were implemented for stop sign and signalized implementations.
- Appropriately warned three drivers who may have inadvertently violated an intersection controlled by a partially obscured stop sign and one driver who might have otherwise violated a red traffic signal.
- The system passed all the objective warning and nuisance tests.
- System performance was very good.
- Issues found with the system during the Pilot FOT were resolved in later releases of the software.

4.2.2 Stop Sign Gap Assist (SSGA)

Stop Sign Gap Assist (SSGA) is a cooperative vehicle and infrastructure system that warns drivers of potential collisions at stop sign intersections by providing approaching cross-traffic information that supports driver decisions in safely traversing stop-sign controlled intersections. The system will support stopped minor-road drivers in identifying unsafe gaps in cross-traffic at major road intersections. The infrastructure application will process available data to post an appropriate advisory message, alert, and/or warning on the driver infrastructure interface (DII) signage when conditions are determined to be unsafe for minor road drivers to proceed into the intersection. An equipped vehicle receives messages from the roadside equipment and will display an appropriate advisory message, alert, and/or warning for the driver on the in-vehicle driver vehicle interface (DVI). (see Figure 4-3)

- *Annual target population*
 - May potentially address up to 279,000 crashes per year [37]
 - May potentially address up to 1,400 annual fatalities [36]

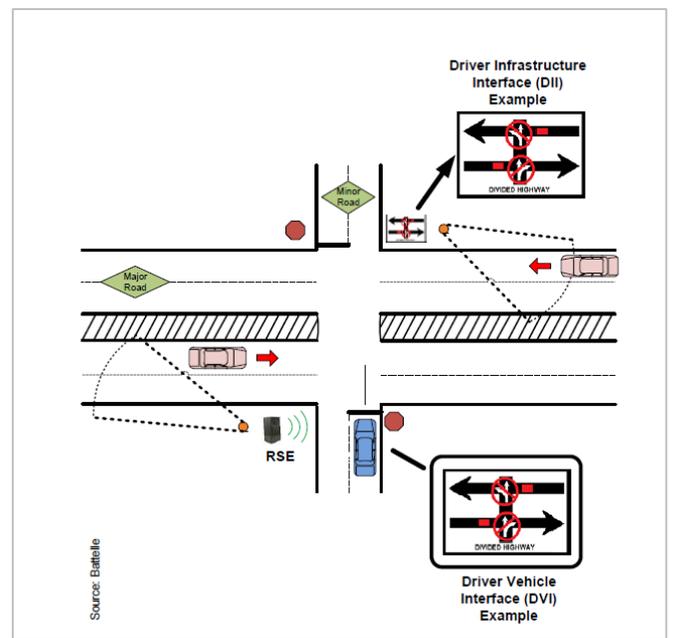


Figure 4-3: Stop Sign Gap Assist Illustration
(Source: Battelle)

Testing Summary

Concept of Operation (ConOps) [41], System Requirements Specification (SyRS) [42] and Prototype Development (PD) [44] efforts are completed and the related documentation has been published.

Simulation laboratory and small-scale deployment tests were implemented as part of the CICAS Stop Sign Assist (SSA) project. The CICAS-SSA project conducted real-world testing of the SSA sign at the intersection of US Highway 52 and Goodhue County Road 9 in Southern Minnesota (summer 2008). Several projects were deployed in Wisconsin and Minnesota (in rural, divided highway environments), using only infrastructure signage, including one in Hennepin County.

Key Findings

- Benefits Expected: Reduced crossing-related crashes and near misses at stop-sign controlled intersections
- US Highway 52/County Rd 9: [44]
 - A majority of 48 participants (and additional 13 truck drivers) used the sign to reduce their risk level at the intersection through rejection of small (risky) gaps.
 - Subjective measures indicated they had a positive opinion of the sign.

The independent evaluation of the Hennepin County, MN, project reported very positive feedback from the general public through a survey process. [45, 46]

- 94.2% were aware of the sign
- 88.5% understood the meaning of the sign
- 79.4% had improved awareness of approaching traffic

4.2.3 Pedestrian in Signalized Crosswalk (PCW) Application

- *Pedestrian in Signalized Crosswalk (PCW)* application is a cooperative V2I system that assists drivers in avoiding crashes involving pedestrians at signalized intersections. The application provides a warning to the vehicle driver when, based on their movement and location of the pedestrian and crosswalk, a potential conflict exists. (see Figure 4-4)
- *Target annual crashes* [37]
 - infrastructure pedestrian detection – may potentially address up to 17,800 crashes per year
- *Associated annual fatalities* [47]
 - pedestrians at intersections – may potentially address up to 950 fatalities per year

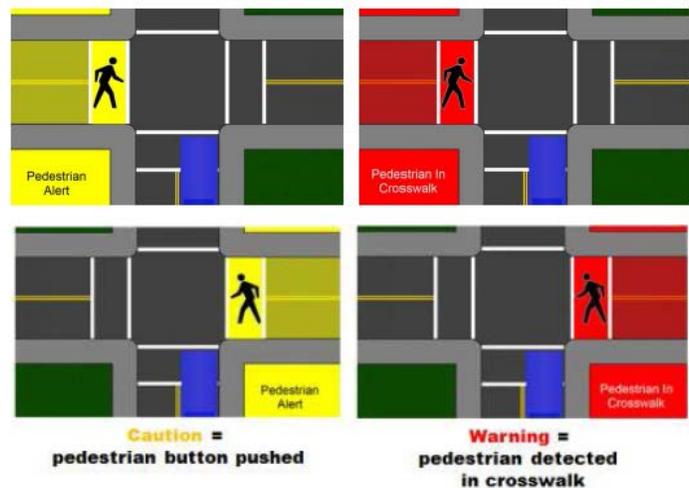


Figure 4-4: Pedestrian in Signalized Crosswalk Illustration
(Source: Battelle)

Testing Summary

Concept of Operation (ConOps) [48], Application Requirements [49] and Architecture and Design Specifications [50] efforts are completed and the Final Report [51] has been published.

- Safety Pilot Model Deployment included a Transit Retrofit Package (TRP)
 - Three University of Michigan buses were equipped with this package, which included Pedestrian in Crosswalk Warning (PCW)
 - 75 drivers drove the equipped transit buses in a naturalistic environment
- Process used allowed for an initial assessment of the model deployment, then an opportunity to fine-tune the system, conceive and implement needed changes to the system, called the Redeployment period, with further evaluation to evaluate the merits of those changes.

Key Findings [52]

The results of the independent evaluation suggest that the TRP safety applications have the potential to improve driver behavior and increase driver and pedestrian safety, but improvements in vehicle location and pedestrian detection accuracy are needed.

- Benefits expected : Reduced crossing-related crashes for pedestrians and vehicle operators/drivers and their passengers
- The performance of the PCW improved based on the modifications made prior to the Redeployment test period.
- Of the PCW alerts where the presence of a pedestrian could be confirmed, 12% were true alerts during the Model Deployment test period and 24% were true alerts during the Redeployment.
- 20% of the PCW alerts during the Model Deployment were issued when the bus went straight through the intersection (did not traverse the equipped crosswalk), but only 9% of PCW alerts from the Redeployment were issued in this scenario.
- The PCW application could be improved by tailoring the timing of the warnings so that they are issued only when the driver is proceeding, or about to proceed, into the equipped crosswalk.

