Connected Vehicle Vehicle-to-Infrastructure Support of Active Traffic Management

Final Report

Contract BDV29-977-41

Prepared for

Florida Department of Transportation

By

Florida International University

Lehman Center for Transportation Research

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DISCLAIMER

METRIC CONVERSION CHART

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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Connected vehicle (CV) technologies promise transformative changes in Active Traffic Management (ATM) of freeways and arterials and have the potential to support Integrated Corridor Management (ICM). The goal of this project was to provide information to support the Florida Department of Transportation (FDOT) and other transportation agencies in their decisions to implement CV-based applications to improve mobility and safety of system performance on urban arterials. This report provides a review of the needed ATM functions for urban arterials, the existing and CV-based applications that can support the provision of the required functions, the experience with the applications, and an estimation of the impacts of the applications on mobility and safety. A methodology is then developed for the selection between CV-based applications and other applications, based on stochastic return on investment analysis and multi-criteria decision analysis (MCDA). This report also demonstrates the application of the developed method for the pre-deployment assessment of system impacts and the selection between alternatives for a project case study and the use of microscopic simulation modeling to assess CV-based applications. Finally, the report identifies the steps needed for planning post-deployment evaluation of CV-based applications to inform future evaluation efforts.</td></tr>
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EXECUTIVE SUMMARY

E1. BACKGROUND

Connected vehicle (CV) technologies promise transformative changes in Active Traffic Management (ATM). The United States Department of Transportation's (USDOT) Dynamic Mobility Applications (DMA) Program identified high-priority DMA applications that utilize Vehicle-to-Infrastructure (V2I) technologies. Many of these applications are directly related to ATM. ATM strategies have been shown to provide significant benefits for both freeways and arterials (Yelchuru et al., 2017b). There is a recognition that the emergence of CV V2I technologies and their use to support ATM will result in significant positive impacts beyond what can be achieved with current technologies (Yelchuru et al., 2017b). V2I will support existing applications and will also allow new applications that are not possible with existing technologies.

The Transportation System Management and Operations (TSM&O) program and the Statewide Arterial Management Program (STAMP) of the Florida Department of Transportation (FDOT) have recognized that ATM strategies are vital to addressing safety, mobility, and reliability elements in the transportation system. FDOT has utilized a systems engineering approach for the deployment of Intelligent Transportation System (ITS) technologies to support the TSM&O program. FDOT's 2017 TSM&O Strategic Plan identified CV as one of the six primary focus areas. Also, the FDOT Districts are interested in exploring the use of CV to support TSM&O to monitor and improve the performance of the systems managed and operated by FDOT or local partner agencies. In the short term, it is expected that CV-based technologies will complement the existing ITS infrastructure elements. However, in the medium to long term, depending on the specific application and CV market penetration, CV-based technologies may replace some components of the existing ITS solutions. Thus, the CV-based technologies may be a:

- **Complementary solution** – CV technologies may not provide equivalent functionality but can enhance existing solutions.
- **Supplementary solution –** CV technologies can enhance and partially replace existing solutions.
- **Alternative solution -** CV technologies can enhance and fully replace existing solutions.

E2. GOALS AND OBJECTIVES

The goal of this project was to support the FDOT and other transportation agencies in their decisions to implement V2I-based ATM strategies to improve mobility and safety performance on urban arterials. The specific objectives of this project were:

- Identify CV applications that can be used to meet the needs and objectives of arterial ATM in Florida,
- Identify methods that can be used to select between CV applications and traditional applications as part of the systems engineering process associated with ATM deployment,
- Identify the steps needed for post-deployment evaluation and performance measurements of CV applications to support arterial ATM, and

- Identify various technical and institutional considerations in the planning, design, and deployment of the identified CV applications.

E3. CV APPLICATIONS TO SUPPORT URBAN ARTERIALS ATM

This project started with a review of documents of related initiatives and deployments to inform the project activities in planning ATM on urban arterials. The review included the systems engineering process, planning for operations, related service packages of the ITS architecture, the 2017 FDOT TSM&O Strategic Plan, the 2018 FDOT STAMP Action Plan, and the 2019 FDOT Connected and Automated Vehicles (CAV) Business Plan. The project then identifies existing ATM applications and CV-based applications that can be used to support the goals and objectives of the FDOT TSM&O program on urban arterials. The review was based on the services and applications identified in the national ITS architecture, United States Department of Transportation (USDOT) CV Dynamic Mobility Applications (DMA) program, USDOT Safety Applications program, the Federal Highway Administration (FHWA) Active Transportation and Demand Management (ATDM) program, the three CV pilots currently funded by the USDOT (the New York City, New York; Wyoming; and Tampa, Florida), and existing and planned deployments by FDOT around Florida. The existing and emerging CV-based applications were then mapped to the goals and objectives of the FDOT TSM&O program and were related to typical functions required to address needs associated with arterial operations. Existing methods to select between deployment alternatives were then reviewed and recommendations were given related to the development of a method to support the investment in CV-based deployment to support TSM&O on urban arterials, based on this review.

E4. EXISTING AND CV-BASED SOLUTIONS TO PROVIDE THE REQUIRED FUNCTIONS

A summary of the identified required functions to support urban arterial management and operations and the existing and CV-based solutions that can provide these functions are shown in Table E-1. The estimates of the mobility and safety modification factors for the identified solutions are provided in Table E-2. Since CV-based solutions are still in the early stages of development and deployment, limited information was available about their impacts. It should be noted that the values in Table E-2 were estimated for the purpose of use in the return on investment analysis based on a limited amount of data, particularly for CV-based applications. The identification involved a high level of judgement and was based on imperfect information. Thus, these values should be carefully reviewed. The use of these values in the benefit-cost analysis should involve conducting sensitivity analysis or risk analysis, as described later in this document.

Table E-1 Existing Solutions and CV-Based Solutions to Provide the Required Arterial ATM Functions

Function	Existing Solutions	CV-Based Solutions
Data Collection to Support System Management		
Data Collection to Support Performance Measurements	Point detectors for volume measurements and AVI (e.g., Bluetooth or Wi-Fi readers) or third-party vendor data for travel time and partial O-D estimation.	CV as probes can be used to estimate travel time. Other potential measures, depending on data availability from vehicles, can include vehicle classification, acceleration/deceleration, number of stops, number of brakes, potential for crashes, emission, fuel consumption, and weather and lighting conditions.
Automatic Incident Detection	Based on point detectors or travel time measurements based on AVI or private-sector data.	Based on travel time estimated from CV data; potentially other new measures based on CV data, such as acceleration/deceleration, braking, and changing lanes.
Support of Off-line Signal Control	Based on historical traffic counts, field observations, and optimization tools. Recently, high-resolution controller data has been used.	CV combined with high-resolution controller and other available data sources.
Provision of Signal Control to Accommodate Varying Conditions		
Adaptive Signal Control	A number of off-the-shelf adaptive signal control systems are available.	Systems based on fused data from CV and existing detectors are in the development and pilot deployment stages. CV-based applications and additional features, including using vehicle trajectories to support timing, multimodal control, under-saturation/over-saturation consideration, dilemma zone protection, etc.

Table E-1 (Continued)

Function	Existing Solutions	CV-Based Solutions
Transit Signal Priority (TSP)	Local and central TSP strategies (conditional and unconditional) can be implemented using current signal control systems.	Extend existing TSP by potentially considering it as part of multimodal signal optimization. Detection of buses at a distance from the signal allows better control and consideration of nearside bus stops. Bus-specific status information can be used in priority decisions. Additional strategies are possible, such as queue clearance ahead of buses making left turns.
Freight Signal Priority (FSP)	FSP can be implemented using current signal control systems.	Same extensions as with TSP.
Pedestrian Signal Control	Walk signal can be provided based on push buttons.	Pedestrian detectors or information from pedestrian mobile devices can be used as part of the multimodal signal optimization with potential consideration of special needs pedestrians.
Emergency Vehicle Preemption (ESP)	Central and local ESP are possible with current signal control.	Early detection of emergency vehicles to allow better control and queue clearance ahead of the signals.
Speed Adjustment to Support Arrival on Green		
Green Light Optimal Speed Advisory (GLOSA)	Cellular-based applications by private sector companies to provide traffic signal information to drivers who subscribe to their services, usually in coordination with the original equipment manufacturers (OEMs).	CV-based applications providing information and guidance to drivers as they approach traffic signals to allow them to adjust their speeds to reduce the probability of stopping at downstream intersections. More advanced applications combine adaptive signal control with GLOSA.

Table E-1 (Continued)

Function	Existing Solutions	CV-Based Solutions
Glide Path (Involving Partial Automation)	Not supported by existing solutions.	This application automatically adjusts the speeds of vehicles to allow them to arrive on green.
Support of Incident and Emergency Response		
Increasing Incident Zone Site Emergency Responder and Vehicle Safety and Mobility	Limited site information, such as merging and speed guidance for drivers or limited warnings about approaching vehicles to emergency responders.	CV-based applications involve providing in-vehicle messages that guide drivers in their merging and speed decisions and alerts to responders about vehicles approaching in an unsafe manner.
Emergency Vehicle Staging and Routing	Computer-aided dispatch (CAD) and automatic vehicle location (AVL) provide significant resource tracking and routing support. However, there is limited dynamic routing based on real-time information. Site staging is largely human-driven.	CV-based application will provide continuous en-route information, support establishing incident scene work zones, and support additional dispatching and staging. The decisions will be based on data and modeling analytics.
Evacuation Support	Limited routing information and limited support of the functional needs of people.	CV-based applications will provide routing, shelter, and gas information to all evacuees and dispatch and route resources to the functional needs of people.
Dynamic Information and Guidance to Support Management		
Provision of Traveler Information	Travel time and incident information provided by public and private sector platforms.	Pre-trip and en route predictive multi-modal information.
Provision of Guidance	Mainly route information by private sector phone apps.	Route guidance potentially combined with time shift and mode shift guidance.

Table E-1 (Continued)

Function	Existing Solutions	CV-Based Solutions
Optimization of Guidance Combined with Signal and Other Management System Optimization	NA	Optimize guidance combined with transportation system management optimization.
Support of Signalized Intersection Safety		
Permissive Left Turn and Right Turn on Red Support	Protect turns and improve geometry to improve sight distance.	To prevent a side collision, the application will provide guidance in accepting safe gaps in opposing traffic and possibly alerts of red violation and a dynamic all-red clearance interval when an opposing vehicle is about to violate the red interval.
Red Light Violation and Rear-End Collision Reduction	Red light violation cameras. Signs with flashing lights.	The application warns drivers who are approaching a signalized intersection if they are on a trajectory to violate a red signal.
Reduce Pedestrian-on-Crosswalk Crashes	Onboard vehicle sensors, such as Mobileye image processing devices.	CVs receives information from the infrastructure (roadside units) that indicates the possible presence of pedestrians in a crosswalk at a signalized intersection.
Support of Visually Impaired Pedestrian in Crossing the Street	Accessible pedestrian signal and pushbutton (e.g., using audible tone).	Allows "automated pedestrian call" from smartphones for visually impaired pedestrians and provides information to the visually impaired to support crossing.
Support of Unsignalized Intersection Safety		
Warn Drivers of Potential Stop Sign Violation	No existing solution. Although the general warning of a stop sign has been given using signs with flashing lights.	Application warns the driver if the vehicle is predicted to violate a stop sign.

Table E-1 (Continued)

Function	Existing Solutions	CV-Based Solutions
Support Gap Acceptance at a Stop Sign	Few rural intersections in the nation have been equipped to warn drivers of conflicts (insufficient gaps).	Application provides advisory information to cross-street drivers at a stop-sign controlled intersection to support their gap selections at the intersection.
Hazard Warning		
Warning Drivers of Unsafe Speeds	Speed police enforcement Speed sign beacons Speed violation cameras Private sector phone apps indicate when driver is over the speed limit.	Reduced Speed/Work Zone Warning (RSWZ) warns drivers that they are operating at speed higher than the speed limit and/or provides information regarding changes in lane configuration.
Warning Drivers of Unsafe Speeds on Curves	Infrastructure-based warning systems.	CV-based Curve Speed Warning (CSW) system that warns drivers of unsafe speeds.
Warning Drivers of Oversize Vehicles	Infrastructure-based warning systems.	CV-based Oversize Vehicle Warning (OVW) system that warns drivers when the size of vehicle exceeds the limit at the location.
Warn Drivers of Bad Weather and Pavement Conditions	Infrastructure-based warning systems.	CV-based Spot Weather Information Warning (SWIW) application.
Railroad Crossing Warning	Active Rail Crossing Warning systems, including existing warning devices, such as flashing light signal, automatic gate, warning bells, and additional flashing light signals.	CV-based application warns drivers if they are on a crash-imminent trajectory to collide with a train at a railroad crossing.

Table E-2 Summary of Mobility and Safety Impacts of Existing and CV-Based Solutions to Address Arterial Management Needs

Function	Existing Solutions	CV-Based Solutions
Data Collection to Support System Management		
Travel Time Estimation	80% to 90% accuracy and reliability of travel time based on AVI or third-party data.	85% to 95% accuracy for 5% and 10% CV market penetrations, respectively.
Incident Detection Time	4-8 minutes with full deployment of point sensors.	2-4 minutes with 10% market penetration of CV.
Support of Off-line Signal Control	7.5% retiming coordinated signals and 11.5% coordinating isolated signal.	TBD
Provision of Signal Control to Accommodate Varying Conditions		
Adaptive Signals	5% for saturated conditions and 10% for undersaturated conditions over time-of-day control.	**Congested:** • 5% without CV • 15% with 100% CV MP • Linear interpolation between 5% and 15% for lower market penetration **Uncongested:** • 10% without CV • 25% with 100% CV MP • Linear interpolation between 10% and 25% for lower market penetration
Transit Signal Priority	12% reduction in travel time applied to buses that are not on time. Increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels.	**Congested:** 12% decrease in bus travel time with an increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion level. **Uncongested:** 15% to 25% decrease in bus travel time, depending on CV market penetration. Increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion level.

Table E-2 (Continued)

Function	Existing Solutions	CV-Based Solutions
Freight Signal Priority	12% reduction in travel time applied to trucks that are not on time. Increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels.	**Congested:** 12% decrease in freight travel time with an increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels. **Uncongested:** 15% to 25% decrease in freight travel time, depending on CV market penetration. Increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels.
Pedestrian Control	NA	TBD
Emergency Vehicle Preemption	15-45 seconds per intersection and 10% reduction in the probability of death for each one-minute faster response.	TBD
Speed Adjustment to Support Arrival on Green		
Green Light Optimal Speed Advisory (GLOSA)	No current applications.	3% to 5% improvement in fuel consumption and delay
Glide Path (Involving Partial Automation)	No current applications.	10% to 20% improvement in fuel consumption and delay.
Support of Incident and Emergency Response		
Increasing Incident Zone Site Emergency Responder and Vehicle Safety and Mobility	NA (Limited existing applications)	14% reduction in network-wide travel time, 8% increase in speed, 1% to 90% reduction in hard deceleration.
Emergency Vehicle Staging and Routing	NA (Limited existing applications)	Emergency vehicle travel time reduced by up to 23% and number of stops by up to 15%. Overall reduction in incident duration by 15%.

Table E-2 (Continued)

Function	Existing Solutions	CV-Based Solutions
Evacuation Support	Dynamic Information and Guidance to Support Management.	The application decreases the congestion time by 20%; and the wait time for transit services by 90%. On average, evacuees seeking lodging experienced a 2-hour travel time benefit.
Dynamic Information and Guidance to Support Management		
Provision of Traveler Information	5% to 20% diversion, depending on incident impact severity.	15% to 50% diversion, depending on incident impact severity.
Provision of Guidance	15% to 35% diversion, depending on incident impact severity.	25% to 80% diversion, depending on incident impact severity.
Optimization of Guidance Combined with Signal and Other Management System Optimization	NA	TBD
Support of Signalized Intersection Safety		
Permissive Left-Turn and Right-Turn on Red Support	10% to 55%	With 100% CV market penetration: Signalized Left-Turn Assist (SLTA): 36% to 70% reduction in intersection crashes; Signalized Right-Turn Assist (SRTA): 25% to 50% reduction in intersection crashes.
Red Light Violation and Rear-End Collision Reduction	20% to 40%	With 100% CV market penetration, Red-Light Violation Warning (RLVW): 25% to 50% reduction in intersection crashes.
Reduce Pedestrian-on-Crosswalk Crashes	7% to 45%	50% to 100% reduction in pedestrians-on-crosswalk crashes with 100% market penetration.
Support of Visually Impaired Pedestrian in Crossing the Street	Accessible pedestrian signal is expected to significantly reduce visually impaired incidents.	Expected to reduce visually impaired incidents more than the accessible pedestrian signal.

Table E-2 (Continued)

Function	Existing Solutions	CV-Based Solutions
Support of Unsignalized Intersection Safety		
Warn Drivers of Potential Stop Sign Violation	9% to 67%	Reduce 50% to 100% of this type of crash with 100% market penetration.
Support Gap Acceptance at a Stop Sign	NA	Reduce 28% of this type of crash with 100% market penetration.
Hazard Warning		
Warning Drivers of Unsafe Speeds	5% to 41%	Reduce up to 50% of this type of crash with full deployment.
Warning Drivers of Unsafe Speeds on Curves	2% of this type of crash.	Reduce 20% to 30% of this type of crash with full deployment.
Warning Drivers of Oversize Vehicles	50% of this type of crash.	Reduce 75% to 90% of this type of crash with full deployment.
Warning Drivers of Bad Weather and Pavement Conditions	15% of this type of crash.	Reduce up to 50% of this type of crash.
Railroad Crossing Warning	45% to 50% of this type of crash.	Reduce 50% of this type of crash.

E5. CONCEPT OF OPERATIONS OF THE USE OF CV ON URBAN ARTERIALS

As indicated in Section E1, there are options available to agencies to provide the required functions for managing and operating arterial streets. The selection between these options and planning for their deployments and operations must start with a Concept of Operations (ConOps) according to the systems engineering process. This document provides information and methods that support agencies in their development of a ConOps as part of the systems engineering process for a typical urban arterial in Florida with the consideration of CV applications. The document presents a vision of the system after CV-based implementation, current situation of ITS deployments, stakeholders associated with the deployment, nature, and justification of the required changes, an overview of the system, including the hardware and software components, and a method for assessing system impacts and selecting between alternatives.

VISION

The 2019 FDOT Connected and Automated Vehicle (CAV) Business Plan is aimed at "*Vision Zero with a fatality-free roadway network and a congestion-free transportation system in Florida using CAV technologies"* (FDOT, 2019). Thus, the vision of implementing CV-based technologies on Florida's arterials can include improving the mobility, reliability, and safety of all users of the system (passenger cars, transit, commercial vehicles, pedestrians, and/or bicycles, depending on the facility) and supporting transportation agencies in the planning, management, and operations of the systems. In any event, the implementations should be related to the needs of the project stakeholders and related to the goals and objectives of the 2017 FDOT TSM&O Strategic Plan, 2018 FDOT STAMP Action Plan, and 2019 FDOT CAV Business Plan.

The investment in CV-based applications will be selected based on multi-criteria analyses that consider other solutions for the identified issues facing the facility. In addition to the positive impacts of CV-based deployments beyond what can be achieved with existing technologies, the implementations of the CV-based solutions will have the added benefits of contributing to increasing the capability maturity of the transportation agency with respect to emerging technology applications and, according to the 2019 FDOT CAV Business Plan, the possibility of contributing to the growth of the economy. Thus, transportation agencies may be willing to accept the initial risks associated with the CV deployment to acquire the capability and demonstrate the technology performance and impacts.

GOAL AND OBJECTIVES

The 2019 FDOT CAV Business Plan states that "*The CAV technologies have the potential to significantly reduce highway crashes that result in traffic fatalities. This is consistent with FDOT's vision and that of Vision Zero. The CAV technologies also have the potential to improve travel time, increase vehicle and person mobility, enhance multimodal operations, and positively affect the economy in Florida*" (FDOT 2019).

Thus, a potential example of a goal for CV-based deployment on an arterial facility in Florida can be to improve the mobility, reliability, and safety of the arterial's facility in a cost-effective manner, while increasing the capability maturity of the agency in using emerging technology and supporting the growth of the economy in Florida. Specific objectives will have to be stated that are related to the goal based on the identified needs and issues of the facility. Output and outcome performance measures will then have to be set that are related to the project's objectives for pre-deployment and post-deployment assessment of system performance.

DESCRIPTION OF THE CURRENT SYSTEM OR SITUATION

According to the systems engineering approach, CV deployment concepts should be needs-driven. Since each site has different needs, the focus and applications of CV deployments should be different for each site. Section E4 provides a detailed description of the typical needed functions of arterial streets, existing solutions, and CV-based applications that are used or can be used to support these needs.

PROJECT STAKEHOLDERS

As with other ITS deployments, there is a need to involve the stakeholders from the beginning to the end of projects that contain CV-based applications. An important lesson learned from the USDOT CV pilot projects is the benefit of successful early and regular involvement, as well as the buy-in of the stakeholders (USDOT, "Connected Vehicle Pilot Deployment Program Connected Vehicle Pilot Deployment Program Success Stories and Lessons Learned," accessed April 2019.) Based on these pilots, it was reported that there is a need to not only engage stakeholders early but to also educate them early. Another lesson learned is that formalized agreements with private partners take time. Thus, there is a need to engage procurement and contract personnel early in the process. It is also important to identify and address stakeholders' concerns and priorities, such as their concerns about privacy, liability, flexibility, security, experience, funding, etc. This report presents a list of typical stakeholders of arterial CV-based applications.

RISKS AND CONSTRAINTS

Deployments of CV-based applications are complex and require the integration of a large number of existing and new infrastructure and mobile elements. There are technical, security, privacy, institutional, financial and procurement issues that need to be considered. Some of the issues and concerns have been or are being addressed by recently completed or ongoing FDOT, USDOT, and as well as other national efforts. Additional answers will be provided as more experience and results are obtained from the connected vehicle pilot deployment and research projects funded by FDOT, USDOT, and other ongoing and upcoming efforts. These issues should be tracked and reassessed as more knowledge is gathered, and as technology, policies, and procedures advance in the coming years. An overview of these issues is presented in this document and can be used as a starting point to identify the risks and constraints when developing the ConOps.

SYSTEM OVERVIEW

An overview of the system's concept and associated components were identified to support the development of the ConOps and the related feasibility analyses. The information provided in this document makes use of a review of national CV deployments and the information presented in the ARC-IT 8.2 (Architecture Reference for Cooperative and Intelligent Transportation). ARC-IT can be accessed at https://local.iteris.com/arc-it/. The service packages and associates physical objects, functional objects, and information flows, and the four views of the architecture can be used as an important source of the initial information for developing the system's concept.

METHODOLOGY FOR THE EVALUATION OF SOLUTION ALTERNATIVES

This report presents a methodology to support the agency decision to adopt a new technology based on agency objectives and local conditions. An assessment of criteria, such as those presented in the 2019 FDOT CAV Business Plan, will have to be made and continuously monitored for the validation or refinement of decisions. The selection of ITS and other conventional types of deployment alternatives requires that the evaluation of these alternatives be relative to each other and to other more conventional improvement alternatives. The methodology is applied to the case study corridor of this project, as discussed in Section E6.

Identification of Selection Criteria: The first step is to identify performance metrics and criteria that can be used by agencies to compare existing and emerging technologies. The performance measures should be assessed and tracked for the present and future years. This assessment should then be used as input for the final decision-making process. The selection criteria can include outcome performance measures, output measures, economic measures, feasibility, and risks and constraints. The 2019 FDOT CAV Business Plan identified criteria for CAV-based project selection. These criteria can be used in the assessment of this project. However, other criteria should be considered and potentially used to reflect the specific regional and local needs and consider project stakeholder inputs.

Provision of Required Functionalities: The provision of required functionalities is expected to be one of the main criteria in the selection process. The provision of a solution according to a systems engineering approach will need to be based on identified functionalities of the system that are related to local needs and issues. This step involves identifying the functions needed to address the needs and issues for the corridor and existing and emerging technology alternatives that support the delivery of the functions (see Section E4). Some of the functions can be supplied by both CV-based solutions and non-CV based solutions. Others can be supplied only by CV-based solutions. For example, support for performance measurement and performance-based planning and operations includes a wide range of existing data collection technologies and sources, such as point detectors, high-resolution controller data, automatic vehicle re-identification, and private sector crowdsourcing, among others. Connected vehicles acting as probes, data generated from travelers, and possibly data generated from automated vehicles have the potential to replace or complement these existing technologies and provide additional functionalities, data elements, and improved performance measurements. Both existing and emerging technologies will need to be assessed utilizing the methods presented in this study. Another example is supporting gap acceptance at signalized and unsignalized intersections, which can only be provided by CV-based applications.

Return on Investment Analysis: An important criterion in the selection of a CV-based solution is return on investment. Traditionally, the return on investment analysis is conducted by calculating deterministic point estimates of the net present value (NPV) or benefit-cost ratio of the project's alternatives. This involves deterministic estimates of the present values of the current and future benefits and costs over the project's economic life. A discount rate is used to calculate the present values of the cash flows. This conventional method may not be able to capture the uncertainty and risks associated with a CV project. The analyst must recognize that a great amount of uncertainty is associated with the parameters that are used to calculate the impacts and costs of the alternatives.

Multi-Criteria Decision Analysis: Measures that are difficult to assesse in dollar values cannot be accounted for using the economic return on investment analysis methods. Thus, these methods are not fully adequate for use in assessing technology alternatives. Multi-Criteria Decision Analysis (MCDA) methods have been proposed to account for both qualitative and quantitative factors in the decision-making process.

E6. DEMONSTRATION OF THE PRE-DEPLOYMENT EVALUATION METHODOLOGY

The method described in Section E5 to select between CV-based and other alternative solutions was demonstrated by applying the methodology to a project case study. The case study focused on SR-924/NW 119 Street from NW 32 Avenue to NW 5 Avenue in Miami, Florida. FDOT is currently deploying an adaptive signal system as part of the SR-924/NW 119th Street Adaptive Signal Control Technology (ASCT) Pilot Project. As stated in Section E5, the method utilizes a stochastic return on investment analyses and multi-criteria decision analysis (MCDA). The stochastic return on investment considers the uncertainty and risks associated with the benefits and costs of the solutions. The MCDA method is used to account for both qualitative and quantitative factors in the decision-making process. The application method was demonstrated for the project's case study, which is SR-924/NW 119th Street ASCT Pilot Project in Miami-Dade County.

IDENTIFICATION OF SELECTION CRITERIA

The first step is to identify performance metrics, and criteria that can be used by agencies to compare existing and emerging technologies. The performance measures should be assessed and tracked for the present and future years. This assessment should then be used as input for the final decision-making process. The selection criteria can include outcome performance metrics, output metrics, and economic metrics. The 2019 FDOT CAV Business Plan identified the criteria in Table E-3 as the measures used for CAV-based project selection. These criteria were used in the assessment of this project; however, other criteria can be used.

Table E-3 Project Selection Criteria Presented in the 2019 FDOT CAV Business Plan

Categories	Criteria	Self-Score
Accelerate the CAV Program	Does this project accelerate the deployment and implementation of CAV technologies in Florida?	
Safety	Does this project directly reduce or have the potential to reduce fatal, serious injury and/or secondary crashes?	
Mobility	From a mobility perspective, does this project directly benefit all modes, including pedestrians, bicyclists, disabled, economically disadvantaged, and aging road users?	
Efficiency and Reliability	Does this project directly benefit (or have potential to impact) efficiency and/or reliability for all travelers, freight, transit riders, aging road users, pedestrians, and bicyclists?	
Feasibility	Is this project implementable (technology-ready), scalable, and portable for statewide deployment?	
	Do proposed technologies comply with or have the potential to comply with relevant state and federal safety laws?	
	Is the proposed project interoperable and/or does it have the potential to become interoperable with the existing or programmed CAV Projects?	
Funds	Does this project leverage federal, local, and/or private funds? Are there any private organizations and/or local agency partners? If yes, what are their match types and roles? Is there an agreement or Memorandum of Understanding (MOU) in place?	
Benefit/Cost	Does this project offer benefits with a high B/C and a good return on investment?	
Data and Security	Does this project collect, disseminate, and use real-time traffic, transit, parking, and other transportation information to improve safety and mobility, and reduce congestion? Explain how the project will safeguard data privacy and deploy a cybersecurity platform.	
Operations and Maintenance	Does this project address staffing, funding, and procedures for operations, maintenance, and replacement of CAV infrastructure, technologies, and applications?	
Project Evaluation	Does this project have pre-defined performance measures? What and how are these outcomes measured?	
	Will there be a before and after analysis performed, and lessons learned documented? If yes, how will this be documented and shared?	
	Is there a systems validation and verification process in place? Explain how this will be performed.	
Total Score		

NEEDED FUNCTIONS

Table E-4 shows the identified needs and issues with the operation and safety of the case study corridor, the required ATM functions, and the existing and CV-based solutions to provide the required functions.

Table E-4 Needs of NW 119th Street and Related Existing and CV-Based Solutions

Need	Needed Function	Potential Existing Solution	Potential CV-based Support
Improve mobility and safety based on performance measurements	Data Collection to Support System Management	Bluetooth readers have been installed on SR-924 segments. New 2070LX controllers will provide high resolution controller data.	CV data can be used to support performance measure estimation (travel time, arrival on green, movement delays, etc.). The data can also be used for incident detection.
Improve mobility and safety for all modes (car, truck, transit, and pedestrian) by providing optimal signal control	Provision of Signal Control to Accommodate Varying Conditions	FDOT District 6 has already selected an adaptive signal control that is being implemented on the SR-924 corridor.	I-SIG may not be justifiable because an adaptive signal control is being installed on the facility. The vendor and contractor of the system should be contacted to determine if I-TSP, I-FSP), PED-SIG, and I-EVP can be implemented in conjunction with the installed adaptive control.
High left-turn crashes at the intersections of NW 32nd Avenue, NW 27th Place, and NW 27th Avenue	Left-Turn Movement Support	Implement protected-only WBL and EBL movements at the three intersections.	Implement Signalized Left Turn Assist (SLTA) at the three intersections.

Table E 2 (Continued)

Need	Needed Function	Potential Existing Solution	Potential CV-based Support
High right-turn crashes between NW 27th Avenue to NW 7th Avenue	Right-Turn Movement Support	Implement no right-turn-on-red at the subject intersections between NW 27th Avenue to NW 7th Avenue.	Right Turn Assist (RTA) system at the subject intersections
22 red light violation crashes from NW 27th Avenue to NW 7th Avenue	Red Light Violation Warning Dilemma Zone Protection	Potentially install Red Light Violation Camera. Increase the yellow plus all-red interval.	Red-Light Violation Warning (RLVW) system Dilemma Zone Protection as part of Multi-Modal Intelligent Traffic Signal Systems (MMITSS)
Pedestrian crashes observed at a number of intersections with moderately high level of pedestrian activities observed at or near NW 17th Avenue intersection	Pedestrian on Cross-Walk Warning	Provide pedestrian warning signs (W11-2) for the signalized pedestrian crossing at E Golf Drive. A new signalized intersection is being implemented.	Pedestrian in Signalized Crosswalk (PSCW) application at E Golf Crossing, Miami-Dade Community College Intersection, and NW 17th Intersection. A new signalized intersection is being implemented.
The unsignalized intersection of NW 14 Avenue/NW 15 Avenue showed high crash concentration	Warning of Potential Stop Sign Violation and Assistance in Accepting Gaps	Static sign with flashing beacon warning of stop sign.	Stop Sign Gap Assist (SSGA) and Stop Sign Violation Warning (SSVW) can be considered.
A large number of speeding and aggressive-driver-related crashes	Warning of Unsafe Speeds	Speed enforcement	Reduced Speed Warning

BASE CONDITION PERFORMANCE

The first step in pre-deployment evaluation involves estimating the safety and mobility performance for the base conditions without the implementation of improvement alternatives. Please note that there may be existing solutions in place for the base conditions. If this is the case, the CV solution could complement, supplement, or replace the existing solutions. The base safety condition can be estimated, preferably using real-world crash statistics for a three-year period at minimum. Another option is to estimate the safety based on safety performance functions (SPF). Such functions have been developed and calibrated for the state of Florida. In this study, the base safety performance was estimated using crash data collected from the "Signal Four Analytics" system, which is a statewide crash database. Similarly, mobility and reliability can be based on real-world measurements or using a model like the Highway Capacity Manual (HCM) facility procedures or simulation. In this study, the HCM urban street facility procedure as applied in the Highway Capacity Software (HCS) was used to estimate the mobility and reliability for the base conditions.

RETURN ON INVESTMENT (ROI) ANALYSIS

To conduct return on investment (ROI) analysis, the safety and mobility benefits of improvement alternatives, including CV-based applications, are obtained by first estimating the Base (Do-Nothing) mobility and safety performance, as discussed above. Then, the estimates are multiplied by mobility modification factors (MMF) and crash modification factors (CMF). The modification factors are estimated based on a comprehensive review of the literature and should be updated as more information becomes available based on the results from future CV implementation and research efforts. Cost estimates are another required component of the ROI analysis. The cost estimation requires the initial cost, operation and maintenance cost, estimated interest rate, and equipment lifetime. In this study, the cost estimates for the CV-based deployment were identified based on what is reported in the literature. The current and future deployments of CV-based applications in Florida and other parts of the country should provide better cost estimates for use in future analyses.

The mobility and safety benefits, costs, and return on investment (ROI) of implementing alternative applications to address the needs were calculated for the study corridor. These impacts were converted to dollar values and used in conjunction with the costs in the return on investment analysis. A central concept of the calculation of the benefits, costs, and benefit-cost ratio in this project is the consideration of the stochasticity, uncertainty, and associated risks using the Monte Carlo analysis. This is done by expressing the benefit and cost input parameters as probability distributions rather than deterministic values. As a result, the output benefit-cost ratio (BCR) also follows a probability distribution. To do the analysis, the input parameter distributions have to be defined. Commonly used distributions for this purpose are the uniform, normal, and lognormal distributions. The normal distribution follows a symmetrical bell-shaped curve and is simply described using the arithmetic mean (m) and standard deviation (v). However, it is important to consider the skewness of the distribution when analyzing the benefits, and this consideration can be provided by the lognormal distribution. For this project, the lognormal distribution was selected for estimating benefits while considering uncertainty. The parameters of the lognormal distributions were estimated based on the highest and lowest values of the benefits and market penetration reported in the literature. The costs of V2I deployments were estimated based on a uniform distribution between the highest and lowest limits reported in the literature.

The results from 1,000 Monte Carlo simulation runs were used to determine the benefit-cost ratio (BCR) distributions for CV-based safety and mobility solutions, as shown in Figure E-1 to Figure E-6.

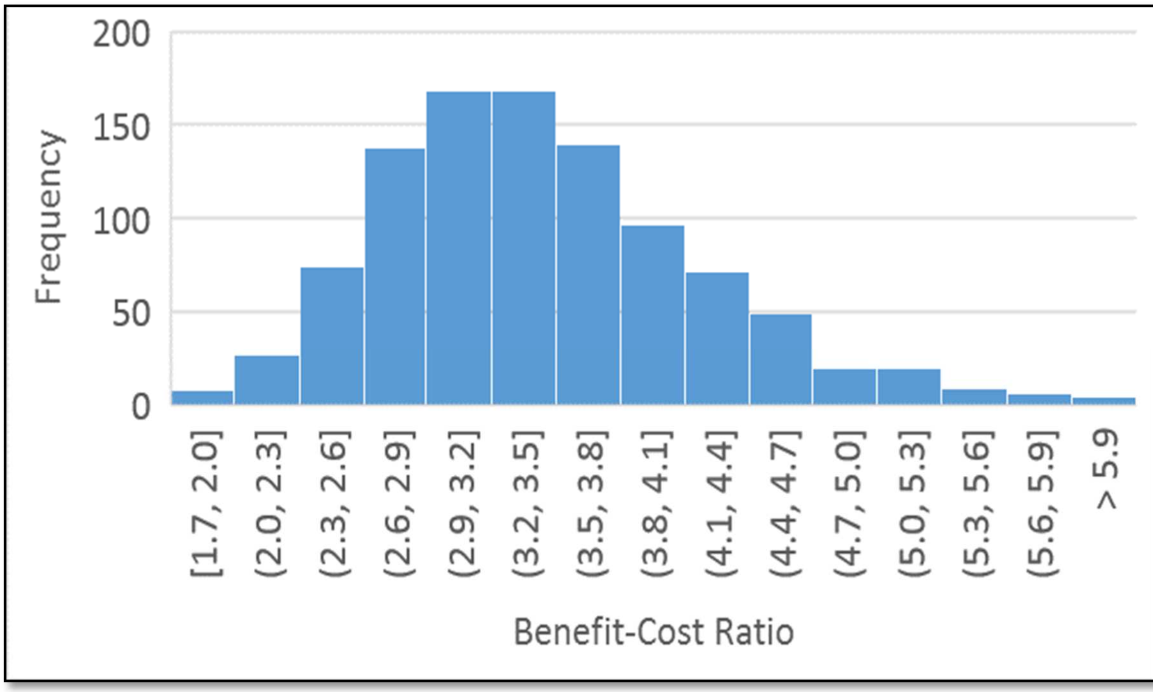


Figure E-1 Distribution of Benefit-Cost Ratios for CV-Based Signalized Intersection

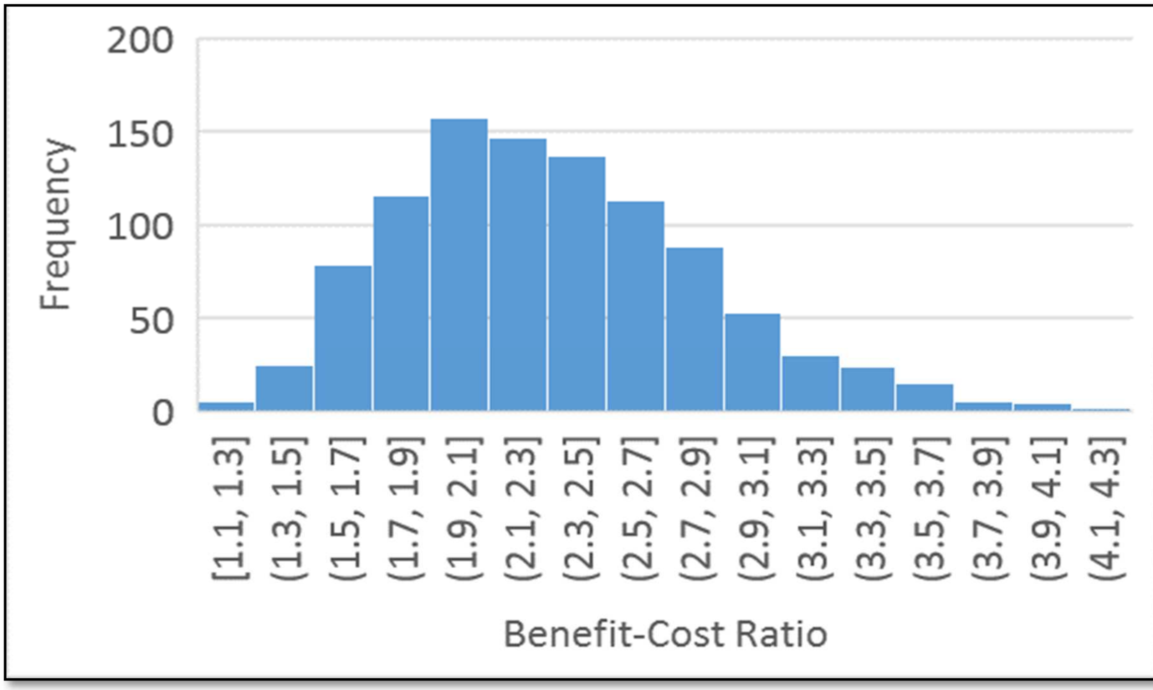


Figure E-2 Distribution of Benefit-Cost Ratios for CV-Based Unsignalized Intersection

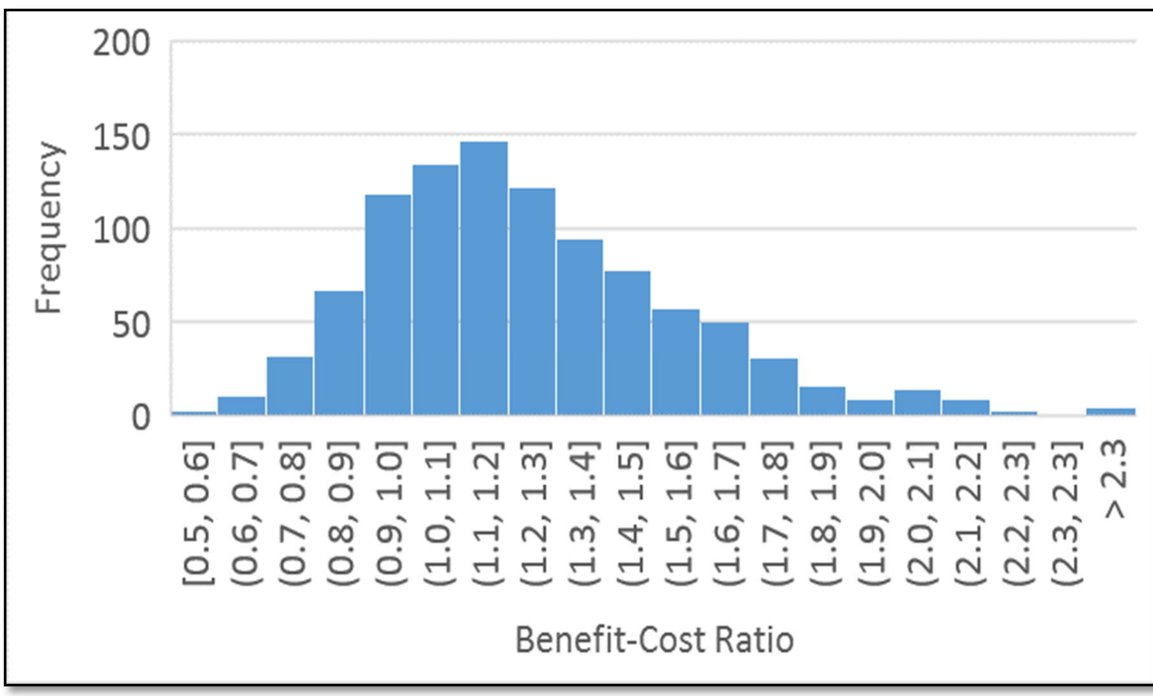
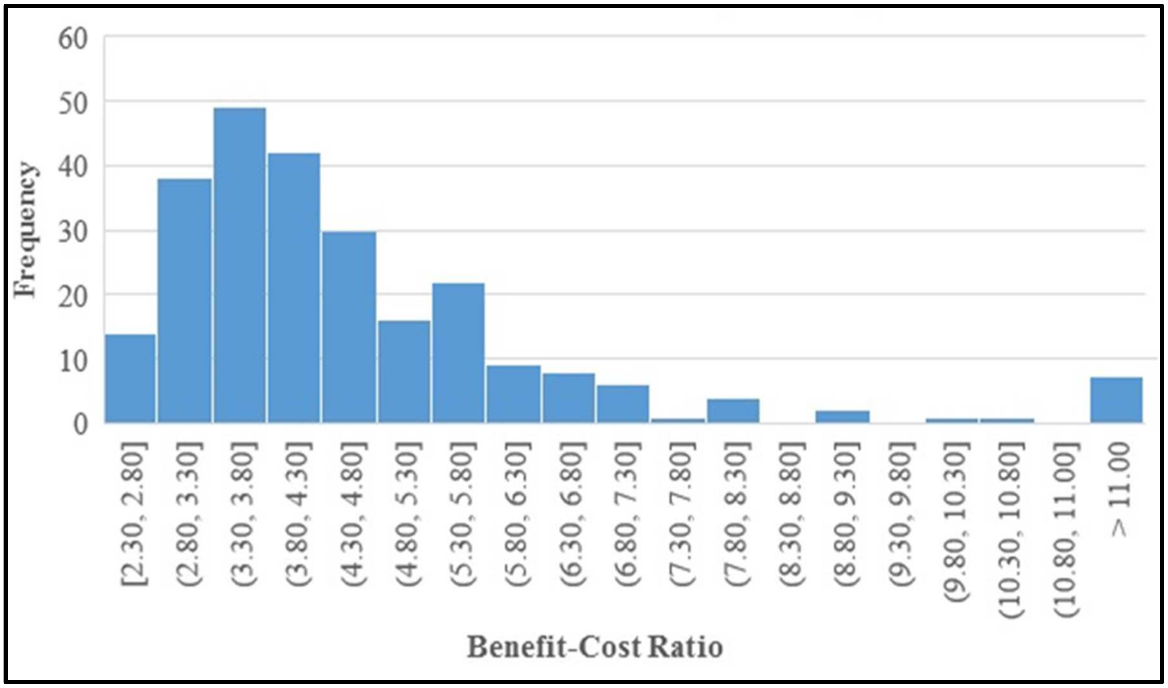
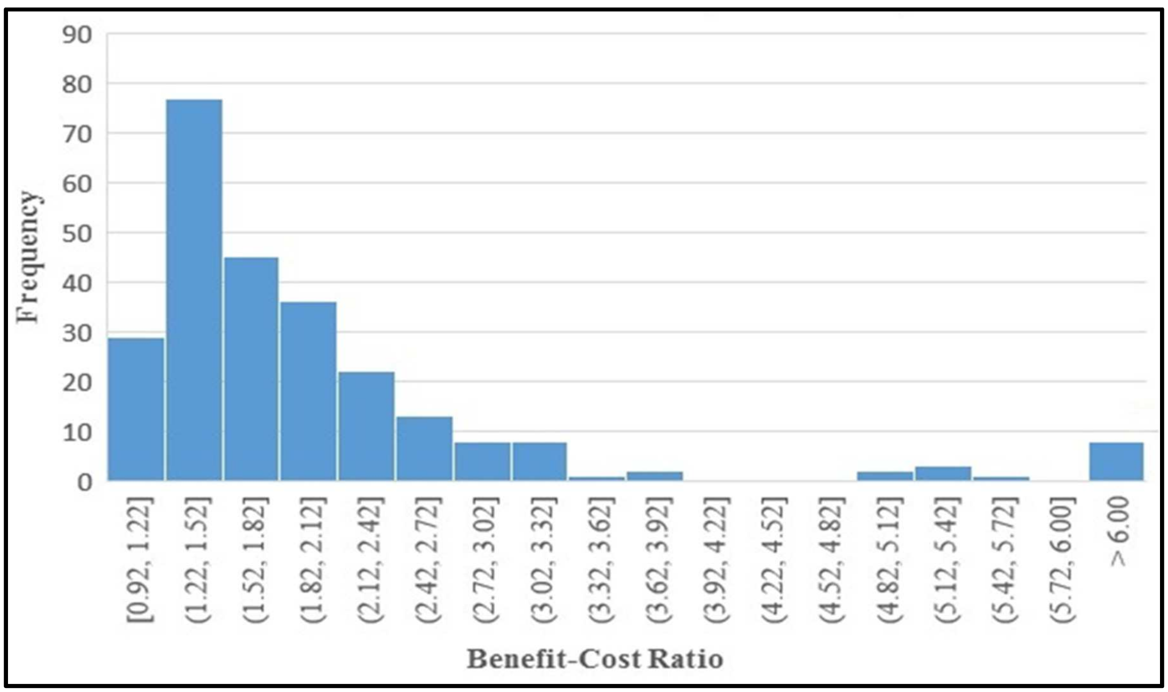


Figure E-3 Distribution of Benefit-Cost Ratios for CV-Based Unsignalized Intersection

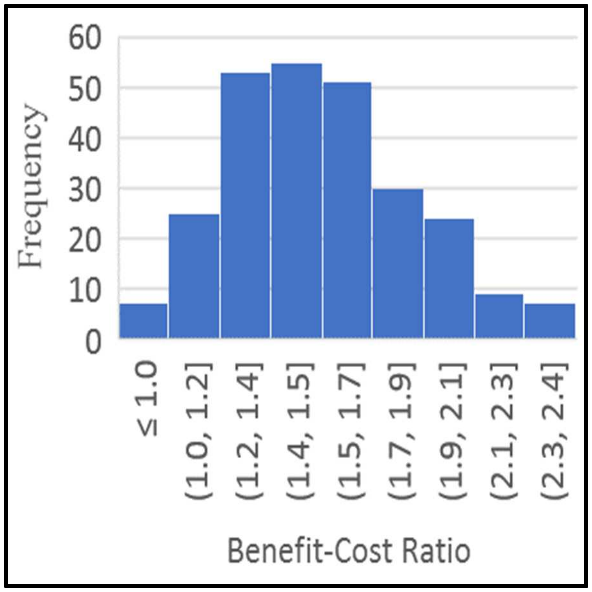


(a) With CV

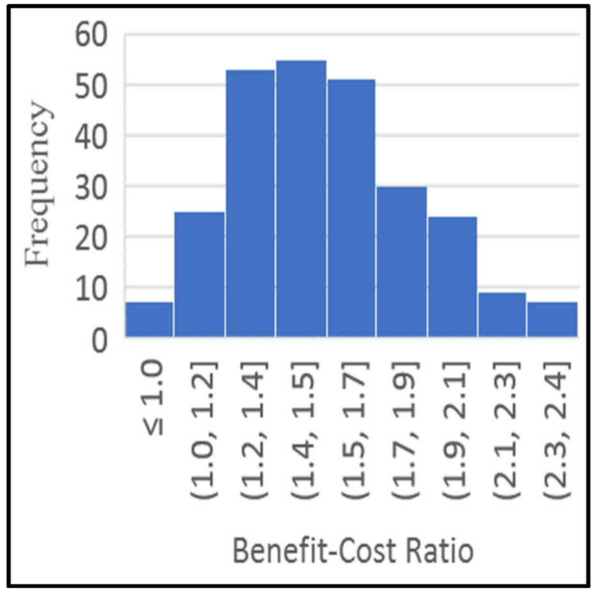


(b) Without CV

Figure E-4 Distribution of Benefit-Cost Ratios for ASCT

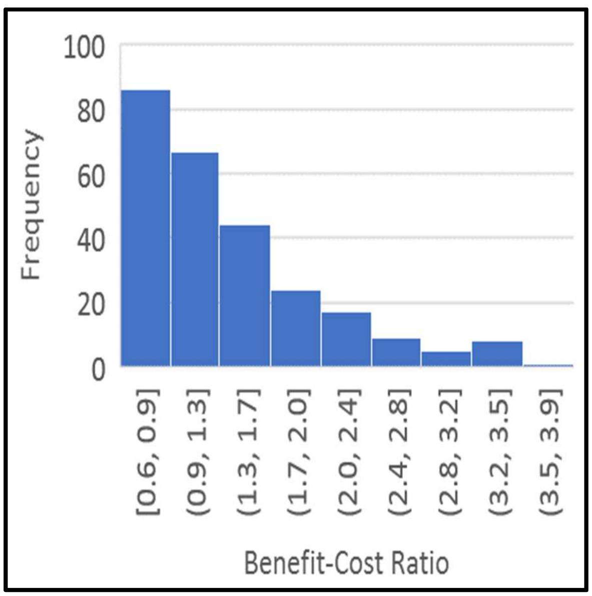


(a) With CV

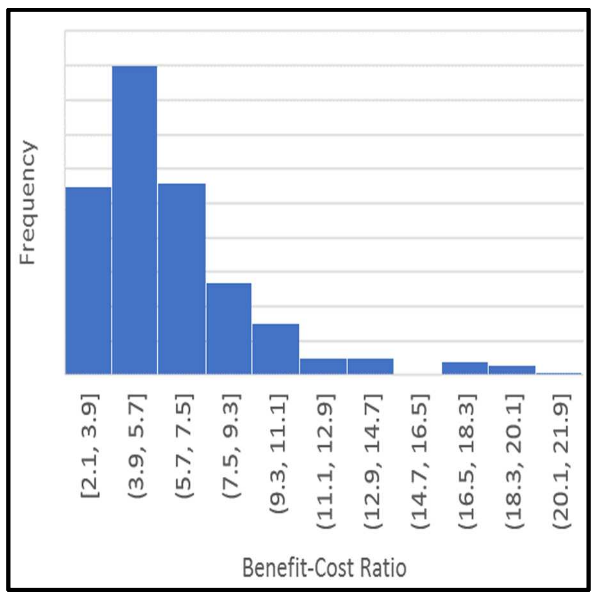


(b) Without CV

Figure E-5 Distribution of Benefit-Cost Ratios for TSP



(a) GLOSA



(b) Glide Path

Figure E-6 Distribution of Benefit-Cost Ratios Speed Adjustments

MULTI-CRITERIA DECISION ANALYSIS

Traditional return on investment analyses of alternatives do not capture the priorities and preferences of the decision makers in relation to the decision criteria. In addition, return on investment analyses do not capture the benefits that cannot be quantified in dollar values. Thus, Multi-Criteria Decision Analysis (MCDA) methods have been used in lieu of or in conjunction with the return on investment. In this project, the MCDA is used in combination with the return on investment analysis described in the previous section.

The Analytical Hierarchy Process (AHP) is the MCDA method selected for use in this study. This method has been used in various fields, including transportation engineering, in supporting complex decisions as it provides a comprehensive hierarchy for structuring project goals, criteria, and representing alternative solutions. It evaluates the project alternatives against each other and provides the best potential solution to achieve the objectives. Utilizing AHP to select between alternatives requires the input of stakeholders to develop a pairwise comparison between the priorities of different criteria. A typical four-level hierarchic structure consists of the main goal that lies at the top of the hierarchy, criteria and sub-criteria in the middle hierarchy levels, and the decision alternatives at the final level (Saaty, 1980).

In this project, a four-level decision-making hierarchy was defined based on the AHP, as shown in Figure E-7. The first level of the decision hierarchy is the main goal of selecting between CV-based solutions and non-CV-based solutions. The second level of the hierarchy includes the high-level objectives that are mapped to the goal. The objectives used in this study were based on those identified in the 2019 Florida's Connected and Automated Vehicles (CAV) Business Plan program. These objectives were used in the assessment of this project, but other objectives and criteria can be used based on agency priorities and preferences. The third level of the hierarchy includes the sub-criteria required for detailed assessments that are associated with the higher-level criteria. The selection criteria can include any outcome performance measures, output measures, economic measures, feasibility, and risks and constraints selected by the users. The last level in the hierarchy is the available alternatives for performing the upper-level tasks. The stochastic BCR analysis is applied using the Monte Carlo simulation and is included as one of the selection sub-criteria in the AHP analysis.

Analytic Hierarchy Process													
Goal	Criteria for Selection Between Different ITS Alternatives												
Critera	Accelerate CAV Program	Improve Performance			Feasibility				Funding			Benefits / Costs	
Priority	0.182	0.227			0.227				0.182			0.182	
Sub-Criteria	-	Safety	Mobility	Reliability	Ease of Implementation	Scalable to the rest of District 6	Lack of experience / Risks in implementatio	Technology Certainty	Fedral Funds	DOT Funds	Local / Private Funds	15th Percentile NPV	Median NPV
Priority	0.182	0.38	0.31	0.31	0.33	0.27	0.27	0.13	0.33	0.33	0.34	0.44	0.56
Final Score		CV- BASED SOLUTIONS				0.63	EXISTING SOLUTIONS					0.37	
CV- BASED SOLUTIONS	0.182	0.71	0.78	0.53	0.56	0.50	0.29	0.29	0.50	0.56	0.50	0.554	0.548
EXISTING SOLUTIONS		0.29	0.22	0.47	0.44	0.50	0.71	0.71	0.50	0.44	0.50	0.446	0.452

Figure E-7 AHP decision-making levels

E7. FITSEVAL TOOL IMPLEMENTATION

A tool is needed to facilitate the pre-deployment return on investment and MCDA methods described in this document. The research team has already developed such a tool as part of another project funded by the FDOT Research Center. The project title is "Estimation of System Performance and Technology Impacts to Support Future Year Planning" and is funded under grant number BDV29-977-37. The tool can estimate the mobility, reliability, and safety impacts of advanced strategies on system performance and can perform the return on investment and MCDA analysis. The tool is an enhanced version of an existing tool referred to as the Florida ITS Evaluation Tool (FITSEVAL), which was initially developed in 2008 for the FDOT. The following are the applications evaluated in the new version, but additional applications can be added to the tool as needed:

- Adaptive signal control with and without connected vehicle (CV) support
- Transit signal priority with and without CV support
- Freight signal priority with and without CV support
- Speed adjustment of CV to support arrival on green
- CV applications to support signalized intersection safety
- CV applications to support unsignalized intersection safety
- CV applications to support hazard warning
- Vehicle automation.