4.2.4 Curve Speed Warning (CSW) Application

- *Curve Speed Warning (CSW)* application is a cooperative vehicle and infrastructure system that assists drivers in avoiding crashes. The application provides a warning to the vehicle driver that the vehicle's current speed may be too high to safely traverse one or more upcoming curves. Alerts are classified by the location of the vehicle within the curve and the vehicle speed at the time of the alert. (see Figure 4-5)
- *Target annual crashes* [37]
 - curve speed warning – may potentially address up to 169,000 crashes per year
- *Associated annual fatalities* [53, 54]
 - Negotiating curve – may potentially address up to ~5,000 fatal crashes per year (estimate based on single vehicle crashes)

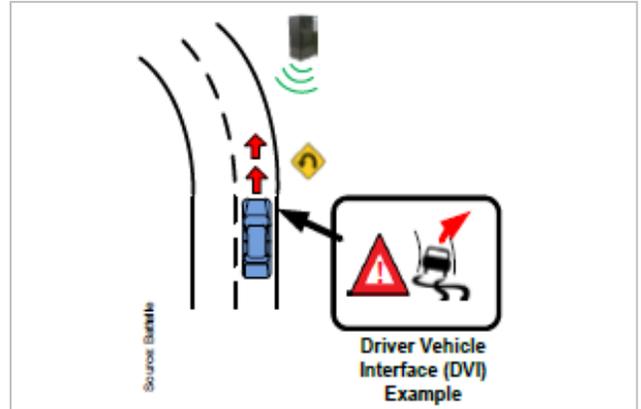


Figure 4-5: Curve Speed Warning Illustration
(Source: Battelle)

Testing Summary

Concept of Operation (ConOps) [48], Application Requirements [49] and Architecture and Design Specifications [50] for transit buses efforts are completed and the Final Report [51] has been published. A broader ConOps [41] and System Requirements [42] are also available.

- Safety Pilot Model Deployment included a Transit Retrofit Package (TRP)
 - Three University of Michigan buses were equipped with this package, which included Curve Speed Warning (CSW)
 - 75 drivers drove the equipped transit buses in a naturalistic environment
- Process used allowed for an initial assessment of the model deployment, then an opportunity to fine-tune the system, conceive and implement needed changes to the system, called the Redeployment period, with further evaluation to evaluate the merits of those changes.

Key Findings [52]

- 57% of the CSW alerts were issued when the TRP bus was either entering or traversing the equipped curve (true alerts)
- Accuracy was sensitive to direction of travel
- Independent Evaluator observed 22 missed CSW alert scenarios during the Model Deployment field test (could be caused by errors in application software or CSW infrastructure functionality)
- Drivers braked within 5 seconds in less than 10% of CSW alerts issued during the Baseline and Model Deployment test periods, but braked within 5 seconds in 60% of CSW alerts during the Redeployment (due only to driver interface improvements)
- Increased deceleration rate within 5 seconds of the alert being issued was observed during the Redeployment (after driver interface was redesigned) as compared to initial Model Deployment and Baseline test periods (see Figure 4-6)
- Drivers traversed the CSW-equipped curve less aggressively during the Redeployment
- Drivers generally found the TRP to be easy to use, giving the CSW the highest rating
- Among the individual TRP applications, the CSW was most desired for its accuracy and usefulness

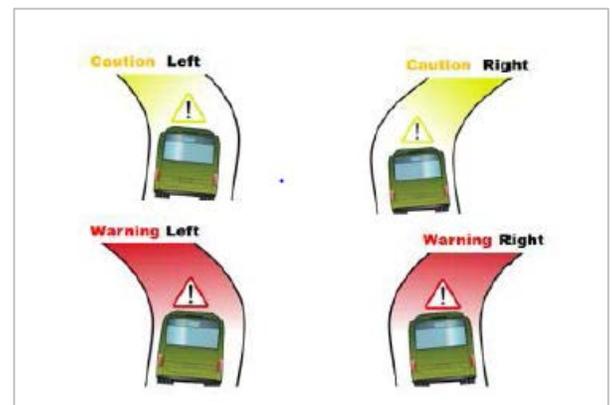


Figure 4-6: CSW Caution and Warning Alerts
(Source: Battelle)

4.2.5 Other V2I Applications

Spot Weather Impact Warning (SWIW)

Spot Weather Impact Warning (SWIW) - An application concept (not yet prototyped) that warns drivers of local hazardous weather conditions by relaying management center and other weather data to roadside equipment, which then re-broadcasts to nearby vehicles (see Figure 4-7). This application aims to reduce crashes and near-misses caused at least in part by locally hazardous weather conditions.

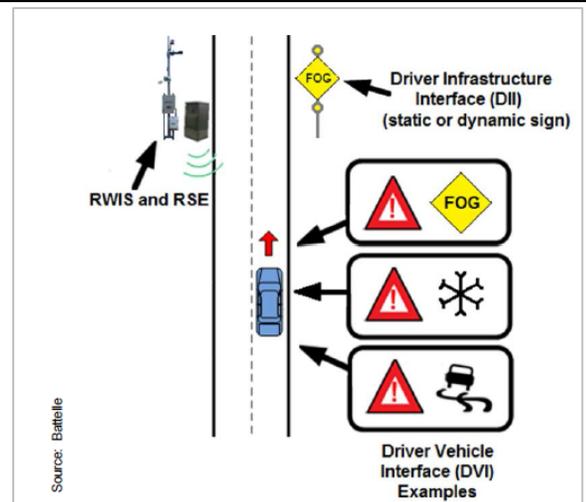


Figure 4-7: Spot Weather Impact Warning Concept of Operations (Source: Battelle)

Reduced Speed/Work Zone Warning (RSZW)

The Reduced Speed/Work Zone Warning (RSZW) is an application concept (not yet prototyped) that utilizes roadside equipment to broadcast alerts to drivers warning them to reduce speed, change lanes, or come to a stop within work zones (see Figure 4-8). This application aims to reduced crashes and near-misses caused at least in part by unsafe speeding or speed variability related to work zone operations or temporary roadway hazards

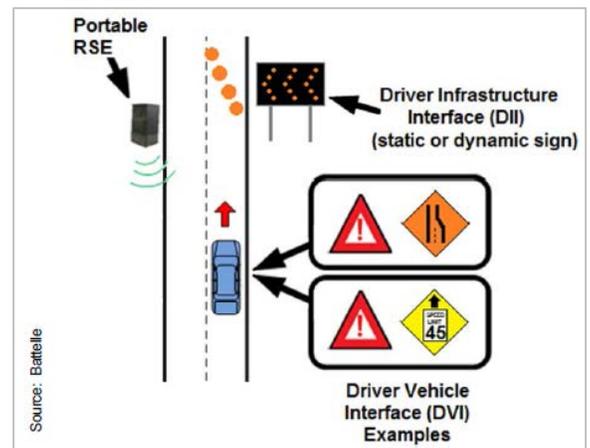


Figure 4-8: Concept of Operations Diagram for Reduced Speed/Work Zone Warning (RSZW) (Source: Battelle)

Other V2I Safety Applications

Other V2I safety applications include Oversize Vehicle Warning (OVW) and Railroad Crossing Violation Warning (RCVW). These applications have developed concepts of operations [55] and system requirements [56], but have not yet been prototyped and tested in an operational environment.