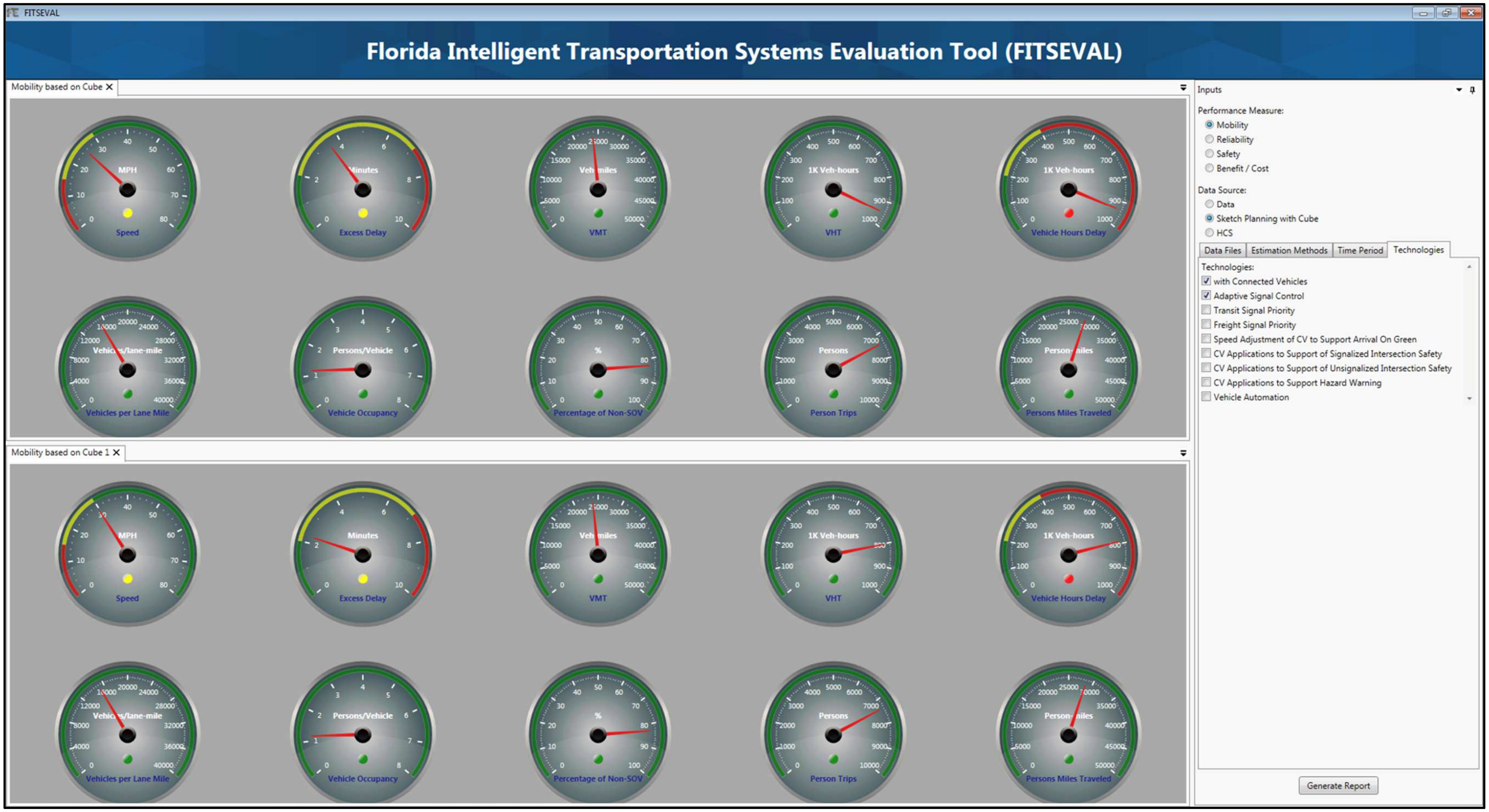


Figure E-8 Comparison of Mobility with and without CV-based Adaptive Signal Control

The new version of FITSEVAL produced as part of Project BDV29-977-37 is a standalone desktop tool that reads files from multiple sources as long as the files are provided in acceptable file formats. The currently acceptable formats are Cube files and Highway Capacity Software (HCS). The source of the data can be any model (simulation or analytical models) or real-world data, as long as it is converted to one of these two formats. Figure E-8 is an example of the screens of the updated FITSEVAL, which show a comparison of the assessed mobility of a corridor with and without connected vehicle (CV)-based adaptive signal control implementation.

E8. SIMULATION APPLICATIONS

Simulation modeling can play a major role in supporting the pre-deployment and post-deployment assessment of CV-based applications, particularly given the limited deployment of these applications and the low market penetrations of the CV that are expected in the near future. For example, this project demonstrates the use of simulation modeling to assess the safety and mobility of one CV-based application, which is the Signalized Left Turn Assist (SLTA). The benefits of SLTA include the reduction in left-turn crashes, improvement of left lane capacity, and reduction in left-turning vehicle delay. The mobility benefits can be assessed based on the examination of the output of a utilized microscopic simulation model, which, in this project, is the VISSIM (**V**erkehr **I**n **S**tädten **SIM**ulationsmodell; Planung Transport Verkehr AGP – TV, Karlsruhe, Germany). The safety benefits of SLTA can be determined using surrogate safety measures through a combination of the micro-simulation model VISSIM and the Surrogate Safety Assessment Model (SSAM).

An important aspect of simulating CV-based applications is the need for more detailed calibration based on microscopic measures estimated using more fine-grained data. This project demonstrates how such calibration is performed to support the microsimulation-based modeling of SLTA. This calibration is based on a real-world gap acceptance distribution for a permissive left-turn phase at a signalized intersection.

Simulation runs were performed to assess the impacts of the SLTA for different market penetration rates (10%, 20%, 50%, 80%, and 100%). The impact of using SLTA on left-turn vehicle delay is shown in Figure E-9. It can be inferred from the figure that the SLTA can reduce the average left-turn delay significantly as the market penetration increases. With a 100% market penetration, the average delay for all vehicles could be reduced by approximately 38%. These results indicate the potential operational benefits of SLTA in increasing the left-turn capacity and reducing the delays. In addition, results show the importance of calibrating VISSIM for driver's gap acceptance behavior.

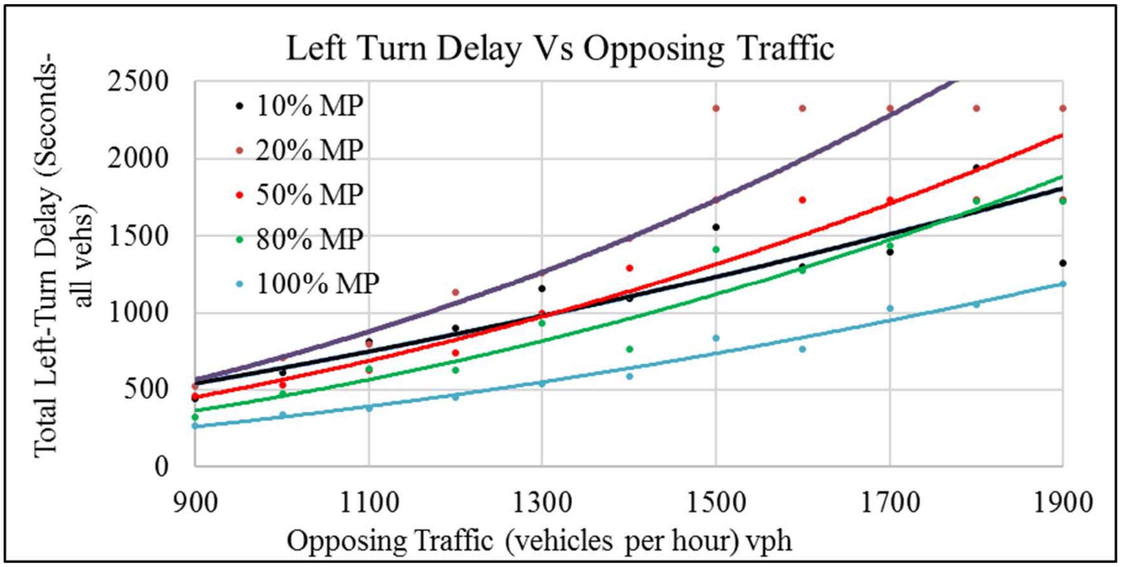


Figure E-9 Relationship between Left-Turn Delay and Opposing Traffic with Different CV Market Penetration (MP)

E9. POST-DEPLOYMENT EVALUATION

The previous sections have addressed the pre-deployment assessment of CV-based applications based on return on investment and multi-criteria analysis. This section addresses the post-deployment evaluation. The post-deployment evaluation is an important part of the systems engineering process used in intelligent transportation system (ITS) projects. The output from the evaluation can support the decisions made regarding changes and upgrades to the systems. In addition, post-deployment evaluation is important because it helps decision makers understand the actual return on investment, and whether the deployment objectives have been met. Results from the post-deployment evaluation of advanced strategies also provide critical inputs to the pre-deployment assessments of the types discussed earlier, as well as to the development and validation of sketch planning tools and modeling tools used to assess the advanced strategies.

The evaluation should be based on a plan that is developed with project stakeholder involvement. The plan should include:

- ***Identification of the Goal, Objectives, and Performance Metrics of the Evaluation***: This identification should be based on stakeholder inputs and be related to the project objectives that in turn should be related to the strategic objectives and key performance indicators of the organization. The metrics should be identified for each operation scenario or use case and can include output and outcome performance metrics. When identifying the metrics, consideration should be given to the available data. If the needed data to measure a performance metric is not available, then this metric should not be included. The evaluation plan should also categorize the evaluation metrics and associated hypotheses into evaluation analysis areas that are related to the evaluation objectives.
- ***Identification of Evaluation Targets and Hypotheses***: The targets and associated hypotheses should be defined relative to internal benchmarks (e.g., exceeds the post-deployment performance) or external benchmarks that "perform better than national set

values," or achieve global best practice (e.g., incident clearance time equal to or better than other districts in the state). The post-deployment assessment presented earlier in the report can be also used as the basis for setting the targets.

- ***Identification of Threats and Challenges:*** The evaluation plan should identify challenges, constraints, and threats associated with the evaluation. Several factors or threats can affect the validity of the evaluation. Thus, the evaluation plan should identify these factors, how they affect the evaluation, and how they are accounted for. For example, the findings and the results from the post-deployment evaluations are at risk of being biased due to the influence of other causes, such as exogenous confounding factors. Another example of a threat to validity is what is referred to as "selection bias," in which there is a difference between the group receiving treatment (e.g., CV technology) and the control or comparison group that is not receiving the treatment (e.g., not receiving the CV technology). In this case, the selected group for the evaluation may have specific socio-economic characteristics like age, income, education, gender, etc. that may not be representative of the whole population of drivers.
- ***Evaluation Design:*** The evaluation plan should also include a description of the utilized experimental design. In general, the evaluation designs can be categorized into three types: Random Experimental Designs, Quasi-Experimental Designs, and Pre-Experiment Designs. When choosing the experimental design, several factors will need to be considered, including the ability to address potential threats to validity, data availability, budget, and time.
- ***Analysis Plan:*** The analysis of the collected data should be based on an Analysis Plan that is included as part of the evaluation plan. The analysis plan will detail the methods and calculations used to assess the impacts of the deployment on system performance. The analysis plan will discuss the statistical methods used to describe, categorize, and cluster the data, in addition to the methods used to test the hypotheses of meeting the specified targets. The analysis plan will also specify statistical methods to address any identified threats or biases. Visualization techniques, such as graphs and dashboards can be great tools to communicate the evaluation results.
- ***Data Plan and Collection:*** The data for the evaluation need to be collected and processed according to a data plan that ensures that the collected data are sufficient and do not add biases to the evaluation. The data required in the plan must be based on the evaluation performance metrics, and the evaluation design must be as discussed in the previous sections. The data plan will include the data elements required to collect each performance metric, including the data source(s) for each data element; data resolution; spatial and temporal coverage; frequency; and data quality metrics, such as accuracy/validity, completeness, availability/accessibility, and timeliness. The data plan should also include a data management plan that describes how the data will be treated, archived, and preserved.
- ***Use of Modeling and Simulation in Post-Deployment Evaluation:*** In some cases, it is difficult to estimate the impacts of real-world deployment, particularly in the case of connected vehicles where the market penetration of these vehicles is small. In such cases, there is a potential for using analysis, modeling, and simulation (AMS) tools similar to those used in the pre-deployment evaluation, as discussed earlier to supplement the field evaluation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AACN	Advanced Automatic Crash Notification Relay
AADT	Annual Average Daily Traffic
AAM	Active Arterial Management
AASHTO	American Association of State Highway and Transportation Officials
ACC	Adaptive Cruise Control
AHP	Analytical Hierarchy Process
AM	Ante Meridiem (Before Midday)
ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
ASCT	Adaptive Signal Control Technology
ATDM	Active Transportation and Demand Management
ATIS	Advanced Travel Information Systems
ATM	Active Traffic Management
AV	Automated Vehicle
AVI	Automated Vehicle Identification
AVL	Automatic Vehicle Location
BCR	Benefit-Cost Ratio
BSM	Blind Spot Monitoring
BSW	Blind Spot Warning
CACC	Cooperative Adaptive Cruise Control
CAD	Computer-Aided Dispatch
CAV	Connected and Automated Vehicle
CCTV	Closed Circuit Television
CFR	Code of Federal Regulations
CFRPM	Central Florida Regional Planning Model
CI	Consistency Index
CICAS	Cooperative Intersection Collision-Avoiding System
CMAQ	Congestion Mitigation and Air Quality
CMF	Crash Modification Factor
CMM	Capability Maturity Model
CMP	Congestion Management Plan/Process
CO	Carbon Monoxide
ConOps	Concept of Operations
CSW	Curve Speed Warning
CV	Connected Vehicle
CVO	Commercial Vehicle Operations
DHSMV	Florida Department of Highway Safety and Motor Vehicles
DII	Driver Infrastructure Interface
DIVAS	Data Integration and Video Aggregation System
DMA	Dynamic Mobility Applications
DMS	Dynamic Message Sign
DSRC	Dedicated Short-Range Communication
DTA	Dynamic Traffic Assignment
DVI	Driver-Vehicle Interface
EVAC	Emergency Communications for Evacuation

EVACINFO	Evacuation Information
EVP	Emergency Vehicle Preemption
FAST	Fixing America's Surface Transportation
FCW	Forward Collision Warning
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FITSEVAL	Florida ITS Evaluation
FSP	Freight Signal Priority
FSUTMS	Florida Standard Urban Transportation Model Structure
FTA	Federal Transit Administration
FTP	Florida Transportation Plan
GLOSA	Green Light Optimal Speed Advisory
GUI	Graphical User Interface
HAR	Highway Advisory Radio
HAWK	High-intensity Activated crossWalK
HCM	Highway Capacity Manual
HCS	Highway Capacity Software
HOV	High-Occupancy Vehicle
HSM	Highway Safety Manual
ICM	Integrated Corridor Management
INC-ZONE	Incident Scene Work Zone Alerts for Drivers and Workers
I-SIG	Intelligent Traffic Signal System
ITS	Intelligent Transportation System
ITSDCAP	Intelligent Transportation Systems Data Capture and Management
JPO	Joint Program Office
KITS	Kimley-Horn Integrated Transportation System
LCCM	Life Cycle Cost Model
LCW	Lane Change Warning
LL	Lower Limit
LOS	Level of Service
LRTP	Long Range Transportation Plan
MCDA	Multi-Criteria Decision Analysis
MPO	Metropolitan Planning Organization
MAP-21	Moving Ahead for Progress in the 21st Century
MPAD	Mean Percentage Absolute Difference
MPD	Mean Percentage Difference
MMF	Mobility Modification Factor
MMITSS	Multi-Modal Intelligent Traffic Signal Systems
MUTCD	Manual of Uniform Traffic Control Devices
NCDC	National Climatic Data Center
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NPMRDS	National Performance Management Research Data Set
OV	Opposing Vehicle
OVW	Oversize Vehicle Warning
PATH	California Partners for Advanced Transit and Highways

PCW	Signalized Crosswalk Warning
PDO	Property Damage Only
PM	Post Meridiem (After Midday)
P-PEG	Project-Performance Enhancement Goal
PSCW	Pedestrian in Signalized Crosswalk
PTI	Planning Time Index
QLOS	Quality/Level of Service
Q-WARN	Queue Warning
RCVW	Railroad Crossing Violation Warning
RDCW	Road Departure Crash Warning
RESP-STG	Incident Scene Pre-Arrival Staging Guidance for Emergency Responders
RISC	Rapid Incident Scene Clearance
RITIS	Regional Integrated Transportation Information System
RLVW	Red Light Violation Warning
ROI	Return-On-Investment
RSU	Roadside Unit
RSZW	Reduced Speed Zone Warning
RTA	Right Turn Assist
RTMC	Regional Transportation Management Center
RWIS	Road Weather Information System
SDPD	Standard Deviation of Percentage Difference
SITSA	Florida State ITS Architecture
SLTA	Signalized Left Turn Assist
SOV	Single Occupancy Vehicle
SPaT	Signal Phase and Timing
SPD-HARM	Dynamic Speed Harmonization
SPF	Safety Performance Function
SSAM	Surrogate Safety Assessment Model
SSGA	Stop Sign Gap Assistance
SSM	Surrogate Safety Measures
SSVW	Stop Sign Violation Warning
STAMP	Statewide Arterial Management Program
STSMO	Subcommittee on Transportation System Management and Operations
SV	Subject Vehicle
SWIW	Spot Weather Information Warning
THEA	Tampa Hillsborough Expressway Authority
TOPS-BC	Tool for Operations Benefit Cost Analysis
TMC	Transportation Management Center
TPO	Transportation Planning Organizations
TSM&O	Traffic System Management and Operation
TSP	Transit Signal Priority
TTC	Time-to-collision
UL	Upper Limit
USDOT	United States Department of Transportation
V2I	Vehicle to Infrastructure
V2V	Vehicle-to-Vehicle

VISSIM	Verkehr In Städten SIMulationsmodell
VOT	Value of Time

1. INTRODUCTION

This chapter presents a background statement, project objectives, and document organization.

1.1 BACKGROUND STATEMENT

Connected vehicle (CV) technologies promise transformative changes in Active Traffic Management (ATM). The United States Department of Transportation (USDOT) Dynamic Mobility Applications (DMA) Program identified high-priority DMA applications that utilize Vehicle-to-Infrastructure (V2I) technologies. Many of these applications are directly connected to ATM. ATM strategies have been shown to provide significant benefits for both freeways and arterials (Yelchuru et al., 2017b). There is a recognition that the emergence of CV V2I technologies and their use to support ATM will result in significant positive impacts beyond what can be achieved with current technologies (Yelchuru et al., 2017b). V2I will support existing applications and will also allow new applications that are not possible with existing technologies.

The Transportation System Management and Operations (TSM&O) program and the Statewide Arterial Management Program (STAMP) of the Florida Department of Transportation (FDOT) have recognized that ATM strategies are vital to addressing safety, mobility, and reliability elements facing in the transportation system. FDOT has utilized a systems engineering approach to the deployment of Intelligent Transportation System (ITS) technologies to support the TSM&O program. FDOT's 2017 TSM&O Strategic Plan identified CV as one of the six primary focus areas. Also, the FDOT Districts are interested in exploring the use of CV to support TSM&O to monitor and improve the performance of the systems managed and operated by FDOT or partner local agencies. In the short term, it is expected that CV-based technology will complement the existing ITS infrastructure elements. However, in the medium- to long-term, depending on the specific application and CV market penetration, CV-based technology may replace some components of existing ITS solutions. Thus, CV-based technology may be a:

- **Complementary solution** – CV technology may not provide equivalent functionality but can enhance existing solutions.
- **Supplementary solution –** CV technology can enhance and partially replace existing solutions.
- **Alternative solution** – CV technology can enhance and fully replace existing solutions.

1.2 GOALS AND OBJECTIVES

The goal of this project was to support the FDOT and other transportation agencies in their decisions to implement V2I-based ATM strategies to improve mobility and safety performance on urban arterials. The specific objectives of this project were to:

- Identify CV applications that can be used to meet the needs and objectives of arterial ATM in Florida,
- Identify methods that can be used to select between CV applications and traditional applications as part of the systems engineering process associated with ATM deployment,
- Identify the steps needed for post-deployment evaluation and performance measurements of CV applications to support arterial ATM, and
- Identify various technical and institutional considerations in the planning, design, and deployment of the identified CV applications.

1.3 DOCUMENT ORGANIZATION

This section includes a description of the remaining chapters of this document.

Chapter 2 includes a review of documents of related initiatives and deployments to inform the project activities in planning ATM on urban arterials.

Chapter 3 first provides a review of ATM functions to meet the needs of a project, as well as existing and CV-based applications that can support the provision of the required functions and the performance of the existing and CV applications in providing the required functions. This chapter also introduces the method developed to select between deployment alternatives, including the identification of selection criteria, assessing the ability of the alternative solutions to provide the required functionalities, assessing the mobility and safety performance of the alternatives, conducting return on investment analysis, and conducting multi-criteria decision analysis.

Chapter 4 provides information that supports agencies in their development of a Concept of Operations (ConOps) as part of the systems engineering process for an urban arterial in Florida with the consideration of CV applications.

Chapter 5 demonstrates the application of the method for the pre-deployment assessment of system impacts and selection between alternatives outlined in Chapter 3 to the project case study as outlined in Chapter 4. Then, a demonstration of how simulation modeling can be used to support the assessment of CV-based applications is presented. Finally, information is provided regarding planning and conducting a post-deployment evaluation of CV-based applications.

2. CV APPLICATIONS TO SUPPORT URBAN ARTERIAL ATM

This chapter begins with a review of documents of related initiatives and deployments to inform the project activities in planning ATM on urban arterials. The review included the systems engineering process, planning for operations, related service packages of the ITS architecture, the 2017 FDOT's TSM&O Strategic Plan, the 2018 FDOT STAMP Action Plan, and the 2019 FDOT Connected and Automated Vehicles (CAV) Business Plan. The chapter then identifies existing ATM applications and CV-based applications that can be used to support the goals and objectives of the FDOT TSM&O program on urban arterials. The review was based on the services and applications identified in the national ITS architecture, United States Department of Transportation (USDOT) CV Dynamic Mobility Applications (DMA) program, USDOT Safety Applications program, the Federal Highway Administration (FHWA) Active Transportation and Demand Management (ATDM) program, the three CV pilots currently funded by the USDOT (the New York City, New York; Wyoming; and Tampa, Florida pilots), and existing and planned deployments by FDOT around Florida. The existing and emerging CV-based applications were then mapped to the goals and objectives of the FDOT TSM&O program and were related to typical functions required to address the needs associated with arterial operations. Existing methods to select between deployment alternatives were then reviewed and recommendations were given related to the development of a method to support the investment in CV-based deployment to support the TSM&O of urban arterials based on this review.

2.1 RELATIONSHIP TO THE SYSTEMS ENGINEERING PROCESS

The Federal Highway Administration (FHWA) published Rule 940, and the Federal Transit Administration (FTA) published a policy for utilizing systems engineering analyses for ITS projects that use highway trust funds. The systems engineering approach has also been strongly recommended for use in other ITS projects. The systems engineering Guide produced by the United States Department of Transportation (USDOT, 2007; Hadi, 2017) provides guidance to agencies on how to use the systems engineering approach during the various stages of the ITS project life cycle. This report provides information to support the FDOT in the early stages of the systems engineering process, as shown in Figure 2-1 of the deployment of ATM on urban arterial streets with the consideration of CV technologies. In particular, the information provided in this document is related to the Regional Architecture and Feasibility Study/Concept Exploration steps for pre-deployment analysis. The report also presents information on supporting the system validation step utilizing a post-deployment evaluation.

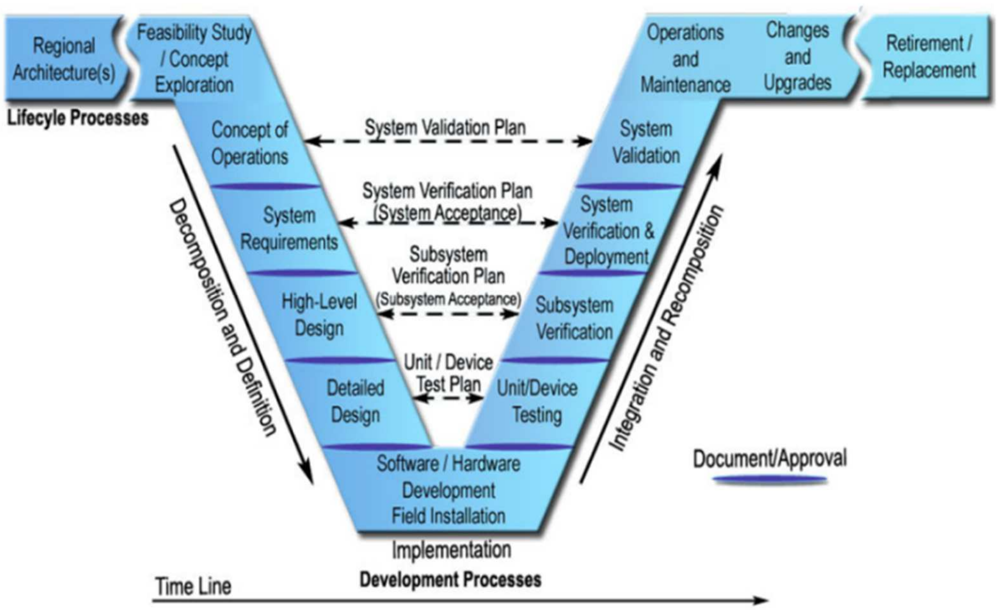


Figure 2-1 Systems engineering Approach

Among other elements, the systems engineering approach requires the analysis of alternative system configurations and technology options based on identified stakeholder needs, goals, objectives, issues, and requirements. A main component of the systems engineering approach related to the subject of this research is the need to conduct a feasibility study, in which the technical, economical, and political feasibilities of the considered strategies and technologies are assessed, benefits and costs are estimated, and key risks and constraints are identified.

As shown in Figure 2-2, according to the USDOT Systems Engineering Guide, the feasibility study will need to consider alternative solutions to satisfy the identified needs and select and justify the most viable option. The alternatives analysis is expected to be repeated during the project's life cycle as more information becomes available about the project. If emerging technologies are to be considered, either in lieu of or in combination with existing ITS technologies, methods and guidance will be needed to support their selection considering the existing solutions and conditions. As stated earlier, the objective of this project is to provide this type of support.

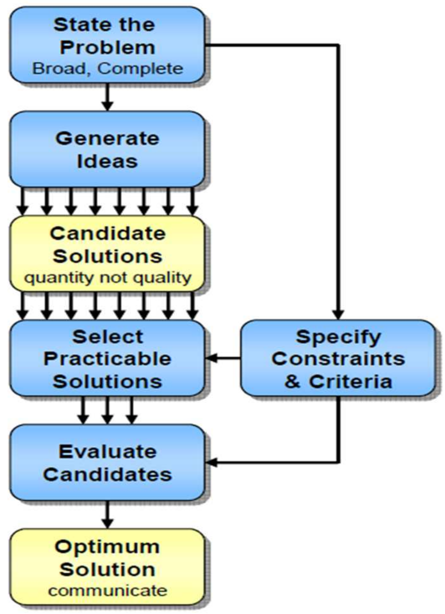


Figure 2-2 Basic Trade Study Techniques in the Concept Exploration as Presented in the Systems Engineering Guide (USDOT, 2007)

2.2 RELATIONSHIP TO THE ITS ARCHITECTURE

An important aspect of the systems engineering process is the compliance with the regional ITS architecture. The regional ITS architectures in Florida have been developed as part of the Florida State ITS Architecture (SITSA) development effort originally implemented in 2005. SITSA consists of seven regional architectures: Florida Statewide, Florida District 1, Florida District 2, Florida Districts 4 & 6, Florida District 5, Florida District 7, and Florida's Turnpike Enterprise. SITSA governs the planning, design, development, integration, implementation, maintenance, and operation of Florida's ITS projects. The most recent version of SITSA (FDOT, 2016) was released in stages from late 2015 to early 2016, depending on the specific regional architecture. This latest release is based on Version 7.0 of the National ITS Architecture. The architecture was developed and updated using inputs from interviews, documents, and stakeholder workshops.

SITSA includes service packages that are related to ATM and a few service packages that are related to crash avoidance vehicle safety. An example of these related service packages, as included in the Southeast Florida ITS Architecture (FDOT District 4 regional ITS architectures), are displayed in Table 2-1. Unfortunately, however, Version 7 of the ITS Architecture, on which the current release of SITSA is based, does not include CV applications. These applications were included later in Version 8 of the architecture, currently referred to as the Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) (USDOT, 2018a). ARC-IT merges, unifies, and enhances Version 7.1 of the National ITS Architecture and is an architecture developed specifically for CV applications and is referred to as Connected Vehicle Reference Implementation Architecture (CVRIA). Table 2-2 presents the service packages in ARC-IT related to the subject of this study that are not included in SITSA and should be included in future releases of SITSA. With regard to the safety applications, Table 2-2 includes Vehicle-to-Vehicle (V2V) applications and autonomous vehicle applications (in italic font), in addition to V2I applications that are of main interest to this project.

Table 2-1 ATM and Vehicle Safety-Related Service Packages in the SITSA Southeast Florida ITS Architecture

Area	Service Package	Name
Traffic Management	ATMS01	Network Surveillance
	ATMS02	Traffic Probe Surveillance
	ATMS03	Traffic Signal Control
	ATMS06	Traffic Information Dissemination
	ATMS07	Regional Traffic Management
	ATMS08	Traffic Incident Management System
	ATMS09	Transportation Decision Support and Demand Management
	ATMS13	Standard Railroad Grade Crossing
	ATMS15	Railroad Operations Coordination
	ATMS19	Speed Warning and Enforcement
	ATMS20	Drawbridge Management
Maintenance and Construction	MC08	Work Zone Management
	MC09	Work Zone Safety Monitoring
Transit Management	APTS09	Public Transport Signal Priority
Traveler Information	ATIS01	Broadcast Traveler Information
	ATIS02	Interactive Traveler Information
	ATIS05	ISP Based Trip Planning and Route Guidance
Emergency Management	EM02	Emergency Routing
	EM04	Roadway Service Patrols
Archived Data Management	AD2	ITS Data Warehouse
Vehicle Safety Systems	AVSS05	Intersection Safety Warning
	AVSS10	Intersection Collision Avoidance

Table 2-2 Additional Relevant Service Packages from ARC-IT

Area	Short Name	Name
CVO	CVO06	Freight Signal Priority
Data Management	DM02	Performance Monitoring
Public Safety	PS03	Emergency Vehicle Preemption
	PS06	Incident Scene Pre-Arrival Staging Guidance for Emergency Responders
	PS07	Incident Scene Safety Monitoring
Support	SU01	Connected Vehicle System Monitoring and Management
	SU02	Core Authorization
	SU03	Data Distribution
	SU04	Map Management
	SU05	Location and Time
	SU06	Object Registration and Discovery
	SU07	Privacy Protection
	SU08	Security and Credentials Management
	SU09	Center Maintenance
	SU10	Field Equipment Maintenance
	SU11	Vehicle Maintenance
	SU12	Traveler Device Maintenance
Traffic Management	TM04	Connected Vehicle Traffic Signal System
	TM12	Dynamic Roadway Warning
	TM21	Speed Harmonization

Table 2-2 (Continued)

Area	Short Name	Name
Vehicle Safety	VS01	Autonomous Vehicle Safety Systems
	VS02	V2V Basic Safety
	VS03	Situational Awareness
	VS04	V2V Special Vehicle Alert
	VS05	Curve Speed Warning
	VS06	Stop Sign Gap Assist
	VS07	Road Weather Motorist Alert and Warning
	VS08	Queue Warning
	VS09	Reduced Speed Zone Warning / Lane Closure
	VS10	Restricted Lane Warnings
	VS11	Oversize Vehicle Warning
	VS12	Pedestrian and Cyclist Safety
	VS13	Intersection Safety Warning and Collision Avoidance
	VS14	Cooperative Adaptive Cruise Control
	VS15	Infrastructure Enhanced Cooperative Adaptive Cruise Control
	VS16	Automated Vehicle Operations
	VS17	Traffic Code Dissemination
Weather	WX03	Spot Weather Impact Warning

2.3 RELATIONSHIP TO PLANNING FOR OPERATIONS

Advancing Metropolitan Planning for Operations Desk Reference (Worth et al., 2010) provides a recommended process to build a transportation plan that is based on operation objectives, performance measures, and related strategies that are relevant to the region, considering the values and constraints associated with each alternative. The process (see Figure 2-3) utilizes an objectives-driven, performance-based approach to planning for operations. As shown in Figure 2-3, the process starts with identifying regional goals and motivations, followed by related operation objectives. A systematic process is used to select management and operation (M&O) strategies to meet the identified objectives. These strategies are then provided as inputs to the metropolitan transportation planning process and associated evaluation process for possible selection and then consideration to be included in the transportation improvement program and other funding programs for implementation. This approach has been recommended to be utilized as part of the Congestion Management Process (CMP) (Worth et al., 2010).

An important foundation of the process is the development of operations objectives. Operational objectives must reflect what the region would like to achieve and what stakeholders believe can be achieved within a certain timeframe. The time period(s) and area for which the objective is to be met also need to be specified. The Desk Reference presents examples of operations objectives and their associated performance measures, data needs, and other related information that are presented and organized in application categories. The identified operations objectives will then need to be used to influence the selection between alternative solutions. An operations objective should have the SMART characteristics defined below:

- The objective is **Specific** (e.g., decrease travel time delay).
- The objective is **Measurable** (e.g., by 10 percent).
- The objective is **Agreed** on by planners, operators, and relevant planning participants.
- The objective is **Realistic** and can reasonably be accomplished within the limitations of resources and other demands.
- The objective is **Time-Bound** (e.g., achieved within 5 years).

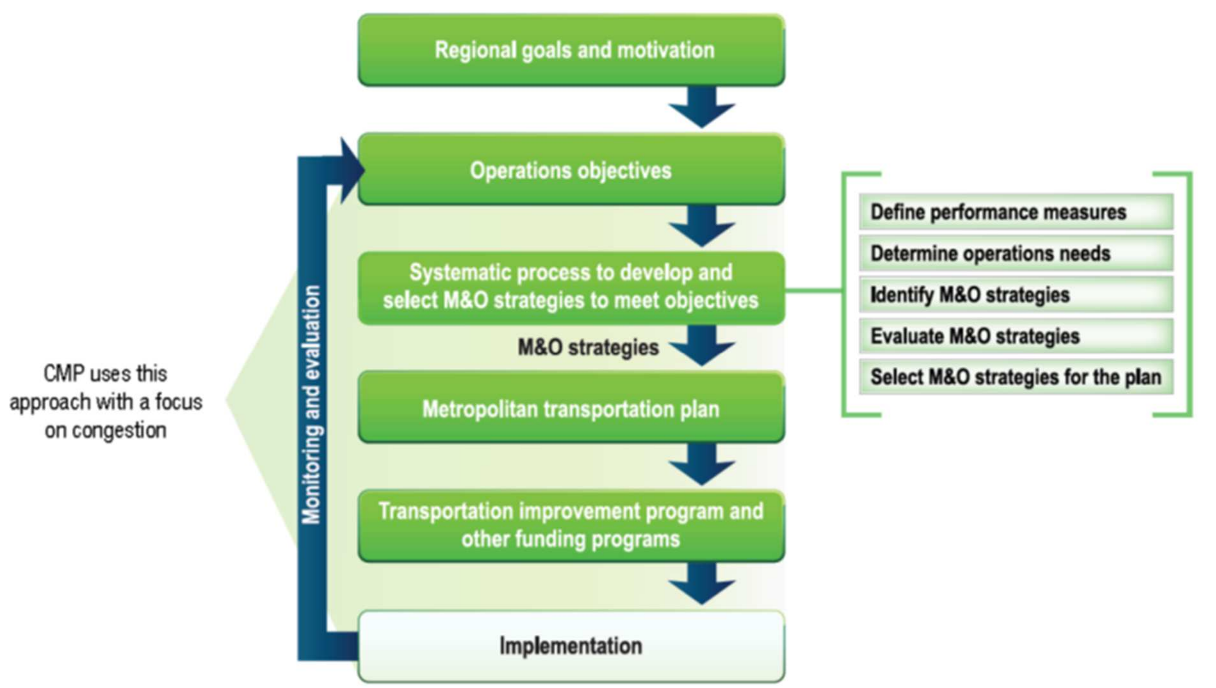


Figure 2-3 Steps of the Planning for Operations Process (Worth et al., 2010)

2.4 RELATED FDOT STRATEGIC PLANS AND ACTION ITEMS

This section presents a review of the goals, objectives, and performance measures of the TSM&O program and the FDOT Statewide Arterial Management Program (STAMP) that provide important inputs to the systems engineering process and planning for operations processes discussed in the previous section.

2.4.1 FDOT TSM&O Strategic Plan

The FDOT TSM&O Division developed the 2017 TSM&O Strategic Plan (FDOT, 2017). The plan includes the vision, mission, goals, objectives, and priority focus areas of the TSM&O program. It also identifies action plans to be accomplished over the next three to five years. Elements of the Strategic Plan that are related to the subject of this study are reviewed below.

The identified vision in the plan is to "increase the delivery rate of fatality-free and congestion-free transportation systems supporting the FDOT vision and Florida Transportation Plan goals." The mission is to "identify, prioritize, develop, implement, operate, maintain, and update TSM&O program strategies and measure their effectiveness for improved safety and mobility." In accordance with the vision and mission of the 2017 TSM&O Strategic Plan, this project will support the FDOT activities to identify and prioritize CV-based applications on urban arterials.

The plan identifies paths to achieve the goals, including active arterial management (AAM), adaptive signal control, incident management, standard operation procedure changes, and performance monitoring. Outcome-based goals in the 2017 TSM&O Strategic Plan are related to the vision and mission with the identified performance areas of mobility, safety, and system up-time. The selected performance metrics for mobility include planning time index (PTI), throughput, and delay reduction for all users, in addition to all lanes cleared times. Districts may select other performance metrics to supplement PTI. Crash rate and severity are selected as the measures for safety. The Strategic Plan specifies that before the end of FY 18/19, the FDOT districts will set PTI and optional throughput and delay reduction goals by route and route segment, with the PTI Goals possibly ranging from 1.1 in rural areas to much higher values in congested urban areas. These performance measures, in addition to possibly other measures, will be used in the assessment approaches of this study.

The Strategic Plan specifies a Project-Performance Enhancement Goal (P-PEG) for TSM&O strategy planning and implementation to achieve safety and mobility goals in a cost-effective manner. The P-PEG guidance for safety and mobility performance metrics includes at least 5% improvement in throughput, PTI, and speed due to the application of strategies selected to improve mobility. Thresholds for crash rate and severity improvements will be set in a future update to the plan.

The Strategic Plan identifies six TSM&O strategies as statewide focus areas: TSM&O Mainstreaming, Arterial Management, Connected Vehicles, Express Lanes, Freeway Management, and Information Systems. Three of these focus areas are related to these project activities, which are listed below:

- Arterial Management, including strategies, such as regular retiming and coordination, Adaptive Signal Control Technology (ASCT), Integrated Corridor Management (ICM), Active Arterial Management (AAM), and Signal Performance Measurement (SPM).
- Connected Vehicles (CV), including dedicated short-range communications (DSRC) for V2I communication, SPaT, Basic Safety Messages (BSM), transit, pedestrian, freight and emergency vehicle priority.
- Information Systems, including SunGuide® Software, FL511, Data Integration and Video Aggregation System (DIVAS), data archival systems, and performance assessment tools.

2.4.2 STAMP Action Plan

The STAMP Action Plan (FDOT, 2018a) was developed to identify action items to advance the FDOT Statewide Arterial Management Program**.** The Action Plan supports the 2017 TSM&O Strategic Plan vision, mission, and priority focus areas, as described in the previous section, with advancing the deployment of field technologies, traffic control strategies, Traffic Management Center (TMC) technologies, operations, and maintenance. The STAMP Action Plan is meant to be a living document and will be updated annually.

The identified actions were classified into five categories: leadership, safety, mobility, system availability, and mainstreaming. As part of the TSM&O Capability Maturity Model (CMM) Workshops, the FDOT Districts identified several performance measures. Figure 2-4 shows the number of votes received for each measure by the attendance of workshops. As shown in the figure, the highest number of votes were received for improving travel time, travel time reliability, and throughput. The improvement in performance is to be attended by all roadway users, regardless of travel mode choice. The Action Plan also identifies action items to support achieving the vision of zero fatality, including reducing bicycle and pedestrian-related crashes.

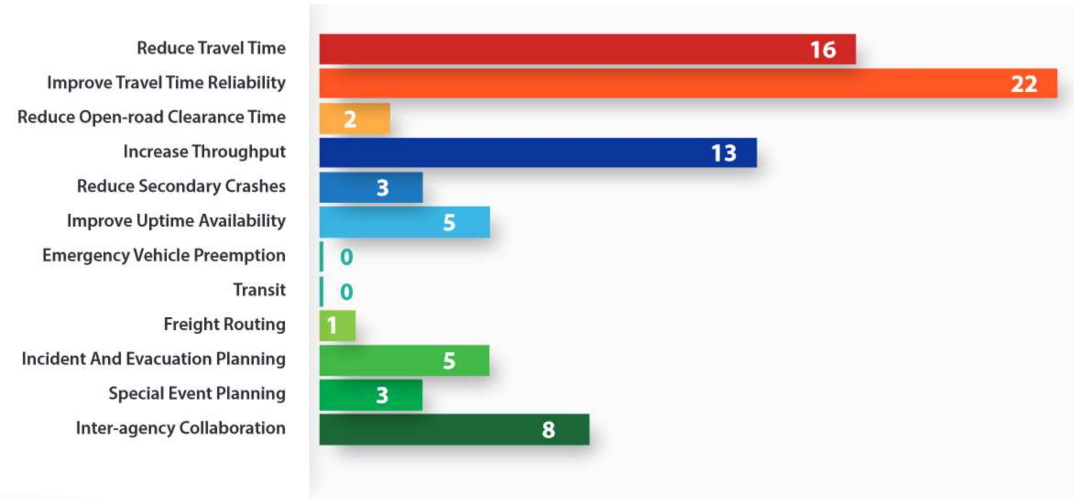


Figure 2-4 Number of Votes Received for Each Measure by the Attendants of the FDOT CMM Workshops (FDOT, 2018a)

The assessment parameters of the action items in the STAMP Action Plan include the time-bound category (four categories from short-term to long-term), effectiveness, cost implications, and accountability. Based on the assessment, the STAMP Action Plan identified the following early initiatives related to the subject of this study:

- Evaluating and deploying detection devices and/or use probe data for performance measures.
- Upgrading agency controllers for the collection of Automated Traffic Signal Performance Measures (ATSPM) and to support CV needs.
- Evaluating and deploying emerging technologies at the field and TMC levels.

The STAMP Action Plan stated that the early initiatives should be tied to the District's performance goals and that a return on investment analysis should be performed before considering any of the elements for deployment.

2.4.3 Connected and Automated Vehicles Business Plan

The 2019 Business Plan of the Connected and Automated Vehicles (CAV) Program of the Florida Department of Transportation (FDOT) was developed based on an extensive coordination effort that includes internal and external meetings and workshops. The business plan includes an institutionalized framework and timeframes to support statewide deployment using expedited planning and outcome-centric goals. The plan identifies specific CAV short-term to long-term action items. The Business Plan addresses the preparation of Florida's infrastructure for CAV deployment by taking into consideration the lessons learned from the FDOT project plan. The following categories were identified as key elements of CAV activities:

- "*Identify policies and governance with a goal to develop and communicate an institutionalized framework for planning, designing, and deploying CAV in Florida to maximize the SME benefits. Leverage program funding and identify other funding opportunities for implementation, operations, and maintenance.*
- *Identify education and outreach program objectives with a goal to create awareness of CAV Program deployments and develop the current and future CAV workforce in Florida.*
- *Develop industry outreach to implement SME outcome-based CAV technologies through active partnerships with the industry, universities, and stakeholders.*
- *Identify and develop technical standards and specifications to create a framework for CAV infrastructure preparedness including general facilities design, software updates, and hardware upgrades.*
- *Establish a platform for CAV implementation readiness in terms of technology implementation, infrastructure improvements, and needs identification.*
- *Move towards full-scale CAV deployment and implementation using the most relevant CAV applications that have the potential to achieve the SME benefits*."

2.5 ACTIVE TRAFFIC AND DEMAND MANAGEMENT (ATDM) ON ARTERIALS

As stated in the previous section, Active Arterial Management (AAM) is an important focus of the FDOT TSM&O program. It is important to provide a quick review of existing Active Traffic and Demand Management (ATDM) strategies that are applicable to arterials before starting the investigation of CV-based strategies. This is in line with the TSM&O Strategic Plan and STAMP requirements of the performance-based selection of strategies, which include existing ATDM strategies and emerging CV-based strategies. As stated in Chapter 1, CV technology can act as Complementary, Supplementary, and/or Alternative Solutions to the existing ATDM technology.

Active Transportation and Demand Management (ATDM) refers to strategies "to improve trip reliability, safety, and throughput of the surface transportation system by deploying operational strategies that dynamically manage and control travel and traffic demand and available capacity, based on prevailing and anticipated conditions" (FHWA, 2017). Active Traffic Management (ATM) is one of the three categories of strategies under ATDM, along with Active Demand Management (ADM) and Active Parking Management (APM). ATM strategies that are applicable to arterials include:

- Adaptive Signal Control Technology (ASCT),
- Dynamic Speed Limit,
- Queue Warning,
- Transit Signal Priority (TSP), and possibly
- Dynamic Lane Use (particularly, if the concept is extended to include dynamic lane assignment to intersection turning movements).

On the other hand, ATM approaches focus on influencing travel behavior with respect to lane/facility choices and operations. ATM strategies that are most relevant to this research project include:

- Predictive Traveler Information,
- Dynamic Routing, and possibly
- Dynamic Managed Lanes (in cases when managed lanes are implemented on urban arterials, such as what was considered for the southern segment of US 1 in Miami-Dade County by the Miami-Dade Expressway Authority in 2013).

FHWA has developed an ATDM Implementation and Operations Guide (Dowling et al., 2013) to support the implementation and operation of ATM to allow more efficient use of their networks through the implementation and operation of ATM strategies. A step-by-step Highway Capacity Manual (HCM)-related analysis methodology to evaluate the impacts of ATDM, as well as measures of effectiveness, were presented in the Guide. It is emphasized in the developed methodology that the ATDM strategies should be assessed under varying demand and capacity conditions.

2.6 DYNAMIC MOBILITY APPLICATIONS

As stated earlier, the USDOT DMA Program identified high-priority dynamic mobility applications that utilize V2I technologies to improve mobility. Table 2-3 shows the identified DMA bundles and applications (USDOT, 2018b). The most relevant applications to this project are INFLO, MMITSS, R.E.S.C.U.M.E, and possibly EnableATIS. The following are brief descriptions of the applications.

Table 2-3 USDOT Program DMA Bundles and Applications

Bundle	Applications
Freight Advanced Traveler Information System (FRATIS)	Freight Specific Dynamic Travel Planning and Performance, Drayage Optimization (DR-OPT)
Integrated Dynamic Transit Operation (IDTO)	Connection Protection (T-Connect), Dynamic Transit Operations (T-DISP), Dynamic Ridesharing (D-RIDE)
Response, Emergency Staging and Commutations, Uniform Management, and Evacuation (R.E.S.C.U.M.E.)	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)
Multimodal Intelligent Traffic Signal System (MMITSS)	Intelligent Traffic Signal System (I-SIG), Transit and Freight Signal Priority (TSP and FSP), Mobile Accessible Pedestrian Signal System (PED-SIG), Emergency Vehicle Preemption (PREEMPT)
Intelligent Network Flow Optimization (INFLO)	Dynamic Speed Harmonization (SPD-HARM), Queue Warning (Q-WARN), Cooperative Adaptive Cruise Control (CACC)
Enable Advanced Traveler Information Systems (Enable ATIS)	EnableATIS (Advanced Traveler Information System 2.0)

The Intelligent Network Flow Optimization (INFLO) consists of three different but related applications (Mahmassani et al., 2012):

- **Q-WARN** provides a vehicle operator with sufficient warning of an impending queue backup, thereby minimizing the occurrence and impact of traffic queues by using CV technologies. This application should be considered for locations with a high potential for rear-end crashes resulting from significant downstream speed reductions or stopped traffic. The conceptual Q-WARN application performs two essential tasks: queue determination (detection and/or prediction) and queue information dissemination. In order to perform these tasks, Q-WARN solutions can be vehicle-based or infrastructure-based or utilize a combination of each.
- **SPD-HARM** dynamically adjusts and coordinates vehicle speeds in order to maximize traffic throughput and reduce crashes. By reducing speed variability among vehicles,

traffic throughput is improved, flow breakdown formation is delayed or even eliminated, and the number and severity of collisions is reduced. Although this application has been mainly tested for freeways, it is related in certain aspects to the Eco-Driving speed approach to signalized intersections.

- **CACC** or Cooperative Adaptive Cruise Control dynamically and automatically coordinates cruise control speeds among platooning vehicles, coordinates in-platoon vehicle movements, reduces drag, maximizes the arrival on green, and reduces startup lost time at signalized intersections. Infrastructure information could be used as inputs to the CACC control, in infrastructure-based CACC.

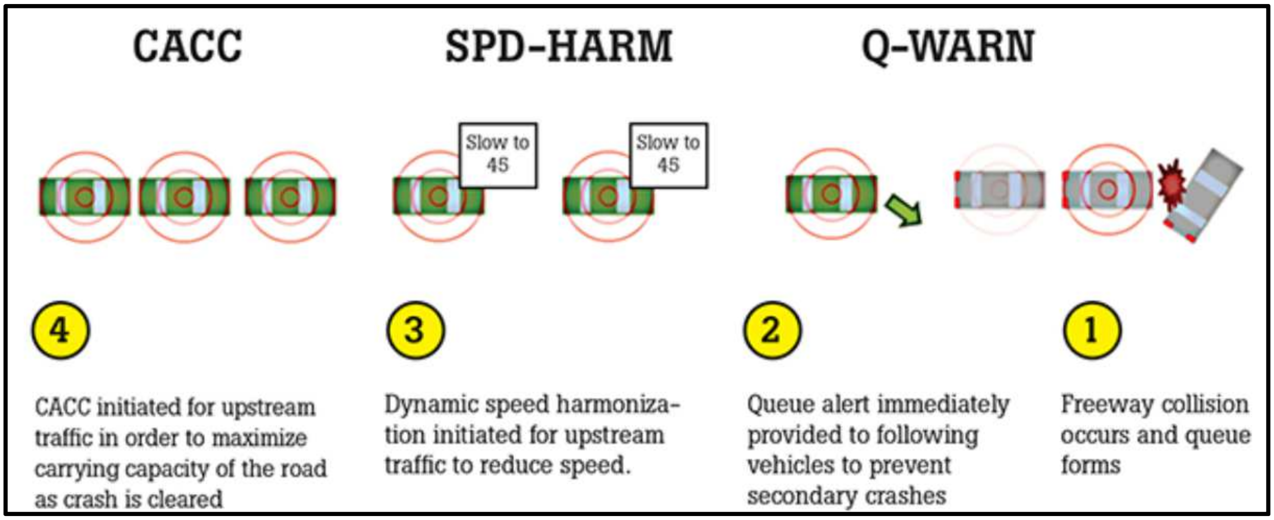


Figure 2-5 Combined Q-WARN/SPD-HARM/CACC Illustration (Mahmassani et al., 2012)

The Multi-Modal Intelligent Traffic Signal Systems (MMITSS) is a next-generation traffic signal system that provides service to all modes of transportation utilizing CV technology (see Figure 2-6). MMITSS consists of five different applications (Ahn et al., 2015):

- I-SIG aims to maximize the throughput of passenger vehicles and minimize the delay of priority vehicles under saturated conditions and minimize the total weighted delay during undersaturated conditions.
- TSP allows transit agencies to manage bus service by adding the capability to grant buses priority.
- PED-SIG integrates information from roadside or intersection sensors and new forms of data from pedestrian-carried mobile devices.
- PREEMPT integrates with V2V and V2I communication systems in preempting signal phases for emergency vehicles.
- FSP provides signal priority near freight facilities based on current and projected freight movements.

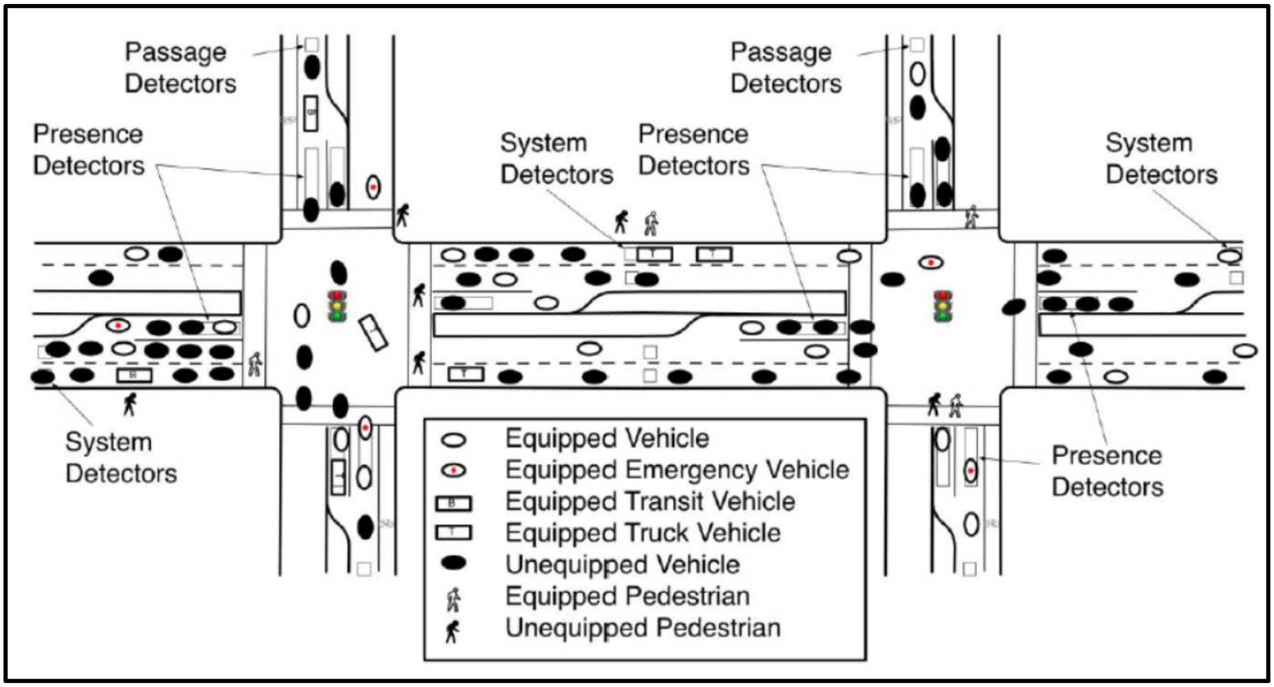


Figure 2-6 Illustration of the MMITSS Concept (University of Arizona et al., 2012)

The Response, Emergency Staging and Communications, Uniform Management, and Evacuation (R.E.S.C.U.M.E.) bundle consists of the four applications listed below (Battelle, 2012), as listed below.

- INC-ZONE is an incident zone application. It warns drivers that are approaching temporary work zones at an unsafe speed and/or trajectory. It also warns public safety personnel and other officials working in the zone.
- RESP-STG is a responder staging application that provides situational awareness information to public safety responders while en route to an incident. It can also help establish incident work zones that are safe for responders, travelers, and crash victims by providing input regarding routing, staging, and secondary dispatch decisions; staging plans; satellite imagery; GIS data; current weather data; and real-time modeling outputs. This new information is expected to provide more accurate and detailed information to support decisions and actions made by responders and dispatchers.
- EVAC10 supports region-wide evacuations by providing dynamic route guidance and information to identify and locate people requiring assistance.
- Advanced Automated Crash Notification Relay (AACN – RELAY) applications are anticipated to help transmit a range of data via other vehicles and roadside hot spots that can help enhance incident response.

EnableATIS consists of four different applications (Burgess et al., 2012):

- ATIS - Multimodal Real-Time Traveler Information that integrates data from different sources and disseminates it to users via different media.

- S-PARK - Smart Park and Ride that monitors and reports the occupancy of parking spaces in real-time, calculates the average travel distance and time to the parking facility and suggests alternative locations.
- T-MAP - Universal Map Application that enables transportation agencies to place real-time information on a universal map.
- WX-INFO - Real-Time Route Specific Weather Information.

2.7 V2I SAFETY APPLICATIONS

There are a number of Vehicle-to-Vehicle and Vehicle-to-Infrastructure applications that are utilized to improve safety. This project focuses on V2I applications to improve safety. V2I safety applications utilize a combination of data from the infrastructure with data from the vehicle to identify crash likelihood and the need for the delivery of hazard warnings to drivers. These V2I safety applications include (USDOT, 2018C; Richard et al., 2015a):

- **Applications enabled by Signal Phase and Timing (SPaT), MAP (intersection geometric description), and possibly GPS correction data messages** sent from Roadside Units (RSU). These applications also include:
  - **Signalized Left Turn Assist (SLTA):** The SLTA system supports drivers who make permissive left turns at signalized intersections. This system identifies the location and speed of vehicles traveling on the opposing thru movement and provides the driver making a left turn with information to assist in selecting an adequate gap when turning. The objective of this system is to help reduce driver errors related to detecting traffic and judging gaps.
  - **Red-Light Violation Warning (RLVW):** This system provides a warning to drivers who may potentially enter the intersection in violation of the signal control. The objective of this system is to reduce the frequency of red-light violations.
  - **Right Turn Assist (RTA):** This application is similar to SLTA but warns drivers making a right turn on red with the potential for a collision.
  - **Pedestrian in Signalized Crosswalk (PSCW):** An application that warns vehicles of a potential conflict with pedestrians that are within the crosswalk of a signalized intersection.
  - **Mobile Accessible Pedestrian Signal System (PED-SIG):** This application provides pedestrian information about crossing signal timing and improves safety for visually impaired pedestrians.
- **Stop Sign Gap Assist (SSGA):** This is a system that supports drivers on minor roads who are attempting to either cross or enter the intersecting major road. SSGA provides drivers with information about oncoming vehicles traveling on the major road. The objective of this system is to help drivers safely travel through or turn onto a highway from a stop-controlled intersection.
- **Reduce Speed/Work Zone Warning (RSWZW) and Road Hazard Warning:** Information is provided to the vehicle to enable alerts or warnings relating to a specific situation, such as warning drivers to reduce speed, change lanes, or come to a stop

within or approaching work zones and other hazards. The data can be obtained from multiple sources, including vehicles, field devices, management and information centers, and third-party data sources.