These and other V2I applications may be very specialized or have not yet been prototyped and deployed, but have some commonality with ITS applications for which data are available. In those cases, the ITS benefits data available from the ITS Knowledge Resources <http://www.itskrs.its.dot.gov> can provide a glimpse of the potential benefits of such systems.

5 Road Weather Management (RWM) Program

5.1 Program Overview

The Road Weather Management Program [57], within the FHWA Office of Operations, seeks to better understand the impacts of weather on roadways, and promote strategies and tools to mitigate those impacts. Envisioned is a system that provides "Anytime, Anywhere Road Weather Information" for road users and road operating agencies, as well as a robust, competitive market for road weather services. The FHWA, in close coordination with the ITS JPO, has been leading a program to (1) maximize use of available road weather information and technologies, (2) expand road weather research and development efforts to enhance roadway safety, capacity, and efficiency while minimizing environmental impacts, and (3) promote technology transfer of effective road weather scientific and technological advances. This work is being executed in partnership with the National Oceanic and Atmospheric Administration (NOAA), the American Association of State Highway and Transportation Officials (AASHTO), nonprofit organizations, and the private sector. Program goals are organized into four areas: Stakeholder Coordination; Road Weather Research and Development; Technology Transfer, Training, and Education; and Performance Management and Evaluation.

Adverse weather conditions have a major impact on the safety and operation of our Nation's roads, from signalized arterials to Interstate highways. Weather affects driver behavior, vehicle performance, pavement friction, and roadway infrastructure. Weather events and their impacts on roads can be viewed as predictable, non-recurring incidents that affect safety, mobility and productivity. Weather affects roadway safety through increased crash risk, as well as exposure to weather-related hazards. Weather impacts roadway mobility by increasing travel time delay, reducing traffic volumes and speeds, increasing speed variance (i.e., a measure of speed uniformity), and decreasing roadway capacity (i.e., maximum rate at which vehicles can travel). Weather events influence productivity by disrupting access to road networks, and increasing road operating and maintenance costs.

In more recent years, the USDOT Road Weather Management Program (RWMP) has focused its applied research efforts on the use of connected vehicles to provide traffic operators, maintenance personnel, and the traveling public with enhanced information on weather and road conditions so they can make more informed decisions.

5.2 RWM Applications and Estimated Impacts

Road Weather connected vehicle applications are the next generation of applications and services that assess, forecast, and address the impacts that weather has on roads, vehicles, and travelers. The applications and services are intended to capitalize on the previous *Clarus* Initiative research that has delivered a network of road weather information by integrating existing data sources. Through additional research, technology development, and community outreach, connected vehicle Road Weather Applications research will develop greater specificity regarding the impact that weather has on roadways and promote strategies and tools that mitigate those impacts. Such strategies will build upon decision support tools currently undergoing development, testing, and deployment (such as those developed

under the Road Weather Management Program, e.g., the *Clarus* Regional Demonstrations and the Maintenance Decision Support System (MDSS)).

In close coordination with and cutting across the efforts under the other connected vehicle research programs, the vision for the Road Weather applications research is to broaden 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. Data from connected vehicles has the potential to:

- Fill in the gaps where there was no previous weather or road condition information;
- Provide continuous coverage on all roads at all times;
- Dramatically enhance existing road weather information and management systems;
- Feed into forecast models, greatly enhancing their capabilities in terms of accuracy and relevancy;
- Spur the development of transformative road weather applications; and
- Bring additional capabilities to other connected vehicle safety, mobility, and environmental applications.

Based on research to date, the benefits of using connected vehicle data for road weather management far outweigh the costs. The broad availability of road weather data from an immense fleet of vehicles will vastly improve the ability to detect, forecast, and communicate weather and road conditions. The RWMP is currently conducting research to demonstrate how weather, road conditions, and related vehicle data can be collected, transmitted, processed, and used for safer, more efficient operations.

The RWM Program performed a high-level, benefit-cost analysis (BCA) that evaluated seven road weather connected vehicle applications. One of the primary goals of the RWMP is to reduce the negative safety impacts of crashes that occur under adverse weather conditions. As a result the program evaluated the number of crashes that can potentially be avoided by implementing the applications and the safety benefits that reduced crashes will in turn yield. Safety benefits within the scope of the analysis were: Crashes Avoided, fatalities avoided, injuries avoided, and property damage avoided (includes both infrastructure and vehicle damage). Table 5-1 provides the total number of crashes, fatalities, injuries, and property damage avoided by all of the applications between the years 2012 and 2055.

Table 5-1: Estimated Total Safety Benefits for RWM Program 2012 to 2055

Crashes Avoided	Fatalities Avoided	Injuries Avoided	Property Damage Avoided
6,417,482	28,099	2,601,571	\$ 15,892,985,409

5.2.1 Weather Data Environment (WxDE), Vehicle Data Translator (VDT), & Integrated Modeling

The WxDE, VDT, and Integrated Modeling for Road Weather Condition Prediction are enabling systems that advance connected vehicle applications by enhancing their utilization of road weather data (see Figure 5-1). Each are described below in more detail [58, 59].

- Weather Data Environment (WxDE)** – The WxDE is a research based data system that acquires, validates, stores, and shares transportation-related weather data. The WxDE collects data in near real-time from both fixed environmental sensor stations (ESS) and mobile sources. It then quality checks the observations, and makes the data available either through a map interface, or through queries and subscriptions. Furthermore, The WxDE integrates with the Research Data Exchange (RDE) so that transportation-related weather data can be easily accessed for researchers and application developers.
- Vehicle Data Translator (VDT)** – The VDT 4.1 incorporates many connected vehicle based data elements, including timestamp, latitude, longitude, air temperature, air pressure, speed, brakes, ABS status, traction control event, wiper status, dew point temperature, and surface temperature. It also ingests weather data from the National Weather Service to perform quality tests on all the mobile observations. The output of the VDT are map-based, one mile road segments with corresponding descriptors of road weather hazards.
- Integrated Modeling for Road Weather Condition Prediction** – This system uses connected vehicle data to predict future road conditions. These predictions can then be incorporated into a host of applications for travelers, transportation operators, and maintenance providers. Advanced algorithms in this system use various types of weather, traffic and maintenance data including, archived and real-time data, as well as probabilistic models and forecasts.



Figure 5-1: Road Weather Connected Vehicle Applications
(Source: BAH)

Testing Summary and Status

Transitioned from the Clarus System (see Figure 5-2), the WxDE is fully operational and allows users to incorporate weather data into the development, testing, and demonstration stages of multi-modal transportation mobility applications. The WxDE is available online and to the public, however registration and approval may be required to access some data.

The VDT is also functional, and has recently been updated to version 4.1 giving the system advanced algorithms to create comprehensive hazard datasets. Nevada, Minnesota, and Michigan are initial deployers of the VDT system in their Integrated Mobile Observation (IMO) projects.

The integrated modeling for road weather condition prediction is still in development and will be introduced in an updated version of the Concept of Operations for Road Weather Connected Vehicle Applications.

Key Findings

- Overall the WxDE website is easy to use and understand but not all the functions are readily clear to new users. The biggest area for improvement is the way data sets are presented to the user when queried. Enhancements are being made to the WxDE to make it more user friendly.
- The VDT collects data from multiple sources via multiple methods. Currently, the system incorporates and utilizes vehicle-based data from the original equipment manufacturers' sensors and aftermarket sensors.