- **Curve Speed Warning (CSW):** The CSW application supports motorists when driving through a roadway curve at a safe speed. The system provides an alert/warning to drivers if their current travel speeds exceed a safe/advisory speed for the curve. In arterial environments, this application is similar to a ramp curve warning.
- **Rail Crossing Application (RCA):** This application includes equipping Railroad (RR) Grade Crossings with Roadside Equipment (RSE) that provides warnings to vehicles about approaching and crossing trains. The warning range of communication technologies, such as Dedicated Short-range Communications (DSRC) increases compared to conventional equipment. The data can be obtained from multiple sources, including vehicles, management and information centers, field devices, and third-party data sources.
- **Spot Weather Information Warning (SWIW):** This system provides drivers with information about potential weather-related hazards and appropriate precautions, such as reduced travel speed. The data can be obtained from multiple sources, including vehicles, management and information centers, field devices, and third-party data sources.

The USDOT focuses their efforts on five V2I safety applications, including Red Light Violation Warning (RLVW), Stop Sign Gap Assist (SSGA), Curve Speed Warning (CSW), Reduced Speed Zone Warning (RSZW), and Spot Weather Information Warning (SWIW). The Concept of Operations (Stephens, 2012a and 2013a) and the requirements (Stephens, 2012b and 2013b) for the five V2I safety applications have already been developed.

2.8 PROBE-ENABLED TRAFFIC MONITORING

The traffic monitoring and data collection functions are required for transportation system management, operations, and planning. Connected vehicle technologies promise to provide transformative changes in traffic monitoring and data collection, including those related to traffic, events, weather, and emissions monitoring. The collected data for real-time and off-line applications will have higher fidelity, more comprehensive coverage of geography, new data types that allow new measures, and a potentially reduced need for infrastructure investments. In general, traffic monitoring and data collection functions can be categorized into the following three categories (Hadi, 2017; Hadi et al., 2017):

- Off-line system performance analysis and modeling: This category includes measuring or estimating various performance measures for off-line use by planners, modelers, and analysts to support general planning and planning for operational decisions.
- Real-time system performance monitoring: This category includes measuring or estimating various performance measures in real-time for use by a system operator or an automated system to support transportation system management and operation decisions. Some of the information is also disseminated to travelers, third-party

traveler information service providers, and other agencies (such as transit, emergency, planning, and other traffic management agencies).

- Incident detection and verification: This involves detecting and verifying the occurrence of the incident and incident attributes, such as the exact location of the incident, number of lanes blocked, identification of the blocked lane(s), the number and types of the vehicles involved in the incident, incident severity, lane clearance, and incident clearance.

Connected vehicle, traveler opt-in and potentially automated vehicle technologies promise to provide several parameters currently provided by other technologies, as well as parameters that cannot be collected by other technologies. The only parameters that cannot be obtained using connected vehicle technologies are volume and density/occupancy/presence unless the market penetration of connected vehicle technologies is 100% (Hadi et al., 2017). However, there is a potential to utilize algorithms that estimate these parameters at a relatively low market penetration by combining data from a limited point detector deployment with connected vehicle data. The following are measures that are expected to be collected using existing and future technologies:

Travel Time/reliability
Volume
Density/occupancy/presence
Origin-destination
Vehicle classification
Queue length/back of queue
Stops, accelerations, and decelerations
Shockwave speed
Intersection movement-level measures
Potential for crashes
Platoon stability/probability of breakdown
Emission
Traveler behaviors and choices
Infrastructure-oriented data

Another critical function of traffic monitoring systems is the fast detection and validation of incident occurrence and attributes to reduce lane and shoulder blockage duration, as well as to allow fast notification by responding agencies. Traffic management centers currently detect incidents utilizing a number of methods, including the processing of data collected from point detectors (and in some cases AVI data), video analytics, and external notifications, including notifications from police and service patrols. Recently, FDOT also obtained third-party private sector incident feeds, which are important, particularly when dealing with incidents occurring on segments that are not well covered by incident management activities, such as urban arterials and rural freeways.

2.9 FLORIDA AND USDOT PILOT DEPLOYMENT APPLICATIONS

To assess the level of experience and issues with CV applications, it is important to review existing implementations of these applications. This section presents a review of the types of CV-based arterial applications implemented in Florida and those implemented as part of USDOT CV pilots.

2.9.1 USDOT CV Pilots

The Connected Vehicle Pilot Deployment Program sponsored by the USDOT is a national effort to deploy, test, and operationalize connected vehicle applications (USDOT, 2018d). The program aims to accelerate deployment, promote interoperability, and support the use of associated data. In September 2015, the USDOT awarded more than $45 million to three sites to pilot CV deployment. These sites are New York City, New York; Wyoming; and Tampa, Florida. The Wyoming deployment focuses on a rural freeway and thus is not considered further in this report.

The USDOT specifies the following requirements for the pilots (Vadakpat, 2018):

- Needs-driven planning and investment to be used
- Multiple connected vehicle applications to be deployed together
- Pilot deployments should leverage USDOT-sponsored research
- Pilot deployments include the capture of data from multiple integrated sources
- Pilot deployment data protecting privacy and intellectual property
- Dedicated Short-Range Communications (DSRC) 5.9 GHz to be utilized
- Well-defined, focused, quantitative performance measures
- Support an independent evaluation effort
- Security and credentialing management system to be utilized

The New York City Connected Vehicle Pilot deployment is implementing CV technologies to improve the safety of travelers and pedestrians in the city. Led by the New York City Department of Transportation (NYCDOT), the pilot aims to reduce crash frequency and severity, reduce violation of the speed limit, and evaluate the benefits of deploying connected vehicle technology in a dense urban environment with frequent interactions among participating vehicles (Walker, 2018; USDOT, 2017a). The deployment provides an opportunity to evaluate CV technology in dense urban transportation systems. The pilot area consists of three distinct areas in Manhattan and Brooklyn. The project will equip up to 8,000 fleet vehicles with after-market safety devices, 5,850 taxis, 700 MTA buses, 1,050 Sanitation and DOT vehicles, and 400 UPS vehicles). The project also includes 100 pedestrian personal information devices (PIDs). The infrastructure components include installing 353 roadside units (RSUs) at high-crash rate arterials and upgrading 239 traffic signals along these arterials.

The Tampa Connected Vehicle Pilot will equip buses, streetcars, and privately-owned vehicles with CV technology to enable them to communicate information with each other, as well as with infrastructure and pedestrians who use a smartphone app (Vadakpat, 2018; USDOT, 2017b). The expected safety and mobility benefits to motorists, pedestrians, and transit operations include crash prevention, enhanced traffic flow, and greenhouse gas reductions. The project is deploying a variety of connected vehicle technologies on and in the vicinity of reversible express lanes and three major arterials in downtown Tampa to address morning peak hour queues, wrong-way entries, pedestrian safety, bus rapid transit (BRT) signal priority optimization, trip time and safety, streetcar trolley conflicts, and enhanced signal coordination and traffic progression. The pilot is deploying onboard CV units on 1,600 privately owned vehicles, 10 buses, and 10 streetcars. Forty roadside units will be installed at the busiest intersections of the pilot area. The goal is to have 500 or more pedestrian participants.

Table 2-4 lists the applications that are being deployed in the New York and Tampa pilots, as well as the associated identified needs, and the initial sets of the identified performance measures. The performance measures were updated in the evaluation plans of the pilots, which will be discussed in Chapter 3.

Table 2-4 The CV Applications Deployed in the New York and Tampa Pilots

Application	New York		Tampa	
	Identified Need	Identified Potential Performance Measures	Identified Need	Identified Potential Performance Measures
Intelligent Traffic Signal System (I-SIG)	Mobility in Heavily Congested Areas	Average speed Average wait time at stops Average travel time Average throughput at intersections •Number of hard accelerations/decelerations	Reduce Queue Backup on Curve and Improve Signal Timing Progression	Congestion Impact Incident Rates Travel Time and Reliability of Travel Time Emission and Fuel Consumption
Transit Signal Priority			Improve bus On-schedule Performance	Transit Ridership Travel Time and Reliability of Travel Time Bus Headway / On-Schedule Performance Bus Tailpipe Emissions Fuel Consumption

Table 2-4 (Continued)

Application	New York		Tampa	
	Identified Need	Identified Potential Performance Measures	Identified Need	Identified Potential Performance Measures
Pedestrian in Signalized Crosswalk Warning	Improve Pedestrian Safety on Heavily Traveled Bus Routes	Pedestrian collisions with transit buses Number of warnings generated	Improve Pedestrian Safety at Mid-Block Crossing Locations	Application Acceptance Transit/ Auto/Pedestrian Conflicts Pedestrian Behavior (e.g., Jaywalking behavior)
Mobile Accessible Pedestrian Signal System	Improve Safety of Visually Impaired Pedestrians	Waiting time at intersections for crossing Number of pedestrian crossing violation reductions	Provide Pedestrian Crossing Signal Timing	Application Acceptance Transit/ Auto/Pedestrian Conflicts Pedestrian Behavior (e.g., Jaywalking behavior)
Curve Speed Warning	Improve Truck Safety on Curves (on ramps)	Accident at ramps Number of warnings generated	Warn Vehicles of Queue Backup in Curve	Incident Rates
Oversize Vehicle Warning	Alerts the driver of restricted roadways and impending height-restricted infrastructure, such as bridge or tunnel clearance	Accident rate		
Red Light Violation Warning	Reduce accidents at high-incident Intersection	Signal violations Accidents at intersections		

Table 2-4 (Continued)

Application	New York		Tampa	
	Identified Need	Identified Potential Performance Measures	Identified Need	Identified Potential Performance Measures
Reduced Speed/ Work Zone Warning	Improve Work Zone Safety and alert drivers of speed limit violation	Average speed at work zone and other zones compared to posted speeds		
In-vehicle information	Provide evacuation and unusual situation alerts	Acceptance and driver interviews		
Intersection Movement Assist (IMA)			Warns driver when it is unsafe to enter intersection	Incident rate
Probe-enabled Traffic Monitoring			Effectively Monitor Peak Queuing and Congestion	City Traffic Management Center (TMC) Operation Enhancements Transit Agency Scheduling Travel Time and Reliability of Travel Time Fuel Consumption

2.9.2 Florida CV Implementations

There are currently several CV projects in the implementation, development, and planning stages statewide (FDOT, 2018b), as shown in Figure 2-7. These deployments have included Signal Phase and Timing (SPaT) and pedestrian safety applications. The following is an overview of these deployments.

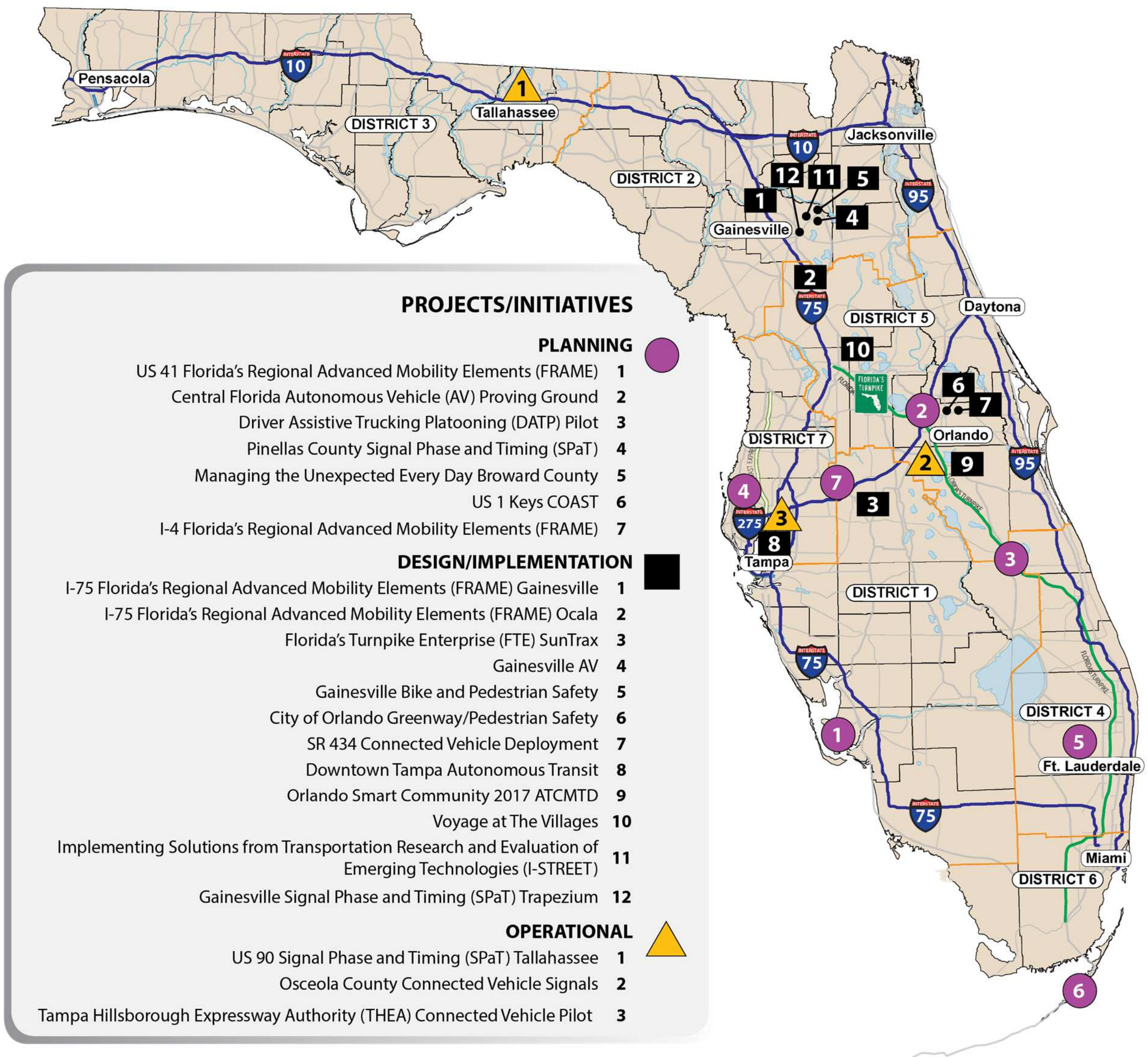


Figure 2-7 Current (Accessed May 2019) CV Deployment in Florida

In addition to the Tampa Hillsborough Expressway Authority (THEA) Connected Vehicle Pilot, the current operational projects include:

- The SPaT project is a partnership between the FDOT and City of Tallahassee to broadcast SPaT information to vehicle onboard units using CV DSRC technology. The goal is to gain experience to support the advancement of V2I capabilities around Florida. The deployment is at 22 signalized intersections equipped with DSRC technology on U.S. 90 Mahan Drive in Tallahassee, Florida. The project was initiated in response to the AASHTO SPaT challenge for all states to utilize DSRC technology to support SPaT deployment at 20 signals by the year 2020 to gain experience with CV technology.

- Osceola County deployed RSUs at two signalized intersections. The deployment was sponsored by the Federal Highway Administration as a pilot project to test DSRC and intersection processing equipment to gain experience and compile lessons learned in the deployment of CV infrastructure and applications. The RSUs were deployed at the intersection of Osceola Parkway and Orange Blossom Trail, and at the intersection of Orange Blossom Trail and Poinciana.

The projects that are in the planning stage are listed below:

- U.S. 41 Florida's Regional Advanced Mobility Elements (FRAME)
- Driver Assistive Trucking Platooning (DATP) Pilot
- Pinellas County Signal Phase and Timing (SPaT)
- Managing the Unexpected Every Day Broward County
- U.S. 1 Keys COAST

The projects that are in the design/implementation stage are listed below:

- I-75 Florida's Regional Advanced Mobility Elements (FRAME) in Gainesville
- I-75 Florida's Regional Advanced Mobility Elements (FRAME) in Ocala
- Florida's Turnpike Enterprise (FTE) SunTrax
- Gainesville AV
- Gainesville Bike and Pedestrian Safety
- City of Orlando Greenway/Pedestrian Safety
- SR-434 Connected Vehicle Deployment
- Downtown Tampa Autonomous Transit
- Orlando Smart Community 2017 ATCMTD
- Voyage at the Villages
- Implementing Solutions from Transportation Research and Evaluation of Emerging Technologies (I-STREET)
- Gainesville Signal Phase and Timing (SPaT) Trapezium

2.10 METHODS TO SUPPORT ITS DEPLOYMENT DECISIONS

Decisions to invest in alternative ITS technologies to support TSM&O are expected to increase in complexity, particularly with the introduction of connected vehicles (CV) and automated vehicles (AV) in the coming years.

The National CV Field Infrastructure Footprint Analysis document produced by the American Association of State Highway and Transportation Officials (AASHTO) (Jill, 2013) pointed out that public agencies will need to assess the use of connected vehicle probe data versus existing methods of data collection.

This section reviews what is known about the factors considered by agencies when investing in ITS and CV and proposed methods to support the decision to deploy ATM and CV-based technologies. This review will provide input to develop a method in this study to support the decision to invest in CV. This review includes the decision factors influencing investment decisions and previous methods used in assessing the return on investment and the utility of an ITS solution for a transportation agency.

The USDOT Connected Vehicle Impacts on Transportation Planning Project documents (Krechmer et al., 2015) mentioned that since the Connected and Automated Vehicle (CAV) is an emerging technology, it may be difficult to quantitatively rank CAV projects using traditional evaluation metrics, such as benefit-cost ratio. The estimates for costs and benefits are still preliminary and depend on many factors, such as market penetration, industry competition, and regional coordination. This will be considered as a method is developed to support the decision-making process.

2.10.1 Decision Factors Influencing ITS and CV Deployment Decisions

To develop methods to support agency decisions with regard to CV deployments on arterials, it is important to understand the factors considered by agencies when deciding to deploy specific ITS or CV technologies.

A survey that was done as a part of the United States Department of Transportation (USDOT) ITS Deployment Tracking Project (Khazraeian, 2017) identified safety and mobility benefits, integration with existing technologies, availability of funding, and equipment price as the major factors in the decision-making process for investing in ITS technologies.

In another study, the USDOT conducted the "Longitudinal Study of ITS Implementation: Decision Factors and Effects" to identify the above-mentioned factors (Shah et al., 2013). The study used an interview-based approach to analyze the decision factors of the public sector and the trucking and automobile manufacturer decision makers. Results indicate that for the public sector, the most important factor was quality and reliability, followed by interoperability considerations, and the demonstration of benefits. The most important external factor was budget and funding sources. For the trucking industry, the most important factors for adopting a new technology were the cost/return on investment, compatibility with existing systems, readiness and maturity of the technology, quality and reliability, and product service and support. The study investigated whether the importance of the factors changes with the phase of ITS implementation. During the initiation phase, budget and funding were the most critical factors (rating of 7.8). The demonstration of benefits and involvement in the project by stakeholders was second, with a rating of 7.2. At the development phase, budget and funding had a rating of 8.4 out of 10, and interoperability came in second, with an average rating of 7.9. In the deployment phase, quality and reliability (8.9 rating) and end-user awareness/understanding (8.4 rating) exceeded budget and funding (8.3 rating). During this phase of ITS implementation, organizational factors become important with an 8.0 rating, including staff knowledge and expertise, clarity in division of responsibilities, and having partners onboard (all with an 8.0 rating). Specified barriers include legal and regulatory, financial and economic, and decision-making barriers. It has been noted that many of these factors are expressed in the framework for the Capability and Maturity Model developed for the TSM&O. Decision makers wanted more information about CV applications and on the business cases of CV-based deployments. Stakeholders expressed that the federal government needs to provide more demonstrations, training, and direction to local and state DOTs.

A study by the Michigan Department of Transportation conducted a survey of public agencies to identify their views of the challenges of various issues to the broader adoption of connected vehicle technologies (MDOT 2012) (Hadi, 2017). Figure 2-8 shows the level of different challenges according to the survey responses. The identified issues with different challenge levels include:

- Funding
- Driver distraction
- Liability concerns
- Maintaining proper system functionality
- Security
- Privacy
- Standard maturity
- Costs

Chapter 4 provides a further discussion of the risks and constraints associated with CV applications.

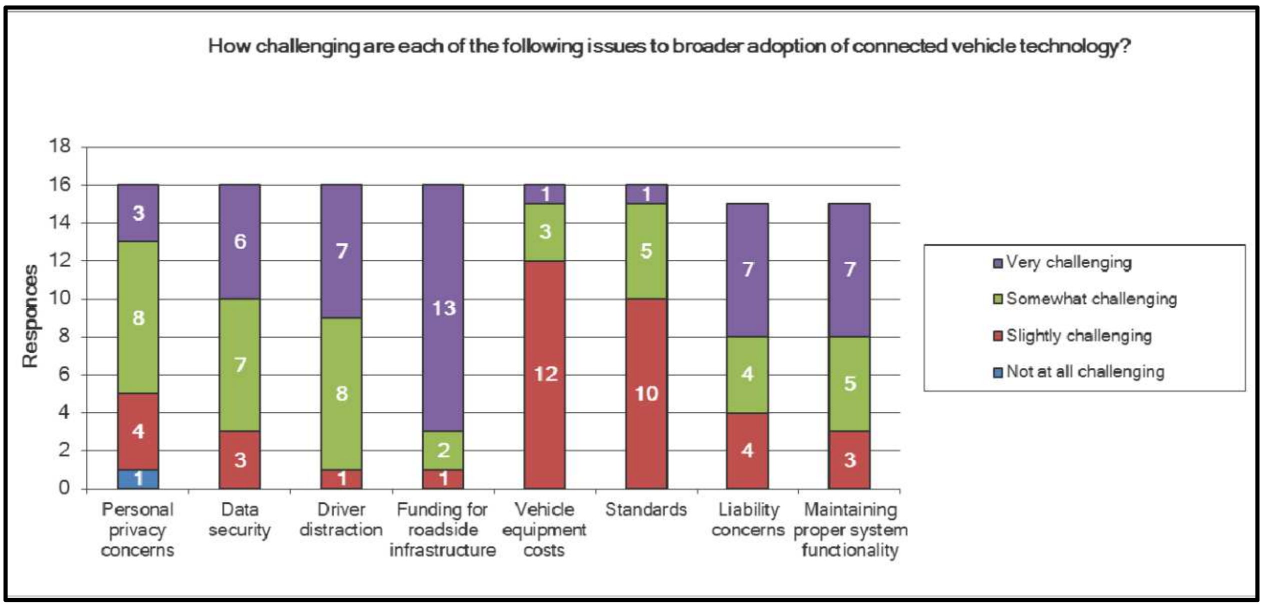


Figure 2-8 Survey Response to the Question of the Challenges of Various Issues to Broader Adoption of Connected Vehicle Technologies (MDOT, 2012)

2.10.2 ATM Screening Guide Method

The Active Traffic Management Feasibility and Screening Guide (Neudorff and McCabe, 2015) presented a recommended process to follow when considering ATM deployment to help identify the specific roadway segments that are most suited for ATM and the appropriate ATM strategies, the expected costs, and range of benefits. The process supports an "objectives-driven, performance-based approach to planning for operations," promoted by the FHWA and the Federal Transit Administration (FTA). The process is summarized in Figure 2-9.

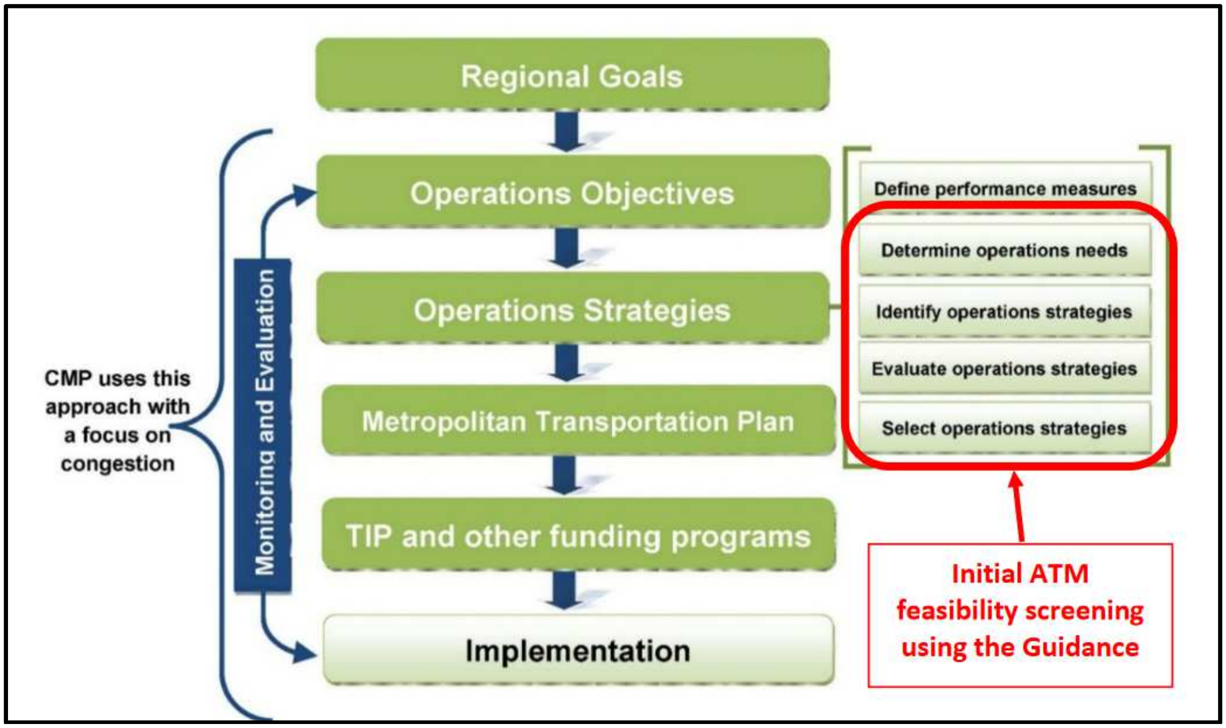


Figure 2-9 Process Recommended in the Active Traffic Management Feasibility and Screening Guide (Neudorff and McCabe, 2015)

The following are the steps of the process mentioned above:

- **Preparation step:** This step involves ensuring that the selected ATM strategies support agency goals, identifying relevant objectives for ATM, linking ATM Strategies with goals and objectives, defining the network to be analyzed, identifying and collaborating with stakeholders, conducting data collection, and reviewing recent literature.
- **Assessment of Agency Policies and Capabilities for Active Traffic Management:** This step involves confirming the existence of the needed supporting institutional framework.
- **Identification of Major Roadway Segments for Potential Active Traffic Management:** In this step, major segments that will likely benefit from deploying ATM (e.g., safety problems, recurrent congestion, and non-recurrent congestion) are identified.

- **Analysis and Prioritization of Individual Roadway Links and ATM Strategies:** This step includes ranking based on traffic operation and safety analysis.
- **Estimate Benefits and Costs:** The final step is to estimate the return on investment utilizing sketch planning tools, highway capacity manual procedures, and/or other methods.

2.10.3 NCHRP 20-07/376 Method

Traditionally, ITS technology and associated strategy alternatives were assessed using return on investment analyses that involve deterministic estimates of the present values of current and future benefits and costs over the project's life. Discount rates are used to calculate the present value of cash flows. However, these methods are unable to capture the risks and uncertainties associated with the investment problem. In addition, these methods cannot account for agency preferences and constraints that cannot be converted to dollar values.

The authors of this study in an NCHRP report (Hadi, 2017) utilized a combination of a stochastic return on investment analyses and the Monte Carlo Simulation and Multi-Criteria Decision Analysis (MCDA) to select between ITS deployment alternatives considering emerging technologies. The study used the Monte Carlo simulation to account for uncertainty by expressing cost and benefit parameters as probability distributions rather than as fixed values. In addition, the study used MCDA to account for both qualitative and quantitative factors in the decision-making process. The MCDA requires stakeholder input in terms of their preferences and priorities, with respect to various decision criteria and an assessment of each alternative to meet each criterion. The Analytical Hierarchy Process (AHP) MCDA method was selected for use in that study. The objectives included in the AHP process are the provision of the required functions (which can be linked to the goal, objectives, and performance measures), achieving the required performance, minimizing the risks and constraints, and maximizing the return on investment. The approach was applied to the selection of CV-based technology to support traffic data collection and monitoring service, which includes incident detection and travel time estimation and traveler information dissemination. The study noted that these applications were used as examples and the methodology can be applied to other ITS services. The results of the selection between the alternatives are expected to be dependent on the input parameters, which vary throughout different agencies and locations.

A four-level decision making hierarchy according to the AHP method was defined for the purpose of alternative selection. An example of the criteria developed to select between emerging and existing traffic monitoring and data collection technologies is shown in Table 2-5. As shown in Table 2-5, the top level of the decision hierarchy or goal for the case study service is "To select between CV and existing detection technologies for providing traffic data collection and monitoring service." The two middle levels of the hierarchy include the overall objectives and the sub-criteria associated with each of the objectives. And the lower level is the alternative level. The monetizable measures are assessed in the stochastic NPV analysis using the Monte Carlo simulation, and the NPV results are included as a criterion in the AHP analysis. The non-monetizable measures are included as additional measures in the AHP analysis.

Table 2-5 Criteria for Selection between Emerging and Existing Traffic Monitoring and Data Collection Technologies

Goal	Objectives	Sub-Criteria	Alternatives
Selecting between CV and existing detection technologies for providing traffic data collection and monitoring service	1-Provision of the required functions	1.1- Ability to measure travel time	CV data
		1.2- Ability to measure volume and/or density	Point detectors
		1.3- Ability to measure new measures (acceleration noise, stops, breaks, windshield wipers on/off, light on/off, emission, potential for crashes, etc.)	
	2-Achieving the required performance	2.1- Mean absolute error in measurement	
		2.2- Standard deviation of error of measurement	
		2.3- Detection timeliness	
	3-Minimizing the risks and constraints	3.1- Technology uncertainty	
		3.2- Standard stability	
		3.3- Uncertainty in business model	
		3.4- Data archiving and processing and technical skill concerns	
		3.5- Funding (initial and recurring)	
		3.6- Data availability and sharing concern	
		3.7- Security and privacy concerns	
	4-Maximizing the return on investment based on NPV	4.1- Median present worth (based on Monte Carlo analysis)	
		4.2- 15% present worth (based on Monte Carlo analysis)	

2.10.4 SPaT Challenge Resource Team Method for Corridor Selection

The goal of the SPaT Challenge is to encourage state or local agencies throughout the United States to deploy SPaT message broadcasts at approximately 20 intersection locations, typically in a corridor or network setting. The SPaT Challenge Resource Team was formed by the V2I Deployment Coalition to support the National Connected Vehicle SPaT Deployment Challenge (National Operations Center of Excellence, 2018). The Resource Team has developed guidelines for selecting corridors to implement SPaT technologies, although it realized that often the final selection of early technology deployments depends on institutional decision as much as on a technical or cost-based decision. Thus, the Guidelines stated that it is expected that each agency will select corridors/networks for SPaT implementation based on their own decision-making process.

The Guidelines identified at least two high-level types of decision criteria:

- ***Need for V2I Applications.*** This involves selecting a corridor with a need for V2I-based applications. Examples of the needs include:
    - Need for transit signal priority - TSP functions with V2I applications may include more sophisticated priority algorithms based on more detailed information provided by SPaT and could include feedback sent to the driver regarding whether the priority request was accommodated.
    - Signalized corridors operating at or near capacity during peak periods - A SPaT deployment in the short term could enable Intelligent Signal Systems in the future that benefit from the additional information provided through V2I communications.
    - Urban arterials that can be part of an Integrated Corridor Management (ICM) deployment.
    - A corridor or a network with heavier than normal emergency vehicle traffic that currently utilizes emergency vehicle preemption.
    - A corridor with higher than normal red-light violations and/or crashes related to red light violations.
    - A corridor with higher than normal commercial vehicle/freight traffic to enable applications, such as the Freight Signal Priority.
    - A corridor with a major special event venue - A SPaT deployment can now support adaptive or reactive special event signal timing and traveler information dissemination systems.
- ***Infrastructure Compatibility.*** This involves selecting a corridor with infrastructure that is ready and compatible for SPaT deployment now or in the near future, and whether or not the infrastructure includes:
    - Traffic signal controller and software that outputs the SPaT message.
    - Traffic signal controller and software are able to receive and process messages for applications that require this capability, such as TSP and Intelligent Signal Systems.
    - The signal controller cabinet has a space for adding equipment, as needed for the application.
    - There are available ports in the traffic signal controller to connect to the DSRC antennae (or intermediate server), as needed.
    - There is backhaul communication or capability to add the required infrastructure to support backhaul communications to the signal controller.
    - The positions of the DSRC antennas have been identified considering the needed line of sight visibility to vehicles.
    - Cable communications between the controllers and the DSRC Antenna locations are possible, and power can be made available to the pole where the DSRC antennae would reside.
    - GPS coverage at the candidate intersection(s) is reliable and has good coverage with limited "urban canyons" effects or errors introduced by atmospheric conditions.
    - Traffic signal controller operating with a high-quality time source (i.e., +/-250 milliseconds or more)?

2.10.5 FHWA Near-Term V2I Transition and Phasing Analysis Tools

AASHTO has developed a set of tools for assisting transportation agencies with decision making and preparing/planning for connected vehicle deployments. The tools include the Application Prioritization Tool (APT), Lifecycle Cost Model (LCCM), and Infrastructure Planning Tool (IPT).

- The Application Prioritization Tool (APT) (Booz Allen Hamilton, 2014) identifies relevant CV V2I applications based on needs, issues, and impacts for a given deployment. Table 2-6 presents the intended impact (need) specification input by the user to the APT tool for an urban arterial.
- The LCCM (Platte, 2016) prompts the user to specify which application is to be costed out, as well as the quantities of specific components. The tool considers overlays as percentages of the total capital costs. These can include Operating & Maintenance (O&M) costs, Systems engineering and installation costs which are captured as overlays that are applied annually. Table 2-7 presents a list of the inputs to the LCCM for an urban arterial.
- The Infrastructure Planning Tool (IPT) (Walker, 2015) simultaneously compares up to five applications based on four dimensions: 1) initial capital (equipment) cost; 2) number of corridors/locations/road segments; 3) secondary advantages of an application, and 4) replacement interval of the equipment. The objective of the IPT is to provide users with a top-level overview of the infrastructure components required to establish a CV V2I application. Additionally, the IPT helps users compare infrastructure trade-offs between multiple V2I applications at once. The raw scores for each dimension are presented in Table 2-8. The IPT captures the raw score and multiplies it with the dimension weight to arrive at a total weighted score. Table 2-9 shows an example of the application of the tool to select deployment alternatives.

Table 2-6 Need Specification Input to the APT Tool for an Urban Arterial

	STEP 3:	
	Please select all of the options below that represent the impacts you are hoping to achieve with the deployment you are considering Select options by indicating Y (Yes) or N (No) in front of each possible impact	
Intended Impacts:	Improved queue detection	
	Improved queue warning and response strategies	
	Improved driver warning and alerts	
	Reduced queue severity	
	Reduced intersection queues	
	Reduced crashes	
	Reduced congestion	
	Improved traffic throughput	y
	Improved speed harmonization	y
	Enhanced data-driven operational strategy implementation	
	Improved communication of roadway, vehicle, and incident data	
	Optimized signalized intersections	
Intended Impacts:	Reduced pedestrian related incidents at signalized crosswalks	y
	Reduced incidents at non-signalized intersections	y
	Reduced incidents at non-signalized intersections with stop signs	
	Improved adherence to stop sign right of way	
	Improved driver warning and alerts	

Table 2-7 Input to the LCCM Tool

Step 1. Application Selection Input	
Application Selection	
Please select application	Dynamic Speed Harmonization - Cellular (SPD-HARM)
Please select application	Dynamic Speed Harmonization - DSRC (SPD-HARM)
Please select application	

Step 2. Select Application Building Block Quantities	
Dynamic Speed Harmonization - Cellular (SPD-HARM) Application Building Block	
Key Variable	Quantity
How many Drivers for Transit Vehicles will be included in this deployment?	1
How many Drivers for Trucks will be included in this deployment?	1
How many Transit Vehicles will be included in this deployment?	1
How many Trucks will be included in this deployment?	1

Step 2. Select Application Building Block Quantities	
Dynamic Speed Harmonization - DSRC (SPD-HARM) Application Building Block	
Key Variable	Quantity
How many Drivers for Transit Vehicles will be included in this deployment?	1
How many Drivers for Trucks will be included in this deployment?	1
How many Road Segments will be included in this deployment?	1
How many Signalized Intersections will be included in this deployment?	1
How many Transit Vehicles will be included in this deployment?	1
How many Trucks will be included in this deployment?	1

Table 2-8 Raw Score for Each Dimension Used in the IPT Tool

Scoring	Initial Capital Cost
1 (Best)	$0-$100,000
2 (Slightly Above Average)	$100,001-$150,000
3 (Average)	$150,001-$170,000
4 (Slightly Below Average)	$170,001-$200,000
5 (Worst)	$200,001+

Scoring	# of Corridors
1 (Best)	1 Corridor
2 (Slightly Above Average)	2 Corridors
3 (Average)	3 Corridors
4 (Slightly Below Average)	4 Corridors
5 (Worst)	5+ Corridors

Scoring	Replacement Interval
1 (Best)	21-25+ years
2 (Slightly Above Average)	16-20 years
3 (Average)	11-15 years
4 (Slightly Below Average)	6-10 years
5 (Worst)	1-5 years

Scoring	Secondary Application Feature
1 (Best)	2+ Additional Impacts
2 (Slightly Above Average)	
3 (Average)	1 Additional Impact
4 (Slightly Below Average)	
5 (Worst)	0 Additional Impacts

Table 2-9 Example of IPT Tool to Select Alternative Scenarios

		Connected Eco-Driving - Cellular (CED)			
Evaluation Criteria	**Weight [%]**	Raw Score	Weighted Score	Initial Equipment Cost (Taken from LCC):	Additional Notes:
(1) Initial Capital Cost	35%	1	0.35	(3) $67,336	User-defined:$0-$100k
Secondary Application Impact	25%	1	0.25	(4) Improve Safety Improve Mobility (a)	
# of Road Segments	10%	1	0.1	1 (b)	
Replacement Interval (years)	30%	5	1.5	2 (c)	
	100%				
Total Score		(2)	2.2		

2.11 POTENTIAL PROCESS TO SUPPORT DEPLOYMENT ALTERNATIVE SELECTION

This section presents an overview of a process designed to assist with deciding on investing in ATM and CV-based technologies. The steps of the process are identified below. The following chapters of this document will present additional details about these steps and the application of the methodology to a project case study.

Identifying the Needs, Functions and Alternative Solutions: The first step involves identification of the needs of the corridor under consideration and the associated functions to address these needs as related to the goal areas and operational objectives. Then, alternative solutions to address these needs are identified by providing the associated functions. The alternative solutions to be considered can include existing and/or emerging strategies and applications that provide the functions. The emerging technologies, however, can provide additional functions not provided by the existing alternatives. A catalog of the required functions and solutions are provided in Chapter 2.

Identifying the Performance of Each Alternative Solution: This step determines the performance of each alternative solution based on a detailed review of current knowledge base, data analysis, sketch planning-level modeling, and/or other levels of analysis and modeling. This report presents a review of what is currently known about the performance of existing and emerging ATM and CV-based solutions and provides a list of mobility modification factors (MMF) and crash modification factors (CMF) for use in the assessment of alternative solutions.

Evaluating the Return of Investment of Deployment Alternatives: This step utilizes information from the previous steps to estimate the dollar value of the impacts of alternative deployments. These estimates are then combined with the estimates of the deployment cost for the estimation of return on investment for each alternative.

Conducting Multi-Criteria Assessment of Deployment Alternatives: This study will investigate the use of a Multi-Criteria Decision Analysis (MCDA) method to account for both qualitative and quantitative factors in the decision-making process. The MCDA requires stakeholder inputs regarding their preferences and priorities, with respect to various decision criteria and an assessment of each alternative to meet each criterion. It is anticipated that the objectives included in the process will include the provision of the required functions, achieving the required performance, minimizing the risks and constraints, and maximizing the return on investment. Examples of the risks and constraints can include uncertainty in the benefits, protecting the existing investment, technology uncertainty, technology and standard immaturity, cost uncertainty, security and privacy, and data availability and sharing concerns.

Table 2-10 Catalog of Functions and Alternative Solutions to Support the Mobility and Reliability of All Users Goal Area of the FDOT TSM&O Strategic Plan (FDOT, 2017)

Function	Existing Solutions (Non-CV Solutions)	CV-Based Support	Current Plan in Florida and CV Pilot Sites	Related SE Florida SITSA Packages	Related Additional ARC-IT Packages not in SITSA
Optimize signal timing control	Retime signals using data collected manually or using existing detection technologies. High resolution controller data have started to be used to support retiming.	I-SIGCVDAT CV Data for Intelligent Traffic Signal System -CV will provide data that will replace some of the existing data collection sources (travel time at relatively low market penetration and volume at high market penetration. In addition, CV will provide trajectory data that can be used by itself in conjunction with high resolution data to allow more advanced signal retiming.	Tampa and New York pilots SR-434 Connected Vehicle Deployment City of Orlando Greenway/Pedestrian Safety	ATMS01 Network Surveillance, ATMS02 Traffic Probe Surveillance, and ATMS03 Traffic Signal Control AD2 ITS Data Warehouse	SU01- Connected Vehicle System Monitoring and Management DM02- Performance Monitoring

Table 2-10 (Continued)

Function	Existing Solutions (Non-CV Solutions)	CV-Based Support	Current Plan in Florida and CV Pilot Sites	Related SE Florida SITSA Packages	Related Additional ARC-IT Packages not in SITSA
Utilize signal control that accommodate varying conditions	Adaptive signal control. It is one of the FDOT STAMP focus areas. There is an increasing interest in these strategies in Florida.	MMITSS I-SIG - Traffic conditions data can be collected through CV-based technologies, initially in combination with sensors. New measures, such as vehicle trajectories can be used as part of the adaptive signal control. There is a potential to optimize timing and trajectories.		ATMS01 Network Surveillance, ATMS02 Traffic Probe Surveillance, and ATMS03 Traffic Signal Control	TM04 Connected Vehicle Traffic Signal System
Allow safe and efficient pedestrian signal control	Pedestrians request walk signals. In addition, infrastructure-based detection has been used to detect bicycles and pedestrians, but is not widely used.	MMITSS PED-SIG Integrates information from roadside or intersection sensors and new forms of data from pedestrian-carried mobile devices. Disabled or senior pedestrians can request a walk signal and/or extended green time through mobile devices.	Tampa and New York Pilot	ATMS01 Network Surveillance and ATMS03 Traffic Signal Control	TM04 Connected Vehicle Traffic Signal System

Table 2-10 (Continued)

Function	Existing Solutions (Non-CV Solutions)	CV-Based Support	Current Plan in Florida and CV Pilot Sites	Related SE Florida SITSA Packages	Related Additional ARC-IT Packages not in SITSA
Maximize the utilization of green with a given set of signal timing parameters		Eco-arrival and Infrastructure-based CACC to inform vehicles regarding the beginning of green or automates their speed selection to allow drivers to arrive on green.	New York Pilot		ST08: Eco-Approach and Departure at Signalized Intersections VS15 Infrastructure Enhanced Cooperative Adaptive Cruise Control
Improve emergency vehicle response time	Central software-based and field-based signal preemption	MMITSS PREEMPT - CV communication supports the preemption requests and provides a response to the vehicle to advise whether priority has been granted.		EM02 Emergency Routing	TM04 Connected Vehicle Traffic Signal System
Improve transit and freight measures. Improve Bus On-schedule Performance	Transit Signal Priority (TSP Transit vehicle requests extend green or provide early termination of red using central software or field-based priority.	MMITSS TSP and FSP - CV communication support priority requests and provide a response to the vehicle by advising whether priority has been granted.	TSP in Tampa	APTS09 Public Transport Signal Priority	CVO06 Freight Signal Priority TM04 Connected Vehicle Traffic Signal System

Table 2-10 (Continued)

Function	Existing Solutions (Non-CV Solutions)	CV-Based Support	Current Plan in Florida and CV Pilot Sites	Related SE Florida SITSA Packages	Related Additional ARC-IT Packages not in SITSA
Utilize connected vehicle data for off-line planning and real-time monitoring		Probe-enabled Traffic Monitoring		AD2 ITS Data Warehouse	SU01- Connected Vehicle System Monitoring and Management DM02- Performance Monitoring
Provide information to travelers to influence their behavior in support of management and provide evacuation and unusual situation alerts	Dynamic message signs, 511 traveler phone and website. Potential for predictive traveler information and dynamic routing.	Evacuation Information (EVACINFO) delivers messages to travelers in connected vehicles and other mobile devices in an integrated and coordinated manner. Possibly, jointly optimize route diversion and signal optimization.		ATIS01 Broadcast Traveler Information ATIS02 Interactive Traveler Information ATIS05 ISP Based Trip Planning and Route Guidance EM10 Disaster Traveler Information	

Table 2-11 Catalog of Functions and Alternative Solutions to Support the Safety of All Users Goal Area of the FDOT TSM&O Plan

Function	Existing Solutions (Non-CV Solutions)	CV-Based Support	Current Plan in Florida and CV Pilot Sites	Related ARC-IT Packages not in SITSA
Improve queue detection, warning, and response strategies	Possibly, using point detection and infrastructure-based DMS	Queue Warning (Q-WARN)		VS08 Queue Warning
Improve driver warnings regarding the need to slow down due to hazardous conditions, lane closures, and work zones		Reduced Speed/ Work Zone Warning	New York Pilot	VS09 Reduced Speed Zone Warning / Lane Closure VS10 Restricted Lane Warnings VS15 Infrastructure Enhanced Cooperative Adaptive Cruise Control
Reduce pedestrian and bicycle crashes at intersection crosswalks		Pedestrian in Signalized Crosswalk Warning	Tampa and New York pilots US 90 Mahan Drive in Tallahassee, FL Gainesville SPaT Trapezium City of Orlando Greenway/Pedestrian Safety	VS12 Pedestrian and Cyclist Safety

Table 2-11 (Continued)

Function	Existing Solutions (Non-CV Solutions)	CV-Based Support	Current Plan in Florida and CV Pilot Sites	Related ARC-IT Packages not in SITSA
Reduce red light violations and associated crashes		Red light Violation Warning	New York pilot	VS13 Intersection Safety Warning and Collision Avoidance VS15 Infrastructure Enhanced Cooperative Adaptive Cruise Control
Improve pedestrian and bicycle safety on heavily traveled bus routes and midblock crosswalks		Pedestrian in Signalized Crosswalk Warning	Tampa and New York pilots	VS12 Pedestrian and Cyclist Safety
Provide pedestrian information about crossing signal timing improve safety of visually impaired pedestrians		Mobile Accessible Pedestrian Signal System	Tampa and New York pilots	VS12 Pedestrian and Cyclist Safety
Improve truck safety on curves (on ramps) and warn approaching vehicles of queue backup in curve		Curve Speed Warning		VS05 Curve Speed Warning
Reduce permissive left-turn crashes				VS13 Intersection Safety Warning and Collision Avoidance
Alerts the driver of height-restricted infrastructure		Height Restriction Warning (using vehicle height detectors)		VS11 Oversize Vehicle Warning

Table 2-11 (Continued)

Function	Existing Solutions (Non-CV Solutions)	CV-Based Support	Current Plan in Florida and CV Pilot Sites	Related ARC-IT Packages not in SITSA
Reduce right-turn crashes				VS13 Intersection Safety Warning and Collision Avoidance
Reduce wrong way driving		Wrong-Way Driving Warning and Control		VS03 Situational Awareness
Increase the safety of work zones and incident investigation sites	Various TIM and work zone strategies and MOT	INC-ZONE and RESP-STG warn drivers that are approaching work zones at an unsafe speed and/or trajectory. It also warns responders and workers in the zone. It also provides input regarding routing, staging, and secondary dispatch decisions.		PS06 Incident Scene Pre-Arrival Staging Guidance for Emergency Responders PS07 Incident Scene Safety Monitoring
Route emergency vehicles		**RESP-STG** provides emergency vehicles with the best route to incident locations.		PS02 Routing Support for Emergency Responders PS03 Emergency Vehicle Preemption

3. IDENTIFICATION OF NEEDED FUNCTIONS AND ASSOCIATED IMPACTS

This chapter includes a review of the ATM functions required to meet project needs, existing applications to provide each of these functions, CV-based applications that can support the provision of the required functions, and the performance of the existing and CV applications in providing the required functions.

3.1 ARTERIAL STREET APPLICATIONS AND ASSOCIATED PERFORMANCE

Safety and mobility needs can be addressed by functionalities that can be provided by existing and/or emerging technologies, applications, and strategies. This section includes a review of the required functions, existing applications to provide each of these functions, CV applications that can support the provision of the functions, and the performance of the existing and CV applications in providing the required functions. The identified, required ATM functions addressed in this section fall into the following categories:

- Data collection to support system management, including probe data collection to support segment performance measurements, automatic incident detection, and support of off-line signal control.
- Provision of signal control to accommodate varying conditions, including adaptive signal control, transit signal priority (TSP), freight signal priority (FSP), pedestrian signal control, and emergency vehicle preemption.
- Speed adjustment to support arrival on green, including green light optimal speed advisory (GLOSA) and Glide Path (involving partial automation).
- Support of incident and emergency response, including increasing incident zone site emergency responder and vehicle safety and mobility, emergency vehicle staging and routing, and evacuation support.
- Dynamic information and guidance to support management, including the provision of traveler information, provision of route, mode and trip time guidance, and optimization of guidance combined with signal and other management system optimization.
- Support of signalized intersection safety, including permissive left and right turns on red support, red light violation and rear-end collision reduction, reduce pedestrian on crosswalk crashes, and support of visually impaired pedestrian in crossing the street.
- Support of unsignalized intersection safety, including warning drivers of potential stop sign violation and support gap acceptance at a stop sign.
- Hazard warning, including warning drivers of unsafe speeds, warning drivers of unsafe speeds on curves, warning drivers of oversize vehicles, warning drivers of bad weather and pavement conditions, and warnings at railroad crossings.

3.1.1 Data Collection to Support System Management

3.1.1.1 Provided Functions

Probe data can be collected and fused with data from other sources to determine segment level, intersection level, and intersection movement level performance measurements to support better control and management of traffic. The functions can be classified in the following three categories.

- ***Performance Measurement:*** This includes measuring or estimating segment performance measures, such as volume and speed, that can be used by a system operator, planner, or an automated system to support planning, management, and operational decisions. The measurements can also be used as the bases to derive information for dissemination to travelers, third-party data aggregators, traveler information service providers, and other agencies, such as transit, emergency, planning, and other traffic management agencies.
- ***Incident and Congestion Detection:*** This involves detecting and verifying the occurrence of congestion, incident and associated attributes, including the exact location of the incident, number of lanes blocked, identification of the blocked lane(s), the number and types of vehicles involved in the incident, incident severity, lane clearance, bottleneck attributes, back of queue, and incident clearance.
- ***Support of Off-Line Signal Timing Control:*** This function provides probe data to support signal timing control. The probe data can be used in combination with high-resolution controller data, data from other sources, and modeling to derive signal timing parameters and provide time to switch between signal timing plans.

3.1.1.2 Existing Solutions

- ***Performance Measurement:*** Point detectors have been used to measure traffic speeds at a point, and these speeds are then used to estimate the travel times between segments. For urban arterials, point detectors at midblock are useful in providing segment volume and possibly free-flow speed. However, they are not appropriate for measuring segment level travel time on arterials. For the purpose of travel time estimation, automated vehicle identification (AVI) technologies, particularly those utilizing Bluetooth and Wi-Fi readers, have been used. Data from third-party vendors have also been used for travel time measurements. AVI and third-party vendor data can also provide partial origin-destination (O-D) matrices that are particularly useful for transportation engineering and planning studies. High-resolution controller data have recently been used to estimate intersection and movement level performance measures.

- ***Incident and Congestion Detection:*** A critical function of traffic monitoring systems is the fast detection and validation of incident occurrence and attributes to reduce lane and shoulder blockage durations, as well as to allow fast notification of responding agencies. Traffic management centers currently detect incidents utilizing a number of methods, including processing of data collected from point detectors (and in some cases AVI data) and external notifications, including notifications from the police, service patrols, and video analytics. Recently, agencies have also obtained third-party private-sector incident feeds (from WAZE), which are important, particularly when dealing with incidents occurring on segments that are not well covered by incident management activities, such as urban arterials and rural freeways.

- ***Support of Off-Line Signal Timing Control:*** For decades, traffic signal management agencies have used signal timing optimization tools combined with the fine-tuning of signal timing based on a limited amount of data and field observations in their updates of time-of-day signal timing plans. Traditionally, signal control optimization and management processes have been based on turning volume data collected for one day and approach volumes collected for three to seven days. The data are then used to prepare inputs to signal optimization models. Agencies normally fine-tune the signal timing after implementation to account for the differences between the model results and the real-word measurements and observations. The agencies then update the signal timings either at predetermined intervals or when getting complaints from the public. In recent years, new data collection technologies have emerged, including the use of high-resolution controller data and other data to estimate Automated Traffic Signal Performance Measures (ATSPM) (Sharma et al., 2007; Mackey, 2014; Day et al., 2015). Such data can be used to fine-tune signal timing parameters to improve progression and minimize delay.

3.1.1.3 CV-Based Solutions

CV technology allows for the collection of data and information that can be used with data from other sources to provide the functions outlined in Section 3.1.1. CV will provide vehicle trajectories, or more likely partial vehicle trajectories since the vehicle ID will be updated at five-minute intervals according to the CV Society of Automotive Engineers (SAE) J2735 standards (SAE, 2016) to protect privacy. This data can be used as an important source to support transportation system management, including detecting incidents, estimating network and segment performance measures, and estimating intersection level measures to support off-line signal control optimization. The intersection level measures can be derived based on a combination of high-resolution controller data and CV data. Some of the parameters that can be better estimated with CV vehicle data rather than high-resolution controller data include queue length, delay, arrival on green/progression, number of vehicles in the dilemma zone when the service phase maxes out, arrivals on yellow and red, transit and freight delay, and pedestrian delay. These measures can be used by transportation agencies to assess the mobility and safety performance of the system and support system management and control.

Depending on the type of data that will be available from the Controller Area Network (CAN bus) of a vehicle and what is specified in the CV message standards, CV data will allow for the estimation of a number of other segment and trip level measures that cannot be estimated by existing technologies or require additional detection. These measures can be used as inputs for a new generation of traffic management and operation strategies, as well as to provide additional support for the planning, design, and operation of transportation systems. The measures include vehicle classification, acceleration/deceleration, number of stops, number of brakes, potential for crashes, emission/fuel consumption, and weather and lighting conditions.

3.1.1.4 Reported Performance of Existing Solutions

Estimating segment travel times is particularly difficult on arterial streets due to lower volumes (thus lower sample sizes), interrupted flow operations that cause variations in travel times in time and space, driveways, adjacent land uses, and activities that may affect the data collection effort. As stated earlier, there has been an increasing use of automatic vehicle re-identification techniques, such as Bluetooth, Wi-Fi, and electronic toll collection–based systems, for travel time estimation for performance measurements. A study conducted in the state of Washington evaluated the accuracy of these methods to measure the travel times of an urban arterial (Wang et al., 2014). The tested commercial products were an automatic license plate reader (ALPR) system, matching based on vehicle signatures using magnetometers, two Bluetooth and Wi-Fi-based systems, and a third-party feed. The ALPR system was used as a ground truth system becuase it had been previously evaluated and proven to be accurate enough to serve as the source of ground truth data. The study found that the mean absolute percentage error (MAPE) of the data collected from the Bluetooth devices and the combined Bluetooth–Wi-Fi device compared to the ALPR measurements ranged between 13% and 20%. The MAPE of the magnetometer-based measurements ranged between 18% and 25%. The error rate of the third-party vendor measurements ranged between 15% and 48%. Some of these reported errors are surprisingly high. An evaluation of probe data for the I-95 coalition in 2013 found that third-party probe data can adequately detect congestion on arterial streets when the number of signalized intersections per mile is less than or equal to one on principal arterials with an annual average daily traffic (AADT) of 40,000 vpd or more (Young et al., 2015). However, the study found that the data increasingly underestimates congestion as the number of intersections increases. This is because with an increased number of intersections there is a increase in the variations in travel times, decrease in volume, and a smaller sample size than statistically required (Young et al., 2015). In general, the sample sizes of Bluetooth data, Wi-Fi data, and third-party vendor data are not sufficient for low traffic volume conditions. In addition, the Bluetooth and Wi-Fi readers cannot be placed a short distance apart due to the inaccuracy of the identification of the position of the vehicles within the detection radius. Thus, they cannot be used to determine travel time on short urban arterial links between intersections.

Martin et al. (2009) presented a comprehensive review of previous studies that assessed various incident detection algorithms based on point detectors. The conclusion was that for most algorithms, the maximum mean detection time was five minutes. However, it should be mentioned that such a conclusion should be considered with caution since the incident detection performance is expected to depend on the congestion level and traffic demands. Most existing incident detection algorithms cannot detect the incident until the queue caused by the incident reaches the upstream detector and/or there are significant impacts on throughputs, which may take a long time or may never happen if the demands are low and the queues due to incidents are short or do not exist. On arterial streets, the detection is complicated by the queues due to signal control operations that may not allow for the fast detection of additional queues due to incidents.