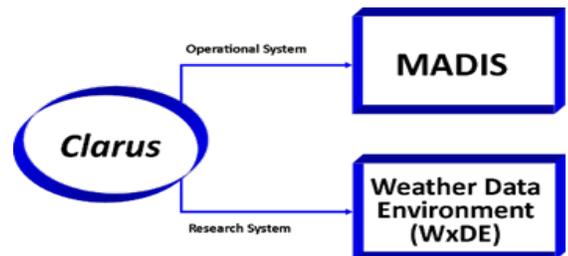


Figure 5-2: Clarus Transition (Source: BAH)

5.2.2 Weather Responsive Traffic Management: Variable Speed Limits (VSL)

VSL system is a Weather-Responsive Traffic Management strategy that adjusts speed limits or restrictions in response to deteriorating weather conditions (see Figure 5-3). Connected vehicle systems enhance the operation of VSL systems and dramatically improve safety during severe weather events. Additional road weather information can be gathered from connected vehicles and used in algorithms to refine the posted speed limits to reflect prevailing weather and road conditions. A VSL application would use data from connected vehicles to determine precipitation types and amounts, visibility, or road surface slickness for segments of the roadway network under VSL control. The data would be combined with other information on prevailing traffic volumes and speeds.



Figure 5-3: Variable Speed Limit Sign over Steven's Pass on US -2 in Washington State
(Source: Washington DOT)

Testing Summary and Status

Oregon DOT [60] has incorporated VSL into their Advanced Traffic Management (ATM) System (see Figure 5-4). ODOT's OR 217 ATM project added variable advisory speed (VAS) signs that change based on current traffic and weather conditions. These signs advise motorists to slow down before reaching a traffic queue, a stall, congestion or other obstructions. The weather responsive VAS system uses data from devices that provide grip factor (relative friction of the road- way), visibility, and roadway surface classification. This VAS system is unique because it is the first fully automated weather responsive system in the country that proactively manages vehicle speed. OR 217 will also have weather systems that will be incorporated into the VAS. This is the first in the country to fully include automated weather and congestion advisories.

Washington State DOT (WSDOT) has installed variable speed limits signs in two passes: US-2 at Stevens Pass and I-90 at Snoqualmie Pass. The Snoqualmie Pass system consists of radar detection, six weather stations, nine variable message signs (VMS), and radio and microwave transmission systems. Speed limits are changed in 10 mph increments. If traction tires are advised, the speed limit is reduced to 55 mph; if traction tires are required, the speed limit is reduced to 45 mph; and if chains are required, the speed limit is reduced to 35 mph. The Steven's Pass system operates using similar concepts.

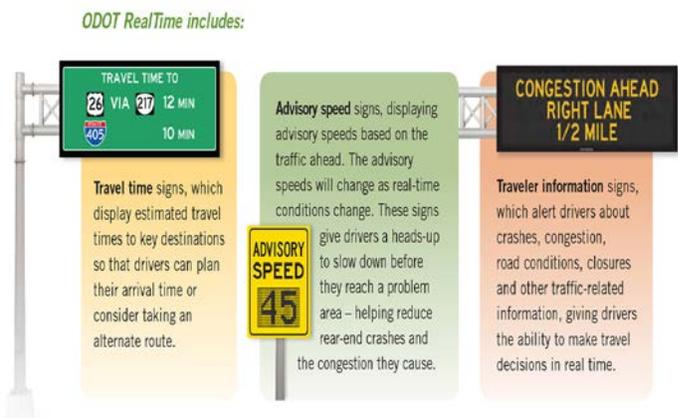


Figure 5-4: ODOT Real Time (Source: ODOT)

Key Findings

- ODOT studies have shown that during winter weather conditions, the number of crash-related incidents was reduced by 25%
- An evaluation of the effectiveness of the Snoqualmie Pass variable speed limit (VSL) system on I-90 in Washington showed that the system reduced average speed by up to 13 percent during unsafe driving conditions

5.2.3 Weather Responsive Traffic Management – Traveler Information via Citizen Reporting

Crowdsourcing is a way to obtain data or information from large groups, usually using the internet or social media outlets. Individuals contribute information on road and weather conditions information, which help TMC operations. Citizen reporting is the most accurate and comprehensive form of crowdsourcing. Citizen reporting differs from other crowdsourcing efforts in that it is developed and controlled by the State DOTs and requires training to use. Citizen reporting programs allow agencies to build the data collection application to suit their needs, funnel the information into pre-existing TI architectures, and train the reporters to ensure a high quality of information.

Testing Summary and Status

Utah DOT's Citizen reporting program [61] uses a smartphone application interface that gives trained citizens the ability to report road conditions to local agencies, which complements information gathered by field crews (see Figure 5-5). The citizen reporting program helps fill information gaps that exist in road condition reports, as well as support more timely and accurate forecasts. The UDOT Citizen Reports App is available for download at general purpose outlets such as Google Play. In 2014, Utah DOT had approximately 550 registered citizen reporters who submitted over 1800 individual reports. Information spot checks are used to help indicate if a particular user repeatedly submits inaccurate reports. Administrators can then eliminate that user's ability to post reports.

Plans already exist for two-way data sharing with other systems including the National Weather Service and Waze. UDOT is considering extending the system's geographic coverage and making it a multi-state project. Also, integrating citizen reporting information into road weather connected vehicle applications is currently being explored and will be introduced in an updated version of the Concept of Operations for Road Weather Connected Vehicle Applications.

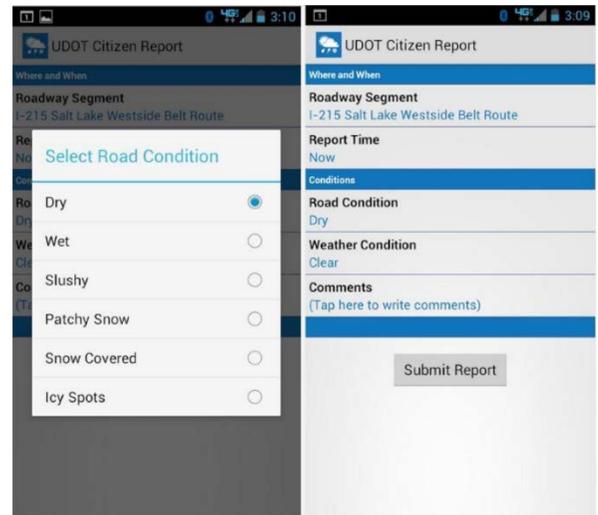


Figure 5-5: Screenshots of UDOT Citizen Report smartphone app (Source: UDOT)

Key Findings

- Most of the trained reporters actively submitted reports
- Reports were submitted for primary, secondary and tertiary road segments
- An average of 8.5 reports were submitted per day on storm days
- Citizen reports were 99+% accurate
- On storm days, the submittal rate with no delay is 76%.
- Interviews with UDOT staff indicated that citizen reports provided increased situational awareness for TOC operators. This can potentially improve safety and mobility on affected roads.
- UDOT survey indicated 35%-50% benefited indirectly from local media for storm information to support their travel decisions; 5%-10% used UDOT traffic forecasts directly. UDOT shares information with the local media.
- As part of two post storm surveys, 83% to 95% of respondents said they were satisfied with UDOT's road weather forecasts and the traffic app/website.
- Two focus group sessions revealed frequent use of the UDOT traffic app during storms, and the citizen reporter program is viewed as useful and providing accurate information
- Data constraints this season did not allow for a complete assessment of specific safety and mobility benefits to UDOT groups outside of Operations; however, these benefits will be evaluated in the near future as more data becomes available.

5.2.4 Enhanced Maintenance Decision Support Systems (EMDSS)

The EMDSS represents the latest innovation in snow control (see Figure 5-6). It incorporates connected vehicle data, processes it through the VDT, and uses the outputs into the road weather forecast and maintenance decision processes. The information may come from either vehicles operated by the general public and commercial entities (including passenger cars and trucks) or specialty vehicles and public fleet vehicles (such as snowplows, maintenance trucks, and other agency pool vehicles). EMDSS also acquires data from fixed Environmental Sensor Station (ESS) sites and National Weather Service. As a result, end users can obtain information along the entire stretch of roadway, and not just at ESS sites. The roadway and connected vehicle data are used to generate improved plans and recommendations to maintenance personnel. This enables maintenance managers to better monitor and react to changing road conditions. They will be better equipped to make spot treatments on the road, improving safety, mobility, and reducing the environmental impact of de-icing chemicals. It allows enhanced ability to assess the nature and magnitude of storms, determine staffing needs, plan road treatment strategies and timing, and activate pre-treatment/post-treatment systems.

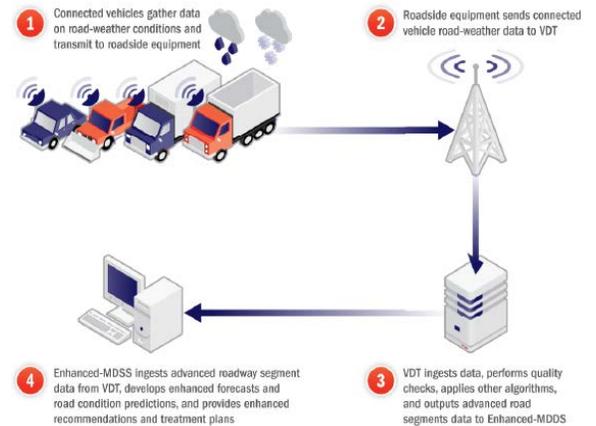


Figure 5-6: EMDSS Data Flow
(Source: Road Weather ConOps)

Testing Summary and Status

EMDSS became operational in Michigan, Nevada and Minnesota over the 2013/2014 winter [62]. The system was tested in these states and observations were made to evaluate the accuracy and usefulness of the system outputs. These observations were shared with the development team to refine and enhance the VDT algorithms. A snapshot of the forecast output from EMDSS is provided in Figure 5-7. The evaluation approach was tailored to each state based on available data and the extent to which the EMDSS application was used by maintenance personnel. Some factors that shaped the evaluation approach for each State are listed below.

- Applications other than EMDSS, that are currently being used by States to augment winter maintenance operations
- The extent to which the EMDSS application was used by maintenance personnel
- The extent to which maintenance operators followed the treatment recommendations of the EMDSS application
- Evaluation of the accuracy of the EMDSS recommendations as compared to actual field maintenance actions

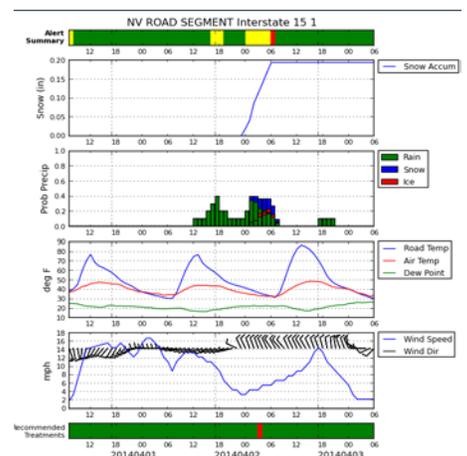


Figure 5-7: EMDSS Forecast Output
(Source: BAH)

Key Findings

These results and findings are based on observation during the 2013/2014 winter season. Several enhancements were made to the VDT algorithms to improve accuracy and forecasts of EMDSS since these observations were made. The EMDSS will be re-evaluated with the improved algorithms.

- Though the application provides forecasts that help maintenance personnel get a fair idea of nature and magnitude of storms, accuracy of these forecasts were not high. Short term forecasts (up to 12 hrs) are accurate but medium to long term (24hrs to 48hrs) forecasts lack accuracy.
- There is potential for the application to help maintenance personnel draft efficient strategies to optimize labor, equipment and chemicals but with current accuracy levels these are hard to achieve.
- The timing of treatment recommendations were not consistent. However it is expected to improve as more vehicles in the traffic stream get equipped with CV technology.

5.2.5 Motorists Advisories and Warnings (MAW)

The MAW is a transformational approach to providing hyper-local, near real-time road weather information to the travelling public. Incorporating (see Figure 5-8) connected vehicle data enabled VDT outputs; the MAW provides current inferences for visibility, road condition, and road precipitation. It also blends the connected vehicle data enabled VDT outputs with a forecast engine to provide 24-hour forecasts of road weather conditions. The information may come from either vehicles operated by the general public and commercial entities (including passenger cars and trucks) or specialty vehicles and public fleet vehicles (such as snowplows, maintenance trucks, and other agency pool vehicles). The raw data is processed in a controlling center to generate road segment-based data outputs. The processing also includes a road weather motorist alerts algorithm to generate short time horizon alerts that are pushed to user systems. In addition the information collected can be combined with observations and forecasts from other sources to provide medium (next 2-12 hours) or long term (more than 12 hours) advisories through a variety of interfaces including web based and connected vehicle based interfaces. Using the MAW, drivers will be able to plan routes in advance of their travel, including knowing which way to go and whether to delay travel, based on route-specific road weather conditions. While on the road, a phone application keeps drivers abreast of changing road weather conditions. The phone application provides short term warnings or advisories to individual motorists.

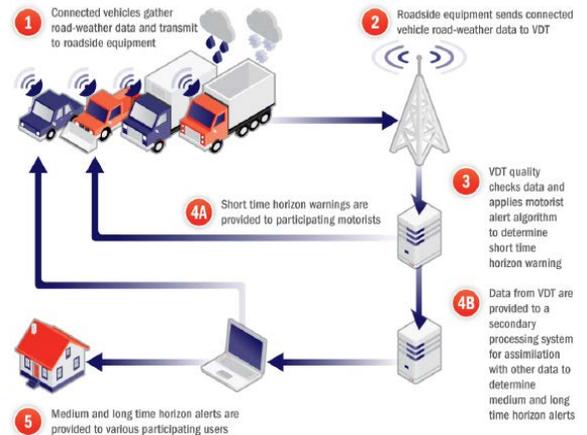


Figure 5-8: MAW Data Flow
(Source: Road Weather ConOps)

Testing Summary and Status

MAW became operational in Michigan, Nevada and Minnesota during the winter of 2013/2014 [62]. The application was not available to the public and the phone application was only available in Android devices. Since State DOT employees were provided iPhones the phone application was not tested in Michigan and Nevada. Only the desktop version of the MAW application was tested in Michigan and Nevada while both were tested in Minnesota. The output from the MAW was used as input into Michigan DOT traveler information systems. These findings were shared with the development team to refine and enhance the VDT algorithms. A snapshot of the advisories from the MAW is provided in Figure 5-9.