With regard to retiming signal control based on existing data collection technologies (excluding high-resolution controller data), Hadi et al. (2008) estimated, based on an extensive review of literature, that retiming coordinated signal control improves performance by 7.5% and coordinating isolated signals improves performance by 11.5%.

3.1.1.5 Reported Performance of CV-Based Solutions

There are a number of studies in the literature that focus on travel time estimation utilizing connected vehicle data. Zou et al. (2010) estimated travel time based on CV data using the traffic simulation of a hypothetical network that simulates vehicles broadcasting Probe Data Messages (PDM) data according to the Society of Automotive Engineers (SAE) J2735 standards [1](SAE, 2016). They found an average error percentage of 27.6%, 12.5%, and 8.2% for 1%, 5%, and 10% CV proportions, respectively. The researchers of this study (Iqbal et al., 2017 and 2018) developed a method to assess the impact of connected vehicle market penetration on the accuracy of travel time estimation. As shown in Figure 3-1, the errors in travel time estimation for arterial segments are reduced with the increase in CV market penetration. Market penetrations of about 5% and 10% produce a Mean Absolute Percentage Error (MAPE) of about 9% and 5%, and a Standard Deviation of Percent Error (SDPE) of about 14% and 6%, respectively. However, large errors can be observed when examining the 85th and 95th percentile error figures when CV market penetration is low. For planning purposes, a low market penetration of about 3%-4% on urban arterials are sufficient to produce required data quality, especially when averaged over multiple days. However, a CV market penetration that is greater than 10%-15% is required for a higher data quality. It should be noted that these CV market penetration numbers may vary with segment roadway configurations and traffic characteristics.

Connected vehicle data has also been used by several researchers to detect incidents. Utilizing microscopic simulation, Crabtree and Stamatiadis (2007) examined the use of CV data communicated using DSRC to detect freeway incidents. The utilized algorithm was based on comparing measured travel time and "normal" travel time estimated based on no-incident condition data. The results showed that the proposed algorithm can rapidly and reliably detect incidents. The study concluded that for a CV proportion of 30% (25% of the connected vehicles were trucks and 5% were cars), the mean time to detect (MTTD) ranges from two to four minutes

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[1] The Society of Automotive Engineers (SAE) J2735 standards defines the format and structure of message, data frames, and data elements for exchanging data between connected vehicles (vehicle to vehicle or V2V) and between the vehicles and the infrastructure (V2I).

for a DSRC roadside unit (RSU) spacing of 2.0 miles and 2.5 minutes to 14 minutes for a reader spacing of 10 miles. The analysis conducted by the researchers of this study indicated that even with a 3% market penetration on a congested freeway, the queue buildup due to incidents can be detected about four minutes earlier than point detectors, on average. This conclusion was based on simulating a freeway segment with heavy traffic (Hadi et al., 2017).

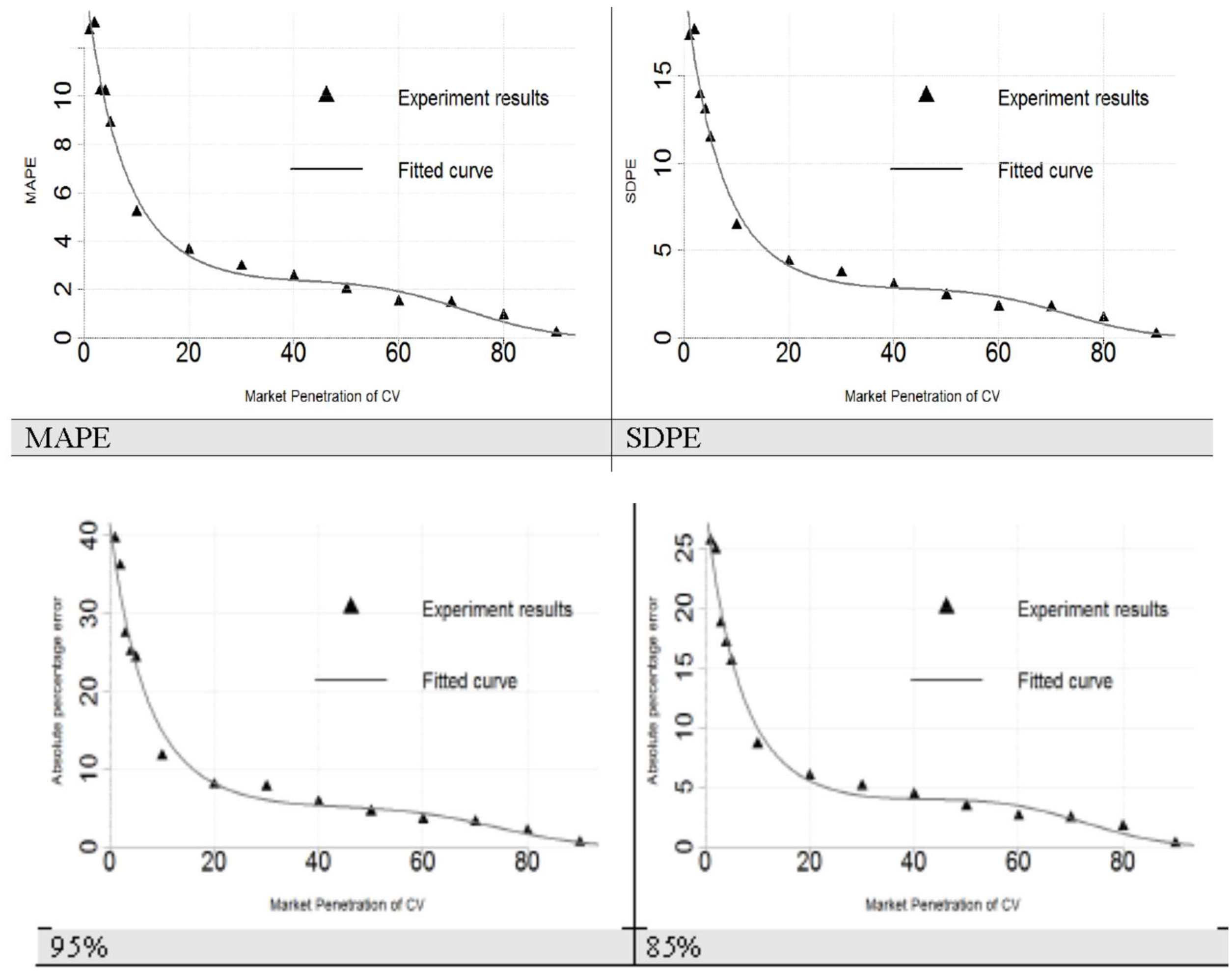


Figure 3-1 Travel Time Accuracy as a Function of CV Market Penetration for an Arterial Segment (Iqbal et al., 2017)

No research has been found regarding the quantitative benefits of using CV and high-resolution data to support signal retiming. An additional review is currently being conducted for this purpose.

3.1.2 Provision of Control to Accommodate Varying Conditions

3.1.2.1 Provided Functions

This function involves the use of detailed data from multiple sources for a better adaptation of signal control to multi-modal demands and changing conditions.

3.1.2.2 Existing Solutions

There has been an increasing interest in utilizing adaptive signal control to improve the performance of urban arterials. In fact, adaptive signal control is one of the six focus areas in the FDOT Transportation System Management and Operations (TSM&O) Strategic Plan, as stated in Chapter 2. These systems provide significant advancements over commonly used time-of-day control. Adaptive Signal Control Technology (ASCT) has been proposed since the 1980s as an alternative to time-of-day operations to better accommodate varying traffic conditions. These systems utilize traffic sensors to provide inputs to the associated algorithms and have seen a considerable increase in their deployment in recent years. In fact, ASCT is one of the FDOT Statewide Arterial Management Program (STAMP) focus areas and there is an increasing interest in these strategies in Florida.

However, there are some limitations in existing ASCT systems. In addition to the need for sensors, these systems utilize aggregate traffic data from point detectors, such as volumes and occupancies. Existing adaptive systems and associated algorithms are still constrained by the low fidelity of data available from current point detection technologies. These constraints limit the system's awareness of the state of traffic, which reduces the performance of adaptive signal control. Overall, existing signal control systems have focused on general traffic, without consideration of the multi-modal aspect of traffic streams. In some cases, rail and emergency preemption, transit signal priority (TSP), and to lesser degrees, freight signal priority (FSP) and advanced pedestrian detection and signal control have been implemented. However, these systems have not been integrated in a multi-modal adaptive signal control and suffer from the low fidelity of the available data.

TSP and FSP use technology to detect approaching high priority vehicles and alter signal timings to provide priority to transit vehicles. The priority provisions are classified into two categories: conditional and unconditional. To obtain conditional priority, when detected, the bus must meet the specified conditions, such as the number of passengers, route schedule adherence, or the time since the last priority was awarded. Utilized priority strategies include green extension, early green, and to lesser extents actuated transit phase, phase insertion, and phase rotation (Urbanik et al., 2015).

Different approaches have been used to address the dilemma zone issue, including the use of infrastructure-based warning flashers to warn drivers of vehicles at risk, extending the all-red phase to avoid side-angle crashes, providing a dilemma zone protection system that is capable of extending or early terminating the green phase, and implementing a detection control system that finds the minimum green phase duration to minimize the number of vehicles in the dilemma zone and vehicle delays in the other phases based on the upstream detection zones and detection zones close to the stop line (Park and Chung, 2017).

3.1.2.3 CV-Based Solutions

CV technology provides the opportunity for multi-modal adaptive control that utilizes detailed data based on approaching vehicle trajectories. The modes can include general passenger vehicles, pedestrians, transit, freight, rail, and emergency vehicles. Connected vehicles will be able to provide detailed information about vehicle position, speed, acceleration, and so on, that will enable more adaptive signal control that takes full advantage of this data. Since it will take some time for CV market penetration to reach a level that is sufficient to fully support adaptive signal control, algorithms that utilize existing data, as well as connected vehicle data, will be potentially used in the near to mid-term future. There are many research efforts on utilizing CV technologies for adaptive signal control. These efforts are not reviewed in this report since they are not ready for implementations. The effort reviewed in this report is the Multi-Modal Intelligent Traffic Signal System (MMITSS) originally developed by the University of Arizona. This application will be evaluated as part of the Tampa CV deployment. The New York City CV Pilot has an application referred to as I-SIGCVDAT–CV, which involves the use of CV data. This application utilizes CV data as an input to the existing Adaptive Control Decision Support System (ACDSS) in the city to supplement or replace the existing data from the electronic toll tag reader system, which provides travel time and speed information to the system.

The University of Florida developed a system that optimizes automated vehicle trajectories when the traffic stream consists of autonomous, connected, and conventional vehicles. This system was tested in Tallahassee with the involvement of the FDOT Traffic Engineering Research Laboratory (TERL).

The MMITSS software was developed as part of the Cooperative Transportation System Pooled Fund Study for the use of CV data for signal control. An important and new capability of MMITSS is the management of multiple requests for priority that may be received from multiple vehicles. These requests can come from emergency vehicles, transit vehicles, freight vehicles, bicyclists, and/or pedestrians, and there are different levels of priority for eligible vehicles of different modes or within the same mode. This can facilitate regional policies and preferences for priority control. The priority decisions can be centralized for a coordinated priority strategy for a section of signals or localized at the intersection level. One of the reported advantages of MMITSS is its ability to place the call and extension of phases with various classes of vehicles. This can be accomplished since the request for a service message contains information about the mode, vehicle class, priority level, and desired time of service. MMITSS has a number of applications:

- **I-SIG:** The Intelligent Traffic Signal System (or ISIG) provides adaptive control and connectivity with the traffic signal control. Within the MMITSS ConOps, I-SIG is supposed to provide four classes of functionalities: Basic Signal Actuation, Coordinated Section of Signals, Congestion Control, and Dilemma Zone Protection. MMITSS is supposed to use CV data and data from field sensors (e.g., loop detectors or pedestrian push buttons) to provide these functions. CV-equipped vehicles provide information about their position and speed when they are within the communication range. A maximum DSRC communication range of 2,600 ft to 3,300 ft has been specified (Siemens, 2018; Tennessee DOT, 2018). This information is used to improve basic traffic signal operations, as well as in the assessment of performance. The signal control system has the ability to inform travelers to know their status in the priority request scenarios. MMITSS can also be used to select the signal timing parameters for better capacity utilization and coordination between signals. Another advantage of MMITSS is the ability of the system to accurately estimate phase failures and the persistence of congested conditions and spillbacks. This allows the system to apply signal timing plans that can accommodate oversaturated conditions. MMITSS also has the ability to address the dilemma zone issue on high-speed approaches. A dilemma zone occurs when a vehicle cannot stop safely when the traffic signal changes from green to yellow and can be further impacted by adverse weather conditions and the presence of heavy vehicles. The Basic Signal Actuation in MMITSS can manage the dilemma zone situation. MMITSS I-SIG has been designed to maximize the throughput of passenger vehicles under saturated conditions and minimizes the total weighted delay during under-saturated conditions. These objectives can be set as variables, depending on agency goals.

- **Intelligent Transit Signal Priority (I-TSP) and Intelligent Freight Signal Priority (I-FSP):** Because CV-equipped priority vehicles can be tracked at a relatively long distance upstream of the intersection (a distance up to 3,000 ft upstream), the downstream signals can recognize the need to provide the priority earlier than what can be currently done with local priority implementations. This allows the controller to better prepare for the priority, such as serving the phases with non-priority calls to reduce the delays for the vehicles served by these faces. Another extension of the basic priority application in MMITSS is dynamically modifying signal timing to allow transit vehicles making a left turn that are blocked by either a short left-turn pocket or long queue for the through movement that blocks the access of the left-turning bus to the left-turn pocket. When such a condition is detected, the system grants priority for the through movement to clear the queue to allow the transit vehicle to access the left-turn pocket sooner and grant priority for the left-turn movement to reduce delay of the transit vehicle. In addition, onboard CV units can be used to inform priority drivers that their priority requests will be met. Another challenge that faces existing TSP implementations is the uncertainty of dwell time associated with nearside bus stops. The nearside stop issue can be addressed by including bus door open/close status in the priority request messages combined with MAP information at the near side stop. The queue between the bus and the nearside stop is also considered.
- **Intelligent Pedestrian (I-PED):** MMITSS can also improve pedestrian mobility at intersections by integrating traffic and pedestrian information from pedestrian detectors and pedestrian-carried mobile devices, referred to as nomadic devices (Lee et al.,

2012). The system uses this information to provide dynamic pedestrian signals or to inform pedestrians when to cross by using real-time Signal Phase and Timing (SPaT) messages. In some cases, a higher priority is given to pedestrians, such as for persons with disabilities that need additional crossing time or in special conditions (e.g., weather or special events). MMITSS will also be able to manage pedestrian crosswalks when certain conditions occur, such as overcrowding pedestrians at curbs.

- **Intelligent Emergency vehicle preemption (I-EVP):** Emergency vehicle preemption (EVP) allows safe and efficient movement of emergency vehicles through the intersections. Since MMITSS provides additional and timely information regarding the queue lengths and arrival times at the signal, it can clear the queues and hold the conflicting phases to facilitate emergency vehicle movement. This should provide better performance of EVP compared to the legacy EVP applications under congested conditions.

3.1.2.4 Reported Impacts of Existing Solutions

Hadi et al. (2008) conducted an extensive review of literature on adaptive signal control, which estimated that adaptive signal control will result in a 10% additional reduction in travel time over time of day control. However, the improvements that adaptive signal control provide are expected to diminish for oversaturated conditions.

Figure 3-2 shows the ranges of reported benefits from adaptive signal control systems across several measures, including safety, mobility and environmental improvements (Hale et al., 2017). The Colorado Department of Transportation (CDOT) evaluated two different adaptive signal systems on two different corridors. The mobility benefits for both corridors combined included a 9-19% improvement in travel times and an increase in the average speed by 7-22%. The environmental benefits found by CDOT included a 2-7%reduction in fuel consumption and a reduction of pollution emissions by up to 17% (Hatcher et al., 2017).

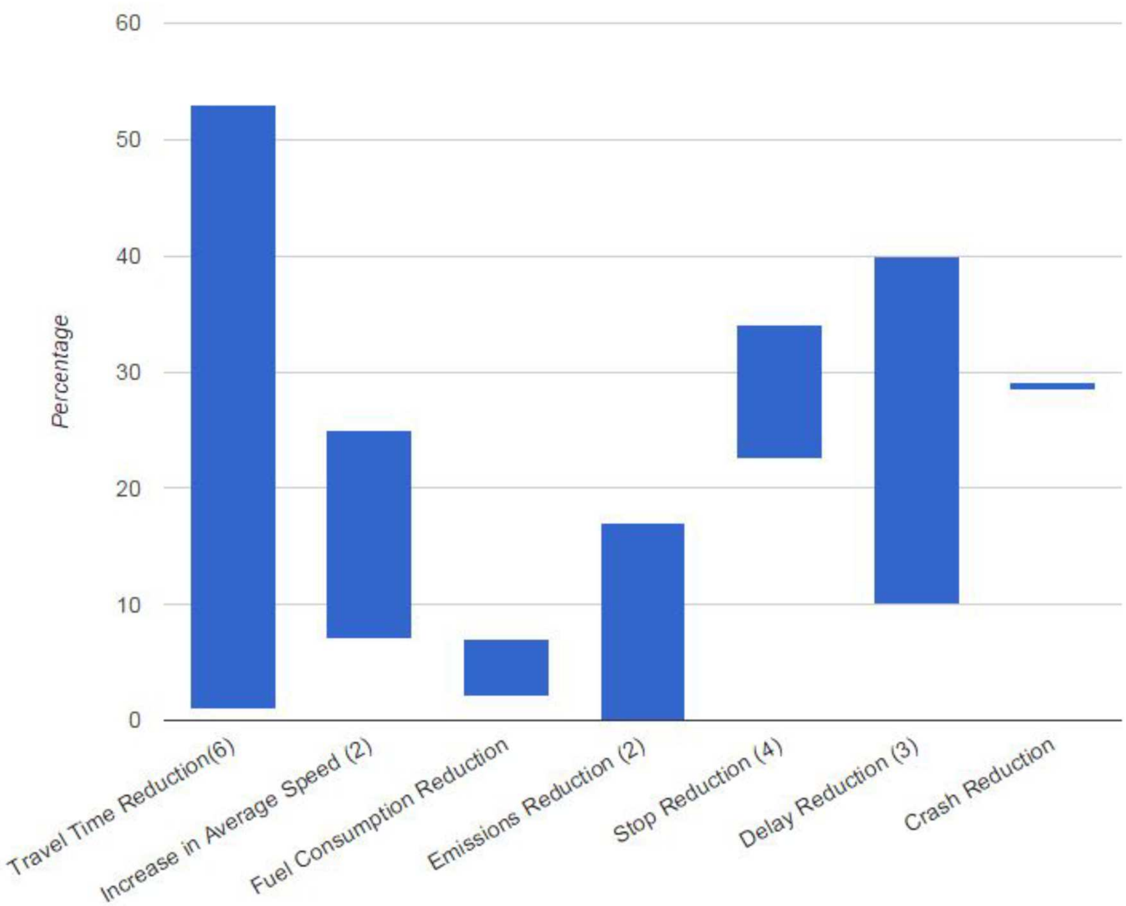


Figure 3-2 Adaptive Signal Control Benefits Found in the Knowledge Resource Database from 2003 to 2016 (ITS Knowledge Resources)

Hadi et al. (2008) conducted an extensive review of TSP benefits that estimated that the reduction in bus delay per intersection can range from 15 to 30 percent, depending on the red time that the bus encounters, which is a function of the congestion level in the system for the period under investigation. For cross-street traffic, the delay was estimated to increase by 6 percent during the peak periods, and by 0 percent during the off-peak periods. In addition to reducing the person-hour of delay at the signalized intersection, the reduction in the travel time of buses due to TSP can have a secondary benefit of decreasing the number of required buses for the same bus frequency.

A comprehensive Transit Cooperative Research Program (TCRP) report from 2010 on TSP provides a set of benefit ranges that may be experienced by an agency deploying TSP based on case studies from a few dozen cities. Transit travel time savings were between 2 and 18 percent, with Los Angeles and Chicago observing a 7.5 and 15 percent reduction, respectively. Overall, the implementing agencies indicated that the bus delay was reduced between 15 and 80 percent.

Figure 3-3 shows ranges of benefits from selected entries in the Intelligent Transportation Systems (ITS) Knowledge Resource database at the following link: http://www.itsknowledgeresources.its.dot.gov/. Benefits of TSP systems include travel time savings, reduced delay for buses at intersections, and reduced emissions.

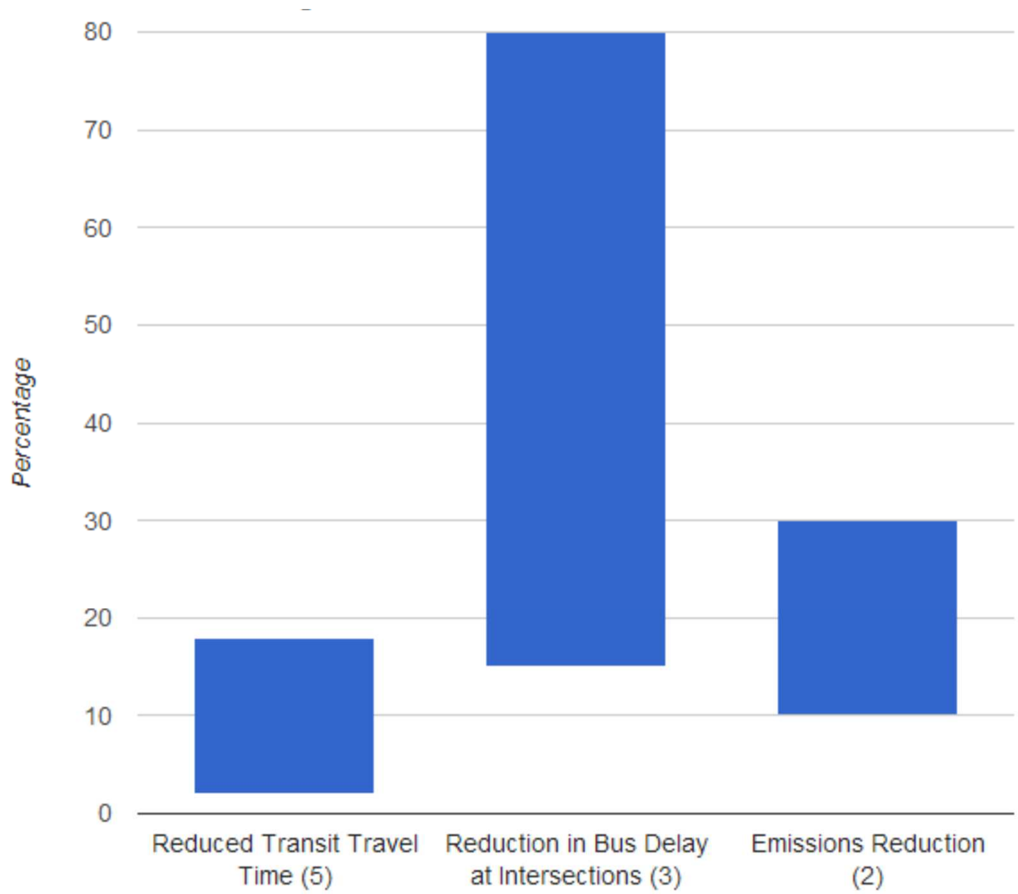


Figure 3-3 Benefits of Transit Signal Priority Systems (ITS Knowledge Resources)

Hadi et al. (2008) conducted an extensive review of the literature and concluded that the savings in emergency vehicle travel time is 15 seconds per passed intersection. However, this value could be significantly higher, depending on the congestion level in the network. A 10% reduction in the probability of death was also assumed for each one minute of faster response.

3.1.2.5 Reported Impacts of CV-Based Solutions

MMITSS I-SIG has been designed to maximize the throughput of passenger vehicles under saturated conditions and minimize the total weighted delay during undersaturated conditions (Cordahi et al., 2016). These objectives can be set as variables, depending on agency goals. The ability to switch objectives, if it works as intended, should provide significant benefits during congested conditions, for which existing adaptive signal control based on minimizing delays is not expected to produce good results.

As with other CV-based deployments, very limited information on the benefits of MMITSS is currently available. The 2015 MMITSS impact was assessed in a Virginia simulation testbed, a Phoenix, Arizona simulation testbed, a San Mateo simulation testbed, and an Arizona field test (Ahn et al., 2015). The Arizona field study found that I-SIG marginally improved travel times for both equipped and unequipped vehicles compared to the base case scenarios. However, the study found that I-SIG considerably improved travel time reliability by up to 56 percent compared to the base case.

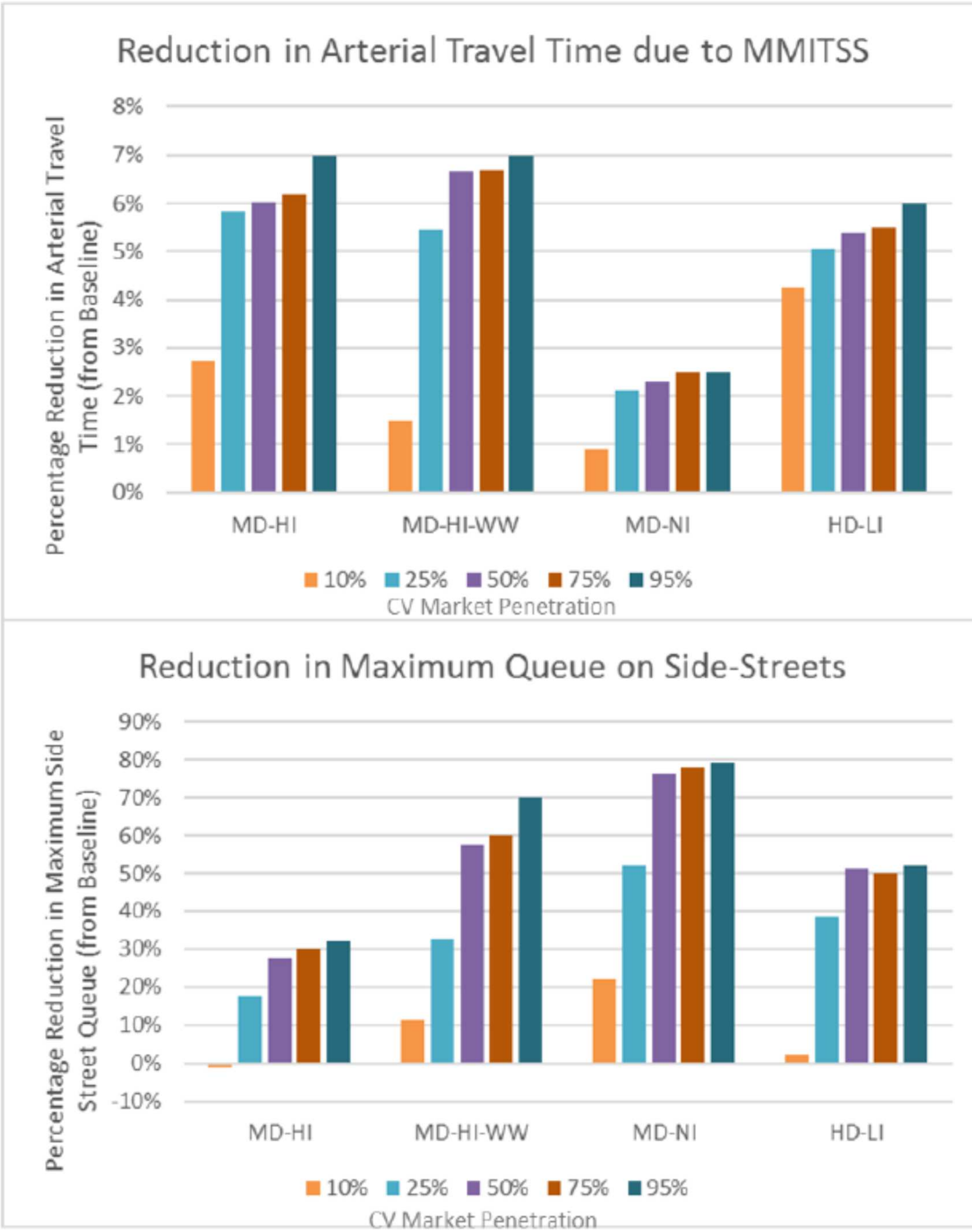
Table 3-1 shows results from the Arizona simulation study, which found that I-SIG achieved vehicle delay reductions of 20 percent compared to existing actuated control. The simulation results imply that I-SIG reallocates signal phase times to reduce system-wide intersection delays. The Virginia simulation study demonstrated that I-SIG reduced vehicle delay by up to 35% and increased the average traffic stream speed by up to 27%.

Table 3-1 System-Wide Benefits of I-SIG in Terms of Average Vehicle Delay (Ahn et al., 2015)

	Arizona I-SIG Simulation Results			Virginia I-SIG Simulation Results		
	V/C (0.5)	V/C (0.85)	V/C (1.0)	V/C (0.5)	V/C (0.85)	V/C (1.0)
I-SIG 25% CV	13.9%	11.5%	10.1%	16.7%	35.5%	23.5%
I-SIG 50% CV	17.3%	20.0%	10.4%	24.1%	23.3%	3.4%
I-SIG 75% CV	16.2%	20.6%	9.5%	25.2%	23.0%	2.9%

Ahn et al. (2015) reported a 15% to 30% improvement in truck and bus travel times when simulating I-TSP and I-FSP based on Arizona and Virginia simulation studies. In some cases, increases in other movement delays were observed.

The I-SIG was also assessed at various levels of market penetration as part of the San Mateo simulation testbed (Walker and Galgano, 2015). I-SIG was used for the evaluation with the goal to optimize the signal timing based on minimizing the travel time. The results for four operation scenarios (combinations of demand level, incidents, and rain conditions) are shown in Figure 3-4. As shown in Figure 3-4, the improvement in arterial travel time due to MMITSS increases as the CV market penetration level increases. For example, under medium demands and high incident operation conditions, the reduction in arterial travel time increases from 2.8%at a 10% market penetration to 7% under a 95% market penetration. More impressive is the impact of I-SIG on side street queues by initiating phase transitions as it receives advanced calls from connected priority vehicles. The application showed that with a 10% market penetration, the system is able to reduce the maximum queue by over 20%. At a 95%market penetration, up to an 80% reduction in arterial side-street queues was observed.



Legend:
MD-HI = Medium Demand/High Incident, MD-HI-WW = Medium Demand/High Incident/Wet Weather; MD-NI = Medium Demand/No Incident; HD-LI = High Demand/Low Incident

Figure 3-4 The Results of Four Operation Scenarios for the San Mateo Simulation Testbed (Walker and Galgano, 2015)

3.1.3 Speed Adjustment to Support Arrival on Green

3.1.3.1 Provided Functions

This application supports drivers by allowing them to arrive on green through vehicle speed adjustment based on real-time signal control information.

3.1.3.2 Existing Solutions

There have not been pure infrastructure applications deployed to provide information to support the arrival on green. Private sector companies have applied business models and made arrangements to provide traffic signal information to drivers who subscribe to their services, usually in coordination with Original Equipment Manufacturers (OEMs). In such arrangements, private sector companies enter into agreements with public sector signal management agencies to access real-time signal control information and utilize analytics based on data to predict the required speed to arrive on green. Thereby, these companies collect the data without major infrastructure investments on their part. This application can be considered a private sector-based connected vehicle-based application that uses cellular communication technology. However, the service is mainly offered to the customers of specific OEMs.

3.1.3.3 CV-Based Solutions

Green Light Optimal Speed Advisory (GLOSA), a CV-based application, provides information and guidance to drivers as they approach traffic signals to allow them to adjust their speeds to reduce the probability of stopping at the downstream intersection. The speeds are calculated based on the vehicle's location, and SPaT messages are communicated to the vehicle using dedicated short-range communication (DSRC) or cellular communication. A more advanced application, referred to as Glide Path automatically adjusts the speeds of the vehicles to allow them to arrive on green. An extension of this application is to combine adaptive signal control with GLOSA to optimize the signal control.

3.1.3.4 Reported Performance

The USDOT evaluated the support of an eco-approach and departure at signalized intersections in a 2012 USDOT experiment at their test facility in the Washington, D.C. area. Drivers were provided with speed recommendations using onboard displays. The results were promising; however, the experiment also identified potential driver distraction issues. The evaluation indicated that this application can provide a 5-10% fuel reduction benefit for an uncoordinated corridor (Hatcher et al., 2017). For a coordinated corridor, the application provided up to 13% fuel reduction benefits. However, only 8% of the benefits were attributable to signal coordination, while 5% was attributed to the application. The results suggest that there is up to a 5%

improvement in fuel consumption and environmental measures at 100% connected vehicle penetration, with a 1-4% improvement at lower market penetrations.

In 2014, realizing the potential distraction issue, the USDOT initiated another project referred to as the GlidePath Prototype Application Project, in which automated longitudinal control capabilities are provided, along with the eco-approach and departure algorithm. The experimentation showed up to a 22% reduction in fuel consumption and carbon dioxide (CO_2) emission for a single vehicle at a single fixed timed intersection of uninformed drivers. Informing drivers of the optimal speed without the partial GlidePath resulted in a 7% fuel savings. Thus, the GlidePath application provided a 15% improvement over the GLOSA information provision. This improvement occurred by minimizing the lag in speed changes to keep the optimal speed and approach.

3.1.4 Support of Incident and Emergency Response

3.1.4.1 Provided Functions

The support of incident and emergency management Response function includes the utilization of technologies to support incident responders so that they respond safely, effectively, and promptly to incidents and to warn drivers approaching the incident scene. The provided functions will also include supporting emergency-response agencies and the general public during evacuation events.

3.1.4.2 Existing Solutions

Incident response is an important aspect of traffic and emergency management that greatly influences the mobility and safety of the transportation system. The National Unified Goal (NUG) agreed upon by the National Traffic Incident Management Coalition (NTIMC) is to achieve responder safety, safe and quick clearance, and prompt, reliable, and interoperable communications. These goals are currently achieved by activating a "planned" strategy for the personnel and resource deployment to the incident scene. It has been realized that information management technology is needed to support incident response by providing time-sensitive information to determine the level of the required response. This information may include the location, traffic impacts, type of the vehicles involved, presence of an injury or fatality, and other special conditions. Currently, the level of required response is determined by an on-scene responder or by a dispatcher at the center, possibly through communication with traffic management centers (TMC) with the associated systems requiring a large degree of human interaction.

There is a need to provide incident site information to increase vehicle and emergency responder safety. Incident information is usually provided to travelers en route or pre-trip by using methods, such as dynamic message signs, 511 traveler phone service, traveler information websites, and smartphone apps. This information delivery is generally designed to influence strategic traveler decisions, such as route diversion, mode shift, and trip time shift. However, there is currently limited information provided to drivers to support their tactical decisions in the vicinity of the incident, such as the provision of merging and speed guidance for vehicles approaching an incident. In addition, there is also no wide deployment of warning systems for on-scene emergency responders.

ITS technologies currently support responders in their routing to the incident scene, which includes signal preemption, computer-aided dispatch (CAD), and automatic vehicle location (AVL) systems. CAD provides mapping capabilities, resource locations and availability, and routes to the incident scene. However, only limited real-time routing information is provided to the responder. AVL allows tracking of the dispatched vehicles. However, the current responder staging process is human-driven based on the information received through communication with responders on the scene.

3.1.4.3 CV-Based Solutions

The Response, Emergency Staging and Communications, Uniform Management and Evacuation (R.E.S.C.U.M.E.) is a bundle of the Dynamic Mobility Applications (DMA) program of the USDOT that utilizes CV technologies to support incident management and evacuation under emergency conditions. It consists of the following applications:

Advanced Automatic Crash Notification Relay (AACN-RELAY) allows vehicles to automatically transmit an emergency message that includes key incident data. The transmission can be sent through cellular communication to an emergency management center or a short-range wireless transmission to other CV-equipped vehicles. This application is particularly important in rural or remote areas. The AACN capability is currently provided by private subscription services whose level of information of an incident varies, and the percentage of the participating vehicles is relatively small. In addition, the capabilities of current AACN systems are impacted by the unavailability of cellular coverage at the crash scene, including damage to the infrastructure by a hurricane or by some other area-wide catastrophic event. DSRC-based communications can be used to relay the information with the CV-based application. No current AACN system has the ability to communicate with other vehicles or with roadside equipment to relay information on incidents. The CV-enabled AACN-RELAY will also provide the ability to access important information, such as medical records of vehicle occupants or Hazardous Materials (HAZMAT) vehicle information. However, the R.E.S.C.U.M.E. Concept of Operations document points to the advancement of the in-vehicle “infotainment” system and the increase in the cellular coverage and suggests that the need for AACN-RELAY is diminishing, particularly in urban areas.

Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG): The RESP-STG application will provide continuous en-route information, support establishing incident scene work zones, and support additional dispatching and staging. The decisions will be based on data and modeling analytics. The RESP-STG application will require comprehensive information to be made available electronically to emergency responders dispatched to the scene of a crash. Modifications to emergency response vehicle computers will allow more information to be included in the decision support systems, such as digital mapping, weather conditions, local population densities, and Electronic Patient Care Records (ePCRs). Still or video images of an incident scene, surrounding terrain, and traffic conditions will be available to guide responder and dispatcher decisions and actions.

Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE): The INC-ZONE application is designed to improve safety and mobility at the incident sites. INC-ZONE involves providing in-vehicle messages that guide drivers in their merging and speed decisions. In-vehicle incident scene alerts are also provided to increase driver safety and incident zone personnel. Alerts are provided to drivers who are exceeding the parameters for safe driving. The application uses the vehicle's location relative to the incident zone and the vehicle speed and trajectory to determine the need for the alert. The system also provides warnings to workers when a vehicle is being operated in an unsafe manner as it approaches the incident zone. The warning systems can be based on advanced roadway sensors and/or CV data. An additional aspect of the INC-ZONE application would be to also notify law enforcement personnel of excessive speeds and other dangerous conditions.

Emergency Communications for Evacuation (EVAC): The purpose of the EVAC application is to facilitate the evacuation for the non-functional and functional needs of people and those who support them. For the functional needs people, emergency management agencies will have the ability to push information, such as evacuation orders by evacuation zone to registered users. To assist with a functional needs evacuation, available transportation resources will also be dispatched and routed, and traveler information will be provided. For non-functional needs evacuees, the EVAC application will provide dynamic evacuation routes. The EVAC application will be also able to provide shelter availability and capability, and food and fuel locations along the evacuation route.

3.1.4.4 Reported Performance

As stated above, INC-ZONE and RESP-STG warn drivers that are approaching work zones at an unsafe speed and/or trajectory. In addition, INC-ZONE warns responders and workers in the work zone of vehicles approaching in an unsafe manner, and RESP-STG provides information and guidance to support emergency resource routing, staging, and secondary dispatch decisions. It is expected that these applications improve responder and driver safety and efficiency. These benefits are expected to increase with the increase in CV market penetrations. Unfortunately, the assessment of the benefits of these systems does not appear to be adequate at this time.

A simulation study that utilized an 8.5-mile segment of the U.S. 101 corridor in San Mateo, California as a case study found that the average network-wide delay was reduced by up to 14% during the incident when INC-ZONE was applied, in addition to an increase in the average speeds by up to 8%. There was also a decrease in the hard-braking events in the incident zone. A reduction in maximum deceleration was found to be between 1-89% for different operational conditions, with the highest improvement in the scenarios with dry conditions and a long incident. The simulation study found that RESP-STG can potentially reduce an emergency vehicle's travel time by up to 23% and their number of stops by up to 15% (Cordahi et al., 2015a). For short incident scenarios, the reduction in network delay was between 1-7%, and the increase in average speeds was between 0.25-3% for rainy conditions. For long incident scenarios, the reduction in network delay was between 1-14%, and the increase in the average speed was between 1-8% for dry conditions. These benefits were calculated assuming a 15% reduction in clearance times under dry conditions.

The R.E.S.C.U.M.E. prototype was developed and demonstrated in Columbus, Ohio and Sykesville, Maryland. Twelve scenarios were used to illustrate the functionality of the RESP-STG and INC-ZONE applications. The Maryland site conducted interviews with test participants. The majority of traffic management and emergency management agencies recognized the potential of the R.E.S.C.U.M.E. applications to reduce total response and clearance time, delays, and secondary incidents once these applications become widely adopted.

The Emergency Communications for Evacuation (EVAC) application provides functionalities, such as route guidance, communications about transit services, and lodging and fueling assistance. It is expected that this application is beneficial in reducing travel time and overall network congestion and reducing evacuee stress. EVAC was assessed using simulation modeling based on the Greater New Orleans evacuation model. This evaluation of EVAC was conducted by assuming the Hurricane Katrina evacuation of New Orleans in 2005. The modeled functionalities included the provision of traveler information on traffic and road conditions, location of available lodging, and location of fuel, food, water, cash machines, and other necessities. The sensitivity of the potential benefit of the EVAC functionality was examined by simulating it under three levels of EVAC market penetration: 15%, 25%, and 50%. The results indicate that the application decreases the congestion time by 20% (Cordahi et al., 2015b). The wait time for transit services was reduced by over 90%for EVAC-equipped transit vehicles. At the 50% penetration, fuel-related breakdowns were reduced by more than 50%. On average, evacuees seeking lodging experienced a two-hour travel time benefit.

3.1.5 Dynamic Information and Guidance to Support Management

3.1.5.1 Provided Functions

The Dynamic Route Guidance to Support Management functions includes the provision of information to travelers to improve the mobility and reliability of their trips. It includes the provision of route guidance information to travelers to help divert them to less congested conditions. An extension of this application is to optimize the signal control considering the provision of route guidance information.

3.1.5.2 Existing Solutions

Traveler information can be disseminated using smartphone applications, onboard vehicle units, dynamic message signs, public and private sector phone apps, TV and radio stations, websites, onboard navigation systems, and/or other media. Many of the existing platforms are provided by the public sector. However, the decreasing operating budgets and the fast advancements in private sector applications motivate public agencies to examine the performance of their platforms to determine if investing in these platforms is justifiable (Adler et al., 2014; Shuman et al., 2015).

Alternative route information is currently mainly provided by private sector applications. However, such routing information is not used for optimizing transportation management and operations and is not integrated with other applications, such as signal control, ramp control, managed lane, and incident management.

3.1.5.3 CV-Based Solutions

The rapid growth in smartphone ownership and the introduction of the smartphone and social media applications that provide context-specific information services to mobile users is significantly changing the outlook and usage of traveler information systems. The introduction of smartphone-vehicle integration applications (such as Carplay and Android Auto, vehicle 4G cellular, and possibly satellite and future 5G connectivity) and DSRC technologies will further allow transformative changes in traveler information systems.

EnableATIS is a USDOT-defined CV application that provides a time-dependent shortest path from origin to destination for travelers (pre-trip planning) or from the current location to a destination (en route rerouting). Two future concepts were outlined in the FHWA EnableATIS documents, as listed below (Adler et al., 2014; Burgess et al., 2012).

- The Laissez-Faire operational scenario (see Figure 3-5) is a continuation of current advancements, with an incremental enhancement over time, assuming an increasing level of data and data processing and use, and continued innovation in delivery mechanisms. The Laissez Faire operational environment can be considered the continuation of the current trend of having private-sector innovations lead the advancements of traveler information systems. This approach tries to improve the individual traveler experience without much consideration of the impacts on the system. There are a limited number of incentives, which concerns private sector application developers in terms of improving system performance. As market penetration rates for traveler information devices increase, overreactions to the information provided by individual private sector applications will result in the deterioration in system performance.
- The Preferred Ultimate Scenario (see Figure 3-6), according to the EnableATIS document, is the robust operational scenario. This scenario assumes a public and private sector leadership in delivering a comprehensive, multisource and multimodal

data environment to enable an advanced traveler information services that consider achieving optimal system conditions, as well as optimal user conditions.

The operational scenarios will allow multimodal integration, facilitated sharing of data, end-to-end trip information and planning, and the use of analytics and logic to generate predictive information specific to users. EnableATIS utilizes fused real-time and historical data from multiple sources, including probe and infrastructure traffic data, transit data, road-weather data, traveler choice data (e.g., origin, destination, desired departure time, arrival time, mode, and route), parking data, construction data, control data, and event data. The system uses this data to predict travel times for different trip alternatives and provide end-to-end planning information, including suggesting potential departure times, routes, mode, parking, and other trip-related information. The information could include travel times, travel time reliability, and costs for each alternative.

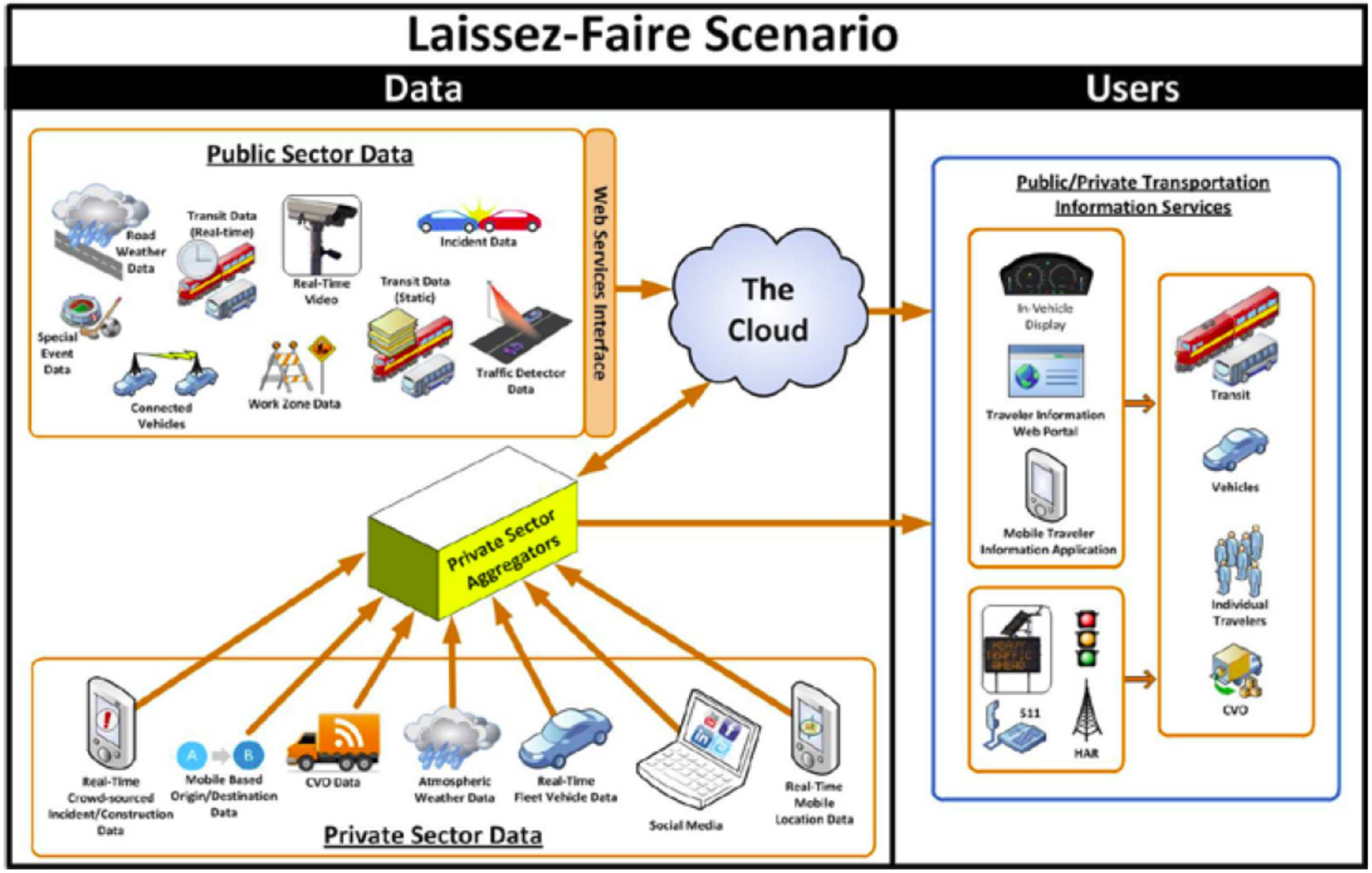


Figure 3-5 Laissez-Faire EnableATIS Operational Scenario (Burgess et al., 2012)

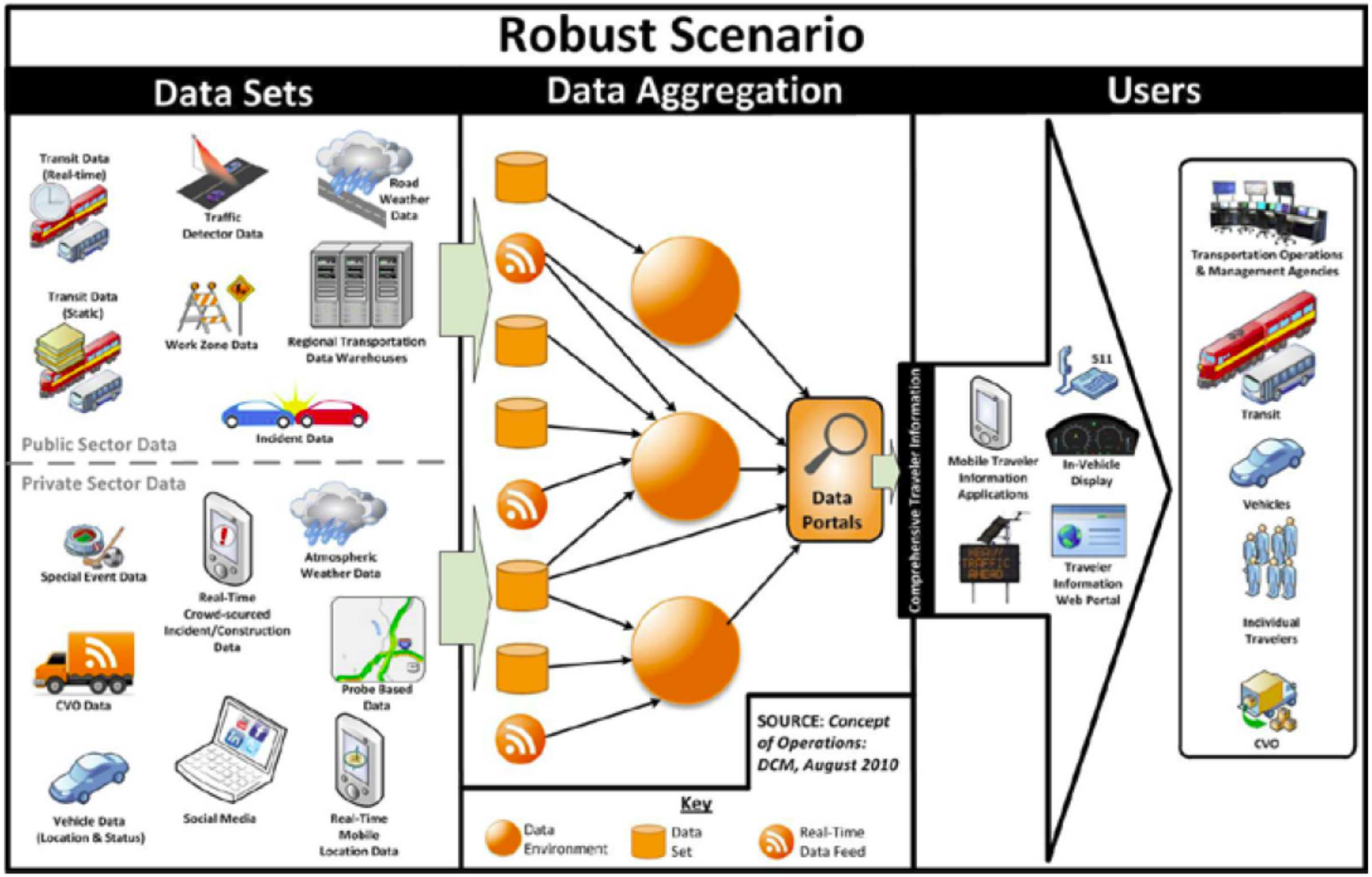


Figure 3-6 Robust EnableATIS Operational Scenario (Burgess et al., 2012)

3.1.5.4 Reported Impacts of Existing Solutions

The improvements in system performance, which is attributed to information and route guidance provision, are due to traveler diversion, which is due to the provision of information. Previous efforts have utilized stated preference, preferred preference, and sensor data to estimate diversion. It is recognized that stated preference surveys overestimate diversion. Thus, the results from these surveys will not be reviewed further in this document.

Chatterjee and MacDonald (2004) conducted an extensive survey in six European countries to examine the impact of Dynamic Message Signs (DMS) on traffic diversion and found with the driver questionnaire results that the diversion rates are 0% to 7% for incident messages and 0% to 35% with route guidance information. An Enterprise Pooled Fund Study *(*Deeter 2012*)* found an increase in the diversion rate that ranges from 0% to 12% due to DMS. A study in Maryland *(*Haghani et al., 2013*)* found that the diversion rate ranged between 5% and 18% based on Bluetooth detector data. Foo and Abdulhai (2006) estimated a diversion rate of 5.55% with the provision of DMS on Highway 401 in Toronto, Ontario, Canada, which was based on traffic detector data. Hadi et al. (2013) conducted a study on the diversion of traffic in incident conditions based on detector data and found that the diversion rate ranges from about 8% for one out of five-lane blockages to about 25% when four out of the five lanes were blocked.

The above review indicates that based on a revealed preference survey and data collected from field sensors, 5% to 20% of traffic can be estimated to divert during incidents that impact the travel time on freeway facilities, depending on the incident impact severity. The corresponding diversion rates due to route guidance that uses private-sector apps can be assumed to be 15% to 35% of those accessing the apps, depending on the severity of the incidents. It should be mentioned that due to the rapid changes to traveler information systems, including the wider utilization of private-sector apps and the advancement in public agency systems when reviewing past studies on the subject, more weight should be given to more recent studies.

3.1.5.5 Reported Impacts of CV-Based Solutions

EnableATIS was assessed as part of the USDOT AMS testbed, which is a part of the USDOT effort (Yelchuru et al., 2017b). The application is supposed to use path-specific travel-time information to guide travelers to use the optimal routes. The evaluation was done utilizing the Phoenix transportation coded in a mesoscopic simulation-based Dynamic Traffic Assignment (DTA) tool called DTALite. Several scenarios of non-recurrent congestion were modeled. Both pre-trip and en-route information are included in the evaluation. The research also evaluated the effectiveness of EnableATIS in comparison to dynamic message signs (DMS), referred to as variable message signs (VMS) in the project documentation and in the figures presented in this section. The baseline is the "Do Nothing Case," where no information is provided to travelers and travelers selected routes according to recurrent traffic conditions. As shown in Figure 3-7, the simulation results indicate that the simulated DMS system may increase the system-wide travel time since travelers may divert to a non-optimal route or to routes that improve their individual experience without considering system-wide impacts. As stated above, the CV-based EnableATIS technologies will route vehicles in an optimal manner. It was found, however, that the average travel distance may increase significantly since the routing was based on travel time and not distance. As shown in Figure 3-7, increased market penetrations of pre-trip and en route EnableATIS result in a significant reduction in travel time. However, beyond certain penetration levels, the study reported an increase in travel time when the pre-trip ATIS market penetration increases without an increase in en route ATIS penetration. This points to the need for en route information to continuously update dynamic routing information. Overall, the study reported up to a 40%reduction in travel time when the EnableATIS system is used at the right pre-trip/en route market penetration. However, the study cautioned that in reality, the baseline condition will cause some travelers using pre-trip information to adjust their routes, and thus the savings in travel time due to EnableATIS may not be as much as 40%.

Based on the above review, it will be assumed that up to 85% of travelers that access the CV-based information will divert, change mode, or shift trip time either at their origins or en route, depending on the severity of impacts and whether information or guidance is provided.

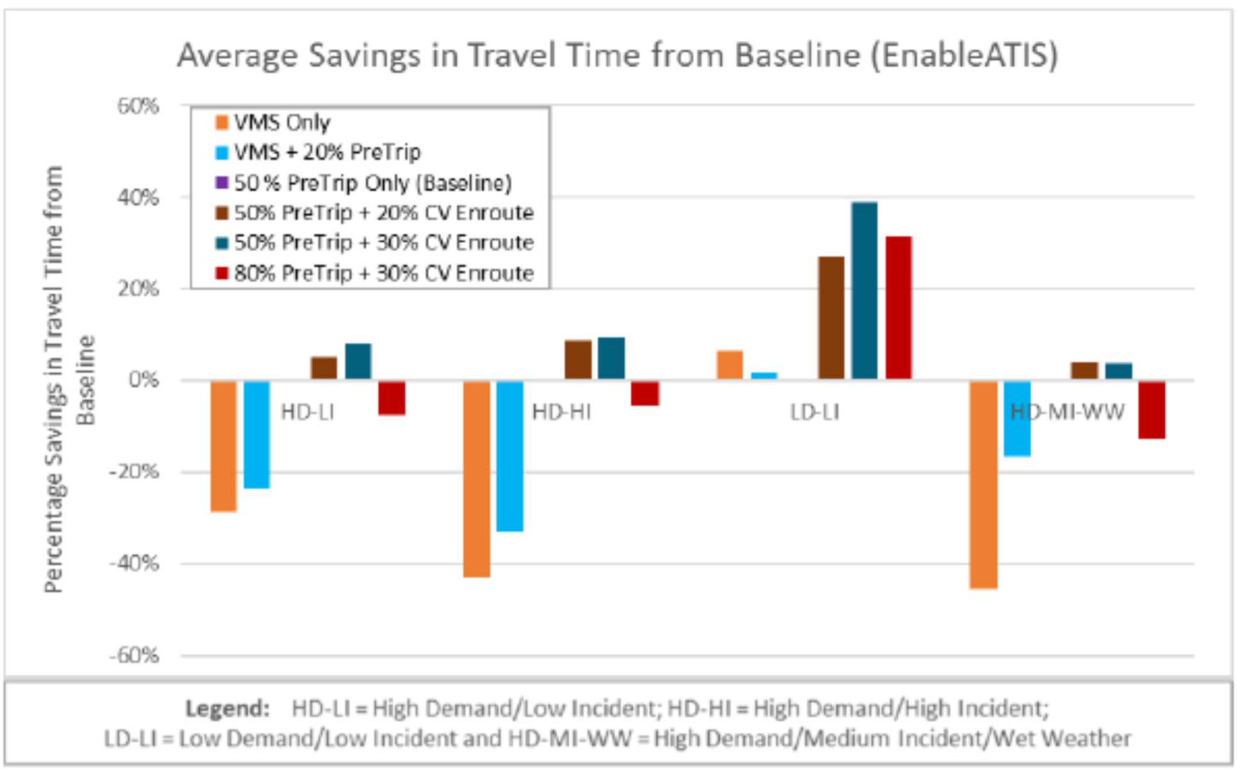


Figure 3-7 Performance of Traveler Information under Different Operational Conditions (Yelchuru et al., 2017a)

3.1.6 Support of Signalized Intersection Safety

3.1.6.1 Provided Functions

The provided functions assist drivers making permissive left turn or right turn on red and warn the driver if the vehicle is predicted to violate a red light or if they are at risk for colliding with pedestrians at a crosswalk of a signalized intersection. The functionality can also assist pedestrians with crossing the street safely.