The evaluation approach was tailored to each state based on available data and the extent to which the MAW application was used by maintenance personnel. Some factors that shaped the evaluation approach for each State are listed below.

- Applications other than MAW currently being used by States to augment road weather traveler information
- How familiar are the maintenance personnel with the application?
- The extent to which the MAW phone application was used by maintenance personnel

Key Findings

These results and findings are based on observation during the 2013/2014 winter season. Several enhancements were made to the VDT algorithms to improve accuracy of MAW advisories. The MAW will be re-evaluated later with the improved algorithms.

- The MAW does provide advisories and warnings with greater temporal and geographic resolution than currently available.
- The MAW phone application does provide short term alerts and advisories and the timing of these warnings were fairly accurate.

The desktop MAW application provides medium and long term (up to 24 hrs) advisories and warnings. Maintenance personnel believe that these alerts have the potential to keep motorists away from roadways when adverse road conditions are accurately forecasted.

Back	MN-53 and 135 - Midway
Weds 11/27 12:00 pm	Clear
Weds 11/27 1:00 pm	Advisory: Precip: moderate snow, Pavement: wet, Visibility: normal
Weds 11/27 2:00 pm	Advisory: Precip: moderate snow, Pavement: wet, Visibility: normal
Weds 11/27 3:00 pm	Advisory: Precip: moderate snow, Pavement: wet, Visibility: normal
Weds 11/27 4:00 pm	Advisory: Precip: moderate snow, Pavement: wet, Visibility: normal
Weds 11/27 5:00 pm	Advisory: Precip: moderate snow, Pavement: wet, Visibility: normal
Weds 11/27 6:00 pm	Advisory: Precip: moderate snow, Pavement: wet, Visibility: normal
Weds 11/27 7:00 pm	Advisory: Precip: moderate snow, Pavement: wet, Visibility: normal
Weds 11/27 8:00 pm	Warning: Precip: moderate snow, Pavement: slick, icy, Visibility: normal
Weds 11/27 9:00 pm	Warning: Precip: moderate snow, Pavement: slick, icy, Visibility: normal
Weds 11/27 10:00 pm	Advisory: Precip: moderate snow, Pavement: slick, snowy, Visibility: normal
Weds 11/27 11:00 pm	Advisory: Precip: moderate snow, Pavement: slick, snowy, Visibility: normal

Figure 5-9: MAW Advisories (Source: BAH)

6 The Role of Dedicated Short Range Communications (DSRC)

As described in the Intelligent Transportation System (ITS) Strategic Research Plan, 2010-2014 [64], the Department is committing to the use of DSRC technologies for active safety for both V2V and V2I applications. While appropriate use of DSRC was encouraged, DSRC was not required in the development of mobility and environmental applications. That said, several application developers have elected to use DSRC as one of the application community technologies in mobility and environmental applications. For example, 7 out of 16 prototyped mobility applications use DSRC due to latency requirements and other DSRC attributes. This section summarizes the role of DSRC in mobility, V2I safety, and environmental applications, test results (where available) regarding DSRC utilization, and the potential benefits of using DSRC in these applications.

6.1 Mobility Applications

The Dallas-Fort Worth (DFW) FRATIS prototype developer used DSRC technology to calculate terminal wait time and compared to the usage of Bluetooth technology for DR-OPT application. A 30-day DSRC pilot demonstration was conducted in January 2014 and concluded that the BSM provides sufficient information needed to calculate wait time. The demonstration also indicated that the reliability of the equipment seems comparable to Bluetooth/Wi-Fi system. However, due to the limitation of only 5 trucks being equipped with DSRC, the use of DSRC to calculate wait time is not yet as accurate as other methods. The team recommended more exploration of the application of DSRC to freight transportation, such as the possibility of using DSRC to track the location of freight trucks in the distribution center and port terminal domains.

The INFLO prototype developer used DSRC technology to broadcast both BSM Part I and Part II data for the SPD-HARM and Q-WARN applications. The team developed an integrated DSRC and cellular communication system that seamlessly sends and receives connected vehicle messages via DSRC when it is available or via cellular communication when not. The demonstration proved the functionality of connected vehicle data capture and dissemination using both cellular communications and DSRC communications. With the potential for implementing connected vehicle applications on personal mobile devices as well as in vehicles, the team further recommended integrating cellular and DSRC connected vehicle data communications and developing a nomadic personal mobile device with integrated DSRC radio.

The MMITSS team used DSRC technology in prototyping the I-SIG, TSP and FSP applications. The team found that nomadic devices are most likely not suitable for I-SIG due to the volume of traffic and the latency in cellular communications as potential limiting factors. DSRC is used for sending BSM, MAP and SPaT data at an intersection. The team developed algorithms to solve the lack of mode information in BSM and to determine which MAP and SPaT are relevant when messages are received from multiple nearby RSU's broadcasting [65].

DSRC messages are exchanged between the oncoming and responder vehicles for the INC-ZONE application to communicate the existence of an incident zone to the oncoming vehicles and to send threat messages from the oncoming vehicle to the responder vehicle. The team also developed and

integrated DSRC, cellular, and Bluetooth communications in both oncoming vehicle and responder vehicle systems using smart phones and DSRC radios for comprehensive communications and efficient installation and operation. It is recognized that the full functionality of this DSRC-enabled system will not be realized without considerable market penetration of DSRC-enabled vehicles.

6.2 Environmental Applications

AERIS applications were designed to work in a connected vehicle environment where vehicles and infrastructure communicate among themselves and with each other to transmit information that can be used for various purposes. DSRC along with other wireless communication means, such as cellular communications, facilitate the transmission of data. For the most part, AERIS ConOps documents were written to be communications agnostic – allowing in many cases for DSRC or other wireless communications to be used to support the applications. For these applications the onboard equipment (OBE) in the vehicles is configured to transmit information, such as vehicle speed and location, to the OBEs of other vehicles or the roadside equipment (RSE) located in fixed locations along the roadway. The RSEs can in turn return information to the vehicles, such as Signal Phase and Timing (SPaT) and MAP information, as well as other dynamic system attributes. This exchange of information opens a large number of opportunities to derive a variety of benefits, such as reduction of vehicle collisions and reduction of travel times and delays as well as a reduction in fuel consumption and emissions.

The Eco-Signal Operations Operational Scenario considers interactions between vehicles and infrastructure (e.g., traffic signals) that are likely to leverage DSRC. Field testing of the Eco-Approach and Departure at Signalized Intersections application used DSRC for communicating SPaT and MAP messages to vehicles as they approached a signalized intersection. By receiving these messages at 10 Hz, it allowed the vehicles to determine the most eco-friendly approach to the intersection. Using DSRC to send BSMs to infrastructure is also likely to support Eco-Signal Timing applications. Finally, DSRC is also a good means for communicating traffic signal priority messages to infrastructure that need to make decisions whether to grant signal priority to approaching vehicles including transit vehicles and freight vehicles.