3.1.6.2 Existing Solutions

Traditionally, left-turn safety problems at intersections have been addressed with solutions, such as replacing a permissive left turn with a protected left turn, which may have negative impacts on mobility. If the left-turn crashes are due to sight distance limitation, geometric design improvements may be introduced.

Red light violations have been addressed using enforcement techniques, such as red light violation cameras, although such cameras have faced political resistance. Signs with a flashing light displaying “Prepare to Stop When Flashing” have been used to warn drivers about the light changing to yellow.

Solutions have also been proposed to address the dilemma zone problem to reduce red-light violations and rear-end crashes due to sharp deceleration. One option is to use a different formula to calculate the clearance interval. This option usually results in a one to three second increase in the clearance interval, depending on the speed limit. The disadvantage of this solution is that it will reduce the efficiency of the intersection. The other disadvantage is that drivers may feel more comfortable driving through the yellow light because of its longer duration. Another solution that has been proposed is to paint a line on the approach at a safe braking distance. In addition, at least one sensor vendor has introduced a feature to detect the presence of each vehicle at the approach and measure its speed and location. This information is then used to estimate the time of arrival at the stop line for each vehicle, and the green light can be extended to accommodate this arrival.

Onboard vehicle sensors have been proposed for installation, particularly on truck and transit, to detect pedestrians and cyclists crossing the street. An example is the Mobileye image processing product that is currently being tested in Miami, Florida and Gainesville, Florida. These products do not require connectivity to the infrastructure. However, they require clear line-of-sight and additional sensors to be installed in the vehicles.

An accessible pedestrian signal and pushbutton have also been implemented. These devices communicate information about the WALK and DON'T WALK intervals at signalized intersections in non-visual formats (e.g., audible tones) to visually-impaired pedestrians.

3.1.6.3 CV-Based Solutions

The applications provided by the CV-based signalized intersection safety warning includes Signalized Left Turn Assist (SLTA), Red Light Violation Warning (RLVW), Right Turn Assist (RTA), Pedestrian in Signalized Crosswalk (PSCW), and Mobile Accessible Pedestrian Signal System (PED-SIG). This latter application also includes signalized midblock crossings. Obviously, these applications should be considered for locations with higher than normal crash types that can be countered using the abovementioned applications. The application concept is to provide information to equipped vehicles for use by the onboard units that determine whether under given current operating conditions there is a need for an alert. The information includes signal and phase timing information, intersection geometry, and position correction information. The driver is issued a warning if the vehicle processing platform determines that there is a need for such a warning. These applications are supported by SPaT, MAP, and position correction messages, which also support other V2I connected vehicle applications, such as GLOSA and GlidePath at signalized intersections.

Signalized Left Turn Assist (SLTA) and Signalized Right Turn Assist (SRTA): SLTA will provide assistance to drivers with making permissive left turns (and although not specified in the USDOT description of the application, right turn on red) at locations where drivers have cognitive, time pressure, or obstruction challenges to make safe left-turn decisions (Richard, et al., 2015a). The system provides guidance in accepting safe gaps in opposing traffic based on opposing vehicles that are approaching and their speeds. The system can also provide red light violation alerts and a dynamic all-red clearance interval when an opposing vehicle is about to violate the red interval to prevent a side collision. In addition to its safety benefits, the system may be able to reduce the number of safe gaps in opposing traffic that are rejected by left turning drivers, thus increasing the efficiency of the turning movement. Considering the low market penetrations of CV in the initial deployments, SLTA will have to rely partially on infrastructure-based sensors to detect the trajectories of approaching vehicles. The specific type of sensor or combinations of sensors that provide these trajectories will have to be identified.

Red-Light Violation Warning (RLVW): The RLVW application warns drivers who are approaching a signalized intersection if they are on a trajectory to violate a red signal (Stephens et al., 2012a). The application monitors vehicle speed and deceleration rate and compares it with the required rate for a safe stop at a traffic signal. The warning is given prior to the point where the vehicle would be unable to safely stop for the red light (i.e., prior to entering the dilemma zone). In addition to reducing the conflicts within the intersection, rear-end crashes may be reduced due to the reduction in sudden and sharp brakes as a vehicle approaches the intersection on yellow or an all-red interval. These systems are more dynamic based on roadway and vehicle operating conditions than current systems that employ static signs that warn a driver to “Prepare to Stop When Flashing.”

Pedestrian in Signalized Crosswalk (PSCW): With this application, connected vehicles receive information from the infrastructure that indicates the possible presence of pedestrians in a crosswalk at a signalized intersection. The infrastructure-based indication could include the outputs of pedestrian sensors or simply be an indication that the pedestrian call button has been activated. The application could also provide warning information to the pedestrian regarding crossing status or potential vehicle infringement into the crosswalk.

Mobile Accessible Pedestrian Signal System (PED-SIG): This application allows for an "Automated pedestrian call" from smartphones for visually impaired pedestrians. The phones can also communicate wirelessly with the traffic signal controller to obtain real-time SPaT information. The application can inform the visually impaired pedestrian as to when to cross and how to remain aligned with the crosswalk.

3.1.6.4 Reported Performance

Claros et al. (2016) found that the implementation of red light violation cameras reduced overall angle crashes by 11.6%, whereas rear-end crashes increased by 16.5%. The net economic crash cost-benefit of the implementation of the cameras was $35,269 per site, per year in 2001 dollars (approximately $47,000 in 2015 dollars). Thus, the implementation produced a positive net present dollar value.

Eccles et al. (2012) analyzed four years of crash data from 2005 through 2008 in order to estimate the number of crashes that could be potentially targeted or reduced by different V2I signalized intersection safety applications. Based on their analysis, the Running Red Light safety application can target 234,881 annual national crashes with a 45% reduction in fatalities or injuries, and an estimated annual dollar benefit value of more than 13 billion dollars. In addition, Driver Gap Assist safety application, such as SLTA can target 200,212 annual national crashes with 44% of fatalities or injuries, and an estimated annual dollar benefit value of more than 10.3 billion dollars. Najm et al. (2010) reported that V2I systems, such as RLVW could address 25% of all light-duty vehicle crashes in the U.S. It has also been reported that left-turn crashes that can be prevented with the SLTA application account for 27% of intersection crashes (Ragland & Zabyshny, 2003).

Lindman et al. (2010) indicate that full deployment of pedestrian collision auto brake features has the potential to reduce pedestrian fatalities by 24% based on a Volvo Cars Traffic Simulator (VCTS). Pecheux and Kennedy (2015) reported, based on a study in Portland, OR, that 23% of pedestrians reported that a crosswalk transit vehicle turn warning system helped them avoid a collision with a bus.

3.1.7 Support of Unsignalized Intersection Safety

3.1.7.1 Provided Function

These applications are intended to improve safety at stop-controlled intersections. The provided functions warn drivers if the vehicle is predicted to violate a stop sign. The provided functionality can also assist drivers in selecting gaps in the opposing traffic stream.

3.1.7.2 Existing Solutions

Presently, there is no widely deployed technology at stop signs that detect the speed of an approaching vehicle and provide warnings to drivers about possible violations. At some locations, stop signs have been equipped with small flashing beacons that flash on either a continuous basis or based on motion detection at a pre-set distance from the sign.

There are currently also a few real-world deployments of systems to warn drivers of conflicts (insufficient gaps). These systems have been deployed mainly at rural, stop-controlled intersections. With these systems, static signs with flashing beacons or dynamic message signs (DMS) are installed on major and minor approaches. Point detection is used to detect vehicles in the intersection and warn vehicles on the major approach.

3.1.7.3 CV-Based Solutions

Stop Sign Violation Warning (SSVW): SSVW warns drivers if their vehicle is predicted to violate a stop sign (Stephens et al., 2012a). The warnings are to be provided at distances to allow a driver to take action to safely stop at the stop sign. The application will reduce crashes with cross-street traffic and may also reduce the number of rear-end collisions. SSVW onboard warnings will be based on data from multiple sources, including current roadway, vehicle operations, and weather conditions by calculating the vehicle trajectories versus the required stopping distance.

Stop Sign Gap Assist (SSGA): The SSGA provides advisory information to cross-street drivers at a stop-sign controlled intersection to support their gap selections at the intersection (Stephens et al., 2012a). The recommendations may vary, depending on the intersection geometry, environmental conditions, identified needs, and other issues. In addition to vehicle displays, the information may be displayed using an infrastructure display, such as a DMS. The infrastructure-based signs will provide warnings of unsafe gaps to drivers of both equipped and non-equipped vehicles.

3.1.7.4 Reported Performance

Eccles et al. (2012) found that the SSVW application can target 44,424 annual national crashes with a 45% reduction in fatalities or injuries and an estimated annual dollar benefit value of 2.0 billion dollars. The results of before and after evaluations of the installations of infrastructure-based SSGA systems showed a 28% reduction in all crashes, and a 54% reduction in traffic conflicts at intersections, such as sudden braking, sudden acceleration or swerving (Stephens et al., 2013a). Stephens et al. (2013a) showed a reduction in right-angle crashes at three different intersections from 17 to 8 crashes from 11 to 2 crashes, and from 19 to 3 crashes. Driver Gap Assist safety applications at Stop-Controlled intersections, such as (SSGA) can target 278,886 annual national crashes with 38% of fatalities or injuries and an estimated annual dollar benefit value of nearly 18.3 billion dollars.

3.1.8 Hazard Warning

3.1.8.1 Provided Functions

A number of CV-based safety applications can be used to improve road safety by warning drivers of approaching queues, work zones, excessive speed, oversize vehicle warning, restricted lane, and railroad crossing warnings.

3.1.8.2 Existing Solutions

Currently, there are a number of infrastructure-based applications that have been implemented to increase safety. For example, speed warnings have been disseminated using DMS or static signs with flashers to warn drivers to reduce their speed during school zone activation or when construction workers are present. Portable trailers in work zones, school zones, and other areas have also been used for this purpose. Radar detection has been used to detect speed. However, these systems do not consider dynamically changing traffic conditions and specific vehicle trajectories.

Oversize vehicle warning (OVW) signs have also been installed to provide warnings to help drivers of oversize vehicles avoid collisions with low- or narrow clearance bridges or tunnels. Infrastructure-based detection systems and DMS have been installed to support these systems. Current Curve Speed Warning (CSW) applications have also been used to provide speed warnings based on roadside infrastructure detection and messaging.

Active Rail Crossing Warning systems have been widely deployed and proven effective in improving safety and operations at highway-railroad grade crossings. Existing warning devices include flashing light signals, automatic gates, warning bells, and additional flashing light signals (Stephens et al., 2013a).

Infrastructure Road Weather Information Systems (RWIS) have also been deployed to provide automated warnings to drivers, including fog, ice, snow, and flooding conditions.

3.1.8.3 CV-Based Solutions

This section describes the proposed CV-based hazard warning systems. Compared to existing deployments, the advantage of CV-based hazard warning systems can include driver-specific accommodation of all vehicle classes and drivers, including inexperienced and older drivers, functionality in all weather and lighting conditions, effective performance in different environments, accuracy and precision in issuing alerts/warnings, and the ability to integrate with connected and automated vehicle applications (Stephens et al., 2013a).

Reduced Speed/Work Zone Warning (RSZW): The objective of the RSZW is to help drivers avoid crashes in reduced speed zones and work zones by warning the drivers that they are operating at a speed higher than the speed limit and/or providing information regarding changes in lane configuration, along with considering traffic and weather conditions, when the driver is at risk of an incident. The purpose of RSZW is to increase the safety of drivers, construction workers in work zones, and children in school zones. Both roadway and onboard warnings will be provided to the driver based on real-time roadway conditions.

Curve Speed Warning (CSW): The CV-based application provides a more dynamic warning specific to each driver and vehicle to reduce the probability of a vehicle speeding around a curve (Stephens et al., 2013a). Additional infrastructure sensors may be needed to detect traffic congestion and visibility.

Oversize Vehicle Warning (OVW): The CV-based OVW application provides a two-stage alert/warning system that is able to warn vehicles further upstream to provide enough time to reroute and avoid the roadway clearance obstacle.

Spot Weather Information Warning (SWIW): SWIW warns drivers that are in extreme weather conditions where precautions are needed, such as the need to reduce speed or seek an alternate route. The Road Weather Information System (RWIS) sensors are used to support the system (Stephens et al., 2013a). An equipped vehicle approaching an equipped roadway segment will receive onboard messages, such as advisory or alert/warning regarding speed, or diversion to an alternate route as recommended by the infrastructure application. The SWIW is expected to be deployed at locations that experience frequently recurring weather-related issues.

Railroad Crossing Warning: This application alerts and/or warns drivers if they are on a crash-imminent trajectory to collide with a train at a railroad crossing. An equipped vehicle approaching an equipped railroad crossing receives messages about the intersection geometry and the presence of a train. The vehicle processing platform will determine the need to issue messages given current operating conditions. The distance at which the information is provided can vary, depending on the vehicle, weather, and other parameters. The application monitors vehicle deceleration rates and compares it with the rate required for a safe stop at a railroad crossing with an approaching or crossing train.

Restricted Lane Warnings: The Restricted Lane Warnings application provides the connected vehicle with restriction information about travel lanes, such as if the lane is restricted to high occupancy vehicles (HOV), transit, or public safety vehicles only, or has defined eco-lane criteria. A connected vehicle can use this information to determine if the vehicle is in a lane that has lane restrictions.

3.1.8.4 Reported Impacts

The ITS Benefits, Costs, and Lessons Learned: 2017 Update Report identified the potential population of crashes that can be addressed by various V2I safety applications (Hatcher et al., 2017). In general, it was reported that Collision Avoidance Systems are expected to reduce fatalities by 4-16% and driver injuries by 19-57%. It was reported that an over-height warning system at a bridge in Maryland decreased the number of tractor-trailer incidents by 75%. It was also found that roll-over advisory systems reduce this type of crash by 20% and speed warning systems by 2-15%. A study on the effect of forward collision warning (FCW) alarms by Fitch et al. (2008) determined that a nationwide deployment of FCW in heavy vehicles could reduce the number of rear-end crashes by 21% (Smith et al., 2015). A simulation study in Australia showed the CV warning systems and automated emergency braking can reduce fatalities by 57%, as reported in the United States DOT ITS Knowledge Resources database.

Based on the FHWA report results by Eccles et al., 2012, the Curve Speed Warning safety application (CSW) can target 168,993 annual national crashes, with 44% of fatalities or injuries and an estimated annual dollar benefit value of 29.0 billion dollars. In addition, the Reduced Speed/Work Zone Warning (RSZW) application targets 16,364 annual national crashes, with a 33% reduction in fatalities or injuries and an estimated annual dollar benefit value of 1.3 billion dollars. The Spot Weather Information Warning (SWIW) application was reported to address 211,304 annual national crashes, with 44% of fatalities or injuries and an estimated annual dollar benefit value of 13.0 billion dollars.

3.2 SUMMARY OF EXISTING AND CV-BASED APPLICATIONS AND IMPACTS

This chapter has identified typical mobility and safety functionalities for the management and operations of urban arterials. It identifies existing and CV-based solutions to provide these functionalities. A summary of the identified existing solutions and associated CV-based solutions are shown in Table 3-2.

The performance of the identified solutions in terms of mobility modification factors and crash modification factors has also been estimated based on the information available in the literature. A summary of the estimates is provided in Table 3-3. As stated earlier, since CV-based solutions are still in the early stages of development and deployment, limited information is available about their impacts. An additional review is being conducted to refine and add to these estimates and additional simulation and analyses will be conducted to support the estimation. It is expected that these factors will have to be updated as more results become available from CV deployments. Some impacts were not identified in this study and are highlighted as TBD in. It should be noted again that the values in Table 3-2 are estimated for the purpose of use in the return of investment analysis based on a limited amount of data, particularly for CV-based applications. The identification involves a high level of judgement and based on imperfect information. Thus, these values should be reviewed with caution. The use of these values in the benefit-cost analysis should also involve conducting sensitivity analysis or risk analysis. This will be addressed in Chapter 4.

Table 3-2 Existing Solutions and CV-Based Solutions to Provide the Required Arterial ATM Functions

Function	Existing Solutions	CV-Based Solutions
Data Collection to Support System Management		
Data Collection to Support Performance Measurements	Point detectors for volume measurements and AVI (e.g., Bluetooth or Wi-Fi readers) or third-party vendor data for travel time and partial O-D estimation	CV as probes can be used to estimate travel time. Other potential measures, depending on data availability from vehicles can include vehicle classification, acceleration/deceleration, number of stops, number of brakes, potential for crashes, emission, fuel consumption, and weather and lighting conditions.
Automatic Incident Detection	Based on point detectors or travel time measurements that are based on AVI or private sector data	Based on travel time estimated from CV data; potentially other new measures based on CV trajectory data, such as acceleration/deceleration, braking, and changing lanes
Support of Off-line Signal Control	Based on historical traffic counts, field observations, and optimization tools. Recently, high-resolution controller data has been used.	CV combined with high-resolution controller and other available data sources
Provision of Signal Control to Accommodate Varying Conditions		
Adaptive Signal Control	A number of off-the-shelf adaptive signal control systems are available	Systems based on fused data from CV and existing detectors are in the development and pilot deployment stages. CV-based applications and additional features, including using vehicle trajectories to support timing, multimodal control, undersaturation/oversaturation consideration, dilemma zone protection, etc.

Table 3-2 (Continued)

Function	Existing Solutions	CV-Based Solutions
Transit Signal Priority (TSP)	Local and central TSP strategies (conditional and unconditional) can be implemented using current signal control systems	Extend existing TSP by potentially considering it as part of multimodal signal optimization. Detection of buses at a distance from the signal allows better control and consideration of nearside bus stops. Bus-specific status information can be used in priority decisions. Additional strategies are possible, such as queue clearance ahead of buses making a left turn.
Freight Signal Priority (FSP)	FSP can be implemented using current signal control systems	Same extensions as with TSP.
Pedestrian Signal Control	Walk signal can be provided based on push buttons	Pedestrian detectors or information from pedestrian mobile devices can be used as part of the multimodal signal optimization with potential consideration of special needs pedestrians.
Emergency Vehicle Preemption (ESP)	Central and local ESP are possible with current signal control	Early detection of emergency vehicles for better control and queue clearance ahead of the signals.
Speed Adjustment to Support Arrival on Green		
Green Light Optimal Speed Advisory (GLOSA)	Cellular-based applications by private sector companies to provide traffic signal information to drivers who subscribe to their services usually in coordination with OEMs	CV-based applications providing information and guidance to drivers as they approach traffic signals to allow them to adjust their speeds to reduce the probability of stopping at downstream intersections.
Glide Path (Involving Partial Automation)	Not supported by existing solutions	This application automatically adjusts vehicle speeds to arrive on green.

Table 3-2 (Continued)

Function	Existing Solutions	CV-Based Solutions
Support of Incident and Emergency Response		
Increasing Incident Zone Site Emergency Responder and Vehicle Safety and Mobility	Limited site information, such as merging and speed guidance for drivers or limited warnings about approaching vehicles to emergency responders	CV-based applications involve providing in-vehicle messages that guide drivers in their merging and speed decisions and send alerts to responders about vehicles approaching in an unsafe manner.
Emergency Vehicle Staging and Routing	Computer-aided dispatch (CAD) and automatic vehicle location (AVL) provide significant resource tracking and routing support. However, there is limited dynamic routing based on real-time information. Site staging is largely human-driven.	CV-based application will provide continuous en-route information, support establishing incident scene work zones, and support additional dispatching and staging. The decisions will be based on data and modeling analytics.
Evacuation Support	Limited routing information and limited support of functional needs people	CV-based applications will provide routing, shelter, and gas information to all evacuees and dispatch and route resources to functional needs people.
Dynamic Information and Guidance to Support Management		
Provision of Traveler Information	Travel time and incident information provided by public and private sector platforms	Pre-trip and en route predictive multi-modal information
Provision of Guidance	Mainly route information by private sector phone apps	Route guidance potentially combined with time shift and mode shift guidance
Optimization of Guidance Combined with Signal and Other Management System Optimization	NA	Optimize guidance combined with transportation system management optimization

Table 3-2 (Continued)

Function	Existing Solutions	CV-Based Solutions
Support of Signalized Intersection Safety		
Permissive Left Turn and Right Turn on Red Support	Protects turns and improves geometry to improve sight distance	to prevent a side collision, the application will provide guidance in accepting safe gaps in opposing traffic and possibly send alerts of red violation and a dynamic all-red clearance interval when an opposing vehicle is about to violate the red interval.
Red Light Violation and Rear-End Collision Reduction	Red light violation cameras and signs with flashing lights	The application warns drivers who are approaching a signalized intersection if they are on a trajectory to violate a red signal.
Reduce Pedestrian on Crosswalk Crashes	Onboard vehicle sensors, such as Mobileye image processing devices	CVs receives information from the infrastructure (Road Side Unit) that indicates the possible presence of pedestrians in a crosswalk at a signalized intersection.
Support of Visually Impaired Pedestrian in Crossing the Street	Accessible pedestrian signal and pushbutton (e.g., using audible tone)	Allows "automated pedestrian call" from smartphones for visually impaired pedestrians and provides information to the visually impaired to support safe crossing.
Support of Unsignalized Intersection Safety		
Warn Drivers of Potential Stop Sign Violation	No existing solution, although general warning of a stop sign has been given using signs with flashing light	Application warns the driver if the vehicle is predicted to violate a stop sign.
Support Gap Acceptance at a Stop Sign	Few rural intersections in the nation have been equipped to warn drivers of conflicts (insufficient gaps)	Application provides advisory information to cross-street drivers at a stop-sign controlled intersection to support their gap selections at the intersection.

Table 3-2 (Continued)

Function	Existing Solutions	CV-Based Solutions
Hazard Warning		
Warning Drivers of Unsafe Speeds	Speed police enforcement	Reduced Speed/Work Zone Warning (RSWZ) warns drivers that they are operating at a speed higher than the speed limit and/or providing information regarding changes in lane configuration
Warning Drivers of Unsafe Speeds on Curves	Infrastructure-based warning systems	CV-based Curve Speed Warning (CSW) system that warns drivers of unsafe speeds
Warning Drivers of Oversize Vehicles	Infrastructure-based warning systems	CV-based Oversize Vehicle Warning (OVW) system that warns drivers when the size of a vehicle exceeds the limits at the location
Warn Drivers of Bad Weather and Pavement Conditions	Infrastructure-based warning systems	CV-Based Spot Weather Information Warning (SWIW)
Railroad Crossing Warning	Active Rail Crossing Warning systems, including existing warning devices, such as flashing light signal, automatic gate, warning bells, and additional flashing light signals	CV-based application that warns drivers if they are on a crash-imminent trajectory to collide with a train at a railroad crossing

Table 3-3 Summary of Mobility and Safety Impacts of Existing and CV-Based Solutions to Address Arterial Management Needs

Function	Existing Solutions	CV-Based Solutions
Data Collection to Support System Management		
Travel Time Estimation	80% to 90% accuracy and reliability of travel time based on AVI or third-party data	85% to 95% accuracy for 5% and 10% CV market penetrations, respectively
Incident Detection Time	4-8 minutes with full deployment of point sensors	2-4 minutes with 10% market penetration of CV
Support of Off-line Signal Control	7.5% retiming coordinated signals and 11.5% coordinating isolated signal	TBD
Provision of Signal Control to Accommodate Varying Conditions		
Adaptive Signals	5% for saturated conditions and 10% for undersaturated conditions over time-of-day control	**Congested:** • 5% without CV • 15% with 100% CV MP • Linear interpolation between 5% and 15% for lower market penetration **Uncongested:** • 10% without CV • 25% with 100% CV MP • Linear interpolation between 10% and 25% for lower market penetration
Transit Signal Priority	12% reduction in travel time applied to buses that are not on time. Increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels.	**Congested:** 12% decrease in bus travel time with an increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels. **Uncongested:** 15% to 25% decrease in bus travel time, depending on CV market penetration. Increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels.

Table 3-3 (Continued)

Function	Existing Solutions	CV-Based Solutions
Freight Signal Priority	12% reduction in travel time applied to freights that are not on time. Increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels.	**Congested:** 12% decrease in freight travel time with an increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels. **Uncongested:** 15% to 25% decrease in freight travel time, depending on CV market penetration. An increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels.
Pedestrian Control	NA	TBD
Emergency Vehicle Preemption	15-45 seconds per intersection and a 10% reduction in the probability of death for each one-minute faster response	TBD
Speed Adjustment to Support Arrival on Green		
Green Light Optimal Speed Advisory (GLOSA)	NA	3% to 5% improvement in fuel consumption and delay
Glide Path (Involving Partial Automation)	NA	10 to 20% improvement in fuel consumption and delay
Support of Incident and Emergency Response		
Increasing Incident Zone Site Emergency Responder and Vehicle Safety and Mobility	NA	14% reduction in network-wide travel time, 8% increase in speed, 1% to 90% reduction in hard deceleration
Emergency Vehicle Staging and Routing	NA	Emergency vehicle travel time reduced by up to 23%, and their number of stops by up to 15%. An overall reduction in incident duration by 15%.

Table 3-3 (Continued)

Function	Existing Solutions	CV-Based Solutions
Evacuation Support	Dynamic Information and Guidance to Support Management	The application decreases the congestion time by 20%; and the wait time for transit services by 90%. On average, evacuees seeking lodging experienced a 2-hour travel time benefit.
Dynamic Information and Guidance to Support Management		
Provision of Traveler Information	5% to 20% diversion, depending on incident impact severity	15% to 50% diversion, depending on incident impact severity
Provision of Guidance	15% to 35% diversion, depending on incident impact severity	25% to 80% diversion, depending on incident impact severity
Optimization of Guidance Combined with Signal and Other Management System Optimization	NA	TBD
Support of Signalized Intersection Safety		
Permissive Left Turn and Right Turn on Red Support	10% to 55%	With 100% CV market penetration: Signalized Left Turn Assist (SLTA): A 36% to 70% reduction in intersection crashes; Signalized Right-Turn Assist (SRTA): A 25% to 50% reduction in intersection crashes
Red Light Violation and Rear-End Collision Reduction	20% to 40%	With a 100% CV market penetration, Red-Light Violation Warning (RLVW): 25-50% reduction in intersection crashes
Reduce Pedestrian on Crosswalk Crashes	7% to 45%	50% to 100% reduction in pedestrians on crosswalk crashes with 100% market penetration

Table 3-3 (Continued)

Function	Existing Solutions	CV-Based Solutions
Support of Visually Impaired Pedestrian in Crossing the Street	Accessible pedestrian signal is expected to reduce visually impaired incidents.	Expected to reduce visually impaired incidents more than the accessible pedestrian signal
Support of Unsignalized Intersection Safety		
Warn Drivers of Potential Stop Sign Violation	9% to 67%	Reduce 50% to 100% of this type of crash with 100% market penetration
Support Gap Acceptance at a Stop Sign	NA	Reduce 28% of this type of crash with 100% market penetration
Hazard Warning		
Warning Drivers of Unsafe Speeds	5% to 41%	Reduce Up to 50% of this type of crash with full deployment
Warning Drivers of Unsafe Speeds on Curves	2% of this type of crashes	Reduce 20% to 30% of this type of crash with full deployment
Warning Drivers of Oversize Vehicles	50% of this type of crashes	Reduce 75% to 90% of this type of crash with full deployment
Warning Drivers of Bad Weather and Pavement Conditions	15% of this type of crashes	Reduce Up to 50% of this type of crash
Railroad Crossing Warning	45% to 50% of this type of crash	Reduce 50% of this type of crash

3.3 PROJECT CASE STUDY

The procedure to select between deployment alternatives is applied to a case study to demonstrate its use. The case study focuses on SR-924/NW 119 Street from NW 32 Avenue to NW 5 Avenue in Miami, Florida. FDOT is currently deploying an adaptive signal system as part of the SR 924/NW 119th Street Adaptive Signal Control Technology (ASCT) Pilot Project. The goal of this project is as follows: "*The project goal is to improve the efficiency of NW 119th Street between NW 32nd Avenue and NW 5th Avenue and NW 27th Avenue between NW 110th Street and NW 119th Street to all users, using sustainable signal technology to minimize congestion and increase vehicle and person throughput where possible, without compromising safety for all users.*" The intent is to provide safety, mobility, and reliability improvements for commuters, freight, and transit users along the corridor and also manage fluctuations due to special regional events, traffic incidents, and the impacts from proposed regional developments.

Metric Engineering, Inc., conducted a study for FDOT to perform an arterial analysis for the facility, and the final operational analysis report was produced in March 2018 (Metric Engineering, 2008). Prior to implementing the ASCT Project, C. H. Perez & Associates Consulting Engineers, Inc., (P&A) was retained by the FDOT District Six Traffic Operations Office to perform a Resurfacing, Restoration, and Rehabilitation (3R) Safety Review along SR-924/NW 119 Street from NW 27 Avenue to NW 7 Avenue. The 3R Safety Review report (P&A, 2017) was produced in February 2017 to identify existing safety concerns and recommended countermeasures targeted at the crash patterns found within the 3R Roadway project limits. Choice Engineering Consultants, Inc., was retained by the HNTB Corporation for the FDOT District Six Traffic Operations Office to perform a crash analysis of the SR-924/NW 119 Street study segment from east of the Gratigny Parkway Expressway terminus (west of NW 32 Avenue) to east of NW 5 Avenue. A crash analysis technical memorandum (Choice Engineering 2017) was produced in April 2017 to identify crash patterns and associated probable causes to document the existing safety conditions of the corridor. All of these studies were utilized in the current research project to identify the needs of the implementation of CV technology for the corridor and the required functions to be provided by the CV V2I applications for the facility.

Based on the operational analysis report produced by Metric Engineering, Inc., the Annual Average Daily Traffic (AADT) on the intersections along the corridor varies from 87,000 vpd (vehicle per day) at NW 27 Avenue to 22,400 vpd at NW 5 Avenue. The 4-hour turning movement counts indicate that the AM and PM peak hours occur at 7:30 AM and 5:00 PM, respectively. Eastbound traffic is slightly heavier than westbound traffic during the morning peak, and westbound traffic is heavier than eastbound traffic during the afternoon peak. An analysis of travel time runs reveals that the majority of delays and queues occur between NW 32nd Avenue and NW 22nd Avenue during the AM peak period and near NW 7 Avenue and I-95 during the PM peak period. Long queues, blocking off intersections, and delays were observed on the segment between NW 32nd Avenue and NW 22nd Avenue during both morning and afternoon peaks and on the segment between NW 7th Avenue and I-95 during the afternoon peak.

The segment between NW 32nd Avenue and NW 27th Avenue, which includes closely spaced, major signalized intersections, has a particularly high crash frequency. In particular, the westbound left turn on NW 27th Place and to a lesser degree the westbound left-turn movement on NW 32th Avenue and the eastbound left-turn movement on NW 27th Avenue have high crash rates. These movements do not get gaps in the eastbound traffic flow to perform the left-turn movement during the permissive phase. The turn bays were often blocked by the through queues along the corridor. Some of the factors for the high left-turn crashes are listed below:

- High left-turning volume
- Exposure of left-turn traffic across four opposing lanes
- Thru queue from adjacent NW 2th Avenue
- Signal limiting visibility
- Excessive speed
- Limited left-turn storage
- Poor left-turn lane alignment
- Sight distance restricted by trucks

To improve the mobility and safety performance along NW 119th Street, the operational analysis report recommended implementing better signal coordination to address crashes related to congestion and poor signal progression (varying cycle lengths), especially on the identified high crash segment from NW 10th Avenue to NW 5th Avenue. It also suggested to examine signal timing offsets for the NW 27th Avenue, NW 22nd Avenue, and NW 7th Avenue corridors prior to the implementation of signal timings for potential cross-street coordination impacts.

The high crash location segments mentioned above have high rear-end crashes that were attributed to the following factors:

- Congestion/Signal progression
- Excessive speed
- Pavement conditions (low friction)
- Signal conspicuity (visibility)

The high crash locations at NW 32nd Avenue and NW 27th Avenue have high sideswipe crashes that were attributed to the following factors:

- Aggressive driving
- Abrupt lane changing
- Congestion
- Trap lane conditions

At NW 5th Avenue, vehicle collisions with bicyclists were observed due to bicyclists crossing at the north or south legs within the crosswalk markings. This was attributed to poor lighting, careless driving, and violation of right-of-way.

The implementation of adaptive signal control was expected to help to reduce crashes caused by congestion and poor signal progression, such as rear-end and sideswipe, which are two of the major crash types along the study corridor as revealed by the 3R safety review report and the crash analysis technical memorandum. Since improving the mobility of transit, freight, and pedestrian movements, the main objectives of ATM, TSP, FSP, and advanced pedestrian control should be examined to determine if they can be implemented in conjunction with the adaptive signal control system currently being implemented.

Based on the crash analysis technical memorandum produced by Choice Engineering, the percentage of left-turn crashes at the intersections of NW 32nd Avenue, NW 27th Place, and NW 27th Avenue along NW 119th Street in three years (from 2012 to 2014) are 18%, 62%, and 24%, respectively.

Therefore, one of the recommendations in the operational analysis report is to implement the protected-only phase for the WBL and EBL movements at these three intersections to reduce angle and left-turn crashes. A potential CV-based alternative deployment is to use the Signalized Left Turn Assist (SLTA) system at the three intersections to support drivers making permissive left turns at the signalized intersections. The 3R safety review report revealed that the right-turn crashes at the NW 10th Avenue and NW 7th Avenue intersections are abnormally high. Right-turn crashes, especially at NW 10th Avenue, accounted for 10% of the crashes. Another CV V2I application, Right Turn Assist (RTA), can be applied to warn the drivers making a right turn on red of the potential for collision.

Based on the 3R safety review report, there were a total of 22 red light violation crashes that occurred at the segment from NW 27th Avenue to NW 7th Avenue along NW 119th Street, from 2012 to 2014. It accounted for 4.0% of the crashes in the segment. The potential CV V2I application that can help reduce the frequency of red-light violations in the study area is the Red Light Violation Warning (RLVW) system. It provides a warning to drivers who may potentially enter the intersection in violation of the signal control.

The 3R safety review report also revealed that there were three pedestrian crashes at the NW 22nd Avenue intersection and two pedestrian crashes at the NW 17th Avenue intersection. A moderately high level of pedestrian activity was observed at or near the NW 17th Avenue intersection. There was also one pedestrian crash at the NW 7 Avenue intersection and one pedestrian crash at the NW 30th Place intersection. The crash analysis technical memorandum revealed that there were two collisions with a bicyclist at the NW 5th Avenue intersection. Both bicycle crashes involved bicyclists crossing at the north or south legs within the crosswalk markings. While the percentage of pedestrian and bicycle crashes were not high compared to other crash types, vulnerable pedestrians and cyclists are at higher risk of fatal or severe injury in the event of a collision with a motor vehicle. The Pedestrian in Signalized Crosswalk (PSCW) is the CV V2I application that can warn drivers of a potential conflict with pedestrians within the crosswalk of a signalized intersection.

The CV V2I applications can help improve the safety of not only the signalized intersections but also the unsignalized intersections. There are ten unsignalized intersections along NW 119th Street between NW 32nd Avenue and NW 5th Avenue, which is only one less than the number of signalized intersections. The crash analysis technical memorandum revealed that the unsignalized intersection of NW 14 Avenue/NW 15 Avenue showed a high crash concentration. To help improve the safety of this unsignalized intersection, the Stop Sign Gap Assist (SSGA) and Stop Sign Violation Warning (SSVW) application can be considered.

Another potential CV V2I application that can be implemented in the study area is Reduced Speed/Work Zone Warning (RSZW). This application can determine a safe speed based on traffic and environmental conditions and provide a warning to drivers about excessive speeds.

Table 3-4 includes a summary of the identified needs for SR-924/NW 119th Street, the necessary functions to address these needs, and the CV-based solutions for each identified need based on the above discussion. The identified needs and solutions will be further revised and updated based on discussions with FDOT District 6 and other SR-924 corridor stakeholders.

Table 3-4 Needs of NW 119th Street and Related Existing and CV-Based Solutions

Need	Needed Function	Potential Existing Solution	Potential CV-Based Support
Improve mobility and safety based on performance measurement	Data Collection to Support System Management	Bluetooth readers have been installed on SR-924 segments. New 2070 controllers will provide high-resolution controller data.	CV data can be used to support performance measure estimation (travel time, arrival on green, movement delays, etc.). The data can also be used for incident detection.
Improve mobility and safety for all modes (car, truck, transit, and pedestrian) by providing optimal signal control	Provision of Signal Control to Accommodate Varying Conditions	The Design-Build Firm has already selected an adaptive signal control that is being implemented on the SR-924 corridor.	I-SIG may not be justifiable since an adaptive signal control is being installed on the facility. The vendor and contractor of the system should be contacted to determine if I-TSP, I-FSP, PED-SIG, and I-EVP can be implemented in conjunction with the installed adaptive signal control.
High left-turn crashes at the intersections of NW 32nd Avenue, NW 27th Place, and NW 27th Avenue	Left-Turn Movement Support	Implement protected-only WBL and EBL movements at the three intersections.	Implement Signalized Left Turn Assist (SLTA) at the three intersections.
High right-turn crashes between NW 27th Avenue to NW 7th Avenue	Right-Turn Movement Support	Implement no right-turn-on-red at the subject intersections between NW 27th Avenue to NW 7th Avenue.	Implement Right Turn Assist (RTA) system at the subject intersections.

Table 3-4 (Continued)

Need	Needed Function	Potential Existing Solution	Potential CV-Based Support
22 red light violation crashes from NW 27th Avenue to NW 7th Avenue	Red Light Violation Warning Dilemma Zone Protection	Potentially installing Red Light Violation Camera. Increase the yellow plus all-red interval.	Red light Violation Warning (RLVW) system. Dilemma Zone Protection as part of MMITSS.
Pedestrian crashes observed at a number of intersections with a moderately high level of pedestrian activities observed at or near the NW 17th Avenue intersection	Pedestrian on Cross-Walk Warning	Provide pedestrian warning signs (W11-2) for the signalized pedestrian crossing at E Golf Crossing. A new signalized intersection is being implemented.	Pedestrian in Signalized Crosswalk (PSCW) application at E Golf Crossing, Miami-Dade Community College Intersection, and NW 17th Intersection. A new signalized intersection is being implemented.
The unsignalized intersection of NW 14 Avenue/NW 15 Avenue showed high crash concentrations	Warning of Potential Stop Sign Violation and Assistance in Accepting gaps	Static sign with flashing beacon warning of the stop sign.	Stop Sign Gap Assist (SSGA) and Stop Sign Violation Warning (SSVW) can be considered
A large number of speeding and aggressive driver-related crashes	Warning of Unsafe Speeds	Speed enforcement.	Reduced Speed/Work Zone Warning (RSZW).

3.4 SUMMARY

This chapter has identified typically needed mobility and safety functionalities for the management and operation of urban arterials. It also identified existing and CV-based solutions to provide these functionalities. The performance of the identified solutions in terms of mobility modification factors and crash modification factors has also been estimated based on the information available in the literature. Additional reviews were being conducted to refine and add to these estimates, and additional simulation and analysis was conducted to support the estimation. It is expected that these factors will need to be updated as additional results become available from CV deployments.

The results from this chapter was used in the methodology developed in this study to conduct a return on investment analysis. The performance improvement information from this chapter was used as inputs to the model and in data analysis to determine the benefits for the case study corridor (a segment of SR-924/NW 119th Street in Miami, Florida). Then, the costs associated with the deployments was estimated.

In addition to the return on investment analysis mentioned above, the use of a multi-criteria decision-making method is discussed later in this document. The method considers, in addition to the benefit-cost ratios, other factors that can affect FDOT's decision-making process in selecting between existing and CV-based technologies. Factors, such as those related to minimizing the risks and constraints, may be included, for example, in the uncertainty of the benefits, and in protecting the existing investment, technology uncertainty, technology and standard immaturity, cost uncertainty, security and privacy, and data availability and sharing concerns.

4. CONCEPT OF OPERATIONS OF THE USE OF CV ON URBAN ARTERIALS

This chapter discusses the information that supports agencies in their development of a Concept of Operations (ConOps) as part of the systems engineering process for an urban arterial in Florida with the consideration of CV applications based on local needs and issues. The document presents a vision of the system after CV-based implementation, current situation of ITS deployment, stakeholders associated with the deployment, nature, and justification of the required changes, an overview of the system, including the hardware and software components, and a method for assessing system impacts and selecting between alternatives.

4.1 VISION

The ConOps of ITS deployments should start with a vision. The vision is a definition of the ultimate system and represents stakeholder consensus, including buy-in from senior management. It is a non-technical narrative description of life after the final ITS implementation viewed from multiple stakeholder perspectives (USDOT 2007). The vision for a street ITS/CV deployment will be different, depending on local conditions and priority.

The vision of the 2019 FDOT Connected and Automated Vehicle (CAV) Business Plan is "*Vision Zero with a fatality-free roadway network and a congestion-free transportation system in Florida using CAV technologies*" (FDOT 2019). Thus, the vision of implementing CV-based technologies on Florida arterials can include improving the mobility, reliability, and safety of all users of the system (passenger cars, transit, commercial vehicles, pedestrians, and/or bicycles, depending on the facility) and to support the transportation agencies in the planning, management and operations of the systems. In any event, the implementations should be related to the needs of the project stakeholders and related to the goals and objectives of the 2017 FDOT TSM&O Strategic Plan, 2018 FDOT STAMP Action Plan, and 2019 FDOT CAV Business Plan.

In addition to the positive impacts of CV-based deployments beyond what can be achieved with existing technologies, the implementations of the CV-based solutions will have the added benefits of contributing to increasing the capability maturity of the transportation agency with respect to emerging technology applications and, according to the 2019 FDOT CAV Business plan, possibly contributing to the growth of the economy. Thus, transportation agencies may be willing to accept the initial risks associated with the CV deployment to acquire the capability and demonstrate the technology performance and impacts. The investment in CV-based applications will be selected based on MCDA, which considers other solutions to the identified issues facing the facility.

4.2 GOAL AND OBJECTIVES

The 2019 FDOT CAV Business Plan states that "*The CAV technologies have the potential to significantly reduce highway crashes that result in traffic fatalities. This is consistent with FDOT's vision and that of Vision Zero. The CAV technologies also have the potential to improve travel time, increase vehicle and person mobility, enhance multimodal operations, and positively affect the economy in Florida*" (FDOT 2019).

Thus, a potential example goal for CV-based deployment on an arterial facility in Florida can be: "The project goal is to improve the mobility, reliability, and safety of the arterial facility in a cost-effective manner, while increasing the capability maturity of the agency in using emerging technology and supporting the growth of the economy in Florida." Specific objectives will have to be stated that are related to the goal based on the identified needs and issues of the facility. Output and outcome performance measures will have to then be set that are related to the project objectives for pre-deployment and post-deployment assessment of system performance.

4.3 DESCRIPTION OF THE CURRENT SYSTEM OR SITUATION

According to the systems engineering approach, CV deployment concepts should be needs-driven. As each site has different needs, the focus and applications of CV deployments should be different for each site. Earlier portions of this report provided a detailed description of the typical needs of arterial streets, existing solutions, and CV-based applications that are used or can be used to support these needs. The following is a summary of the needs.

- Data collection for the purpose of performance measurement and prediction, automatic incident detection, and support of off-line signal control retiming.
- Provision of signal control to improve performance and accommodate varying conditions for all modes of traffic.
- Support of vehicles for arrival on green on arterial streets.
- Support of incident and emergency response activities and response personnel.
- Dynamic traveler information and guidance to support the management of the facility's performance.
- Support of signalized intersection safety, including permissive left turn and right turn on red support, red light violation and rear-end collision reduction, reducing pedestrians and bicycles on crosswalk crashes, and support of visually impaired pedestrians in crossing the street.
- Support of unsignalized intersection safety, including warning drivers of potential stop sign violation and support of gap acceptance at a stop sign.
- Hazard warnings, including warning drivers of unsafe speeds, unsafe speeds on curves, oversize vehicles, bad weather and pavement conditions, and at railroad crossings.

For the specific facility case study of this project, which is a segment of SR-924/NW 119th Street in Miami-Dade County, the following are the identified needs:

- Improve mobility and safety based on better performance measurements.
- Improve mobility and safety for all modes (car, truck, transit, and pedestrian) by providing optimal signal control.
- Reduce the high left-turn crashes at the intersections of NW 32nd Avenue, NW 27th Place, and NW 27th Avenue.
- Reduce the high right-turn crashes of the segment between NW 27th Avenue to NW 7th Avenue.
- Reduce the red-light violation crashes from NW 27th Avenue to NW 7th Avenue.
- Reduce pedestrian crashes observed at a number of intersections.
- Address the safety of the unsignalized intersection of NW 14 Avenue/NW 15 Avenue that showed a high crash concentration.
- Reduce the large number of speeding and aggressive driver-related crashes.

4.4 PROJECT STAKEHOLDERS

As with other ITS deployments, there is a need to involve the stakeholders from the beginning to the end of projects that contain CV-based applications. An important lesson learned from the USDOT CV pilot projects is the benefit of successful early and regular involvement, as well as buy-in of the stakeholders. Based on these pilots, it was reported that there is a need to not only engage stakeholders early but to also educate them early. Another lesson learned is that formalized agreements with private partners take time. Thus, there is a need to engage procurement and contract personnel early. It is also important to identify and address the stakeholders' concerns and priorities, such as their concerns about privacy, liability, flexibility, security, experience, funding, etc.

Typical project stakeholders of an Active Traffic Management and integrated corridor management on arterial streets in Florida include:

- Florida Department of Transportation, including TSM&O, Planning, Transit, and Freight Offices, in addition to the Public Information Officer (PIO)
- Traffic signal control maintaining agencies
- Transit agencies
- Port authorities
- Metropolitan/Transportation Planning Organizations
- Toll authorities
- Emergency and public safety agencies

In addition to these stakeholders, other stakeholders may have to be involved in CV-based deployments, including:

- Municipalities that will have the authority to provide the permits for installation
- Utility owners for possible installation on their infrastructure or for running power
- Federal Communications Commission (FCC) to give authority to broadcast messages from the Roadside Equipment (RSE).
- If there is a need to install CV equipment on fleets, the stakeholders may include fleet managements like commercial vehicle carriers, taxi and limousine service providers, and mail services (UPS, FedEx, U.S. Postal Service, etc.), waste management, and ridesharing providers like Uber and Lyft, among others, for potential installation of the Onboard Equipment (OBE).
- Toll authorities for the potential provision of incentives to their users for installing the OBE
- Drivers
- Pedestrians and bicyclists
- Colleges, schools, and employers in the area
- Event providers (stadiums, arenas, convention centers, etc.)
- Private-sector industry partners
- Freight distribution centers
- Trucking Association
- Local community groups
- Disadvantaged group representatives

4.5 JUSTIFICATION FOR AND NATURE OF CHANGES

This section lists the CV-based applications that can improve the mobility and safety on urban arterials and the justification for implementing them in general and for the case study for the project (a segment of SR-924/NW 119th Street in Miami-Dade County). It should be noted that further analysis of the selected improvements will need to be conducted to select between CV-based and other types of solutions, as discussed later in this document.

Table 4-1 Existing Solutions and CV-Based Solutions to Provide the Required Arterial Functions in Relation to SR-924/NW 119th Street Segment Needs

Needed Change	General Justification	Justification for SR-924/NW 119th Street Segment in Miami-Dade County
Data Collection to Support System Management		
CV Use for Data Collection to Support Performance Measurements and Automatic Incident Detection	CV as probes can be used to estimate travel time. A number of existing technologies and sources can provide this measurement. However, CV-based can complement these sources, and as the market penetration of CV increases, they can be replaced. Other potential measures not possible with existing technology can include vehicle classification, acceleration/deceleration, number of stops, number of brakes, potential for crashes, emission/fuel consumption, and weather and lighting conditions; all depending on data availability from vehicles.	Travel time data collected from third-party vendors and Bluetooth vendor, which are currently used to measure performance on the study segment and can be complemented by data from CV technology to provide additional measures and enhancements to existing measures and calculations. CV data can also be used for incident detection along the corridor.
Support of Fine-Tuning Signal Control	CV combined with high-resolution controller data and other available data sources could be used to support the fine-tuning of signal control.	Existing video detection based adaptive signal control could be fine-tuned using CV data combined with high-resolution controller data. With the detailed measures per turning movements, better decisions can be made regarding signal control effectiveness and necessary updates.
Provision of Signal Control to Accommodate Varying Conditions		
Efficient Adaptive Signal Control	Adaptive signal control systems that use a combination of CV data and infrastructure sensor data have the potential to provide better performance compared to existing systems.	This option is not recommended for SR-924 in the near future since a new adaptive signal control system is being installed. However, as the installed adaptive signal control reaches the end of its life-cycle and the CV-based adaptive signal control matures in a few years from now, this will be a very viable option.

Table 4-1 (Continued)

Needed Change	General Justification	Justification for SR-924/NW 119th Street Segment in Miami-Dade County
Transit Signal Priority (TSP) and Freight Signal Priority (FSP)	Local (distributed) and central TSP strategies (conditional and unconditional) can be implemented using current signal control systems. However, CV-based multimodal applications like in the Multi-Modal Intelligent Traffic Safety System (MMITSS) can better accommodate multiple priority requests from multiple fleets and consider the specific real-time situation of an approaching vehicle, such as the ability of a truck to decelerate by considering its breaking ability and the SPaT information about phase and timing status.	Transit and freight mobility can be improved by utilizing TSP/FSP technology. CV data can assist the detection of buses/trucks at a distance from the signal allowing better granting of priority and consideration of nearside bus stops. Bus-specific status information transmitted to Roadside Units (RSU) can be used in priority decisions considering SPaT information. The TSP application is being implemented and tested in the New York CV pilot (https://www.cvp.nyc/), and lessons learned from that implementation can be used.
Pedestrian Signal Control	In the majority of cases, currently, the walk signal is only provided based on push buttons, although some applications use infrastructure-based detectors to extend the Walk signal. Vehicle to Pedestrian (V2P) Communication is another way for pedestrian crossing detection that has the ability to reduce the pedestrian delay and crashes. Pedestrian detectors or information from pedestrian mobile devices can be used as part of the signal control.	CV-based pedestrian control can be used at locations with high crash frequencies, particularly at intersections with a moderately high level of pedestrian activities, such as the NW 17th Avenue intersection.

Table 4-1 (Continued)

Needed Change	General Justification	Justification for SR-924/NW 119th Street Segment in Miami-Dade County
Emergency Vehicle Preemption (EVP)	Central and local EVP are possible with current signal control. Early detection of emergency vehicles based on CV and more detailed information on vehicle trajectory relative to signal phase status allows for better control and queue clearance ahead of the signals.	Emergency vehicle preemption can be implemented in conjunction with TSP and FSP. This has to be coordinated with the fire and rescue agencies.
Speed Adjustment to Support Arrival on Green		
Green Light Optimal Speed Advisory (GLOSA)	Currently, cellular-based applications by private sector companies provide traffic signal information to drivers who subscribe to their services, usually in coordination with OEMs. If applied by the public sector, this application has the potential to reduce travel times by 5%.	The study corridor has high intersection density. Therefore, the application of GLOSA could potentially reduce the probability of stopping at the downstream intersection and reducing rear-end crashes.
Glide Path (Involving Partial Automation)	This application automatically adjusts the speeds of the vehicles to allow them to arrive on green. It has the potential to reduce the travel time by a 15% increase in the traffic propagation along the corridor.	This application is not a near-future application since it requires a level of automation not currently available in existing vehicles.
Support of Incident and Emergency Response		
Increasing Incident Zone Site Emergency Responder and Vehicle Safety and Mobility	Currently, limited site information is provided to drivers to encourage their behaviors to increase safety and mobility at the incident site. Such information can be provided with this CV-based application, including optimal merging out of the closed lane, speed guidance, and warnings about approaching vehicles in an unsafe manner to emergency responders.	This application can support mobility and reduce secondary crashes at the crash (and work zone) sites. The implementation of this application is recommended to be coordinated as part of a regional implementation. However, piloting it as part of the CV deployment of the corridor is beneficial.

Table 4-1 (Continued)

Needed Change	General Justification	Justification for SR-924/NW 119th Street Segment in Miami-Dade County
Emergency Vehicle Staging and Routing	Currently, there is limited dynamic routing of emergency vehicles based on real-time information, and site staging is largely human-driven. Thus, CV-based applications will provide continuous en-route information, support establishing incident scene work zones, and support additional dispatching and staging. The decisions will be based on data and modeling analytics and will result in better responses to incidents.	This application will reduce the response time to incidents and result in safer and more efficient incident scenes that result in a smaller reduction in capacity. The implementation of this application is recommended to be coordinated as part of a regional implementation. However, piloting it as part of the CV deployment of the corridor is beneficial.
Evacuation Support	Currently, there is an additional need for routing information and for support of individuals with functional needs. CV-based applications will provide routing, shelter, and gas information to all evacuees and dispatch and route resources to individuals with functional needs.	This is a regional application and is not applied to SR-924 in isolation.
Dynamic Information and Guidance to Support Management		
Provision of Traveler Information and guidance	Travel time and incident information is currently provided by public and private sector platforms. This CV-based application has the potential to provide more integrated management and routing strategies.	This application has the potential to be applied to SR-924, particularly if it is integrated with the operations on the adjacent I-95, SR-826, and Gratigny Expressway, I-75, and adjacent arterials to account for the diversion from these corridors to SR-924 during incident conditions.

Table 4-1 (Continued)

Needed Change	General Justification	Justification for SR-924/NW 119th Street Segment in Miami-Dade County
Optimization of Guidance Combined with Signal and Other Management System Optimization	Currently, routing and traffic control are conducted independently. There is a potential to jointly optimize the guidance and transportation system management optimization, such as signal control and metering.	This application, although it may not be ready for immediate application, should be researched for future implementation. For example, having messages on dynamic message signs on SR-924 combined and/or I-95 with changes to I-95 ramp metering and signal control.
Support of Signalized Intersection Safety		
Permissive Left Turn and Right Turn on Red Support	Conventional alternatives to high crash rates associated with permissive turns protect the turns and improve geometry/sight distance. Protecting turns will result in higher delays. The CV-based application will provide guidance in accepting safe gaps in opposing traffic and possibly alerts of red violation and a dynamic all-red clearance interval when an opposing vehicle is about to violate the red interval to prevent a side collision.	This application can provide significant benefits in reducing the high left-turn crash rate at the intersections of NW 32nd Avenue, NW 27th Place, and NW 27th Avenue, and for the high right-turn crashes between NW 27th Avenue to NW 7th Avenue. However, this application has not been implemented and tested as much as the other applications in practice. Thus, it should be considered with caution.
Red Light Violation and Rear-End Collision Reduction	Currently, red light violation cameras are used to reduce crashes; however, such cameras have political challenges. The CV-based applications will involve signs with flashing lights, in addition to messages on the OBE that warn drivers who are approaching a signalized intersection if they are on a trajectory to violate a red signal.	This application will provide benefits for the high red light violation crashes from NW 27th Avenue to NW 7th Avenue. It is one of the applications being implemented and tested in the New York CV pilot (https://www.cvp.nyc/), and lessons learned from that implementation can be used.

Table 4-1 (Continued)

Needed Change	General Justification	Justification for SR-924/NW 119th Street Segment in Miami-Dade County
Reduce Pedestrian on Crosswalk Crashes	One conventional alternative is to provide pedestrian warning signs (W11-2). Non-CV alternatives also include onboard vehicle sensors, such as Mobileye image processing devices. However, these applications are limited by line-of-sight. CV–based applications do not have this issue and will receive information from the infrastructure that indicates the possible presence of pedestrians in a crosswalk at a signalized intersection.	Locations that can benefit from this application include the Miami-Dade Community College Intersection and NW 17th Avenue Intersection. This application is being implemented and tested in the New York CV pilot (https://www.cvp.nyc/), and lessons learned from that implementation can be used.
Support of Visually Impaired Pedestrian in Crossing the Street	Accessible pedestrian signal and pushbutton (e.g., using audible tone). Allows "automated pedestrian call" from smartphones for visually impaired pedestrians and provides information to the visually impaired to support safe crossing.	The need for this application for SR-924 needs to be investigated to determine if there is a high number of visually impaired pedestrians in the area. This application is being implemented and tested in the New York CV pilot (https://www.cvp.nyc/), and lessons learned from that implementation can be used.
Support of Unsignalized Intersection Safety		
Warn Drivers of Potential Stop Sign Violation	Currently, there is no existing solution. Although the general warning of a stop sign has been given using signs with flashing light, this CV application warns the driver if the vehicle is predicted to violate a stop sign.	Potential for implementation at the unsignalized intersection of NW 14 Avenue/NW 15 Avenue, which showed a high crash concentration based on crash statistics data.
Support Gap Acceptance at a Stop Sign	Currently, only a few rural intersections in the nation have been equipped to warn drivers of conflicts (insufficient gaps). This application provides advisory information to cross-street drivers at a stop-sign controlled intersection to support their gap selections at the intersection.	Potential for implementation at the unsignalized intersection of NW 14 Avenue/NW 15 Avenue, which showed a high crash concentration based on crash statistics data.

Table 4-1 (Continued)

Needed Change	General Justification	Justification for SR-924/NW 119th Street Segment in Miami-Dade County
Hazard Warning		
Warning Drivers of Unsafe Speeds	Speed police enforcement. Reduced Speed/Work Zone Warning (RSZW) warns drivers that they are operating at a speed higher than the speed limit and/or providing information regarding changes in lane configuration.	This application can reduce the large number of speeding and aggressive driver-related crashes on the corridor, as confirmed by the safety studies of the facility. This application is being implemented and tested in the New York CV pilot (https://www.cvp.nyc/), and lessons learned from that implementation can be used.
Warning Drivers of Unsafe Driving Conditions	CV-based applications have the potential of reducing crashes due to unsafe driving conditions, such as high speeds on curves, oversize vehicles, bad weather and pavement conditions.	Previous safety studies did not identify such conditions for SR-924/NW 119th Avenue. Further examination of this issue may be needed.
Railroad Crossing Warning	Active Rail Crossing Warning systems have been implemented, including existing warning devices, such as flashing light signals, automatic gates, warning bells, and additional flashing light signals. This CV-based application warns drivers if they are on a crash-imminent trajectory to collide with a train at a railroad crossing.	No railroad crossings near the subject corridor.

4.6 CONSTRAINTS AND CHALLENGES

Deployments of CV-based applications are complex and require the integration of a large number of existing and new infrastructure and mobile elements. There are technical, security, privacy, institutional, financial and procurement issues that need to be considered. Some of the issues and concerns have been or are being addressed by recently completed or ongoing FDOT, USDOT, and other national efforts. Additional answers will be provided as more experience and results are obtained from the connected vehicle pilot deployments and research projects funded by FDOT, USDOT, and other ongoing and upcoming efforts. These issues should be tracked and reassessed as more knowledge is gathered and as the technology, policy, and procedures advance in the coming years.

Figure 4-1 shows the responses of public agencies to a survey of their views of the challenges of various issues to the broader adoption of connected vehicle technologies (MDOT 2012). The identified issues in the survey that were rated by the responders are:

- Funding
- Concern about driver distraction
- Liability concerns
- Maintaining proper system functionality
- Security
- Privacy
- Standard maturity
- Costs

Figure 4-1 shows that the most challenging issues for the broader adoption of connected vehicles are funding for roadside infrastructure, liability concerns, and maintaining proper system functionality. Personal privacy concerns, data security, and driver distraction are considered somewhat challenging. vehicle equipment costs and standards are considered slightly challenging. It should be pointed out that this survey is seven years old, and the views of the agencies may have changed since then.

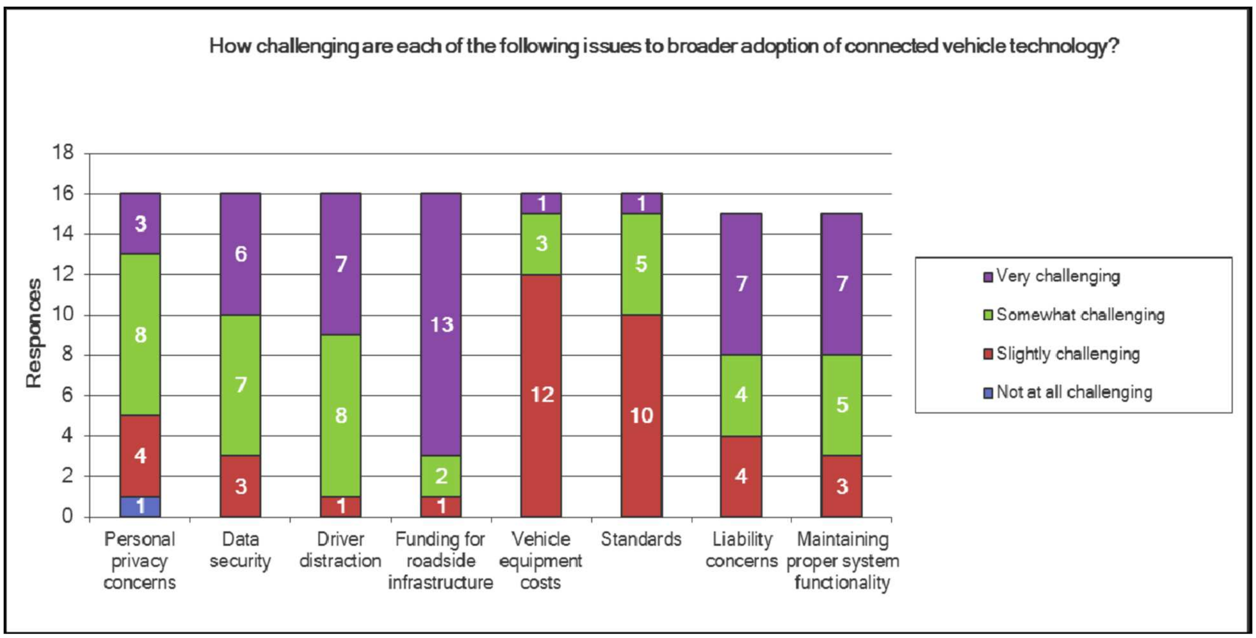


Figure 4-1 Survey Response to the Question of the Challenges of Various Issues to Broader Adoption of Connected Vehicle Technologies (MDOT 2012)

In another study, Barbaresso and Johnson (2014) conducted interviews with agency representatives involved in connected vehicle test projects to identify the technical and institutional challenges in connected vehicle infrastructure deployment. Based on the survey, most agencies expected that the technical issues would be addressed in the next few years but they did not specify how many years is unknown. Obviously, the reality is that these issues will have to be resolved gradually as part of research and development and early deployment efforts. How long this will take depends on the complexity of the issue and the various influencing factors that affect the issue. The identified technical issues include:

- Maturity level of connected vehicle equipment, interoperability, and standards
- Technical obsolescence and changing requirements
- Data management
- Communications and network management
- Network security
- Application support need and consideration
- Optimization of roadside unit deployment

In addition to the technical challenges, six institutional challenges were identified, including:

- Funding (capital, maintenance, and operation costs)
- Required technical skills
- Lack of benefit-cost information
- How data will be accessed and the associated institutional environment
- Standard backward compatibility
- Uncertainty in the business model of connected vehicles

In an NCHRP study conducted by the researchers of this study, Hadi et al. (2017) used the following factors as risks and constraints of using CV technologies for CV-based monitoring and data collection and for traveler information dissemination:

- Technology uncertainty
- Standard stability
- Uncertainty in the business model
- Data archiving and processing; technical skills concerns
- Funding
- Data availability and sharing concerns
- Security and privacy concerns

The remainder of this section discusses some of the issues facing CV-based deployment. An important source of some of the materials in this section are deliverables from the USDOT CV pilots and associated webinars. A large number of documents and webinar materials are available from the effort conducted as part of the CV pilots and can be found at https://www.its.dot.gov/pilots/. The concepts of operations of the Tampa and New York City pilots were developed by Waggoner et al. (2016) and Galgano et al. (2016), respectively.

4.6.1 Achieving the Required Market Penetration

The impact of CV technologies will depend on its market penetration in coming years. In a mature CV environment, government agencies will not be responsible for supplying or procuring the on-vehicle devices and the onboard and smart applications. However, in the near future, for pilot and early implementations of CV, public agencies will have to recruit and train participants in the projects and be responsible for installing and maintaining the devices and apps, as has been done in the USDOT and state pilot projects. Leveraging agency-owned fleets of vehicles, other vehicle fleets in the region, and working with businesses and employers will provide support for this process.

Many CV-based applications usually assume that the supported vehicles will be equipped with CV technology. However, the traffic is expected to be a mix of CV and non-CV for many years to come. Thus, these applications will have to be extended to allow them to function in a mixed environment, requiring additional investment in infrastructure-based sensors and displays.

There have been attempts to forecast CV market penetration. The National Highway Traffic Safety Administration (NHTSA) has been expected to mandate connected vehicle technologies on all new vehicles. Apart from this mandate, after-market plug-in equipment will be available for installation on older cars, yet this is not expected to be mandated. However, this CV mandate on new vehicles was supposed to be issued in the past few years, and it has not been issued yet, and its status is not certain. Wright et al. (2014) suggested three different scenarios for probable CV implementation. The most conservative scenario among the three is called the "15-year organic" scenario, which assumes that the CV will come into the fleet as organic sales of the new capability. The "5-year mandate" scenario is categorized as moderate, in which manufacturers would include Onboard Units (OBUs) in the new vehicles over a five-year period. The best-case scenario is the "1-year mandate" scenario, where all of the new vehicles will be equipped with OBUs, starting from the year that the CV is mandated. Figure 4-2 illustrates the fraction of connected vehicles within the vehicle fleet under different assumptions, as presented by Wright et al. (2014).

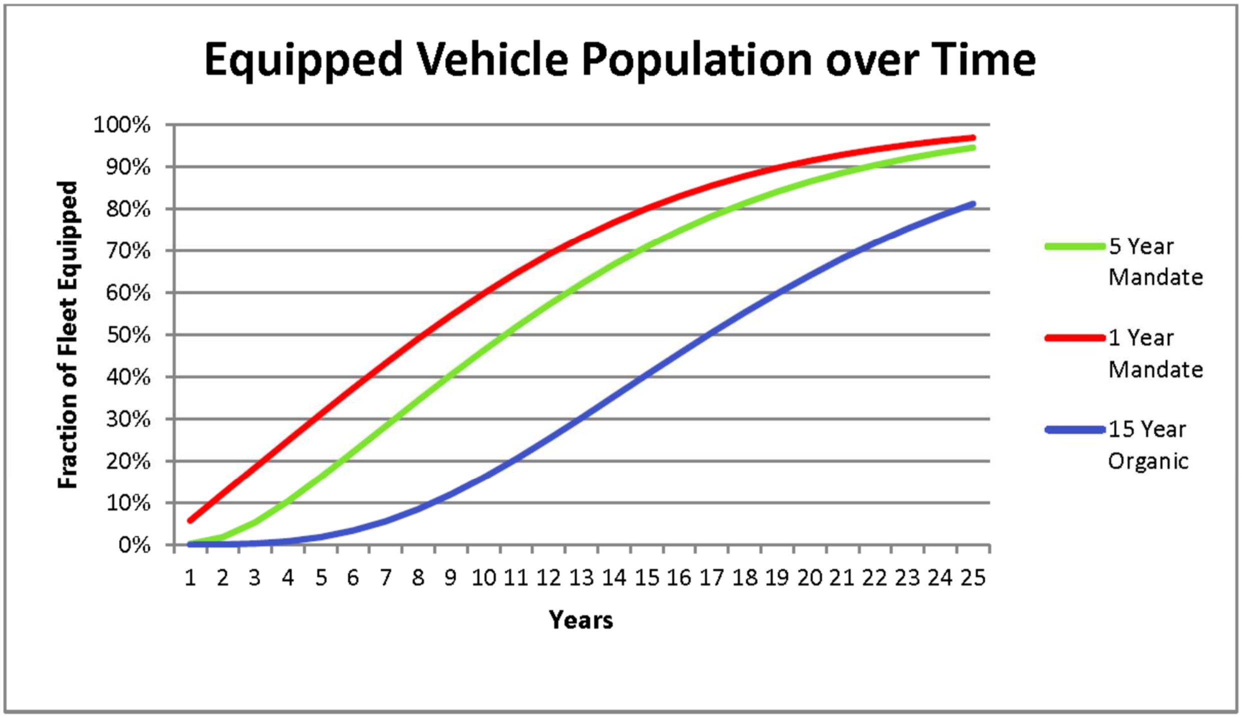


Figure 4-2 Equipped Vehicle Population Over Time (Wright et al., 2014)

Another study (Hill and Garrett, 2011) considered six different possible scenarios to predict the connected vehicle market penetration. Figure 4-3 shows the future market penetration of CV for those different scenarios. The x-axis is the future year, and the y-axis is the proportion of CV's in the vehicle fleet. The Step Application Rate scenario considers 100% market penetration from the very first year of CV deployment, which is presented by a straight line. This scenario represents the situation when the NHTSA agency decision resulted in a mandate to install DSRC radios in all light vehicles (new vehicles are already equipped, and existing vehicles are equipped with aftermarket units). The Step Population Ratio starts from around 10% and rises linearly to 90% by approximately year 15. This scenario would be a result of the NHTSA agency decision to mandate DSRC in all new light vehicles. The other four scenarios follow a typical "S-curve" application rate starting from 0%. The 10-year Application Rate shows a penetration that reaches a peak of 100% by year 17. The 10-year Population Ratio scenario also shows an increase with a slower rate to 85% in approximately 23 years. In the V2V Probability (10-yr) scenario, the market penetration reaches to peak 70% in approximately 23 years. The last scenario, the V2V Probability (Step), considers the increase of a CV market penetration to 83% by approximately year 13.

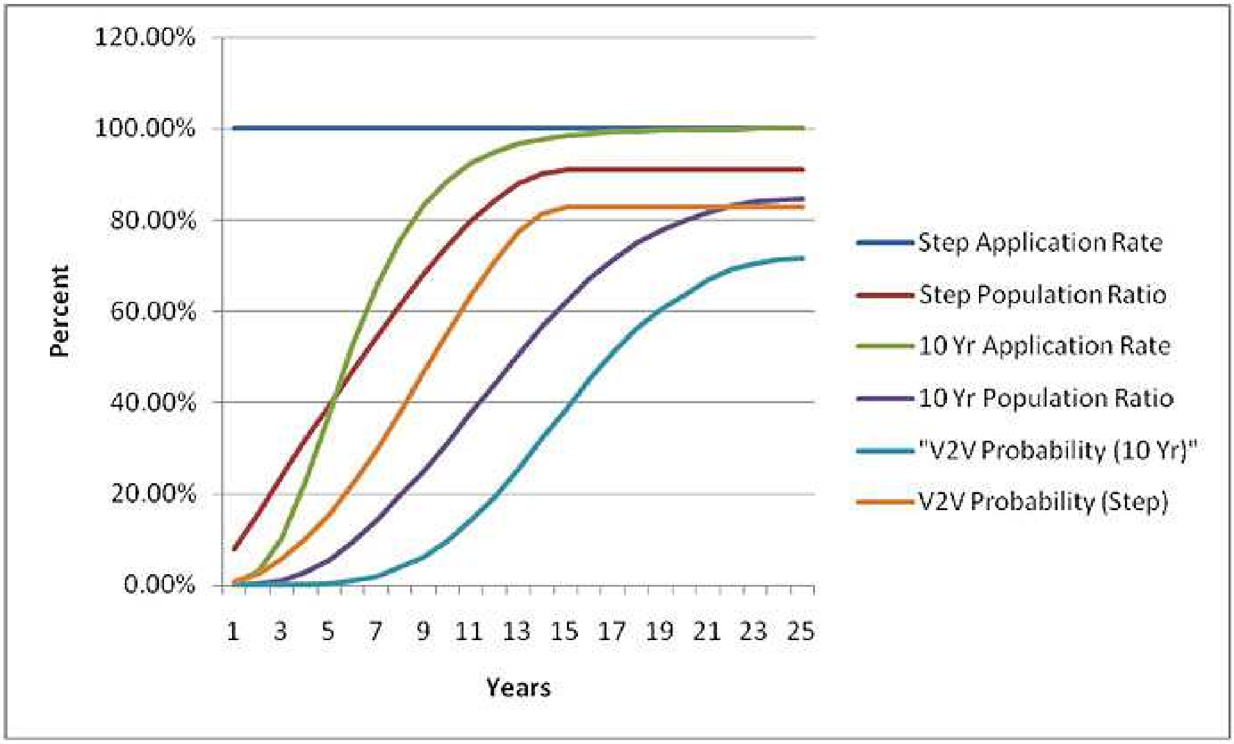


Figure 4-3 Connected Vehicle Market Growth (Hill and Garrett, 2011)

Previous attempts did not consider the variations of market penetrations between regions and zones in each region. In a previous study (Iqbal et al., 2018), the researchers of this project presented a methodology to account for these variations. The method uses data on the distribution of new car ownership as a function of the income in a region.

4.6.2 Experience with CV-based Devices and Applications

A main concern of agencies is the limited experience with and lack of maturity of CV-based devices and applications. Per the 2019 FDOT CAV Business Plan (FDOT 2019), FDOT will "*explore the need for developing the educational outreach program to inform transportation planners, managers, engineers, local agencies, and users (travelling public, motor carriers, other road users) about the CAV Program. Outreach will assist in providing a better understanding of how CAV infrastructure will be deployed and operated, while also addressing the infrastructure requirements, standards, implications, and challenges with CAV deployments.*"

It is expected that FDOT will leverage lessons learned and guidance from previous deployment and evaluation efforts, including those from the three USDOT CV Pilots, Safety Pilot Model Deployment, FDOT, and other state deployments. The applications developed, updated, and tested as part of these efforts should have a higher consideration for implementation since it is expected that the associated issues have been resolved. Some of these applications have been developed by USDOT as open-source applications. They were used as starting points for CV pilot teams to build their Concept of Operations (ConOps) around. The CV device and in some cases signal controller vendors have developed applications that can be utilized and tested, as was done for example in the New York City Pilot. A systems engineering approach should be used for procuring the devices, including the production of all systems engineering process documentation to identify the needs, requirements, specifications, traceability, etc.

The USDOT pilot teams found that the application maturity is lower than what was initially expected and that the development of verifiable system requirements is challenging as the standards are evolving. The teams found no available industry application performance requirements available. Additional recommendations from the pilot teams are to leverage existing device vendor experience, perform technology scans and on-the-road testing to identify promising suppliers who can meet system, cost and project timing. Also, it was reported that the applications should allow the users to manage (tune) the CV applications to accommodate different congestion traffic levels and conditions.

Another important finding from the USDOT pilot teams is that devices, such as the Roadside Units (RSU) and Pedestrian Detection, are relatively mature and less risky to procure. However, the applications on the Onboard Equipment (OBE) and Personal Information Device (PID) are less mature and need further reviews and tests.

4.6.3 Privacy

Privacy is a critical issue for the various stakeholders. Throughout the meetings with the USDOT pilot project stakeholders, these stakeholders indicated that privacy must be met to continue participation in the program. Another concern related to privacy that has been raised by participants is the potential use of the data for enforcement or driver performance assessment. Although the USDOT has policies stating that such data will not be used for these purposes, there is the potential that stored data could be subject to a subpoena or a request based on the Freedom of Information Act (FOIA).

Connected vehicle data, in accordance with J2735 standards, does not have any data elements that identify specific drivers or vehicles. However, if data is to be collected and archived, this issue can become more complex at the present stage of development and will need additional time to understand and determine solutions.

The USDOT pilots have developed documents on the Data Privacy Plan (DPP), which provides guidance regarding the privacy for deployment participant data. The documents discuss the policies and procedures required to assure the protection of Personally Identifiable Information (PII). Examples of solutions applied in the USDOT pilots include having Memorandums of Understanding (MOUs), onboard data encryption, collection time limits, in addition to Data obfuscation, sanitization, and normalization. The obfuscation process is applied to scrub precise time and location data from the logs for privacy while retaining relative details. This results in re-anchoring time/location data to protect the driver/operator while preserving vehicle trajectory details. The non-obfuscated data will be destroyed following the obfuscation process. This whole process, including the parties responsible for archive, process, and access the data, is detailed in the DPP, along with data management plans developed according to the USDOT guidance. The various steps to protect privacy are automated and conducted by the CV pilot research teams.

4.6.4 Liability

Liability can be another potential issue with the CV safety-based application. The New York City legal staff expressed concerns about the deployment of safety-focused applications that may not provide warnings to drivers/operators. It is recommended to develop requirements and associated testing to ensure a high level of accuracy and reliability of the safety alerts. Also, there is a concern about not giving a warning to the driver/operator when operating the devices in stealth modes for use as a baseline during the evaluation, knowing that activating the devices could result in mitigated crashes. However, this has been accepted by the evaluating agencies considering the needs for the evaluation.

4.6.5 Distraction

An important requirement is to avoid distracting drivers with too many audio and visual alarms. The availability of travel information via mobile applications has increased safety concerns in terms of distracting users. Many regions are implementing legislation that bans texting while driving, and some regions have banned the use of the cell phone altogether. The potential distractions due to new CV-based applications have been an important focus of the USDOT pilots. For example, the New York City pilot is utilizing audio output only with the tones and words based on the type of threat and situation, while the Tampa Pilot site uses mirror displays. The evaluation results should inform the future setting of the user interface, but the results have not been published yet.

4.6.6 Security

There is a need to address security in all aspects of the CV applications and interfaces with the existing systems. The USDOT partnered with the automotive industry and industry security experts to design and develop a state-of-the-art security system that is referred to as the Security Credential Management System (SCMS), as a proof-of-concept (POC) message security solution for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. The system employs highly innovative methods of encryption and certificate management to facilitate trusted communication (https://www.its.dot.gov/resources/scms.htm.). SCMS development and testing is a work in progress, and the SCMS POC and associated requirements continue to be refined.

The USDOT and CV Pilot site partners have spent considerable efforts on developing security plans, and then testing and revising the plans based on testing and new information gathered during the project activities. The Security Management Operating Concepts (SMOC) of the pilots outlines the security mechanisms that will be used to protect the information flows within the system, additional practices to protect the privacy and security of data, and management processes and procedures to ensure that security operations are executed in a reliable and trustworthy way. These plans, concepts, and the significant lessons learned should be carefully reviewed and utilized as part of any CV deployment.

4.6.7 Standards Utilization

CV-based deployments should leverage existing standards, specifications, and processes. CV device and interface standards and guidelines exist or are under development. The Tampa CV Pilot team recommended relying on published standards instead of relying on unpublished standards that are still in the development stage and using international standards when U.S. standards do not exist.

The 2019 FDOT CAV Business Plan realizes the importance of standards and that advancing and adopting these standards will assist in expediting the deployment of CAV applications in Florida. Specific action items listed in the business plan include developing a systems engineering process for CAV, implementing the Security Credential Management System (SCMS), exploring cybersecurity and physical security of CAV equipment, and incorporating CAV into FDOT standards and specifications, guides, and manuals.

4.6.8 Data Archiving and Performance Measurements

The CV applications will generate a large amount of data that should be stored and combined with data from other sources to estimate and predict system performance. The archived data can be used as part of decision support systems to support planning, planning for operations, and operations in general. Due to the large amount of generated data, there is a need to determine the data elements that will be communicated to the traffic management center and the aggregation levels of transmission and archiving. This process is also related to the privacy issue mentioned earlier in protecting a participant's personally identifiable information (PII) while also providing sufficient data to support performance measurements. Some of the collected and archived data may require the services of the *Institutional Review Board* (IRB) for the protection of human subjects in research. The purpose of the IRB review is to ensure appropriate steps are taken to protect the rights and welfare of humans participating as subjects in a research project. If the research and evaluation of CV applications use human participants, then the plan will need to specify the need to obtain Human Use Approval from an accredited IRB institution. The project must successfully obtain and document necessary approvals before human subjects can participate in such research.

4.6.9 Funding

Funding, including that required for the deployment, operation, and maintenance, is an important issue facing agencies considering CV deployment. No specific funding has been set aside by the USDOT for the CV deployment other than the CV pilot deployments. However, the USDOT has a number of pilot deployment grant opportunities that can be used for this purpose.

FDOT has recognized the importance of the funding issue, and the 2019 FDOT CAV Business Plan has funding as one of the seven focus areas. The establishment of the FDOT funding strategy is underway with a number of initial steps for the program funding action items already identified in the 2019 FDOT CAV Business Plan (FDOT 2019).

4.7 SYSTEM OVERVIEW

A good starting place for a source of information to have an overview of the system needed for the changes outlined earlier in this report is the information presented in the ARC-IT 8.2 (2019) (Architecture Reference for Cooperative and Intelligent Transportation). The service packages and associated physical objects, functional objects, and information flows, as well as the four views of the architecture, can be accessed at https://local.iteris.com/arc-it and can be used as an important source of information that is further supplemented by information from other sources to complete the system overview. Please note that the current version of FDOT's Florida Statewide and Regional ITS Architectures is based on Version 7.0 of the National ITS Architecture and does not adequately address CV deployment. FDOT plans to update the ITS architecture to be based on the most recent version of ARC-IT in 2019 (Ponnaluri 2018). Below is a set of ARC-IT service packages that support the CV deployments on urban arterials. Additional support is provided by several other ARC-IT packages, and these packages should be reviewed and used in setting the concept of operations of the deployment as part of the systems engineering process (ARC-IT 8.2, 2019).

- SU01- Connected Vehicle System Monitoring and Management
- DM02- Performance Monitoring
- TM04 Connected Vehicle Traffic Signal System
- ST08: Eco-Approach and Departure at Signalized Intersections
- CVO06 Freight Signal Priority
- PT09: Transit Signal Priority
- VS03 Situational Awareness
- VS05 Curve Speed Warning
- VS08 Queue Warning
- VS09 Reduced Speed Zone Warning / Lane Closure
- VS10 Restricted Lane Warnings
- VS11 Oversize Vehicle Warning
- VS12 Pedestrian and Cyclist Safety

- VS13 Intersection Safety Warning and Collision Avoidance
- VS15 Infrastructure Enhanced Cooperative Adaptive Cruise Control
- VS13 Intersection Safety Warning and Collision Avoidance
- PS06 Incident Scene Pre-Arrival Staging Guidance for Emergency Responders
- PS07 Incident Scene Safety Monitoring
- PS02 Routing Support for Emergency Responders
- PS03 Emergency Vehicle Preemption
- TM14: Advanced Railroad Grade Crossing
- MC07: Work Zone Safety Monitoring
- Various traveler information packages

Examples of these service packages are shown in Figures 4-4 to 4-8. The information associated with the listed service packages combined with additional information from multiple sources provided important inputs for this section. In the subsections below, the description of the physical objects and associated functionality and interfaces were used as a starting point in the description of the system components. This information is supplemented with additional information from recently released documents and presentations on the subject.

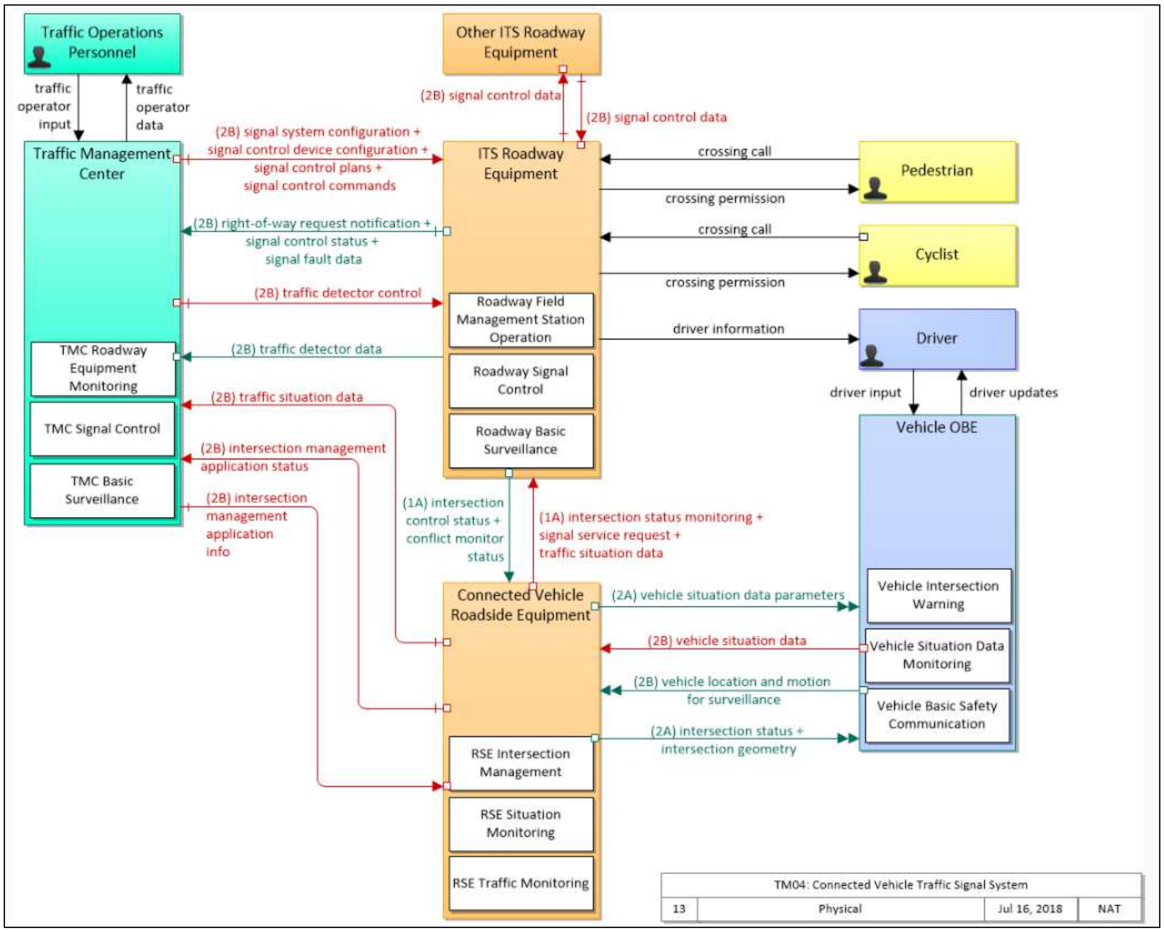


Figure 4-4 TM04 Connected Vehicle Traffic Signal System (ARC-IT 8.2, 2019)

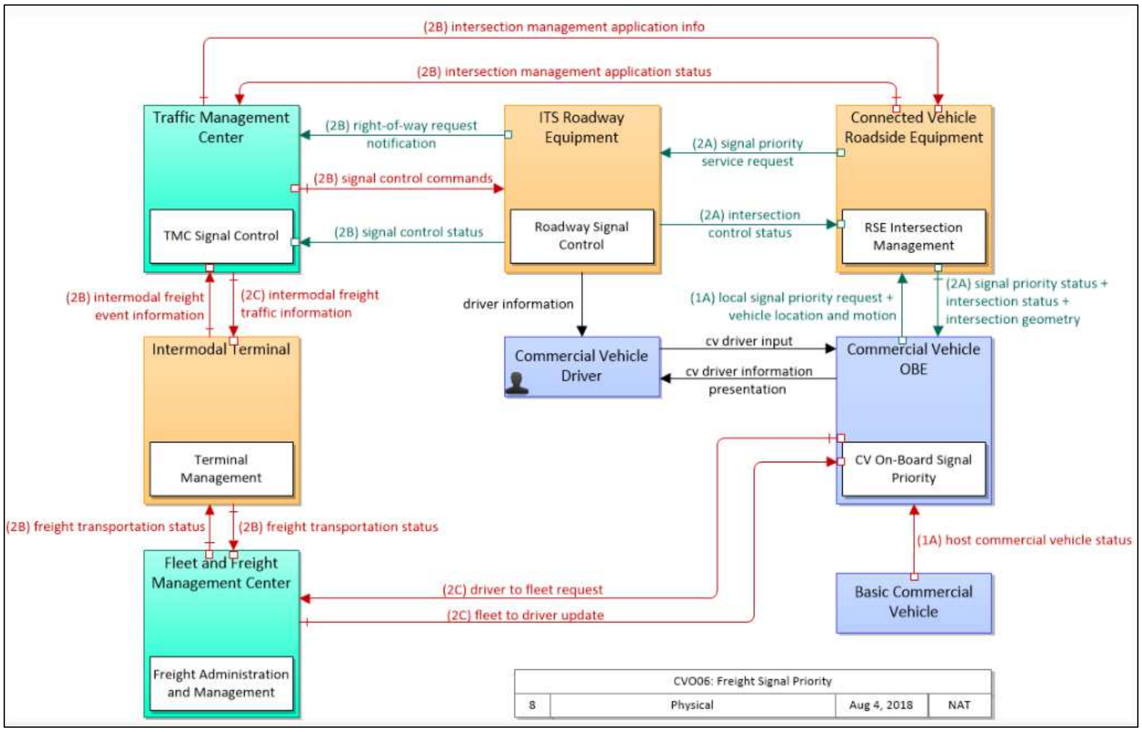


Figure 4-5 CVO06 Freight Signal Priority (ARC-IT 8.2, 2019).

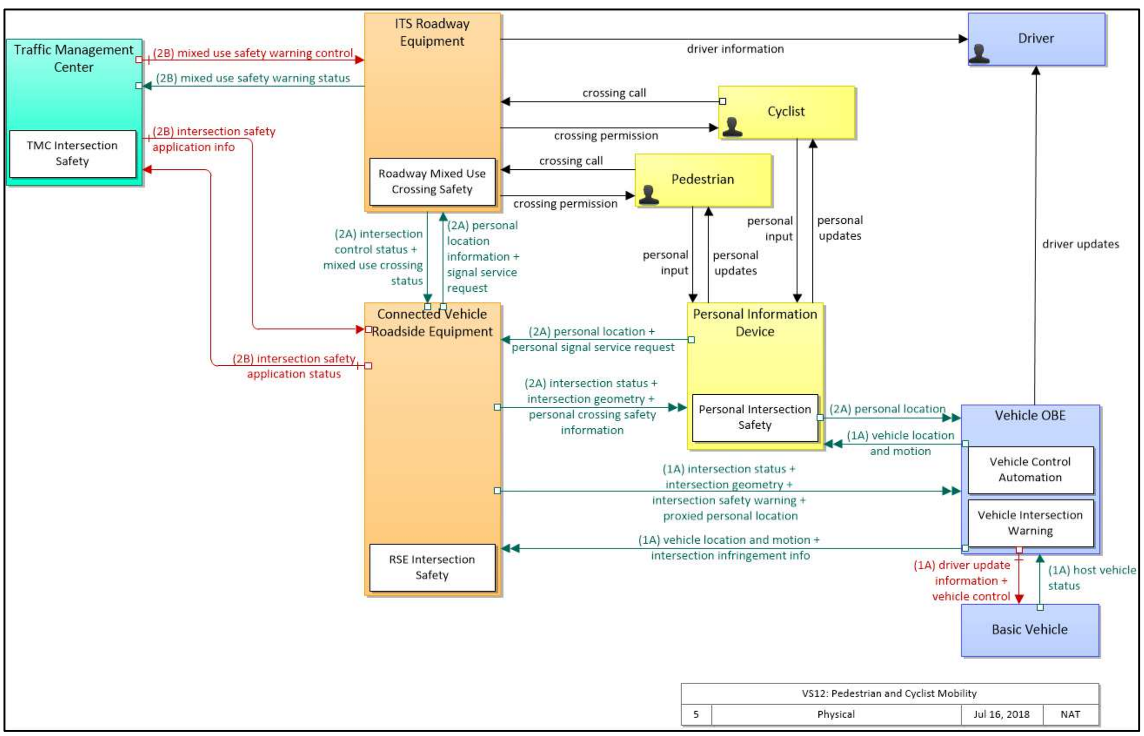


Figure 4-6 VS12 Pedestrian and Cyclist Safety (ARC-IT 8.2, 2019)

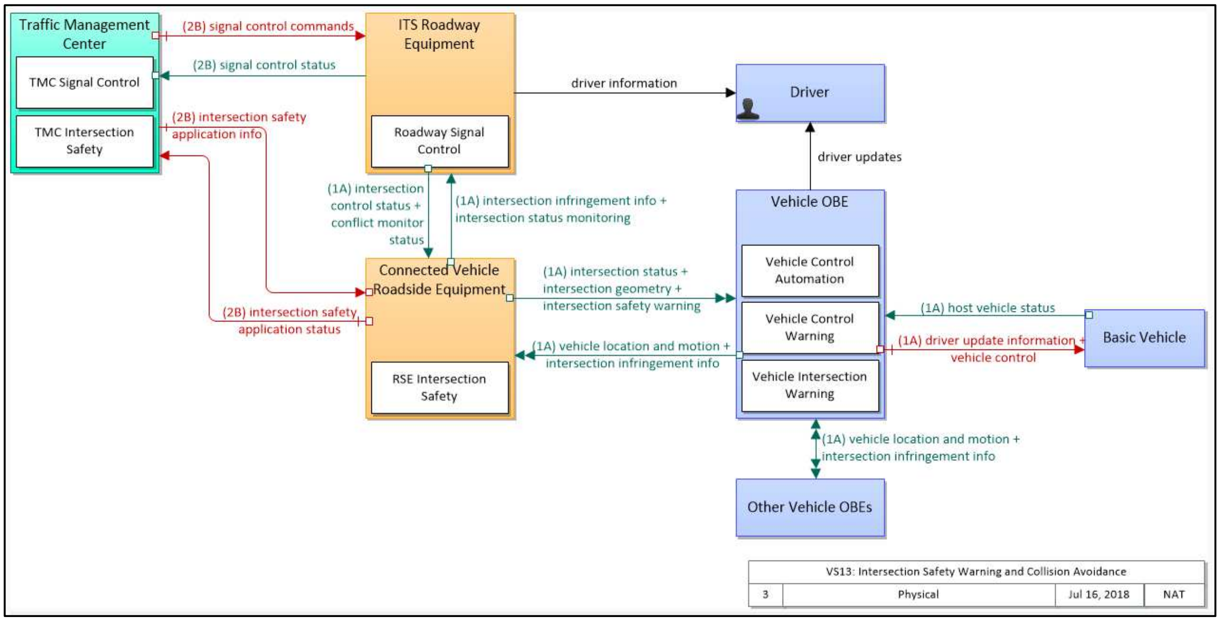


Figure 4-7 VS13 Intersection Safety Warning and Collision Avoidance (ARC-IT 8.2, 2019).

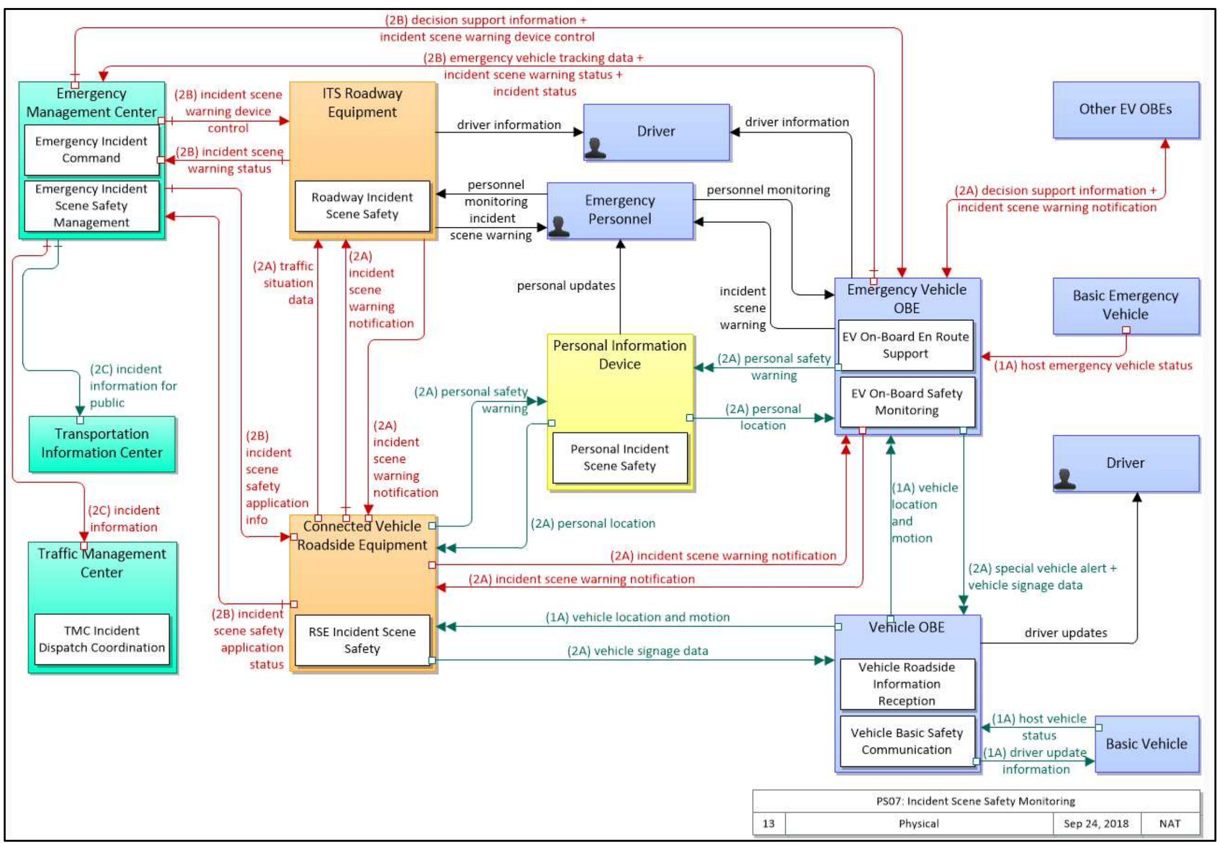


Figure 4-8 PS07 Incident Scene Safety Monitoring (ARC-IT 8.2, 2019)

4.7.1 Traffic Management Center

In CV-based deployments, the Traffic Management Center establishes remote connectivity for monitoring, managing, and configuring the CV-based applications and associated devices. It communicates with various associated ITS Roadway Equipment, including traffic signal controllers, CV processors and other Connected Vehicle Roadside Equipment (RSE) to monitor and manage traffic flow and monitor the condition of the managed facilities and status of field equipment. A central software that is capable of managing the CV equipment will transmit to the field device configuration data, including intersection geometry, warning parameters, and thresholds. Such software will most likely become a module in existing transportation system management software. This flow also supports the remote control of the application, so the application can be taken offline, or be reset, or restarted. Some of the CV management activities of the TMC according to the USDOT New York Pilot includes (https://cvp.nyc/traffic-control-system):

- Security Credentials Management System (SCMS) utilization
- Managing roadside equipment performance (failure identification, repair, maintenance)
- Managing roadside equipment Radio Frequency (RF) footprints
- Managing CV application configuration
- External data distribution
- Data collection from RSE/Aftermarket Safety Devices (ASD)
- Data aggregation, data normalization, and system performance assessment

The central software used by the FDOT Regional Traffic Management Centers (RTMCs) is the SunGuide® software. The SunGuide software is an integration of a set of modules that allows the control of roadway devices, as well as information exchange across a variety of transportation agencies and is deployed throughout the state of Florida. Figure 4-9 provides a graphical view of the SunGuide® software architecture. The managed ITS devices by the SunGuide software include traffic detection devices, cameras and associated encoders and decoders, video walls, dynamic message signs, highway advisory radios, road weather information systems, connected vehicle basic probe data, reversible lane systems, vehicle safety barriers, ramp signals, variable speed limits, wrong-way driving, and express lanes. An initial CV model was incorporated in the SunGuide® software as part of the 2011 CV deployment in Orlando. This SunGuide® module was updated more recently to the new CV standards. According to the 2019 FDOT CAV Business Plan (FDOT 2019), the SunGuide® software will be upgraded in the 2019-2020 time period to allow it to deal with CAV devices.

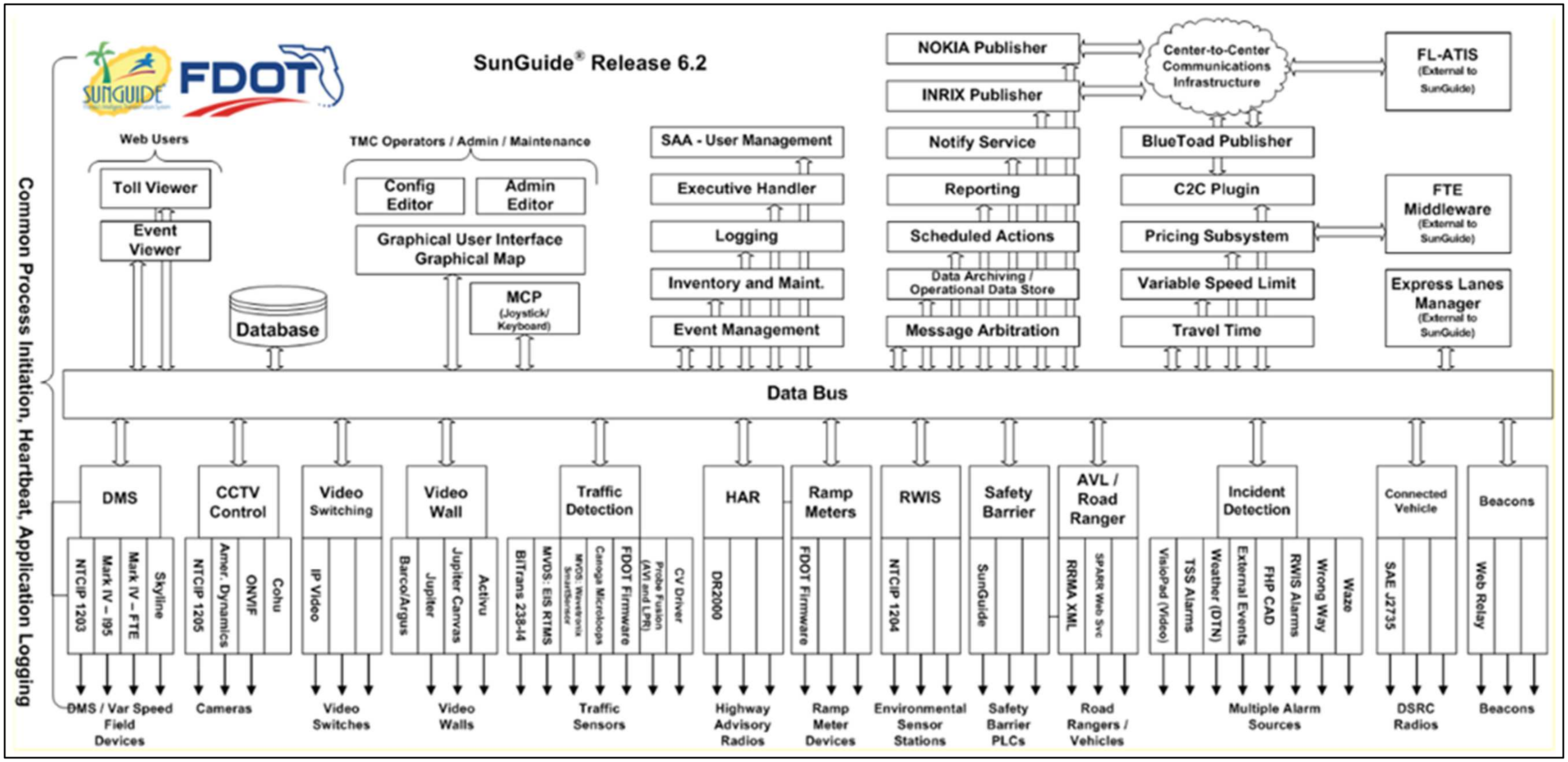


Figure 4-9 SunGuide® Software Architecture

4.7.2 Traffic Controller and Associated Interface

The traffic controller and the associated equipment and interfaces are important components of a number of CV-based applications, such as the Multi-Modal Intelligent Traffic Safety System (MMITSS) applications (signal control based on CV, FSP, TSP, Mobile Accessible Pedestrian Signal System, and emergency vehicle preemption), intersection safety applications, and rail-road crossing applications. The controller must be able to be configured to transmit SPaT messages so that this information can be communicated to CV and PID utilizing RSU DSRC or other communication technologies. The controller must also be able to receive CV and PID information and priority requests utilizing the latest version of the National Transportation Communications for ITS Protocol (NTCIP) 1202 and NTCIP 1211 standards to allow signal control, priority, and preemption.

State of the art traffic controllers that can communicate using NTCIP 1202 v3.05 or later to provide support for SAE J2735 (SAE, 2016) messages will be needed. The 2070 LX controllers and Advanced Traffic Controllers (ATC) have been produced to provide capabilities to interface with the CV RSE. Signal controller vendors have started to produce CV co-processors to provide required functionalities for V2I applications in conjunction with the controller and RSE. The co-processors can either be integrated into the controller or be a standalone component in the cabinet. Some of the required functionalities for the applications are already included in the DSRC RSEs, while others reside on the co-processor. The co-processor provides a direct interface to the other RSE equipment. Figure 4-10 presents a diagram of the infrastructure roadside components from one controller vendor (Econolite) that shows the interfaces between the controller, CV co-processor, RSU, and OBU. As shown in Figure 4-10, the CV roadside unit(s) (RSU) is installed at a location that allows a clear line-of-sight to the vehicles to enable vehicle to infrastructure communications using a Dedicated Short-Range Communication (DSRC) unit in this case. The RSU is connected through a cable to a CV application co-processor (CVCP) in the cabinet that can be in a standalone enclosure or a module that plugs into the controller. The CVCP module allows the interface between the controller and RSU DSRC devices and can enable various CV-based applications that reside on the CVCP.

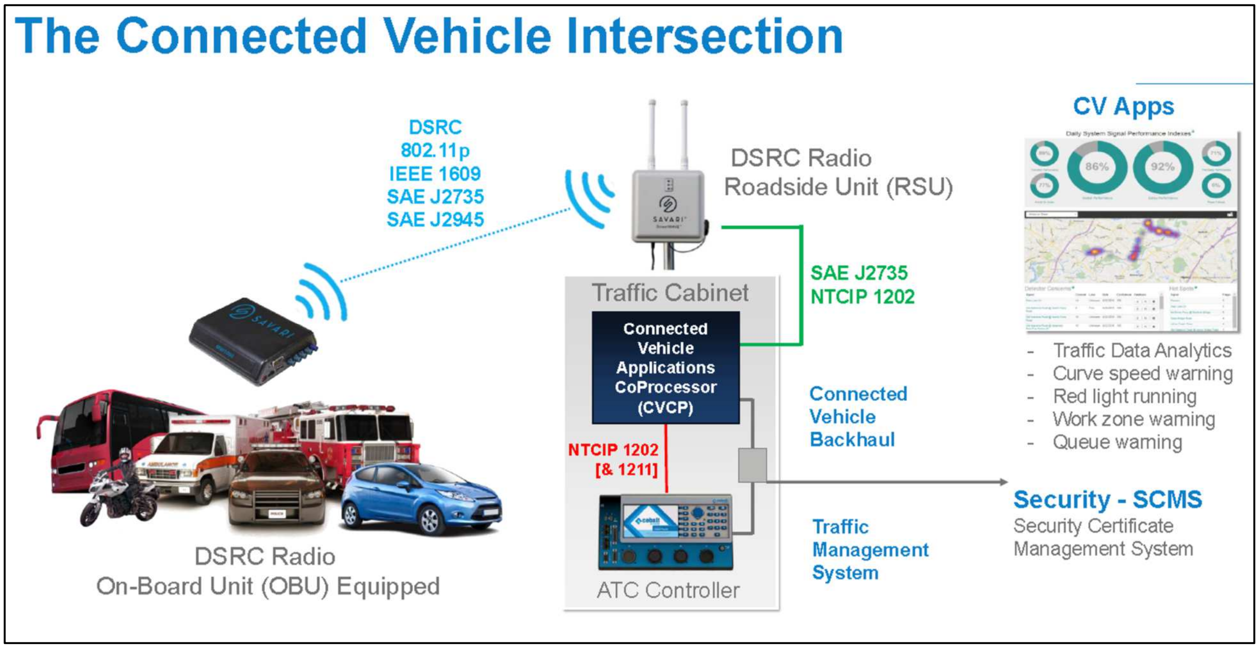


Figure 4-10 The Signal Controller and Econolite CV Co-Processer as Part of the Connected Vehicle Intersection (Provenzano, 2016; Mohaddes, 2017)

Figure 4-11 displays the configuration of the CV-based transit signal priority implementation utilizing the Multi-Modal Intelligent Traffic Signal System (MMITSS) application. Figure 4-11 also illustrates the different components used in the vehicles and at the roadside. As shown in the figure, the MMITSS application is installed on an onboard processor that uses a vehicle's GPS location and the bus schedule as inputs. The processor then determines the on-time performance of the bus and generates signal request messages (SRM), if needed, to meet on-time performance. The processor also sends basic safety messages (BSM) to the infrastructure that then determines the location, speed, and direction of the bus. The processor receives Signal phasing and Timing (SPaT), MAP, and priority status messages, allowing the onboard processor to determine the signal status and whether the priority is granted. The communication between the OBU and RSU and to the infrastructure is sent using DSRC. The RSU communicates with a roadside processor in the cabinet that makes decisions to grant priority requests based on information from the bus and controller and communicates this decision to the controller and roadside unit that in turn communicates the decision to the onboard unit.

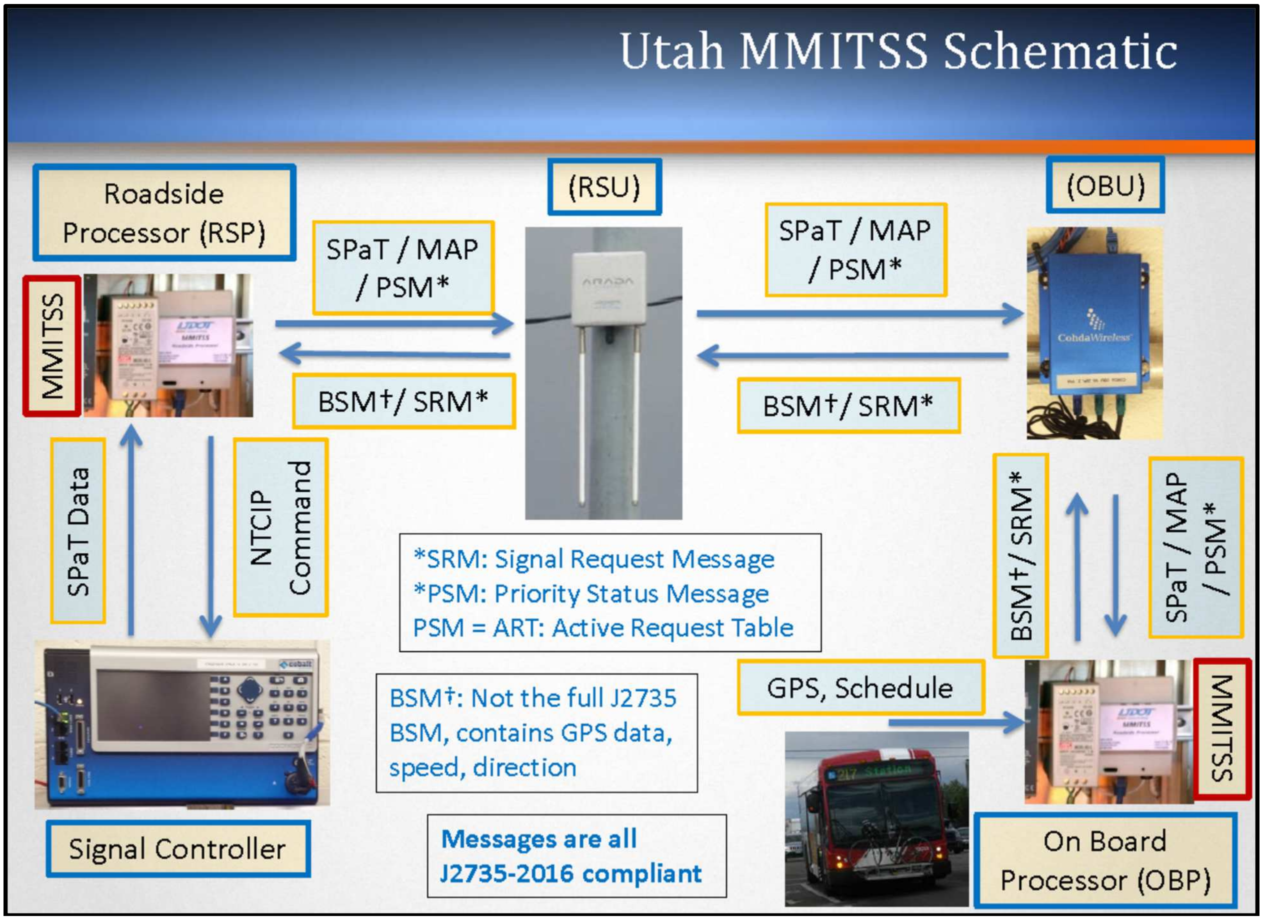


Figure 4-11 The CV-Based Transit Signal Priority Implementation in Utah (Leonard, 2002)

The USDOT has developed the V2I Hub (Zink and Pollinori, 2018) to support jurisdictions in deploying connected vehicle technology. V2I Hub is a software platform that utilizes plugins to translate messages between different devices and run transportation management and connected vehicle applications on roadside equipment. The V2I Hub takes in data received by the RSU from vehicles using the Society of Automotive Engineers (SAE) J2735 standard (SAE, 2016) format and translates the data into an NTCIP format that infrastructure components can understand. It also translates Signal Phase and Timing (SPaT) data from NTCIP to SAE and sends it to the RSU to broadcast to mobile devices and vehicles.