Modeling of the Eco-Lanes Operational Scenario considered two applications—Eco-Cooperative Adaptive Cruise Control (ECACC) and Eco-Speed Harmonization. For ECACC, low latency communications such as DSRC is critical. Vehicles need to communicate accurate information about their location, speed, acceleration, etc. These messages need to be transmitted frequently to ensure safety, especially for vehicles traveling in loose or tightly-spaced platoons. Similar to the mobility speed harmonization application, Eco-Speed Harmonization could use integrated DSRC and cellular communication system that seamlessly sends and receives connected vehicle messages via DSRC when it is available or via cellular communication if not. For this application, DSRC messages including speed recommendations could be sent from RSUs to vehicle OBEs.

While it could be leveraged, the requirement for high speed, low latency communications is not critical for applications included in the Low Emissions Zones and Eco-Traveler Information Operational. For many of these applications higher latency communications such as cellular communication are viable options. However, there is great potential to send messages from RSUs directly to OBEs to support traveler information messages. In a connected vehicle environment, in-vehicles messages have the potential to replace messages disseminated by transportation agencies using dynamic messages signs (DMSs). Sending messages directly to OBEs may be more a more effective dissemination tool than using more traditional ITS devices like highway advisory radios, 511, and DMSs. Additionally, DSRC may also support integrated payment for tolls and parking.

6.3 V2I Safety Applications

Many of the V2I Safety Applications rely upon real-time dynamic information from the infrastructure in order to enable crash-imminent alerts and warnings to the driver. The low latency afforded by 5.9 GHz DSRC enables dynamic information such as real-time signal phase information to be transmitted to vehicles in time to warn drivers to exercise a hard braking maneuver (RLVW). Similarly, applications which require real-time sensing at the field location to enable crash-imminent warnings (SSGA, PCW) are expected to require DSRC. In other cases, provision of the infrastructure-based information may occur ahead of time (e.g., Stop Bar information for SSVW, area weather conditions for SWIW) and may not require extremely low-latency communication, although timeliness remains important. Finally, there are potential variations in the application concept implementation that could affect the need for DSRC. For example, CSW that includes real-time surface condition information, or RSZW with moving work zones, could require DSRC.

6.4 Road Weather Related Applications

Significant effort has been and continues to be expended in the FHWA Road Weather Management Program and in various federal and state connected vehicle programs to identify opportunities to acquire data from vehicles acting as mobile sensor platforms. Federal, state and local transportation agencies have also been working with automakers and communications technology providers to develop and standardize information exchange between vehicles and the transportation infrastructure, enabling a variety of applications that could improve transportation safety, mobility and environmental performance. Accurate, timely and route-specific weather information allows traffic and maintenance managers to better operate and maintain roads under adverse conditions. DSRC enables collection of vehicle-based probe and observation data from mobile sensors on transportation agency vehicles and transmission of the data over to roadside units from where it can be accessed by agency systems. In this way, information from mobile platforms will eventually enable traffic managers and maintenance personnel to implement operational strategies that optimize the performance of the transportation system by mitigating the effects of weather on the roadways.

Though most road weather applications are not affected by higher latency of data transmission, the system should be capable of obtaining vehicle data from SAE J1939 and J1979 diagnostic buses and various peripheral devices on maintenance vehicles. Transmitting this data from 5.9 GHz DSRC on-board equipment (OBE) to compliant roadside units (RSU); and providing the data on the roadside equipment to agency systems when requested makes the applications more reliable and robust. Currently many applications use cellular communications to transmit and receive vehicular and infrastructure data but more state DOTs are looking for a hybrid solution that also involves DSRC communications [63].

As part of the IMO 3.0 project, Minnesota, Michigan and Nevada are in the process of developing, installing and operating a hybrid communication method which includes using 5.9 GHz DSRC on a test corridor in the next year. This will include using DSRC roadside and in-vehicle units to integrate information collected using this system with data collected using current cellular wireless data transmission. Each unit operating on this corridor will be capable of using both communication methods. Furthermore in Minnesota alone each DSRC roadside unit will be directly connected to a fiber optic communications network to provide efficient backhaul of information and serve as a model for future connected vehicle demonstration projects.

7 Conclusions

Looking across the connected vehicle application development efforts, there is a clear demonstrated potential for significant safety, mobility and environmental impacts. These impacts do not accrue uniformly for every application, nor under all conditions. Some key insights include:

Combinations of V2I connected vehicle applications are effective in signalized networks, particularly in prioritizing signal timing and reducing overall delay and fuel consumption.

- In a field test in Anthem (AZ) four signal control applications deployed in coordination (I-SIG, FSP, and the combination of TSP and FSP) reduced vehicle travel time 6-27%.
- A simulation study of three Eco-Signal Operations applications deployed in coordination (Eco-Approach and Departure, Eco-Signal Timing, and Eco-Signal Priority) resulted in a 11% reduction in CO2 emissions and fuel consumption.
- Red Light Violation Warning (RLVW) and Pedestrian in Signalized Crosswalk Warning (PCW) together have the potential to address more than 250,000 crashes and 2,000 fatalities each year.

V2I connected vehicle applications add a potentially new capability to flow management in congested freeway segments, particularly in the mitigation of potentially unsafe speed differentials in advance of bottleneck locations, reducing fuel consumption, or in the reduction of delay generated by major incidents.

- Modeling of speed harmonization applications tailored for either mobility or environmental objectives returned similar findings: more consistent vehicle speeds through bottleneck sections and when optimized for environmental impacts, emissions reduction of 4.5%.
- Average network-wide delay was reduced by up to 14% when the INC-ZONE incident scene management application in a simulation of a major incident response. Similarly, the RESP-STG application can potentially reduce the emergency vehicles' travel time by up to 23% and their number of stops by up to 15%.
- The Curve Speed Warning (CSW) application has the potential to address more than 169,000 crashes and 5,000 fatal crashes per year.
- An evaluation of the effectiveness of the Snoqualmie Pass variable speed limit (VSL) system on I-90 in Washington showed that the system reduced average speed by up to 13% during unsafe driving conditions.

Applications leveraging mobile device technologies can successfully infer travel mode and user activity, and can help better coordinate real-time demand management and reliable transit service provision.

- Two field tests in Minnesota and Massachusetts demonstrated accurate inference of travel mode and user activity without user confirmation.
- The T-CONNECT application demonstration in Columbus demonstrated how transit system user reliability can be improved using mobile phones to assist in securing connections among differing bus fleet operations.
- A modeling study of the Low Emissions Zone application resulted in a 20% reduction in VMT.
- The study concluded that identifying the pedestrian location in the crosswalk is critical to the success of the Pedestrian in Signalized Crosswalk application.
- 83% to 95% of respondents said they were satisfied with UDOT's road weather forecasts and the traffic app/website.

Table 7-1 shows the highlights of estimated impacts, gleaned through limited field testing, simulation/analytical studies, or a combination of both. The magnitude of benefits of many applications are highly dependent on the level of technology deployment at the roadside, in vehicles, or within mobile devices. However, applications targeting fleet vehicles (e.g., transit, truck and public safety vehicles) may be early winners – as well as applications that serve to prioritize or facilitate facility access. Some particular combinations of applications can be particularly effective, leveraging common deployment technologies.