4.7.3 Roadside Equipment (RSE) or Roadside Units (RSU)

The RSUs are used to send messages to and receive messages from nearby vehicles using DSRC or other alternative wireless communication technologies. RSUs can also communicate with adjacent field equipment (such as traffic signal controllers) and centers that monitor and control the units. It includes a processor, data storage, and communication capabilities that support secure communications with passing vehicles, other field equipment, and the center. The selected RSU must meet the USDOT RSU 4.1 specification or higher. Figure 4-12 shows the context diagram of a Basic RSU (Chang, 2017). Additional functionalities may be added by the RSU vendors. More than one RSU may be required, depending on the size and geometry of the intersection.

There has been confusion about the terms RSE and RSU, with some references saying that the RSU and RSE refer to the same thing or that the RSU is the newer name. However, the "ITS Standards for Project Managers" module of the USDOT ITS Joint Program Office ITS Professional Capacity Building Program (USDOT, 2019) differentiates between these two terms, as follows:

- **RoadSide Equipment (RSE)** is a term used to describe the complement of equipment to be located at the roadside; the RSE will prepare and transmit messages to the vehicles and receive messages from the vehicles for the purpose of supporting the V2I applications. This is intended to include the DSRC radio, traffic signal controller where appropriate, interface to the backhaul communications network necessary to support the applications, and support such functions as data security, encryption, buffering, and message processing. It may also be referred to as the roadside ITS station. When only speaking of the DSRC radio, the correct term is RSU (see below).
- **RoadSide Unit (RSU)** is a connected device that is only allowed to operate from a fixed position (which may, in fact, be a permanent installation or from temporary equipment brought on-site for a period of time associated with an incident, road construction, or other events). Some RSEs may have connectivity to other nodes or the Internet."

Figure 4-12 shows the context diagram of an RSU.

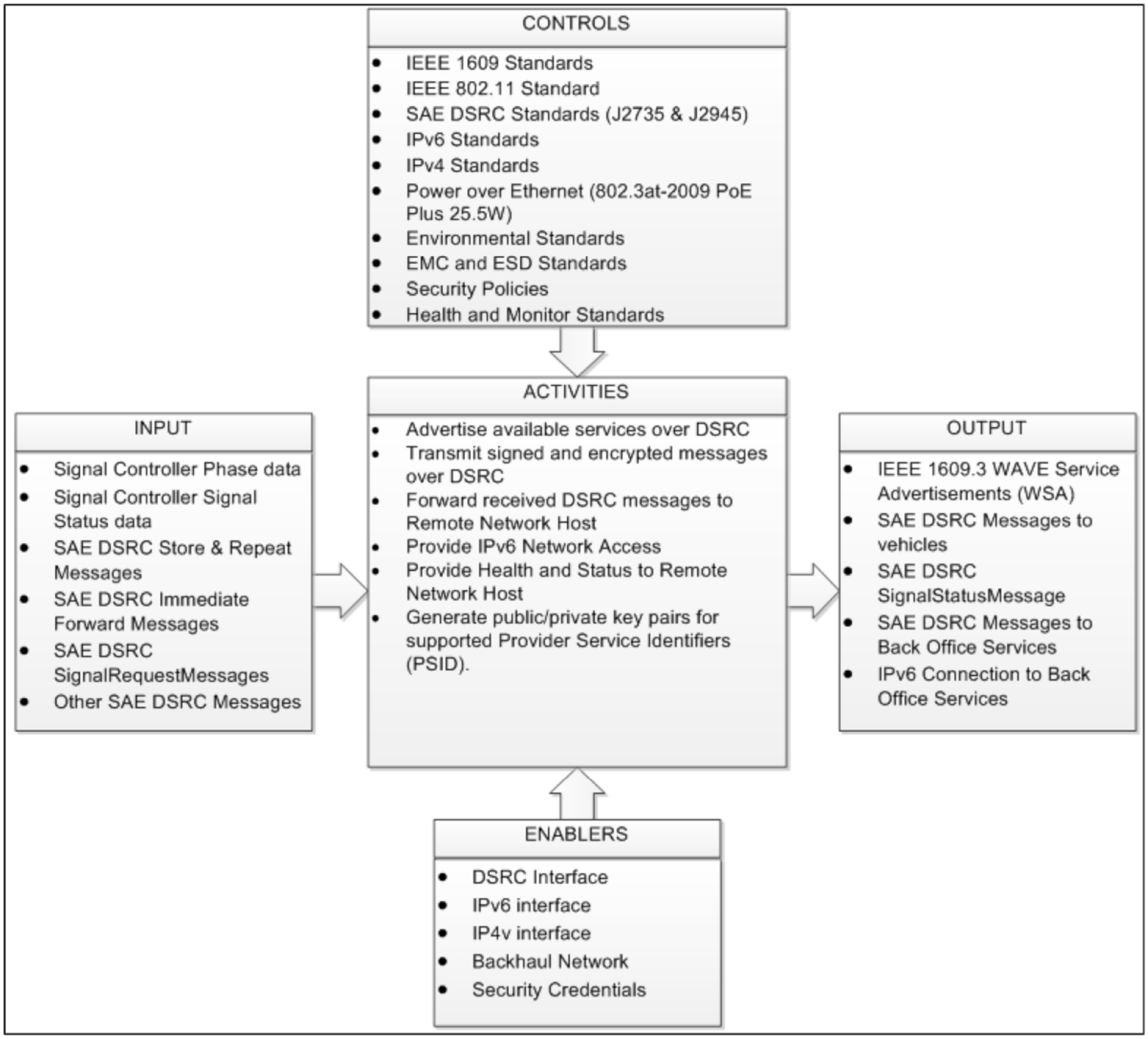


Figure 4-12 Context Diagram of an RSU (Chang, 2017)

RAD-IT lists the following functionalities for the RSEs.

- **RSETraffic Monitoring** function monitors the Basic Safety Messages (BSM) that are shared between connected vehicles and uses this data to produce measures that can be used to manage the network in combination with or in lieu of traffic data collected by infrastructure-based sensors. This function also supports incident detection by monitoring for changes in speed and vehicle control events that indicate a potential incident. The BSM, as defined in the J2735 standards, consists of two parts. Part 1 is sent in every BSM message broadcasted ten times per second and will be mandated to be broadcasted by the NHTSA ruling. It contains core data elements, including vehicle position, heading, speed, acceleration, steering wheel angle, and vehicle size. BSM Part 2 consists of a large set of optional elements, such as precipitation, air temperature, wiper status, light status, road coefficient of friction, Antilock Brake System (ABS) activation, Traction Control System (TCS) activation, and vehicle type. BSM Part 2 elements are sent based on criteria that are not specified in the J2735 standards.

- **RSE Situation Monitoring** is a general functional object that supports the collection of data from passing vehicles and appears to correspond with what is referred to as the "probe vehicle data message" in SAE J2735 standards (SAE, 2016). The data is collected, filtered, and forwarded based on parameters provided by the back office. Parameters are provided to passing vehicles that are equipped to collect and send situation data to the infrastructure in snapshots. In addition, this object collects current status information from local field devices, including intersection status, sensor data, and signage data, providing complete, configurable monitoring of the situation for the local transportation system in the vicinity of the RSE.
- **Intersection Management** communicates with approaching vehicles and a traffic signal controller to allow CV-based signal control application. This function also provides the SPaT message (Signal Phase and Timing) to passing vehicles and includes the current signal state and time until change, MAP (Intersection Map) geometry of the intersection, and location correction. The function should also include conflict monitoring to ensure that the RSU output and traffic signal control output are consistent.
- **Intersection Safety** communicates with approaching vehicles and ITS infrastructure to alert and warn drivers of a potential stop sign, red light, and non-motorized user crossing conflicts or violations.
- **Map Management** obtains current map and geometry data and provides current map and geometry data to connected vehicles.
- **RSE Speed Management** provides infrastructure information, including road grade, roadway geometry, road weather information, and current speed limits to assist vehicles in maintaining safe speeds and headways. It also provides speed recommendations to vehicles based on current conditions and overall speed limits and strategies established by the back office.
- **RSE Speed Warning** notifies connected vehicles that are approaching a reduced speed zone, providing: (1) the zone's current posted speed limit; (2) any roadway configuration changes associated with the reduced speed zone (e.g., lane closures, lane shifts) if applicable; and (3) associated warning information (i.e., the reason for the reduced speed warning). Configuration parameters that define the applicable speed limit(s), geographic location and extent of the reduced speed zone, and roadway configuration information are received from a center or provided through a local interface. The characteristics of individual vehicles may also be monitored and used to warn vehicles with specific limitations that reduce safe operating speeds, (e.g., rollover risk for tall vehicles).
- **Incident Scene Safety** communicates with CV and PID carried or worn by public safety responders to detect vehicle intrusions in designated work areas at an incident

scene and warn responders and drivers of imminent encroachment. Public safety responder movements are also monitored so that the responders can be warned of movement beyond the designated safe zone.

- **Infrastructure Restriction Warning** uses short-range communications to warn vehicles of infrastructure dimensional and weight restrictions.
- **RSE Queue Warning** provides V2I communications to support queue warning systems. It monitors connected vehicles to identify and monitor queues in real-time and provides information to vehicles about upcoming queues, including downstream queues that are reported by the Traffic Management Center.
- **RSE Restricted Lanes Application** uses short-range communications to monitor and manage dynamic and static restricted lanes. It collects vehicle profile information from vehicles entering the lanes and monitors vehicles within the lanes, providing aggregate data to the back-office center. It provides lane restriction information and signage data to the vehicles and optionally identifies vehicles that violate the current lane restrictions. These functions are performed based on operating parameters provided by the back office managing center(s).
- **RSE Rail Crossing Warning** is a connected vehicle application that improves safety at rail crossings. It communicates with wayside equipment that detects or communicates with approaching trains. It provides rail crossing warnings and train arrival information to approaching vehicles and monitors connected vehicles that may intrude on the crossing.
- **RSE Traffic Gap Assist** provides advisory information to minor road drivers at a stop-sign controlled intersection or permitted left turn to facilitate gap selection to proceed through the intersection. The application can be configured, depending on the intersection geometry. It monitors connected vehicle traffic on the major road, augmenting infrastructure traffic detectors to identify and measure traffic gaps. The intersection geometry, measured traffic gaps, and current gap assist sign displays are communicated to the connected vehicle navigating the intersection for use in driver advisories and warnings. The application may also collect vehicle size and performance profile from the connected vehicle to optimize the alerts and warnings to the capabilities of the vehicle and driver preferences.
- **RSE Traveler Information Communications** includes field elements that distribute information to vehicles for in-vehicle display. The information may be provided by a center (e.g., variable information on traffic and road conditions in the vicinity of the field equipment) or it may be determined and output locally (e.g., static sign information and signal phase and timing information). This includes the interface to the center or field equipment that controls the information distribution and the short-range communications equipment that provides information to passing vehicles.
- **RSE Work Zone Safety** communicates with connected vehicles and Personal Information Devices carried or worn by the work crew to detect vehicle intrusions in work zones and warn crew workers and drivers of imminent encroachment. Crew movements are also monitored so that the crew can be warned of movement beyond the designated safe zone.

- **Position Correction Support** broadcasts differential positioning data to enable precise locations to be determined by passing vehicles, supporting connected vehicle applications that require highly accurate positioning. The differential positioning data may be calculated directly by a precisely located RSU operating as a reference station or received from an external reference station and relayed to passing vehicles.
- **RSE Trust Management** manages the certificates and associated keys that are used to sign, encrypt, decrypt, and authenticate messages. It communicates with the Security and Credentials Management System to maintain a current, valid set of security certificates and keys, and identifies logs, and reports events that may indicate a threat to connected vehicle environment security.
- **RSE Privacy Services** operates as a proxy, replacing the mobile device's network address with the RSU's and tags the message so that it can return replies to the mobile device.
- **RSE Support Services** provides foundational functions that support data collection, management, and distribution. It coordinates with Object Registration and Discovery to maintain its registration with respect to location/geographic scope and credentialing information. It maintains the necessary security credentials, authorizations, and associated keys to support communications in the connected vehicle environment. It maintains precise location and time information to support other services.

The RSUs are usually mounted on signal poles, mast arms, and luminaire poles (see Figure 4-13). They use an Omni-directional antenna. However, obstructions can impair the signal, and more than one RSU may be needed.

Figure 4-13 RSU Installed on Mast Arm (Leonard, 2002)

4.7.4 Vehicle On Board Equipment (OBE) and Onboard Unit (OBU)

According to RAD-IT, the vehicle onboard equipment (OBE) provides the vehicle-based sensory, processing, storage, and communications functions that support efficient, safe, and convenient travel. The vehicle OBE includes the common interfaces and functions that apply to all motorized vehicles. The radio(s) supporting V2V and V2I communications are a key component of the vehicle OBE. As is the case with use of the OBE vs. OBU terms, there has been a lot of confusion regarding the use of the terms OBU vs. OBE vs. Aftermarket Safety Devices (ASD). However, the "ITS Standards for Project Managers" module of the USDOT ITS Joint Program Office ITS Professional Capacity Building Program (USDOT, 2019) differentiates between these three terms, as follows:

Onboard Equipment (OBE): "*This term refers to the complement of equipment located in the vehicle for the purpose of supporting the vehicle side of the applications. It is likely to include the DSRC radios, other radio equipment, message processing, driver interface, and other applications to support the use cases described herein. It is also referred to as the vehicle ITS station. When referring to the DSRC radio alone, the correct term is OBU*" (USDOT, 2019).

Aftermarket Safety Device (ASD): "*A connected device in a vehicle that operates while the vehicle is mobile, but which is not connected to the data bus of the vehicle*" (USDOT, 2019).

Onboard Unit (OBU): "*A vehicle-mounted device used to transmit and receive a variety of message traffic to and from other connected devices (other OBUs and RSUs). Among the message types and applications supported by this device are vehicle safety messages, a primary subject of this standard, which is used to exchange information on each vehicle's dynamic movements for coordination and safety*" (USDOT, 2019).

RAD-IT lists the following functionalities for the OBEs:

- **Vehicle Intersection Warning** uses V2V and V2I communications to monitor other connected vehicles at intersections and support the safe movement of the vehicle through the intersection. Driver warnings are provided, and the application may also optionally take control of the vehicle to avoid collisions.
- **Vehicle Communications Support** supports secure, reliable communications with other connected devices. It provides the communications functions that add a timestamp, the message origin, and a digital signature in outbound messages and processes, verifies, and authenticates the same fields in inbound messages. It also encrypts (outbound) and decrypts (inbound) sensitive data.
- **Vehicle Eco-Driving Assist** provides customized real-time driving advice to drivers, allowing them to adjust behaviors to save fuel and reduce emissions. This advice includes recommended driving speeds, optimal acceleration and deceleration profiles based on prevailing traffic conditions, and local interactions with nearby vehicles, i.e., processing Basic Safety Messages (BSMs) to determine the position and speed of vehicles that are between the host vehicle and the intersection. When approaching and

departing signalized intersections, it uses intersection geometry information, the relative position and speed of vehicles ahead of it, and signal phase movement information to provide speed advice to the driver so that they can adapt the vehicle's speed to pass the next traffic signal on green, decelerate to a stop in the most eco-friendly manner, or manage acceleration as the vehicle departs from a signalized intersection. It also provides feedback to drivers on their driving behavior to encourage them to drive in a more environmentally efficient manner. It may also support vehicle-assisted strategies, where the vehicle automatically implements the eco-driving strategy (e.g., changes gears, switches power sources, or reduces its speed in an eco-friendly manner as the vehicle approaches a traffic signal or queue).

- **Vehicle Gap Assist** uses V2I communications to collect traffic gap information and associated alerts and warnings that are displayed to the driver navigating a stop-sign controlled intersection with a major road.
- **Vehicle Environmental Monitoring** collects data from onboard sensors and systems related to environmental conditions and sends the collected data to the infrastructure as the vehicle travels. The collected data is a byproduct of vehicle safety and convenience systems and includes ambient air temperature and precipitation measures and status of the windshield wipers, lights, ABS, and traction control systems.
- **Vehicle Traveler Information** provides drivers with personalized traveler information and/or turn by turn route guidance.
- **Vehicle Map Management** supports map updates and makes current map and geometry data available to other applications. It manages map data onboard and provides map data to end-user applications that provide location-based services.
- **Vehicle Queue Warning** detects vehicle queues and reports queues to other vehicles using V2V communications and to the infrastructure using V2I communications. Vehicle-based queue warning builds on the exchange of vehicle location and motion and maneuvers that support connected vehicle safety applications. This application also receives information about downstream queues using I2V communications. Individualized queue warnings and queue characteristics relevant to the vehicle are provided to the driver.
- **Vehicle Rail Crossing Warning** uses I2V communications to receive alerts of trains entering HRIs and to provide warnings to drivers regarding the trains. The warning can include a second train warning (meaning the HRI gates are about to lower or remain lowered due to the arrival of a second train). The application can also provide vehicle infringement warnings by using the alert information along with vehicle trajectory information to determine that the vehicle will infringe upon a crossing that is (or will be) occupied by a train.
- **Vehicle Speed Management Assist** assists the driver in operating the vehicle within the current speed limit. It monitors current vehicle speed and communicates with the infrastructure to receive current speed limits and associated road configuration change notifications. Driver warnings are issued when unsafe or excessive speeds are detected based on the provided speed limits and current conditions.

- **Vehicle Support Services** provides foundational functions that support data collection, management, and distribution. It coordinates with Object Registration and Discovery to acquire necessary communications or information. It maintains the necessary security credentials, authorizations, and associated keys to support communications in the connected vehicle environment.
- **Vehicle System Executive** provides the operating system kernel and executive functions that manage the software configuration and operation, and supports computer resource management, security, and software installation and upgrades.
- **Vehicle Trust Management** manages the certificates and associated keys that are used to sign, encrypt, decrypt, and authenticate messages. It communicates with the Security and Credentials Management System to maintain a current, valid set of security certificates, and also identifies, logs, and reports events that may indicate a threat to the connected vehicle environment security.
- **Vehicle Situation Data Monitoring** is the highest-level representation of the functionality required to collect traffic and environmental situation data by monitoring and storing the experience of the vehicle as it travels through the road network. Collected data is aggregated into snapshots that are reported when communications are available and with flow control based on parameters provided by the infrastructure. Note that this functional object supports the collection of data for areas remote from RSEs or other communications infrastructure.

4.7.5 Personal Information Device (PID)

The Personal Information Device is generally referred to as a smartphone carried by travelers, workers, or responders. The PID provides the capability for users to receive mobility and safety information. The PID may operate independently or may be linked with connected vehicle onboard equipment. ARC-IT lists the following functions for the PID, among others:

- **Personal Intersection Safety** improves pedestrian, cyclist, and other non-motorized user safety by providing personal location information to the infrastructure that can be used to avoid collisions involving non-motorized travelers. It may also alert the non-motorized user of unsafe conditions, augmenting or extending information provided by signals and signs. The information provided and the user interface delivery mechanism (visual, audible, or haptic) can also be tailored to the needs of the user that is carrying or wearing the device that hosts the application.
- **Personal Incident Scene Safety** improves public safety responder safety by providing responder location information to the infrastructure that can be used to avoid collisions involving public safety responders. The application may also alert responders if they travel beyond the designated safe zone. The information provided and the user interface delivery mechanism (visual, audible, or haptic) can also be tailored to the needs of the user carrying or wearing the device that hosts the application.
- **Personal Location Determination** receives current location information and provides this information to other applications that use the location information to provide

guidance and emergency notification services. It interfaces with and encapsulates positioning technology, such as a GPS receiver embedded in the user's device.

- **Personal Trust Management** manages the certificates and associated keys that are used to sign, encrypt, decrypt, and authenticate messages. It communicates with the Security and Credentials Management System to maintain a current, valid set of security certificates and identifies, logs, and reports events that may indicate a threat to the connected vehicle environment security.
- **Personal Work Zone Safety** improves maintenance and construction crew safety by providing crew location information to the infrastructure that can be used to avoid collisions involving the work crew. The application may also alert workers if they travel beyond the designated safe zone. The information provided and the user interface delivery mechanism (visual, audible, or haptic) can also be tailored to the needs of the user carrying or wearing the device that hosts the application.
- **Traveler's information, Trip Planning, and Route Guidance:** Several functionalities are listed under these applications.

4.7.6 Supporting Traffic Sensors and Traveler Information Systems

Most CV-based mobility and reliability applications require a high CV market penetration to be effective. Some of these applications, however, can be supported by infrastructure-based detection sensors like radar and video image sensors. These sensors can provide macroscopic measures like volume, speed, and occupancy, which can support applications like MMITSS. Other sensors may even produce vehicle trajectories that emulate CV. The essential supporting traffic sensors also include Infrastructure-based Vulnerable Road User (VRU) Detection Sensors to detect pedestrian and bicycles. The abovementioned sensing technologies will continue to be useful until the CV market penetration reaches a level when they are no longer needed.

Similarly, the V2I safety message communication to onboard vehicles will be displayed on a Driver-Vehicle Interface (DVI). With limited market penetration of CV, the safety benefits may be limited. An effort by the USDOT produced guidelines for providing Driver-Infrastructure Interfaces (DIIs) to provide CV information (Richard et al., 2015b). Figure 4-14 shows an example of the DIIs.

Figure 4-14 Example DII to Support an Intersection Safety Warning and Collision Avoidance to Reduce Red-Light Violation (Richard et al., 2015b)

4.7.7 Supporting Services

A number of services are required to support the various CV applications, such as the provision of CV system monitoring and management, CV component maintenance, MAP, data archiving and sharing, location and time provision, Federal Communication Commission (FCC) licensing, security and credential management, and privacy protection. The following are descriptions based on ARC-IT:

- **Connected Vehicle System Monitoring and Management** provides monitoring, management and control services necessary for applications and/or devices operating within the connected vehicle environment. This includes tracking and management of the infrastructure configuration, as well as detection, isolation, and correction of infrastructure service problems. It also includes the monitoring of the performance of infrastructure and mobile equipment.
- **Security and Credentials Management** is used to ensure trusted communications between mobile devices and other mobile devices or roadside devices and also used to protect data from unauthorized access. This service grants trust credentials to qualified mobile devices and infrastructure devices in the connected vehicle environment so that those devices may be considered trusted by other devices that receive trust credentials.

- **RSE Map Management** provides the map functionality necessary to support map data updates to passing vehicles. It collects and provides current map and geometry data to connected vehicles.
- **Location and Time service** identifies the external systems and interfaces that provide accurate location and time to the devices and systems. The New York pilot found challenges with GPS location services in Manhattan and identified the possible need for a supplementary technology.
- **Privacy Protection** provides the privacy protection essential to the operation of connected vehicle applications. Privacy Protection obscures the network identifiers of mobile devices in order to allow communication with credentials management and other centers.
- **Center, Field, and Vehicle Equipment Maintenance** provides the required maintenance support of this equipment.
- **Data Distribution** manages the distribution of data from data providers to consumers and protects that data from unauthorized access.
- **Core Authorization** manages the authorization mechanisms to define roles, responsibilities and permissions for connected vehicle applications. This allows system administrators to establish operational environments where different connected vehicle system users may have different capabilities. For instance, some mobile elements may be authorized to request signal priority, or some centers may be permitted to use the geographic broadcast service, while those without permission would not.
- **Object Registration and Discovery** provides registration and lookup services necessary to allow objects to locate other objects operating within the connected vehicle environment.

4.8 PROJECT SELECTION

The decisions to invest in alternative ITS solutions as part of the alternatives to support arterial management and operations is more complex with the introduction of CAV-based solutions as part of the alternatives. A survey conducted as a part of the United States Department of Transportation (USDOT) ITS Deployment Tracking Project (USDOT 2013) identified safety and mobility benefits, integration with existing technologies, availability of funding, and equipment price as the major factors in the decision-making process for investing in ITS technologies (Gordon and Trombly 2014). As discussed below, the 2019 FDOT CAV Business Plan selection criteria include acceleration of the CAV program, mobility, safety, efficiency and reliability, feasibility, funding, and benefit/cost ratios. The National CV Field Infrastructure Footprint Analysis document produced by the American Association of State Highway and Transportation Officials (AASHTO) pointed out that public agencies will need to assess the use of connected vehicle probe data versus existing methods of data collection (Wright et al., 2014).

This section presents a more detailed description of the methodology proposed in this study and outlined earlier to support the agency decision to adopt a new technology based on agency objectives and local conditions. An assessment of criteria, such as those presented in the FDOT CAV Business Plan, will have to be made and continuously monitored for the validation or refinement of decisions. The selection of ITS deployment alternatives requires the evaluation of these alternatives relative to each other and to other more conventional improvement alternatives. The methodology will be applied to the case study corridor of this project.

4.8.1 Identification of Selection Criteria

The first step is to identify performance metrics and criteria that can be used by agencies to compare existing and emerging technologies. The performance measures should be assessed and tracked for the present and future years. This assessment should then be used as input for the final decision-making process. The selection criteria can include outcome performance measures, output measures, economic measures, feasibility, and risks and constraints. The 2019 FDOT CAV Business Plan identified the criteria in Table 4-2 as the measures used for the CAV-based project selection. These criteria are used in the assessment of this project; however, other criteria can be used.

Table 4-2 Project Selection Criteria Presented in the 2019 FDOT CAV Business Plan

Categories	Criteria	Self-Score
Accelerate the CAV Program	Does this project accelerate the deployment and implementation of CAV technologies in Florida?	
Safety	Does this project directly reduce or have the potential to reduce fatal, serious injury and/or secondary crashes?	
Mobility	From a mobility perspective, does this project directly benefit all modes, including pedestrians, bicyclists, disabled, economically disadvantaged, and aging road users?	
Efficiency and Reliability	Does this project directly benefit (or have the potential to impact) efficiency and/or reliability for all travelers, freight, transit riders, aging road users, pedestrians, and bicyclists?	
Feasibility	Is this project implementable (technology-ready), scalable, and portable for statewide deployment?	
	Do proposed technologies comply with or have the potential to comply with relevant state and federal safety laws?	
	Is the proposed project interoperable and/or does it have the potential to become interoperable with the existing or programmed CAV Projects?	
Funds	Does this project leverage federal, local, and/or private funds? Are there any private organization and/or local agency partners? If yes, what are their match types and roles? Is there an agreement or Memorandum of Understanding (MOU) in place?	
Benefit/Cost	Does this project offer benefits with a high B/C and a good return on investment?	

Table 4-2 (Continued)

Categories	Criteria	Self-Score
Data and Security	Does this project collect, disseminate, and use real-time traffic, transit, parking, and other transportation information to improve safety and mobility, and reduce congestion? Explain how the project will safeguard data privacy and deploy a cybersecurity platform.	
Operations and Maintenance	Does this project address staffing, funding, and procedures for operations, maintenance, and replacement of CAV infrastructure, technologies, and applications?	
Project Evaluation	Does this project have pre-defined performance measures? What and how are these outcomes measured?	
	Will there be a before and after analysis performed, and lessons learned documented? If yes, how will this be documented and shared?	
	Is there a systems validation and verification process in place? Explain how this will be performed.	
	Total Score	

4.8.2 Provision of Required Functionalities

The provision of required functionalities is expected to be one of the main criteria in the selection process. The provision of a solution according to a systems engineering approach will need to be based on identified functionalities of the system related to local needs and issues. This step involves identifying the necessary functions to address the needs and issues for the corridor and the existing and emerging technology alternatives that support the delivery of the functions. Some of the functions can be supplied by both CV-based solutions and non-CV based solutions. Others can be supplied only by CV-based solutions. For example, to support performance measurement and performance-based planning and operations, there is a wide range of existing data collection technologies and sources, such as point detectors, high-resolution controller data, automatic vehicle re-identification, and private sector crowdsourcing, among others. Connected vehicles acting as probes, data generated from travelers, and possibly data generated from automated vehicles have the potential to replace or complement these existing technologies and provide additional functionalities, data elements, and improved performance measurements. Both existing and emerging technologies will need to be assessed utilizing the methods presented in this study. Another example is supporting gap acceptance at signalized and unsignalized intersections, which can only be provided by CV-based applications.

An important step in assessing different technology solutions of a particular subsystem is to identify how these solutions can provide the required functionalities. This will enable the determination of gaps in the functionalities provided by traditional solutions compared to a CV-based solution. For example, the need to alert drivers of bicycles or pedestrians on crosswalks is not possible with traditional ITS technologies, which makes CV-based solutions strong candidates.

4.8.3 Return on Investment Analysis

An important criterion in the selection of a CV-based solution is expected to be the return on investment, as indicated in Table 4-2. Traditionally, the return on investment analysis is conducted by calculating deterministic point estimates of the Net Present Value (NPV) or benefit-cost ratio of the project alternatives. This involves deterministic estimates of the present values of the current and future benefits and costs over the project's economic life. A discount rate is used to calculate the present values of the cash flows. This conventional method may not be able to capture the uncertainty and risks associated with a project (Gilbert 2005). The analyst must recognize that a great amount of uncertainty is associated with the parameters that are used to calculate the impacts and costs of the alternatives. There are three main techniques for incorporating uncertainty into the return on investment analysis: the Black Scholes model, binomial lattice and Monte Carlo methods. The Black Scholes method (Black and Scholes, 1979) has several assumptions that may not be met in transportation system alternative analysis. For example, the method assumes that the volatility (standard deviation of price over time) is constant over the project life, returns to the project are normally distributed, and the project's underlying value is lognormally distributed. The binomial lattice method (Cox et al., 1979) can only consider one source of uncertainty. In addition, a reported weakness of this method is that it needs cumbersome computational effort to reach a certain level of accuracy (Gilbert, 2005). The Monte Carlo method (Boyle, 1977) is capable of integrating multiple sources of uncertainty with no requirements on the distributions and has been used in various fields to account for uncertainty by expressing cost and benefit parameters as probability distributions rather than as fixed values (Yang et al., 2007; Neufville and Scholtes, 2011; Sullivan and Orr, 1982; Cox et al., 1999; Sullivan and LeClair, 1985). The Monte Carlo simulation method can be used to account for uncertainty in the input parameters to the return on investment analysis.

To calculate the NPV, it is necessary to assess the benefits of alternatives and convert these benefits to dollar values and estimate the costs of the projects. The performance improvement information estimated based on the review of literature, as presented in Chapter 3, can be used as inputs to model and data analysis to determine the benefits for the specific corridor under investigation. These estimates are considered to be the initial Mobility Modification Factors (MMF) and Crash Modification Factors (CMF) and should be updated based on the results from future CV implementation and research efforts.

Step 1 – Determination of Operation Scenarios: The impacts of CV will be evaluated under different demand, incident, and weather scenarios since some of the mobility and safety applications are effective only under these scenarios or are more effective under other scenarios. For example, the Support of Incident and Emergency Response provides benefits only when there are incidents, and the benefits depend on lane blockage severity. Adaptive signal control is less effective under oversaturated conditions. The analysis scenarios will be generated in a similar fashion to that of the scenario generator used in the Highway Capacity Manual-based (HCM-based) Active Transportation and Demand Management (ATDM) Analytical Methods for Urban Arterials considering the actual incident, weather, and construction events.

Step 2 – Assessment of Mobility and Reliability Measures for the Base Conditions and improvements: Under each of the operation scenarios identified in Step 1, the HCM-based procedure will be used to estimate the travel time and delays with no improvements, with non-CV-based improvements, and with CV-based improvements. The Highway Capacity Software (HCS), STREETVAL, or other HCM computational engine can be used for this assessment. More detailed simulation models can be also used. The impacts of both traditional and CV-based solutions will be assessed and compared. The improvement impacts will be considered in the analysis either as improvements in the capacity values in the inputs or as a modification of the values of the performance measures of the base condition utilizing multipliers, depending on the application.

Step 3 - Assessment of Safety Measures for the Base Conditions and Improvements: The safety benefits are obtained by first identifying the rate, frequency, and severity of the crash types that are expected to be influenced by the implementation of CV technology utilizing crash data for a three- to five-year period. If needed for the evaluation, the crash frequency may need to be evaluated separately for different operation scenarios. For example, if a deployment is only effective or has a greater effect during rain and wet conditions, then the crash frequencies should be estimated under these conditions. The safety benefits will be estimated for the same scenarios generated for mobility analysis.

Step 4 – Estimation of the Improvement Cost: This step will determine the initial and the recurrent operation and maintenance costs of CV deployment. The AASHTO Life Cycle Cost (LCC) tool will be used to generate the initial cost estimates. These cost estimates will be revised based on inputs from the USDOT CV pilot and FDOT deployments.

Step 5 – Estimation of the Return on Investment: In this step, a stochastic return on investment will be conducted considering uncertainty in the incident/crash frequency, CV market penetrations in future years, traffic demand, incident location, driver response, etc. The result will be a distribution of the benefits of the CV-based and non-CV based applications.

4.8.4 Multi-Criteria Decision Analysis

Measures that are difficult to be assessed in dollar values cannot be accounted for using the economic return on investment analysis methods. Thus, these methods are not fully adequate for use in assessing technology alternatives. Multi-Criteria Decision Analysis (MCDA) methods have been proposed to account for both qualitative and quantitative factors in the decision-making process. This approach has been used in the 2019 FDOT CAV Business Plan as indicated in Table 4-2, and the methods described below can be considered for supporting this approach.

The simplest MCDA approach is the Simple Multi-Attribute Rating Technique (SMART) approach, also known as the Simple Additive Weighting (SAW) method. This approach involves identifying decision criteria, criterion weights, assessment of the values associated with each criterion, normalizing the values to a common scale, and obtaining "scores" based on the values. The result is a weighted score for each of the compared alternatives. When there are a large number of evaluation criteria and the priorities of multiple stakeholders are to be considered, the SAW method cannot sufficiently capture the weights of different criteria. More advanced MCDA methods, compared to the SAW method, have been proposed and successfully used. These methods include the Analytic Hierarchy Process (AHP), Technique for Order Preference Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), Elimination Et Choix Traduisant la Realité (ELECTRE), and others. All of these methods require stakeholder inputs regarding their preferences and priorities with respect to various decision criteria and an assessment of each alternative to meet each criterion. Among these MCDA methods, the AHP method developed by Saaty (1980) has been the most widely used in various disciplines, including transportation engineering. Hence, the AHP method was selected for use in this study.

This study recommends the utilization of a combination of the return on investment described in the previous section and an MCDA method, such as the AHP, SMART, or the Fuzzy TOPSIS, to select between alternatives considering emerging technologies. The result from the NPV analysis can be included as one of the objectives defined for the MCDA evaluation. The results of the selection between the alternatives will be dependent on the input parameters, which are different for different agencies and locations.

5. EVALUATION AND PERFORMANCE MEASUREMENT SUPPORT

This last chapter (Chapter 4) demonstrates the application of the method for the pre-deployment assessment of system impacts and selection between alternatives in the pre-deployment evaluation to the project case study (the SR-924/NW 119th Street segment in Miami-Dade County, Florida). This chapter then briefly introduces the implementation of the developed methodology in a tool developed as part of another project titled "Estimation of System Performance and Technology Impacts to Support Future Year Planning" and was funded under grant number BDV29-977-37. Next, the use of simulation modeling for assessing CV-based applications is demonstrated. Finally, an overview of the steps needed for planning the post-deployment evaluation of CV to inform future evaluation efforts is presented.

5.1 STUDY LOCATION

The project case study is a segment along SR-924/NW 119 Street in Miami-Dade County extending from NW 32nd Avenue to NW 5th Avenue (See Figure 5-1). It is a six-lane divided urban arterial with a posted speed limit of 40 mph. The length of the study segment is 2.79 miles and includes a total of 12 signalized intersections and 9 un-signalized intersections.

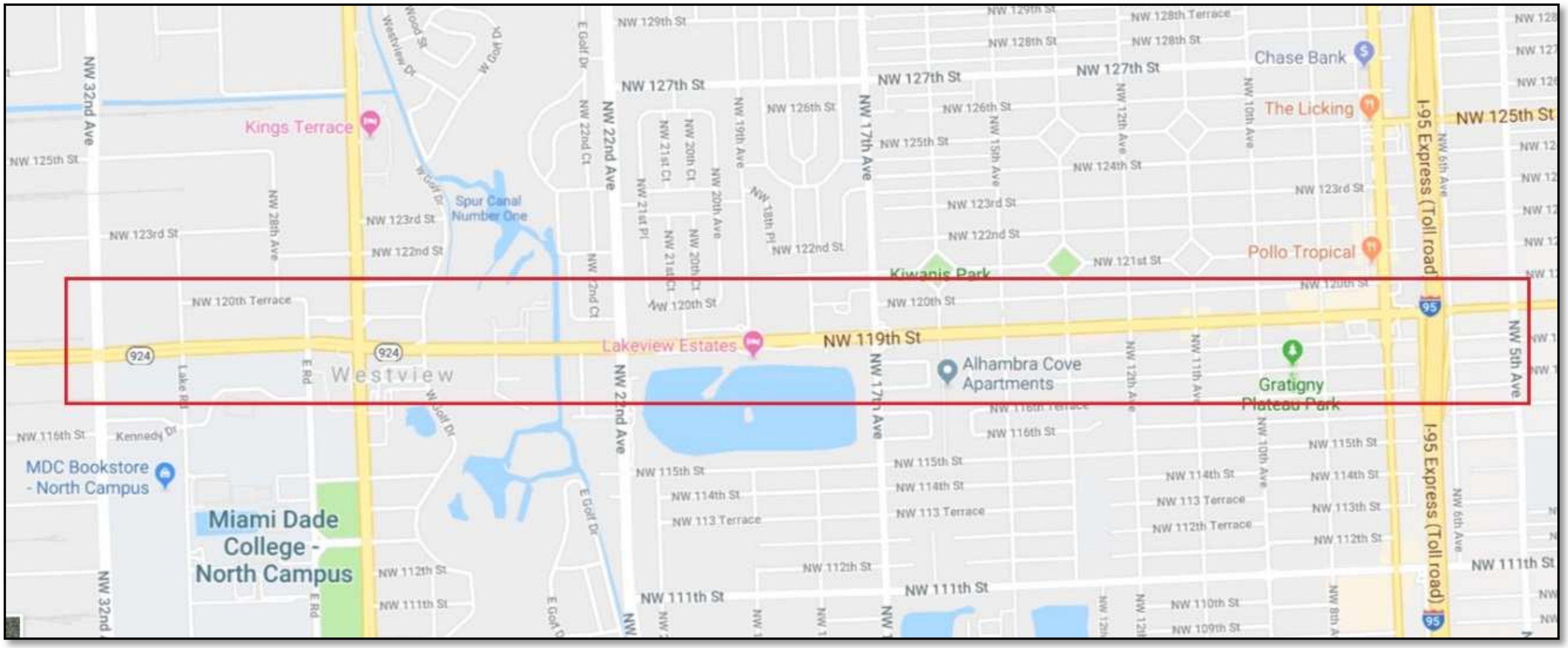


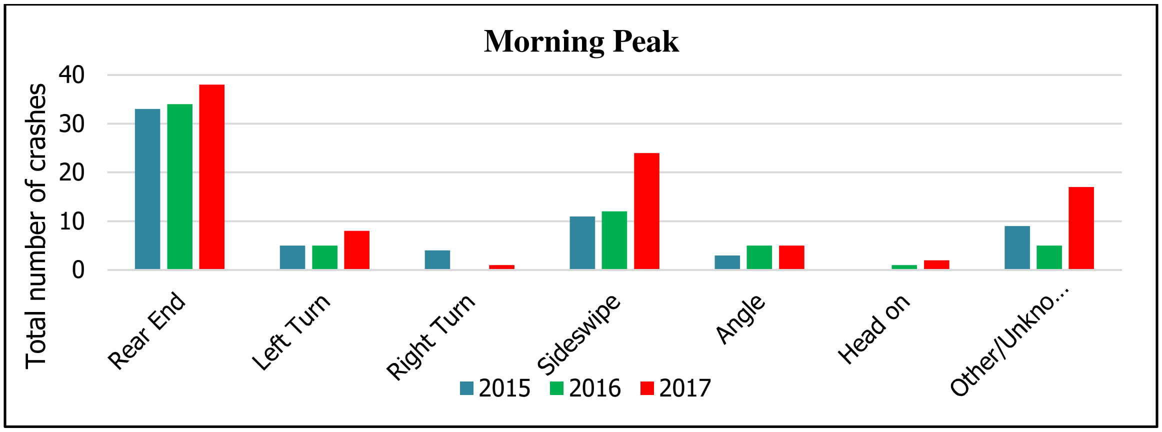
Figure 5-1 Case Study Segment

5.2 BASE CONDITION PERFORMANCE

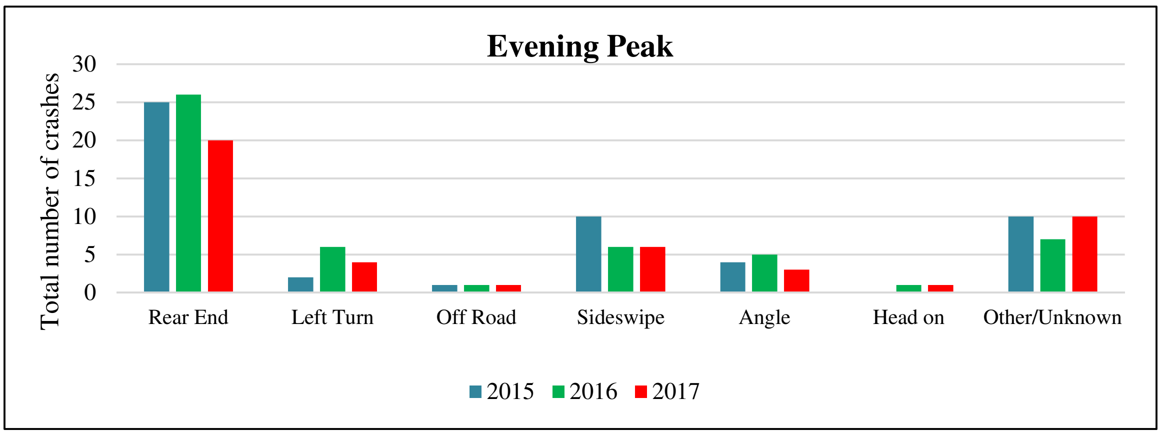
This section describes the methods used to estimate the performance for the base conditions without the implementation of improvement alternatives. Please note that there may be existing solutions in place for the base conditions. If this is the case, the CV solution could complement. supplement, or replace the existing solutions. The safety for the base conditions can be estimated preferably using real-world crash statistics using a minimum three-year crash statistic. Another option is to estimate the safety based on safety performance functions (SPF). Similarly, the mobility can be based on real-world measurements or using a model like the Highway Capacity Manual (HCM) procedure or simulation. This section discusses the utilized methods to estimate base condition performance but any of the above-mentioned methods could have been used.

5.2.1 Safety Performance of Base Conditions

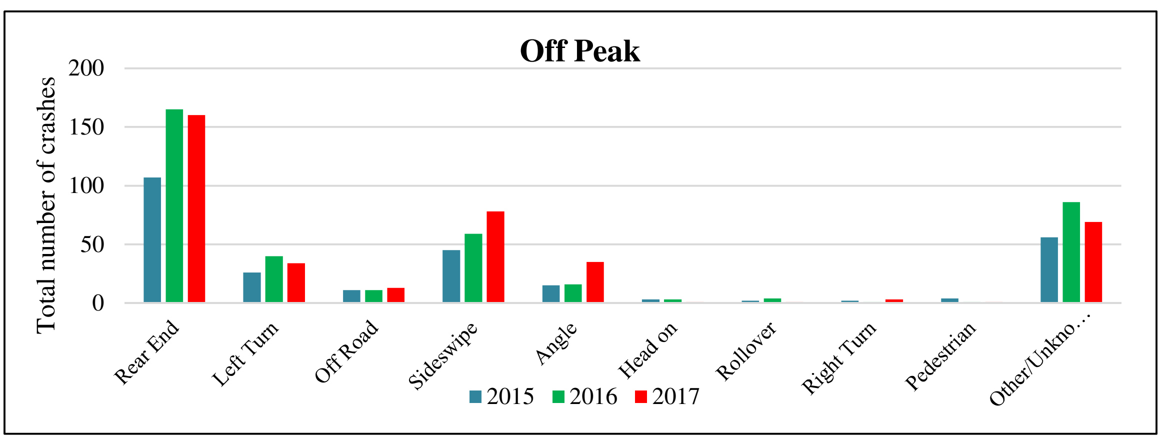
In this study, the base safety performance was estimated using crash data collected from the "Signal 4 Analytics" system, which is a statewide crash database. This system provides records of crashes reported by law enforcement to the Florida Department of Highway Safety and Motor Vehicles (DHSMV). Data were collected for the study segment for the period between January 2015 and December 2017. The total number of crashes was calculated and classified by crash type for the AM peak, PM peak, and Mid-day periods, as shown in Figure 5-2 and Table 5-1. Weekends were included in the safety analysis because safety analysis is usually done for the whole week and because the crash modification factors that were used in the assessment of the safety benefits consider the entire week. All types of injury and property damage only (PDO) crashes were included in the analysis, while fatalities (AM peak, PM peak, Mid-day) were excluded from the total estimated costs to reduce the bias in the benefit estimation due to the extremely small size of fatal crashes (4 out of 535 in 2017). In general, the rear end and sideswipe crashes were the most frequent types of crashes, followed by the left-turn and angle crashes. The number of crashes was calculated based on crash data for each intersection and segment of the facility for use in the analysis.



(a) Morning Peak Period



(b) Evening Peak Period



(c) Off-peak Period

Figure 5-2 Total Crashes by Type for the Study Segment along SR-924

Table 5-1 Number of Crashes by Type for the Study Segment Along SR-924

Crash Type	AM Peak			PM Peak			Mid-day		
	2015	2016	2017	2015	2016	2017	2015	2016	2017
Rear End	33	34	38	25	26	20	107	165	160
Left Turn	5	5	8	2	6	4	26	40	34
Off Road	-	-	-	1	1	1	11	11	13
Sideswipe	11	12	24	10	6	6	45	59	78
Angle	3	5	5	4	5	3	15	16	35
Head on	-	1	2	-	1	1	3	3	1
Rollover	-	-	-	-	-	-	2	4	1
Right Turn	4	-	1	-	-	-	2	1	3
Pedestrian	-	-	-	-	-	-	4	1	1
Other/Unknown	9	5	17	10	7	10	56	86	69

5.2.2 Mobility Performance of the Base Conditions

As stated earlier, the travel time for the base conditions can be estimated based on real-world measurements. These measures of travel time can be also estimated based on various analytical and simulation models. In this study, the HCM urban arterial facility procedure as applied in the Highway Capacity Software (HCS) was used in the analysis. The study corridor was coded in the HCS software to generate the travel time data for different traffic conditions. The advantage of using the HCM procedures compared to real-world data is that they can estimate mobility and reliability for different base conditions that may include geometric improvements, other expected changes, or future years. The benefit of using real-world mobility and reliability measurements is that they provides more direct, and thus accurate, estimation of the metrics for the existing conditions. However, the use of modeling like that of the HCM-based procedures or simulation provide the opportunity to consider other potential capacity improvements (adding lanes) or signal timing changes (modify timing, phase sequence, and left-turn protection) that are implemented in parallel or in lieu of the CV-based solutions. Another advantage of these procedures is that they allow the considering of changes in demands in future years or due to other developments or enhancements that impact the corridor demands. In the demonstration of this study, the HCM modeling is used although real-world data could also have been used.

The first step of utilizing the HCS mobility and reliability modeling procedures is to create a Base file. The Base file consists of geometry data, signal data, and turning movement data for each 15-minute interval for all intersections of the analysis segment. In this study, seven signalized intersections from NW 32nd Avenue to NW 7th Avenue were included in the analysis. Three different Base files were created for the weekday AM peak (7:00 am-9:00 am), Mid-day (11:00 am-1:00 pm), and PM peak (4:00 pm-6:00 pm).

The signal timing parameters for each intersection were collected from the Kimley-Horn Integrated Transportation System (KITS) software developed by Kimley Horn, which is a central signal control software, utilized by Miami-Dade County at the county traffic control center to manage the signals from the center. Weather data (precipitation) needed for the HCS reliability analysis was collected from the National Climatic Data Center (NCDC). The NCDC (2018) provides a summary of weather data for 284 cities and territories in the United States.

Another item needed for the reliability estimation in the HCS is the average crash rates, which are used to estimate the impacts of lane blockages on congestion. The average crash rates for each analysis period were calculated based on the Signal 4 Analytics crash data and used as an input to the HCS. The default values of 1.1 for rainfall and 1.2 for wet pavement were used as crash frequency adjustment factors to account for the increase in crash rates during these conditions.

The HCS reliability procedure was run for a total of 261 working days from April 30, 2017, to April 30, 2018. Since there are eight scenarios per day for each time period (eight 15-minute periods in two hours), there were a total 2,088 scenarios generated by the HCS for the reliability analysis with different demand levels, different incident conditions, and different weather/pavement conditions. The HCS generates a summary table of all scenarios, including segment travel times, travel speeds, and delays. The summary table is not included in this report, but the results are used for further analysis

5.3 RETURN ON INVESTMENT ANALYSIS

The benefits, costs, and return on investment (ROI) of implementing alternative applications to address the needs were calculated for the study corridor using the procedure described in Chapter 4. The benefits were calculated by estimating the safety and mobility impacts. These impacts were converted to dollar values and used in conjunction with costs in the return on investment analysis. A central concept of the calculation of the benefits, costs, and benefit-cost ratio is the consideration of the stochasticity, uncertainty, and associated risks using the Monte Carlo analysis, as discussed in Chapter 4 and detailed further below.

5.3.1 Safety Applications

This section describes a methodology that evaluates the stochastic safety benefits of improvement alternatives, including CV-based applications. The safety improvements are obtained by first calculating the Base (Do-Nothing) crash rate, frequency, and severity of the crash types that are expected to be influenced by the implementation of CV-based technology. Then, the estimated crash frequencies are multiplied by crash modification factors (CMF). The CMFs were estimated based on a comprehensive review of the literature and should be updated as more information becomes available based on the results from future CV implementation and research efforts.

As discussed in previous chapters, a number of vehicle-to-infrastructure (V2I) applications have been suggested to support signalized intersection safety. These applications include Signalized Left Turn Assist (SLTA), Red Light Violation Warning (RLVW), and Pedestrian in Signalized

Crosswalk Warning (PCW). In addition, the introduction of CV technology can provide safety benefits for unsignalized intersections. Two such applications have been proposed: Stop Sign Violation Warning (SSVW) and Stop Sign Gap Assistance (SSGA). SSVW warns the driver if the vehicle is predicted to violate a stop sign. This application will reduce crashes with cross-street traffic and may also reduce the number of rear-end crashes (Stephens et al., 2013a). The SSGA provides advisory information to cross-street drivers at a stop-sign controlled intersection to support their gap selections at the intersection. Moreover, hazard warning applications have been suggested, including Curve Speed Warning (CSW), Railroad Crossing Violation Warning (RCVW), Oversize Vehicle Warning (OVW), and Reduced Speed Zone Warning (RSZW). Based on the review of literature, these V2I safety applications have a significant contribution to the reduction of crash rates and severity, as outlined in Chapter 3.

Risk analysis is used in this study to account for uncertainty in the ROI by expressing the benefit and cost input parameters as probability distributions rather than deterministic values. As a result, the output benefit-cost ratio (BCR) also follows a probability distribution. To do the risk analysis, the input parameter distributions have to be defined. Commonly used distributions for this purpose are the uniform, normal, and lognormal distributions. The normal distribution follows a symmetrical bell-shaped curve and is simply described using the arithmetic mean (m) and standard deviation (v). However, it is important to consider the skewness of the distribution when analyzing the benefits and this consideration can be provided by the lognormal distribution (Limpert et al., 2001). The lognormal distribution is selected in estimating the benefits incorporating the uncertainty in the input parameters in the estimation.

The Monte Carlo simulation procedure is usually used to consider the stochasticity by varying the input parameters based on their specified distributions. The results are probability distributions for each performance metric and ROI metrics. In a previous study by a Florida International University research team (Yang et al., 2007), a general procedure was used to perform risk analysis in the evaluation of intelligent transportation systems benefits and costs. The procedure utilized the lognormal distribution as part of the Monte Carlo simulation process to describe the random variations in the input parameter values. The parameters of the lognormal distributions were estimated based on the highest and lowest values of the benefits and market penetration reported in the literature. However, the cost of V2I deployment was estimated based on a uniform distribution between the highest and lowest limits reported in the literature.

The lognormal distribution is simply described using the median (μ^*) and the multiplicative standard deviation (σ^*) for a given set of data. The lower limit (LL) and upper limit (UL) of an interval at a given confidence level ($1 - \alpha$) can be expressed as follows:

$$LL_{\alpha/2} = \frac{\mu^*}{(\sigma*)^{Z\alpha/2}} \quad 5\text{-}1$$

$$UL_{\alpha/2} = \mu^* \times (\sigma*)^{Z\alpha/2} \quad 5\text{-}2$$

$$\mu = \ln(\mu^*) \quad 5\text{-}3$$

$$\sigma = \ln(\sigma *) \qquad 5\text{-}4$$

where, μ and μ*are the mean and median of lognormal distribution, σ and σ* are the standard deviation and multiplicative standard deviation of the lognormal distribution, LLα/2 and ULα/2 is the lower and upper limits of the variable at given confidence level α, and Zα/2 is the Z-value for the upper and lower limits at given confidence level (1 − α).

If the upper and lower limits of a variable are identified, then the μ and σ can be calculated using the equations mentioned above. The actual mean (m) and actual standard deviation (v) can also be calculated from the lognormal distribution using Equations 5-5 and 5-6.

$$\boldsymbol{m} = \boldsymbol{e}^{\mu+\frac{1}{2}\sigma^2} \qquad 5\text{-}5$$

$$\boldsymbol{v} = \boldsymbol{e}^{\mu+\frac{1}{2}\sigma^2}\sqrt{\boldsymbol{e}^{\sigma^2} - \mathbf{1}} \qquad 5\text{-}6$$

5.3.1.1 Benefit Estimation

The safety benefits were calculated utilizing crash modification factors (CMF) based on an extensive review of previous studies. Chapter 3 of this project presented details of the literature review. For the CV-based application, the values recommended in Chapter 3 are used in this study. A more extensive literature review was performed for selecting CMF for the alternative (non-CV-based) applications. Table 5-2 represents a summary of all of the literature and the associated safety impacts of different applications.

of the Identified CMFs for Safety Applications

CV/Non-CV	Reference	CMF (%)
RSECTION		
n-CV-based	Change from permissive only to flashing yellow arrow permissive only (Simpson and Troy, 2015)	10.8 - 31.1
	Change from permissive only to protected with permissive (Simpson and Troy, 2015)	6.50 - 34.6
	Change from permitted or permitted-protected to protected on major approach (Davis and Aul, 2007)	42
	Change permissive left-turn phasing to protected only (Chen et al., 2015)	55
V-based	Signalized Left Turn Assist (SLTA) (From Chapter 3)	36 - 70
n-CV-based	Prohibit right-turn-on-red (AASHTO, 2010)	2
	Install offset right turn lane (Maze et al., 2010)	6.15
V-based	Signalized Right Turn Assist (SRTA) (From Chapter 3)	25 - 50
n-CV-based	Implement automated red light running enforcement cameras (Hallmark et al., 2010; Haque et al., 2010; Persaud et al., 2005)	20 - 40
	Installation of fixed combined speed and red light cameras (De Pauw et al., 2014)	14 - 28
V-based	Violation Warning (RLVW) (From Chapter 3)	25 - 50
n-CV-based	Rectangular Rapid Flash Beacon (RRFB) (Monsere et al., 2018)	7
	Install pedestrian countdown timer (Kitali et al., 2017)	4.8 – 8.8
	Implement Barnes Dance (Chen et al., 2012)	-10
	Install a pedestrian hybrid beacon (PHB or HAWK) (Fitzpatrick and Park, 2010)	15- 29
	Increase cycle length for pedestrian crossing (Chen et al., 2012)	45
V-based	Pedestrian in Signalized Crosswalk (PSCW) (From Chapter 3)	50 - 100

Table 5-2 (Continued)

Function	CV/Non-CV	Reference	CMF (%)
UNSIGNALIZED INTERSECTION			
Stop Sign Violation Warning	Non-CV-based	Add centerline and STOP bar, replace 24-inch with 30-inch stop signs (ITE, 1993)	67
		Increase retro reflectivity of STOP signs (Persaud et al., 2010)	9.4
		Install double stop signs (ITE, 1993)	55
		Provide flashing beacons at stop-controlled intersections (Srinivasan et al., 2008)	13
		Flashing LED stop sign (Xiong and Davis, 2012)	41.1
	CV-based	Stop Sign Violation Warning (SSVW) (From Chapter 3)	50 - 100
Stop Sign Gap Assist	Non-CV-based	-	-
	CV-based	Stop Sign Gap Assist (SSGA) (From Chapter 3)	28
HAZARD WARNING			
Speed Warning	Non-CV-based	Implement automated speed enforcement cameras (AASHTO, 2010)	17
		Individual changeable speed warning signs (Elvik and Vaa, 2004)	41
		Install Variable Speed Limits (Pu et al., 2017)	29
		Install dynamic speed feedback sign (Hallmark et al., 2015)	5
		Implement mobile automated speed enforcement system (Li et al., 2015)	14.5
	CV-based	Reduced Speed Zone Warning (RSZW) (from Chapter 3)	50
Curve Speed Warning	Non-CV-based	Changeable Curve Speed Warning signs (Tribbett et al., 2000)	2
	CV-based	Curve Speed Warning (CSW) (from Chapter 3)	20-30
Oversize Vehicles Warning	Non-CV-based	Oversize Load signs	50
	CV-Based	Oversize Vehicle Warning (OVW) (from Chapter 3)	75- 90
Spot Weather Information Warning	Non-CV-based	Improving Roadway Condition (Zeng et al., 2014)	15
	CV-Based	Spot Weather Information Warning (SWIW) (from Chapter 3)	50
Railroad Crossing Warning	Non-CV-based	Install flashing lights and sound signals (Elvik and Vaa, 2004)	50
		Automatic gates (Elvik and Vaa, 2004)	45
	CV-based	Railroad Crossing Violation Warning (RCVW) (from Chapter 3)	50

The safety benefit dollar values are also needed to determine the ROI of different applications. A wide range of values has been used in the literature for these parameters. Table 5-3 provides a summary of the incident cost based on the literature review.