The comprehensive role of 5.9 GHz DSRC in V2I connected vehicle applications is still emerging. Within the V2I Safety program, DSRC use is a central tenet of the effort and DSRC is featured in all application concepts. However, application prototypes in this program are still in development and impacts have not yet been estimated. In the other three programs, DSRC is an optional technology to be applied where it is found to be advantageous. In the DMA program 7 of 16 applications successfully utilized DSRC technologies, primarily in and around signalized intersections and incident locations. In the AERIS program, potential opportunities for DSRC have been identified in the concept development efforts for several applications, but have not been directly applied. In the case of the Road Weather Program, a key project is in the process of developing, installing and operating a hybrid communication method which includes using DSRC in a test corridor in the next year.

Table 7-1: Estimated Impacts of Connected Vehicle Applications in Four V2I Research Programs

Impact Area	Estimated Impacts	Relevant Applications ⁵	Program
Safety	Crash population targeted by V2I safety applications at intersections includes up to 575,000 crashes (involving more than 5,100 fatalities) annually ⁶	PCW, RLWW, SSGA, SSVW	V2I Safety
Safety	Crash population targeted by V2I safety applications at curves includes up to 169,000 crashes (including 5,000 fatal crashes) annually ⁶	CSW	V2I Safety
Safety	Reduction of crashes by up to 25% during winter weather due to weather traffic management applications on freeways ⁷	WRM-VSL	RWM
Safety	Reduction in speed variations between freeway segments by 18%-58% and within freeway segments by 10%-47%, resulting in fewer rear-end crashes ⁸	SPD-HARM	DMA
Safety	Fewer instances of hard braking and up to 89% reduction in maximum deceleration in incident zones ⁷	INC-ZONE	DMA
Mobility	Reduction in travel time on arterial corridors by 6% to 27% when combined multimodal traffic signal system is implemented ⁷	I-SIG, FSP, TSP	DMA
Mobility	Reduction in travel time for transit vehicles by up to 10% with priority ⁷	TSP	DMA
Mobility	Reduction in travel time by up to 23% and number of stops by up to 15% for emergency vehicles ⁷	INC-ZONE	DMA
Mobility	Reduction in average network-wide delay of up to 14% due to alerts to incident zone workers ⁷	INC-ZONE	DMA
Mobility	Annual travel time reductions of 246,000-740,000 hours when an integrated corridor management decision support system with eco-capabilities is implemented ⁸	Eco-ICM	AERIS
Mobility	Reduction in travel time on freeways by 33% to 42% when cooperative adaptive cruise control, and speed harmonization are optimized for the environment ⁸	Eco-Lanes	AERIS
Environmental	Fuel savings of 2%-22% when signal operations and freeway lane management are optimized for the environment ⁸	Eco-Lanes, Eco-Signal Operations	AERIS
Environmental	Annual fuel savings of 323,000-981,000 gallons when an integrated corridor management decision support system with eco-capabilities is implemented ⁸	Eco-ICM	AERIS
Environmental	Annual mobile emissions savings of 3,100-9,400 tons when an integrated corridor management decision support system with eco-capabilities is implemented ⁸	Eco-ICM	AERIS

⁵ CSW: Curve Speed Warning; ECO-ICM: Eco-Integrated Corridor Management; FSP: Freight Signal Priority; INC-ZONE: Incident Scene Work Zone Alerts for Drivers and Workers; I-SIG: Intelligent Traffic Signal System; ; PCW: Pedestrian in Signalized Crosswalk; RLWW: Red Light Violation Warning; SPD-HARM: Dynamic Speed Harmonization; SSGA: Stop Sign Gap Assist; SSVW: Stop Sign Violation Warning; TSP: Transit Signal Priority; WRTM-VSL: Weather Responsive Traffic Management - Variable Speed Limits

⁶ Precursor safety analysis finding

⁷ Results based on field testing

⁸ Result based on simulation/analytical study

APPENDIX A. List of Acronyms

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
ACC	Adaptive Cruise Control
AERIS	Applications for the Environment: Real-Time Information Synthesis
AFV	Alternative Fuel Vehicle
AMS	Analysis, Modeling, and Simulation
ATIS	Advanced Traveler Information Systems
BAA	Broad Agency Announcement
BSM	Basic Safety Message
CABS	Campus Area Bus System
CACC	Cooperative Adaptive Cruise Control
CAMP	Crash Avoidance Metrics Partnership
CICAS	Cooperative Intersection Collision Avoidance Systems
CICAS-SSA	Cooperative Intersection Collision Avoidance Systems—Stop Sign Gap Assist
CO ₂	Carbon Dioxide
CONOPS	Concept of Operations
COTA	Central Ohio Transit Agency
CSW	Curve Speed Warning
D/R	Demand-Response
DFW	Dallas Fort Worth
DII	Driver Infrastructure Interface
DMA	Dynamic Mobility Applications
DOT	Department of Transportation
D-RIDE	Dynamic Ridesharing
DR-OPT	Drayage Optimization
DSRC	Dedicated Short Range Communications
DSS	Decision Support System
DVI	Driver-Vehicle Interface
ECACC	Eco-Cooperative Adaptive Cruise Control
EPA	Environmental Protection Agency
EVAC	Emergency Communications and Evacuation
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FOT	Field Operational Test
FRA	Federal Rail Administration
FRATIS	Freight Advanced Traveler Information Systems
FSP	Freight Signal Priority

Acronym	Definition
FTA	Federal Transit Administration
GHG	Greenhouse Gas
GPS	Global Positioning System
ICM	Integrated Corridor Management
IDTO	Integrated Dynamic Transit Operations
INC-ZONE	Incident Scene Work Zone Alerts for Drivers and Workers
INFLO	Intelligent Network Flow Optimization
I-SIG	Intelligent Traffic Signal System
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
MIT	Massachusetts Institute of Technology
MMITSS	Multimodal Intelligent Traffic Signal System
MOVES	Motor Vehicle Emission Simulator
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
OBE	On-Board Equipment
OBU	Onboard Unit
OSU	Ohio State University
OVW	Oversize Vehicle Warning
PCW	Pedestrian Signalized Crosswalk
PED-SIG	Mobile Accessible Pedestrian Signal System
POC	Proof of Concept
Q-WARN	Queue Warning
R.E.S.C.U.M.E	Response, Emergency Staging and Communications, Uniform Management, and Evacuation
RCVW	Railroad Crossing Violation Warning
RESP-STG	Incident Scene Pre-Arrival Staging and Guidance for Emergency Responders
RLVW	Red Light Violation Warning
RSE	Roadside Equipment
RSU	Roadside Unit
RSZW	Reduced Speed Zone Warning
RWM	Road Weather Management
SPD-HARM	Dynamic Speed Harmonization
SRI	Smart Roadside Initiative
SSA	Stop Sign Assist
SSGA	Stop Sign Gap Assist
SSVW	Stop Sign Violation Warning
SWIW	Spot Weather Information Warning

Acronym	Definition
T-CONNECT	Connection Protection
T-DISP	Dynamic Transit Operations
TFHRC	Turner Fairbank Highway Research Center
TRP	Transit Retrofit Package
TSP	Transit Signal Priority
USDOT	U.S. Department of Transportation
V2G	Vehicle-to-Grid
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VII	Vehicle Infrastructure Integration
WSDOT	Washington State Department of Transportation
X2D	Vehicle or Infrastructure-to-Device

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