Table 5-3 Summary of the Incident Cost

Source	Dollar Value
FITSEVAL (Hadi et al., 2008)	Urban Arterial Fatal $2,771,48; Injury $66,397; PDO $1,776 Urban freeway Fatal $3,079,351; Injury $73,390; PDO $1,776
FDOT District 5 implementation of FITSEVAL to prioritize investment (2016)	1 Fatal [K] $10,230,000; 2 Incapacitating [A] $580,320; 3 Non-Incapacitating [B] $157,170; 4 Possible or Minor [C] $97,650; 5 Property Damage Only [O] $7,600.
Sallman et al. (2013)	Fatality Cost - $6,500,00; Injury Cost - $67,000; PDO - $2,300.
Benefit-Cost Analysis (TEC, n.d.)	Blincoe et al. stated that the value of a fatality lies in the range of $2-7 million and assigned a "working value" of $3,366,388. This suggests that a reasonable range is from about 40% lower to about 200% higher than their assigned values, at least for crashes involving significant non-market (quality of life) damages.
Highway Safety Manual (AASHTO, 2010)	1 Fatal [K] $4,008,900; 2 Disabling Injury [A] $216,000; 3 Evident Injury [B] $79,000; 4 Fatal/Injury [K/A/B] $158,200; 5 Possible Injury [C] $44,900; 6 Property Damage Only [O] $7,400.

Based on the literature review mentioned above, the highest and lowest values are selected as the upper limits (UL) and lower limits (LL) of different parameters for different CV-based applications. Then, the means and standard deviations of the lognormal distributions are calculated using Equations 5-1 to 5-6. Table 5-4 shows the distribution of CMF and safety benefit dollar values.

Table 5-4 CMF and Incident Cost Distributions for CV-Based Safety Solutions

	Upper Limit (UL)	Lower Limit (LL)	Median of lognormal distribution (μ*)	Mean of lognormal distribution (μ)	Multiplicative Standard Deviation (σ*)	SD of lognormal distribution (σ)	Actual Mean (m)	Actual SD (v)
CMF for Signalized Intersection								
Existing	56	6.5	19.07	2.94	1.92	0.65	23.63	17.28
CV-Based	70	25	41.83	3.73	1.36	0.31	43.93	14.09
CMF for Unsignalized Intersection								
Existing	67	9.4	25.09	3.22	1.82	0.59	29.99	19.62
CV-Based	90	28	50.20	3.91	1.42	0.35	53.46	19.58
CMF Hazard Warning								
Existing	50	2	10.00	2.30	2.66	0.97	16.14	20.44
CV-Based	90	20	42.43	3.75	1.57	0.45	47.09	22.70
Incident Cost								
Injury Crash (1000 Dollar)	90	60	67.08	4.20	1.19	0.17	68.16	12.27
PDO Crash (1000 Dollar)	3.60	2.50	3.00	1.09	1.11	0.11	3.01	0.33

5.3.1.2 Cost Estimation

Cost estimation is another required component of the ROI analysis. The cost estimation must consider the number and types of equipment required for each type of the evaluated application deployment. The analysis includes initial cost, operation and maintenance costs, estimated interest rate, and equipment lifetime.

Cost estimates for the V2I applications deployment were identified based on the Near-Term V2I Transition and Phasing Analysis Life Cycle Cost Model (LCCM) tool (USDOT, 2015). In addition, other resources were considered in the estimates, such as the cost data reported in the United States Department of Transportation (USDOT) Joint Program Office (JPO) benefit database (USDOT, 2019). The cost estimation for CV-based applications was structured with the assumption that the selected applications within each category will share some of the ITS system components. These common sets of ITS devices include DSRC transceivers (Roadside Equipment RSE), infrastructure sensors, network communications, and interfaces. However, other components of the costs are application-specific and require additional costs for the implementation. For example, the SLTA and RLVW require roadside and onboard software applications that provide violation warning and dynamically extend the all-red interval to prevent collisions. The RLVW, SSGA, and CSW applications require additional Driver Infrastructure Interface (DII) to communicate messages and signal information and timing with technology-equipped vehicles. Moreover, infrastructure-based systems could be added if needed, such as infrastructure-based displays that disseminate messages to all drivers approaching the intersection, not just the drivers with the equipped vehicles (Misener et al., 2010). Based on a published report for the USDOT (Wright et al., 2014), researchers identified initial cost estimates for DSRC-based equipment to support CV-based (V2I) applications deployment. The average equipment costs per DSRC site based on field data from Michigan and Arizona states ranged from to $13,200 to $21,150, respectively. These estimates include DSRC Roadside Units, power connection equipment, labor costs, construction inspection, planning, and design costs. In addition to these estimates, additional costs associated with backhaul communication can be added as needed. The above estimated upper and lower limits for V2I applications deployment are summarized in Table 5-5. It should be noted that these estimates have been identified based on the literature review. CV-based applications are being deployed in Florida, and more accurate cost estimates can be obtained based on these deployments in the applications of the methodology to real-world project. It is recognized that particularly the recurrent operation and maintenance numbers in number 5-5 seem to be low and better numbers should be used once available.

Table 5-5 Estimated Cost of CV-Based Safety Applications Deployment Per Intersection

Application	Capital Cost ($)*		O&M Cost* ($)/Year	
	Upper Limit	Lower Limit	Upper Limit	Lower Limit
Support of Signalized Intersection Safety				
Signalized Left Turn Assist (SLTA)	93,600	62,400	6,600	4,400
Signalized Right Turn Assist (SRTA)	45,400	32,600	6,600	4,400
Red-Light Violation Warning (RLVW)	102,000	68,000	6,600	4,400
Pedestrian in Signalized Crosswalk (PSCW)	186,000	124,000	24,000	16,000
Support of Unsignalized Intersection Safety				
Stop Sign Violation Warning (SSVW)	312,000	208,000	18,000	12,000
Stop Sign Gap Assist (SSGA)	90,000	60,000	10,800	7,200
Hazard Warning				
Reduced Speed Zone Warning (RSZW)/Curve Speed Warning (CSW)	240,000	160,000	12,000	8,000
Oversize Vehicle Warning (OVW)	78,000	52,000	8,400	5,600
Spot Weather Information Warning (SWIW)	138,000	92,000	12,000	8,000
Railroad Crossing Violation Warning (RCVW)	138,000	92,000	12,000	8,000

* It is recognized that the costs particularly the recurrent operation and maintenance numbers in this table seem to be low and better numbers should be used once available.

The upper and lower limits for signalized, unsignalized, and hazard warning is calculated by summing up the lower limits and upper limits of different applications. For example, the upper limit capital cost for the support of un-signalized intersection safety is the summation of upper limit of SSVW ($312,000) and SSGA (90,000) which is equal to ($402,000) If there are no upper or lower limits for a certain application, it was assumed that there is a 20% deviation higher and lower than the reported values. A summary of the total costs is shown in Table 5-6. A uniform distribution was assumed for the costs between the lower limit and upper limit mentioned in Table 5-6. The capital costs that are considered one-time expenses incurred on the initial deployment include infrastructure devices, RSE, and integration. Annual operation and maintenance costs were assigned annually assuming a five-year project lifetime.

Table 5-6 Distribution of the Cost of the CV-Based Safety Application Deployment Per Intersection

Application	Capital Cost ($)		O&M Cost ($)/Year	
	Upper Limit	Lower Limit	Upper Limit	Lower Limit
Support of Signalized Intersection Safety				
CV-based	427,000	287,000	43,800	29,200
Support of Unsignalized Intersection Safety				
CV-based	402,000	268,000	28,800	19,200
Hazard Warning				
CV-based	594,000	396,000	44,400	29,600

5.3.1.3 Monte Carlo Analysis of Safety Applications

The Monte Carlo analysis was applied to estimate the stochastic distributions of the outcome measures, costs, and ROI. Lognormal distributions were used for the input parameters to estimate the benefits using the values listed in Table 5-4. These parameters include the expected market penetration for each future year, as well as crash modification factors and cost of the incident. Uniform probability distribution was used to account for the uncertainty of the parameters of the deployment costs. Market penetration of CV is considered stochastic each year after the CV implementation. Table 5-7 shows the market penetration distribution that was used in this study.

Table 5-7 CV Market Penetration at Future Year*

Year	Mean of Actual Distribution (%)	Mean of Lognormal Distribution	SD of Lognormal Distribution
1	2.9	1.074	0.546
2	7.3	1.99	0.323
3	12.3	2.51	0.300
4	18.4	2.91	0.230
5	24	3.18	0.196

** Source: Iqbal et al., 2018*

The benefit of the CV-based applications ($B_{CV\text{-}Based}$) is calculated using Equation 5-7.

$$B_{CV\text{-}Based} = CMF\ (\mu^*, \sigma^*)_j \times MP\ (\mu^*, \sigma^*)_j \times \Sigma_i\ (N_i\ C_i(\mu^*, \sigma^*)) \qquad 5\text{-}7$$

where, CMF is the crash modification factor, which is a lognormally distribution with a median (μ^*) and multiplicative standard deviation (σ^*), Ni is the number of crashes for the ith crash type, and Ci is the cost of crashes for the ith crash type, which is considered a lognormal distribution. MP is the percentage of market penetration in year j that is lognormally distributed with the parameters listed in Table 5-7.

<u>Estimation of Benefit-Cost Ratio (BCR)</u>

In order to get the benefit-cost ratio of a project, the present value of all of the costs and benefits need to be calculated. The present value (P) is the equivalent present worth the future values considering a discount rate. Considering a five-year project life-cycle, each future year annual cost investment and benefit return was discounted back to a present value. The project total cost or benefit is calculated using Equation 5-8.

$$P = \sum_{n=1}^{5} \frac{F_n}{(1+i)^n} \qquad 5\text{-}8$$

where, n is the total number of time period, i is the interest rate (4%), and F_n is the benefit or cost for time period n.

5.3.1.4 Results

A program code was written as part of this project using the R programming language to generate the probability distributions and to run the Monte Carlo simulation for all of the abovementioned processes. The results from one thousand Monte Carlo simulation runs were used to plot the benefit-cost ratio (BCR) distributions for CV-based safety solutions, as shown in Figure 5-3 to Figure 5-5. A summary of the distribution is provided in Table 5-8. Figure 5-3 to Figure 5-5 show the probability distributions for the benefit-cost ratios (B/C) for signalized intersection, hazard warning, and unsignalized intersection CV-based applications. These distributions show the probability of having any B/C value between a minimum value and a maximum value, rather than one deterministic value as usually produced in commonly used B/C analysis. These distributions allow stakeholders and transportation agencies to consider the uncertainty in the B/C estimation. This is further indicated in Table 5-8 that show three different percentiles of the B/C ratios based on the data shown in Figures 5-3 to 5-5. As shown in Table 5-8; the 15th percentile for the CV-based applications for signalized intersections, Unsignalized intersections, and Hazard Warning were 2.73, 1.79, and 0.93 respectively. The 50th percentile (median) of the BCR were 3.38, 2.26, and 1.18, respectively. The 85th percentile BCR were 4.8, 3.31, and 1.81 respectively. This indicates for example that the median B/C ratio of the signalized intersection applications is 3.38 but there is 15% possibility that is 2.73. On the other hand, the median of the segment is hazard warning applications is 1.18 but there is 15% that it is 0.93, which may or may not be acceptable to the decision maker.

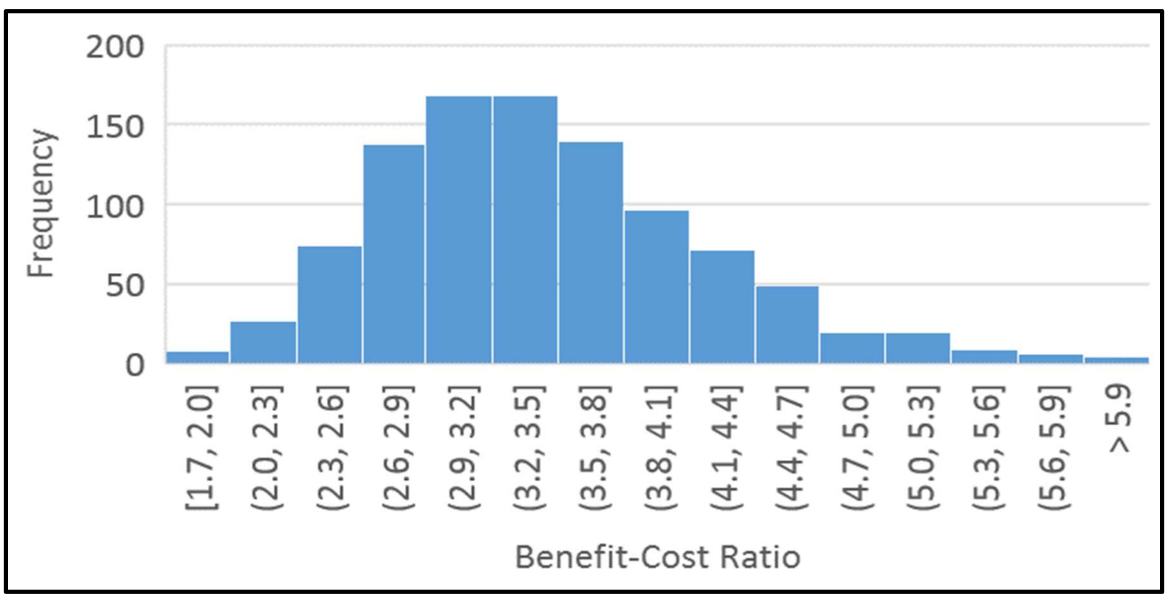


Figure 5-3 Distribution of Benefit-Cost Ratios for CV-Based Signalized Intersection

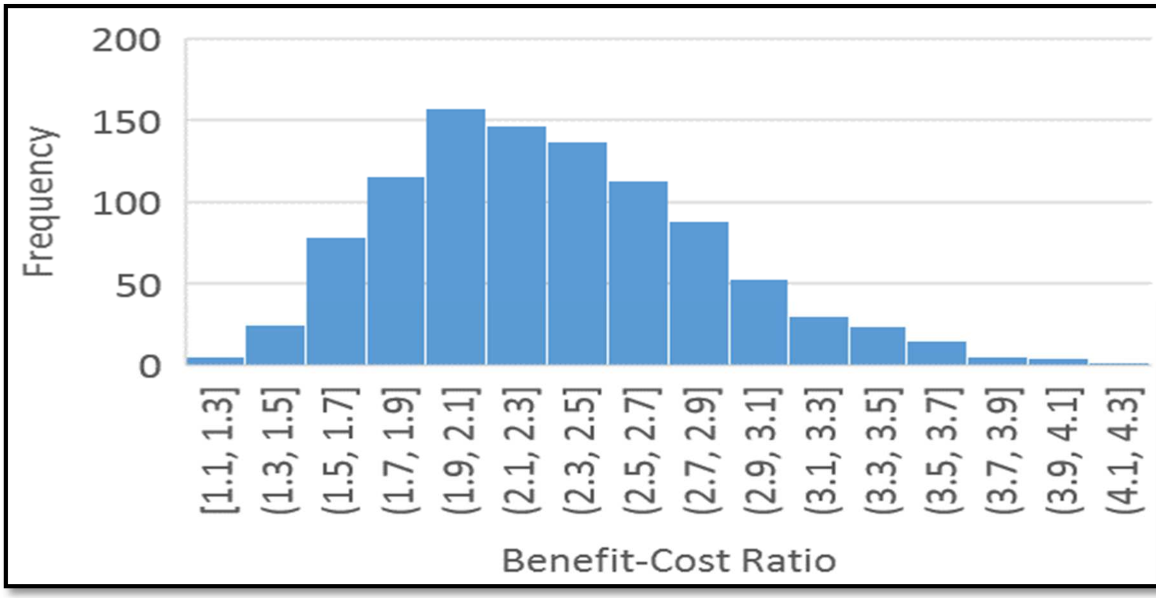


Figure 5-4 Distribution of Benefit-Cost Ratios for CV-Based Hazard Warning

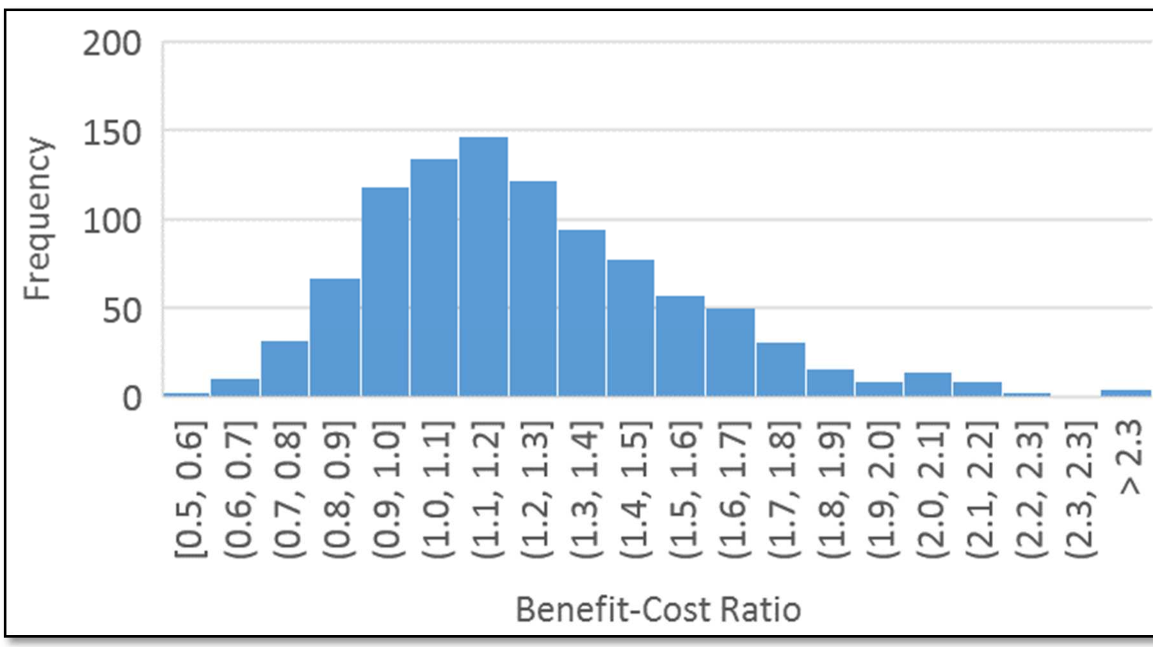


Figure 5-5 Distribution of Benefit-Cost Ratios for CV-Based Unsignalized Intersection

Table 5-8 Benefit-Cost Ratio (BCR) Distribution for Safety Applications

Application	BCR		
	15% Value	Median (50% Value)	85% Value
Support of Signalized Intersection Safety			
CV-based	2.73	3.38	4.824
Support of Unsignalized Intersection Safety			
CV-based	1.79	2.26	3.31
Hazard Warning			
CV-based	0.93	1.18	1.81

5.3.2 Mobility Applications

The estimation of mobility application benefits, costs, and ROI utilize the same Monte Carlo analysis as the one described in the previous section. The mobility applications assessed in this study as a demonstration of the proposed methodology of traffic management strategies on an urban arterial are adaptive signal control with and without CV technology, green-light optimal speed advisory (GLOSA), GlidePath, and transit signal priority.

5.3.2.1 Benefit Estimation

The mobility benefits were calculated utilizing mobility modification factors (MMF) based on an extensive review of previous studies on the subject. A detailed review was conducted, as presented in Chapter 3, to obtain the MMF. An additional review was performed since then to estimate the values of the MMF. A summary is provided in Table 5-9.

In addition to those associated with the MMF, there are several other sources of stochasticity that need to be considered for calculating the benefit value of mobility applications. These parameters include the dollar value of time (VOT), car occupancy (CO), and bus occupancy (BO). A summary of the literature review for these parameters is provided in Table 5-10.

Table 5-9 Summary of the Identified MMFs for Mobility Applications

Outcome Measure	*Source*	*Congested Conditions*	*Uncongested Conditions*
Adaptive Signal	FITSEVAL (Hadi et al., 2008)	10%	
	From Chapter 3	• 5% without CV. • 15% with 100% CV MP • Linear interpolation between 5% and 15% for lower market penetration	• 10% without CV • 25% with 100% CV MP. • Linear interpolation between 10% and 25% for lower market penetration
	10th Street Corridor in Greeley, Colorado Evaluation (Sprague and Archambeau 2012)	9% improvement in travel time	
	HCM Urban STREET ATDM Procedure Document (Hale et al., 2017)	5.1% to 13.5% increase in speed on the major road (average 10.2 mph) 1.2% to 5.4% increase in speed on a minor road (average 4%)	
Transit Signal Priority	FITSEVAL (Hadi et al., 2008)	12% reduction in travel time applied to buses that are not on time. Increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels.	
	From Chapter 3	12% decrease in bus travel time with an increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels	15% to 25% decrease in bus travel time, depending on CV market penetration. Increase in cross-street delay by 6-15 seconds per vehicle, depending on congestion levels.
Green Light Optimal Speed Advisory	From Chapter 3	3% - 10%	
Glide Path	From Chapter 3	10% - 20%	

Table 5-10 The Value of Time, Car Occupancy, and Bus Occupancy Parameters

Parameter	Source	Value
Value of Travel Time (VOT) ($/person-hr)	FITSEVAL (Hadi et al., 2008)	13.45
	Sallman et al. (2013)	14
	2015 Urban Mobility Report (Schrank et al., 2015)	17.67
	FDOT District 5 (2016)	17.67
	NASEM (2014). (Default Values)	19.86
	Benefit-Cost Analysis (TEC, n.d.)	The unit time value for commuters is calculated as 50% of the average wage under level-of-service (LOS) A-C, but increased to 67% at LOS D, 84% at LOS E and 100% at LOS F. For non-commuters, San Francisco planning analysis uses 0.32 of the wage rate.
Car Occupancy (Passenger/car)	Benefit-Cost Analysis (TEC, n.d.)	All Purposes: 1.6, Business: 1.22, Commute: 1.13, Personal: 1.84
Bus Occupancy (Passenger/car)	Based on Miami-Dade Transit data	35 - 60

Based on the review in Table 5-10, the highest and lowest values are selected as the upper limits (UL) and lower limits (LL) of different parameters for different CV-based and non-CV-based applications. Then, the mean and standard deviations of the lognormal distributions are calculated using Equations 5-1 to 5-6. Table 5-11 shows the utilized parameters of the distributions of the input parameters to the mobility parameter return on investment analysis.

Table 5-11 The Parameters of the Distributions of the Input Variables for CV-Based and Non-CV-Based Mobility Solutions

Alternative	Upper Limit (UL)	Lower Limit (LL)	Median of lognormal distribution (μ*)	Mean of lognormal distribution (μ)	Multiplicative Standard Deviation (σ*)	SD of lognormal distribution (σ)	Actual Mean (m)	Actual SD (v)
MMF for Adaptive Signals								
Non-CV-based (%)	5	2	3.16	1.15	1.32	0.28	3.29	0.93
CV-based (Congested) (%)	10	5	7.07	1.96	1.23	0.21	7.23	1.54
CV-based (Uncongested) (%)	20	10	14.14	2.65	1.23	0.21	14.46	3.08
MMF for Transit Signal Priority								
Non-CV-based (%)	12	8	9.80	2.28	1.13	0.12	9.87	1.22
CV-based (%)	25	15	19.36	2.96	1.17	0.16	19.60	3.06
MMF for Green Light Optimal Speed Advisory								
Non-CV-based (%)	Not Applicable							
CV-based (%)	10	3	5.48	1.70	1.44	0.37	5.86	2.22
MMF for Glide Path								
Non-CV-based (%)	Not Applicable							
CV-based (%)	20	10	14.14	2.65	1.23	0.21	14.46	3.08
Other Parameters								
Value of Time ($) (VOT)	14	10	11.83	2.47	1.11	0.10	11.89	1.22
Car Occupancy (CO)	1.3	1.0	1.14	0.13	1.08	0.08	1.14	0.09
Bus Occupancy (BO)	60	35	45.83	3.82	1.18	0.16	46.44	7.66

The existing condition travel times were calculated using the HCS, as described in Section 3.2. The stochastic CMF was applied to the travel times of the existing conditions to get the travel times with different applications.

5.3.2.2 Cost Estimation

As with the safety applications, the costs of the mobility applications were also considered stochastic. The costs included initial capital costs, operation and maintenance costs, estimated interest rate, and lifetime equipment. The cost estimates for the V2I applications deployment were identified based on the Near-Term V2I Transition and Phasing Analysis Life Cycle Cost Model (LCCM) tool (USDOT, 2015). In addition, other resources were considered in the estimates, such as the cost data reported in the United States Department of Transportation (USDOT) Joint Program Office (JPO) benefit database (USDOT, 2019). The identified upper and lower limits for the 95% confidence interval for the costs are shown in Table 5-12. The capital costs that were considered one-time expenses incurred on the initial deployment include infrastructure devices, RSEs, and integration. Annual operation and maintenance costs were assigned annually assuming a five-year project lifetime. It should be noted that these estimates have been identified based on the literature review. CV-based applications are being deployed in Florida, and more accurate cost estimates can be obtained based on these deployments in the applications of the methodology to real-world project. It is recognized that particularly the recurrent operation and maintenance numbers in number 5-5 seem to be low and better numbers should be used once available.

Table 5-12 Distribution of Cost of Mobility Applications Deployment Per Intersection

Application	Initial Capital Cost ($)*		O&M Cost ($)/Year*	
	Upper Limit	Lower Limit	Upper Limit	Lower Limit
Adaptive Signals				
Non-CV-based	90,000	60,000	14,400	9,600
CV-based	120,000	80,000	24,000	16,000
Transit Signal Priority				
Non-CV-based	30,000	20,000	8,400	5,600
CV-based	30,000	20,000	8,400	5,600
Green Light Optimal Speed Advisory				
Non-CV-based	Not Applicable			
CV-based	48,000	32,000	8,400	5,600
Glide Path				
Non-CV-based	Not Applicable			
CV-based	48,000	32,000	8,400	5,600
Onboard Unit	7000 per bus or truck			

* It is recognized that the costs particularly the recurrent operation and maintenance numbers in this table seem to be low and better numbers should be used once available.

5.3.2.3 Monte Carlo Analysis of Mobility Applications

As with the safety applications, the Monte Carlo analysis was applied to estimate the stochastic distributions of the outcome measures, costs, and ROI. The lognormal probability distributions were used for the input parameters to estimate the benefits using the upper and lower limits of each parameter. These parameters include the expected market penetration for each future year, MMF, VOT, car occupancy, and bus occupancy. The uniform probability distribution was used to account for the uncertainty of the parameters of the deployment costs. The market penetration of CV is also considered stochastic, as shown in Table 5-6 for each year after the CV implementation.

The Benefits of Delay Savings for Adaptive Signal Control

The benefits of non-CV-based adaptive traffic signal control can be calculated according to Equation 5-9.

$$\text{Benefits of } ASCT_j = FD_{base} \times MMF(\mu^*, \sigma^*) \times VOT(\mu^*, \sigma^*) \times CO(\mu^*, \sigma^*) \qquad 5\text{-}9$$

where, FD_{base} is the base facility delay (veh-hr), which is an output from the HCS. MMF is the Mobility Modification Factor, VOT is Value of time (Dollar), CO is the car occupancy (person), and j is the year of analysis.

The introduction of CV is expected to increase the effectiveness of adaptive signal control, as described in previous chapters. Equation 5-10 can be used to calculate the benefits considering the impacts of CV market penetration.

$$\text{Benefits of } ASCT_j = FD_{base} \times MMF(\mu^*, \sigma^*) \times MP(\mu^*, \sigma^*)_j \times VOT(\mu^*, \sigma^*) \times OC(\mu^*, \sigma^*) \qquad 5\text{-}10$$

where, MP is the market penetration at year j (from Table 5-6).

Benefits of Delay Savings for Green Light Optimal Speed Advisory (GLOSA) and Glide Path

The Green Light Optimal Speed Advisory (GLOSA) and Glide Path provide speed guidance to vehicles so that they can adjust their speeds accordingly to maximize the probability of arriving on green. The benefits of this application can be calculated using Equation 5-11.

$$\text{Benefits of GLOSA/Glide Path} = V_c * TT_{base} \times MMF(\mu^*, \sigma^*) \times MP(\mu^*, \sigma^*)_j \times VOT(\mu^*, \sigma^*) \times OC(\mu^*, \sigma^*) \qquad 5\text{-}11$$

where, V_c is the critical volume of the study area for the main street approaches (veh), and TT_{base} is the travel time for the base conditions of the main street.

Benefits of Transit Signal Priority or Fright Signal Priority

The benefits of transit signal priority (TSP) or freight signal priority (FSP) can be calculated using the following equations.

$$\text{Benefits of TSP} = (T_{TSP} - D_{TSP}) \times VOT(\mu^*, \sigma^*) \times NE_{bus} \quad 5\text{-}12$$

$$T_{TSP} = (TT_{base} - TT_{base} \times (1 - MMF(\mu^*, \sigma^*) \times P_{on}) \times BO(\mu^*, \sigma^*) \quad 5\text{-}13$$

$$D_{TSP} = (N_i \times D_{cross} \times P_{on} \times V_{cross} \times BO(\mu^*, \sigma^*) \times C)/3600 \quad 5\text{-}14$$

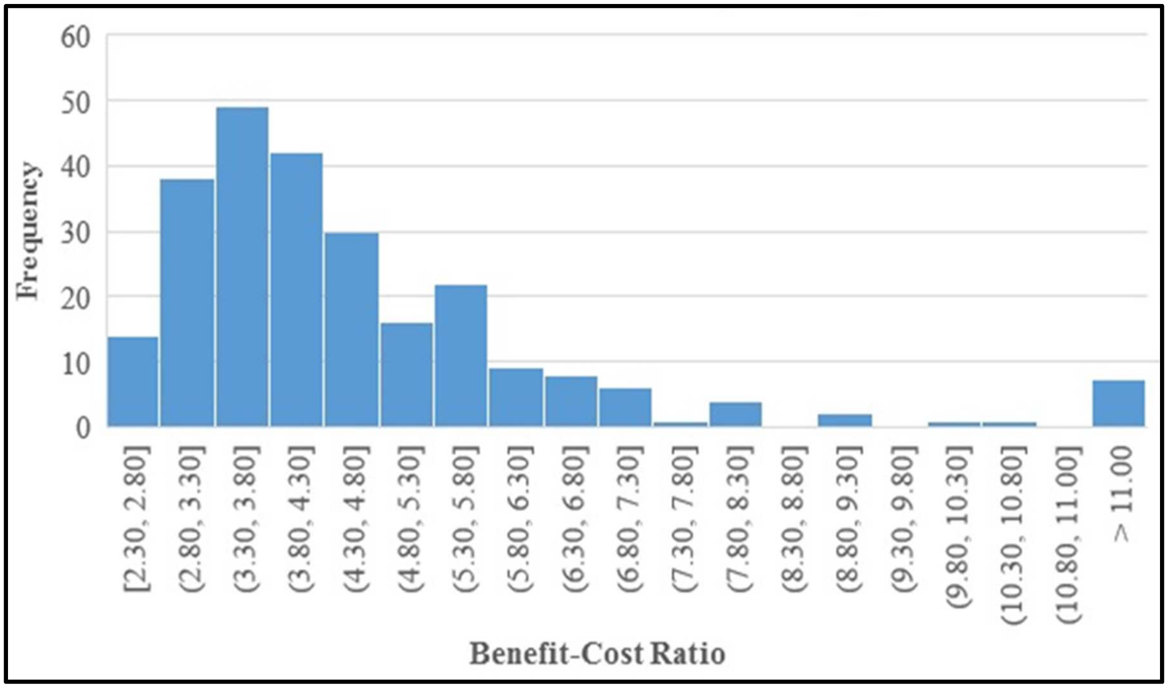
where, D_{TSP} is any disbenefit to the cross-street due to TSP, NE_{bus} is the number of equipped bus, P_{on} is the percentage of buses that meet the on-time performance, N_i is the number of intersections, D_{cross} is the cross-street delay per vehicle, V_{cross} average cross-street volume, BO is the bus occupancy, and C is the cycle length. The above equations assume that the applied TSP is a conditional TSP that is only activated when the approaching bus is not meeting its on-time performance. The percentage of buses that meet the on-time performance (P_{on}) is assumed to be uniformly distributed between 30% and 70%. For the study corridor, the bus runs at 20-minute intervals. Therefore, a total of 12 buses are used in the calculation for the two-hour AM peak (two-hours was identified based on real-world travel time data and can be different in different locations), and 18 buses for the three-hour PM peak in both directions. From the literature, the cross-street disbenefit per vehicle can be assumed to be a 0-15 second additional delay for each granted TSP.

Estimation of Benefit-Cost Ratio (BCR)

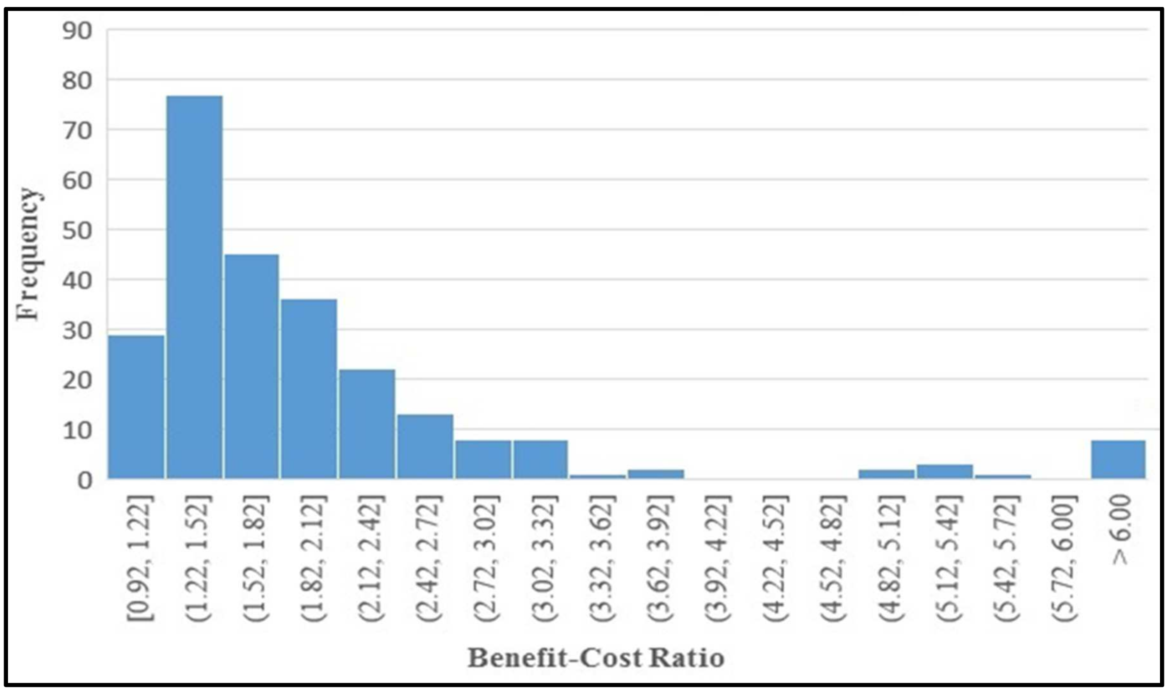
The benefit-cost ratio (BCR) for mobility applications was calculated following the procedure described in Section 4.8.3. Considering a five-year project life-cycle, each future year annual cost investment and benefit return was discounted back to a present value. The project's total cost and benefits were calculated using Equation 5-5.

5.3.2.4 Results

The study also compared the mobility benefits of different connected V2I applications. The results from one thousand Monte Carlo simulation runs were used to plot the benefit-cost ratio distribution for existing (non-CV) and CV-based solutions, as shown in Figure 5-6 to Figure 5-9. A summary of the distribution is provided in Table 5-13.

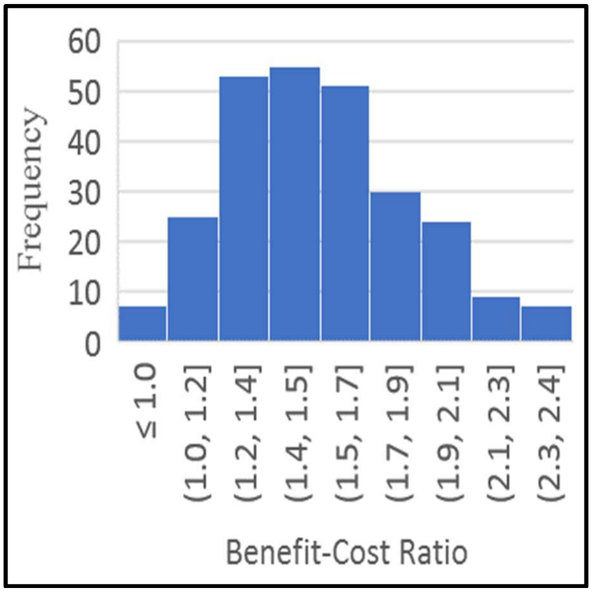


(a) With CV

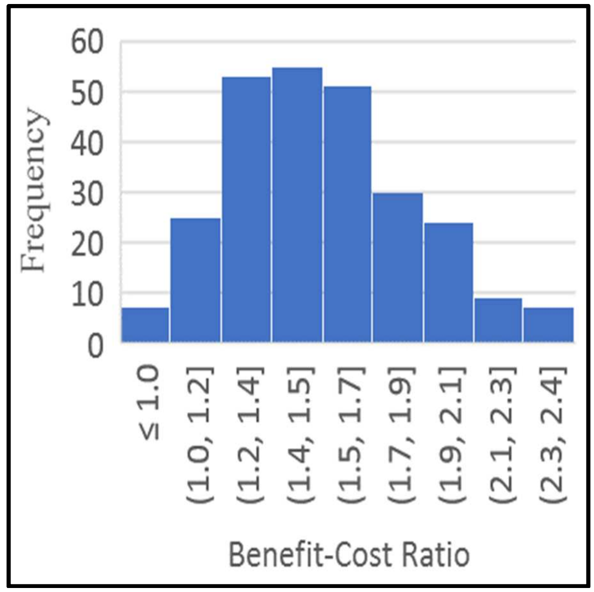


(b) Without CV

Figure 5-6 Distribution of Benefit-Cost Ratios for ASCT



(a) With CV



(b) Without CV

Figure 5-7 Distribution of Benefit-Cost Ratios for TSP

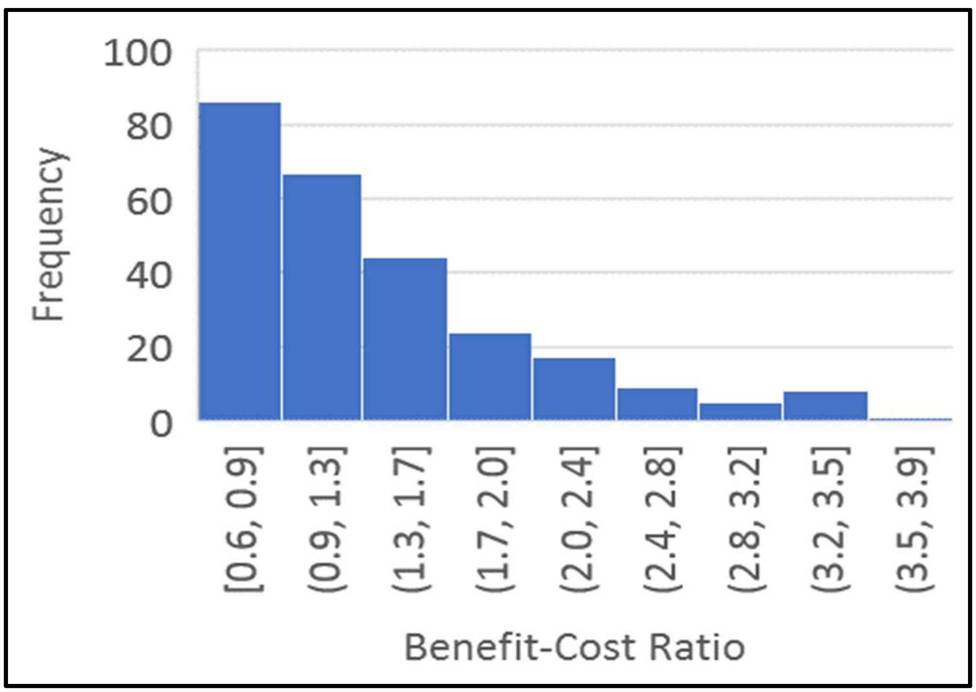


Figure 5-8 Distribution of Benefit-Cost Ratios for GLOSA

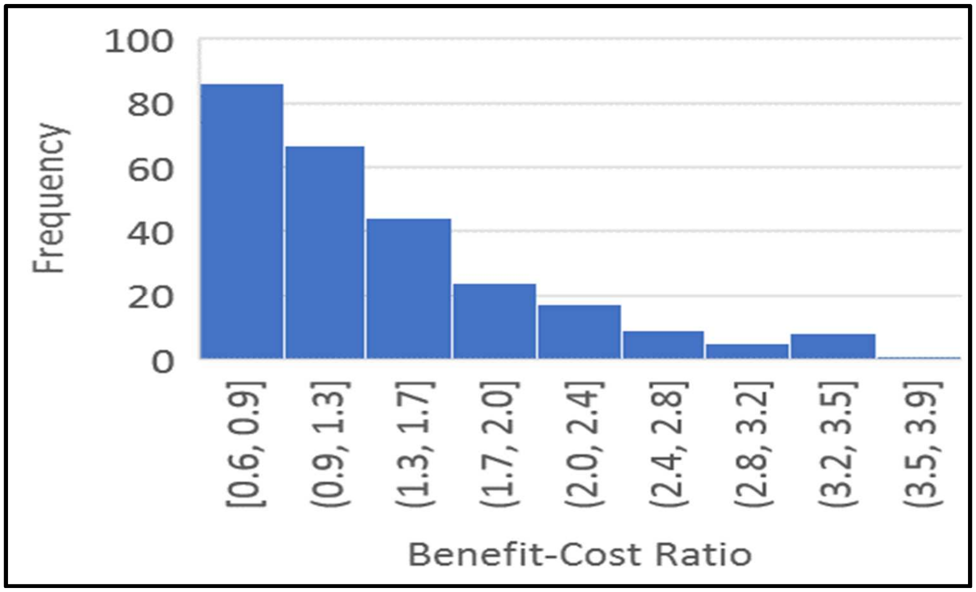


Figure 5-9 Distribution of Benefit-Cost Ratios for Glide Path

Table 5-13 Benefit-Cost Ratio (BCR) Distribution for Mobility Applications

Application	BCR		
	15% Value	**Median (50% Value)**	**85% Value**
Adaptive Signals			
Non-CV-based	1.25	1.67	2.64
CV-based	3.17	4.12	6.48
Transit Signal Priority			
Non-CV-based	0.68	0.85	1.08
CV-based	1.19	1.47	1.84
Green Light Optimal Speed Advisory			
Non-CV-based	Not Applicable		
CV-based	0.77	1.14	2.12
Glide Path			
Non-CV-based	Not Applicable		
CV-based	3.62	5.42	9.66

The results show that the 15%, median, and 85% values of the BCR of the adaptive signal control and transit signal priority is higher when using CV-based technology. For example, for adaptive signal control, the median BCR value is 1.67 for the non-CV-based application and 4.12 for the CV-based application. For transit signal priority applications, the median BCR value is below 1 for a non-CV application. This is due to a small number of buses on the analysis corridor (six buses per hour in both directions) and granting priority is conditional for the bus not meeting its schedule. For GLOSA and Glide Path applications, the median BCR is 1.14 and 5.42, respectively. The results show that from return on investment point of view the CV based application seems to be justified. However, other factors will have to be considered as part of the multi-criteria decision analysis, as described next.

5.4 MULTI-CRITERIA DECISION ANALYSIS

The economic evaluation and assessment of Intelligent Transportation System (ITS) projects can play a major role in deployment decisions. Economic techniques, usually referred to as return-on-investment (ROI) or benefit-cost analysis (BCA), are available to determine the effectiveness and benefits of deployed projects by comparing the costs and benefits of the deployments. ROI analyses have been used to assess the effectiveness of ITS projects. Eliasson and Lundberg (2012) reported on the transportation planner's use of benefit-cost ratios (BCRs) in ranking investments at the planning level for the selection between proposed transportation alternatives. In addition, they carried out a quantitative analysis to relate the BCR of an alternative and its probability to be selected for investment. The results showed that by utilizing BCR as a criterion in the decision-making process, the combined benefits of the selected investments increased from $5.3 billion to $7.6 billion.

Traditional benefit-cost analyses use deterministic values for the input costs and benefit parameters and produce deterministic values of the return on investment of ITS deployments. However, when considering CV-based applications as alternatives to support transportation system management and operations (TSM&O), there is a significant amount of uncertainty associated with the input parameters to the analyses, including the future CV market penetration, the initial and recurrent costs, the impacts and benefits of the deployments, and the dollar valuations of the benefits. Flyvbjerg (2009) reported that neglecting the uncertainty and errors in estimating the input parameters can result in a misleading ROI and unfavorable decisions. Asplund and Eliasson (2016) studied the usefulness of the ROI in the decision-making process for projects that involve degrees of uncertainty. Based on real-world transportation infrastructure investments collected from Sweden and Norway, the results showed that even with high levels of uncertainty, the selected investments according to ROI still achieved 70% higher score than the randomly selected projects.

It is important to consider the integration of multiple sources of uncertainty by expressing the project costs and benefits as stochastic inputs to the evaluation. Yang, Shen, and Hadi (2007) developed a methodology to account for the uncertainty involved in computing the costs and benefits associated with ITS deployment. The study utilized a Monte Carlo simulation to implement the stochastic ROI in conjunction with the ITS Deployment Analysis System (IDAS) sketch planning tool. The costs and benefits input parameters were expressed using probability distributions rather than as fixed parameters. Upper and lower limits for these input variables were estimated based on the reported values in previous studies. Khazraeian and Hadi (2018) reported that stochastic ROI analysis using Monte Carlo Simulation is a better approach compared to other methods, such as the Black Scholes and Binomial Lattice in accounting for parameter's uncertainty.

In addition to the issue of uncertainty in traditional return-on-investment analyses, such analyses do not account for changes in key performance indicators (KPIs) that cannot be converted to dollar values. The methods also do not account for the weights that the project stakeholders put on different KPIs, according to their priorities. The Multi-criteria decision-analysis (MCDA) methods are usually used to account for the changes in metrics that cannot be converted to dollar values and also to account stakeholder's priorities. Annema et al. (2015) studied the benefits of using ROI, MCDA, and the combination of both in the decision-making of transportation professionals and decision-makers. Based on data collected from twenty-one interviews, the results indicated that ROI could be a better tool when combined with MCDA. The MCDA methods include but not limited to, Analytic Hierarchy Process (AHP) (1980); Best-worst multi-criteria decision-making method (BWM) (2015); Evaluation Based on Distance from Average Solution (EDAS) (2015); Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (2012); Stochastic Multi-Criteria Acceptability Analysis (SMAA) (2001); Potentially All Pairwise Rankings of all possible Alternatives (PAPRIKA) (2016). Macharis and Bernardini (2015) reported that AHP developed by Saaty (1980) has been used in almost 33% of the literature that applied MCDA in transportation engineering.

The main goal of this part of the study is to develop a methodology to support the decision to select between CV-based solutions and existing solutions for improving safety on urban arterials. The developed method combines stochastic ROI and MCDA. Although the method in this report is applied to the selection of CV-based application to improve the safety of the arterial segments, it can be applied to any other CV-based applications or ITS deployments.

5.4.1 Methodology

The selection between V2I deployment and existing alternatives requires the evaluation of these alternatives against each other. As stated above, the utilized method for this evaluation in this report combines MCDA and stochastic ROI in supporting the decision to invest in CV-based applications. The utilized MCDA method is the AHP, which is as stated earlier, one of the most widely utilized MCDA in transportation engineering and planning. A four-level decision-making hierarchy is defined based on the AHP procedure (see the example in Table 5-14). The first level of the decision hierarchy is the goal of the analysis to select between connected V2I safety applications and existing solutions. The second level of the hierarchy includes the high-level objectives of the analysis. These objectives can be selected based on stakeholder inputs and should be related to the strategic objectives of the organization(s). The selected criteria in the AHP may include objectives related to outcome performance measures, output measures, economic measures, feasibility, and risks and constraints. The example (Table 5-14) is for an arterial street case study in Florida with the high-level objectives selected based on the criteria presented in the Business Plan of the Florida Department of Transportation (FDOT) Connected and Automated Vehicle (CAV) program (FDOT, 2019). The assessment criteria in Table 5-14 include acceleration of CAV program, improving performance, solution feasibility, initial and recurrent funding availability, and benefit/cost ratios. These criteria are used in the assessment of this study, but any other criteria can be used based on agency priorities and preferences. The third level of the hierarchy includes the sub-criteria required for detailed assessment. The last level in the hierarchy is the available alternatives to support achieving the criteria identified at the upper-level tasks.

Table 5-14 AHP Decision-Making Levels

Goal	Objectives	Sub-Criteria	Alternatives
Selecting between CV-based and existing conventional solutions for improving safety on urban arterials	1- Accelerate CAV program		1. Connected Vehicles to infrastructure (V2I) applications 2. Existing solutions
	2- Improve performance	2.1- Safety	
		2.2- Mobility	
		2.3- Reliability	
	3- Feasibility	3.1- Ease of Implementation	
		3.2- Scalable to the rest of state/region	
		3.3- Technology certainty	
	4- Funding	4.1- Federal Funds	
		4.2- DOT Funds	
		4.3- Local/Private Funds	
	5- Benefits/ Costs	5.1- 15^{th} Percentile B/C ratio	
		5.2- Median B/C ratio	

Benefit-Cost Ratio (B/C) Analysis

As indicated in (Table 5-14), maximizing the ROI is one of the criteria within the utilized AHP. A stochastic approach based on Monte Carlo analysis is used to calculate the BCR, to account for the risks and uncertainties, as discussed in Section 5.3. The Benefic-Cost distribution results from Section 5.3 is utilized in this chapter for AHP application.

Analytical Hierarchy Process (AHP) Application

The AHP was selected for use as the MCDA in this study. The AHP includes three parts: the hierarchic breakdown structure, prioritization procedure, and ranking alternatives. A typical four-level hierarchic structure as described earlier was used in this study. The prioritization procedure involved assigning weights for each evaluation criterion based on the importance of that criterion in achieving the overall goal. A pairwise comparison matrix was created to compare the importance of criteria relative to each other, and a normalized matrix is derived based on Equation 5-15. A criteria weight vector is calculated from the averaging of each row in the normalized matrix, based on Equation 5-16. The prioritization procedure then involves assigning scores to each alternative based on its performance relative to the considered criterion. Finally, a global score is assigned for each alternative allowing the ranking based on the scores.

$$\bar{a}_{ij} = \frac{a_{ij}}{\Sigma_j^m = a_{ij}} \qquad 5\text{-}15$$

$$w_j = \frac{\Sigma_{j=1}^m \; \bar{a}_{ij}}{m} \qquad 5\text{-}16$$

where, a_{ij} is the matrix element in row i and column j, $\bar{a}_{ij}$ is the normalized matrix element, m is the number of criteria to be evaluated, and w_j is the weight of each criterion.

Comparing alternatives requires subjective judgment from transportation professionals, due to the uncertainty of variables and the presence of qualitative measures. Thus, it is crucial to determine the consistency of the opinions of the decision-makers. Saaty (*1980*) proposed a measure called Consistency Index (CI) as shown in Equation 5-17 to show the degree of AHP consistency by comparing CI to a predefined index called Random Consistency Index (RI).

$$CI = \frac{\lambda \text{max} - n}{n-1} \quad \text{5-17}$$

The Consistency Ratio (CR) is calculated to compare the CI relative to the RI. The CR is considered acceptable if the value is less than or equal to 10%.

5.4.2 Analysis and Results

This study compared the safety benefits of conventional solutions with alternative connected V2I applications. These applications include CV-based support of signalized intersection safety, CV-based support of unsignalized intersection safety, and CV-based support of hazard warning. The results from one thousand Monte Carlo simulation runs were used in the estimation. The benefit-cost ratio distributions for conventional and CV-based solutions are shown in Figure 5-10.

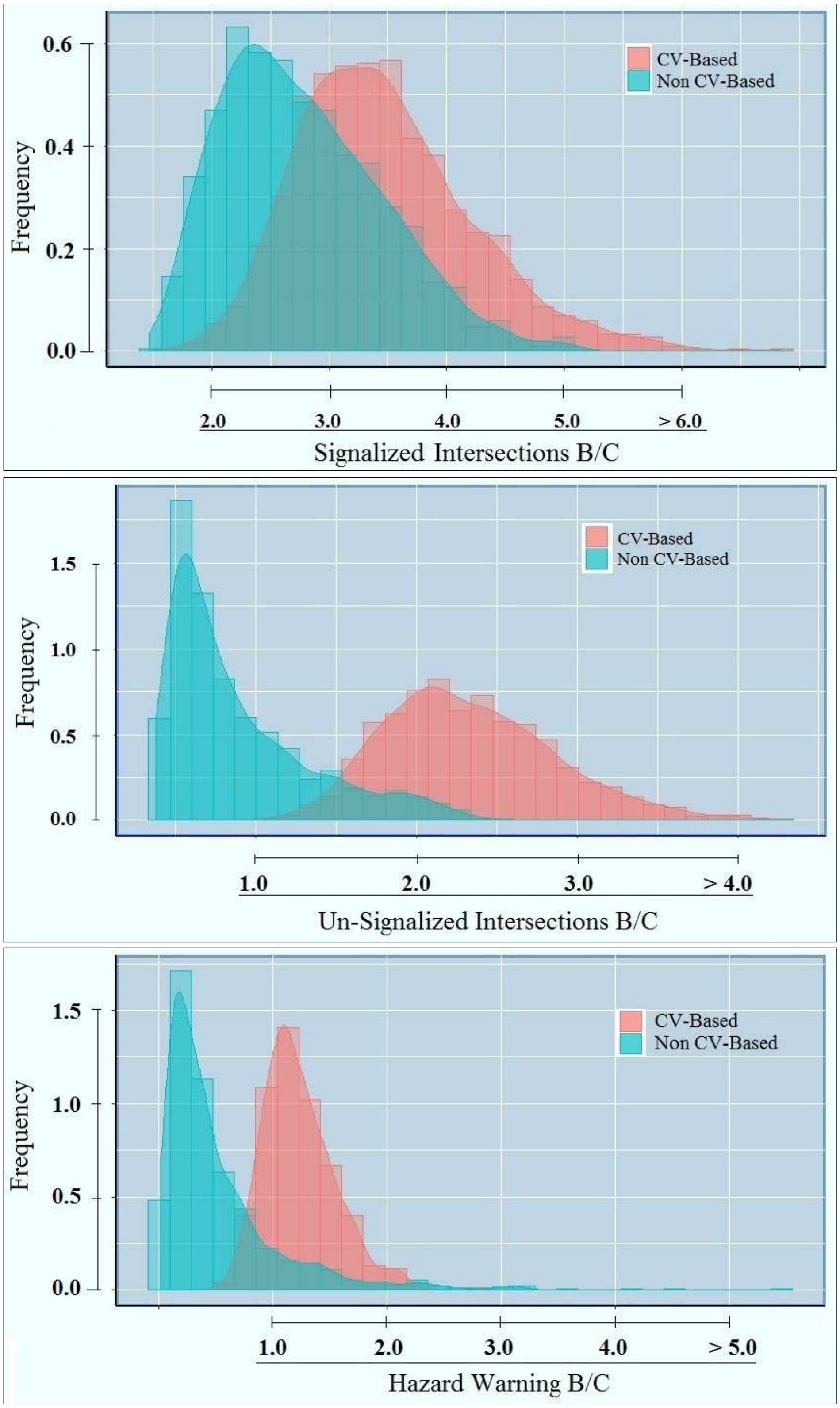


Figure 5-10 Distribution of the benefits of the existing and CV-Based solutions

The 15th and median percentiles of the benefit-cost ratios were also used as sub-criteria in the AHP. Please, note that, for the demonstration of the methodology, the return-on-investment analysis was done for each of the three categories (signalized, unsignalized and hazard segment-based applications) assuming that all relevant conventional and CV-based solutions associated with each category are utilized. The analysis can also be done for individual applications based on the actual crash history and the needs of the analyzed transportation network. For example, a crash analysis may suggest that the only needed signalized intersection application is Red Light Violation Warning, and then only that application would be included in the analysis.

The B/C of CV-based signalized intersection applications ranged from 1.73 to 6.84 with a median of 3.38 and a mean absolute deviation (MAD) of 0.58. The B/C of CV-based unsignalized intersection applications ranged from 1.11 to 4.25, with a median of 2.26. The B/C for hazard warning ranged from 0.5 to 2.79, with a median of 1.18. The Non-CV-based applications had lower B/C, as shown in (Table 5-15).

Table 5-15 Benefit-Cost Ratio (B/C) Distribution for Safety Applications

Application	**B/C**		
	15% Value	**Median (50% Value)**	**85% Value**
Support of Signalized Intersection Safety			
Non-CV-Based	2.07	2.67	3.99
CV-Based	2.73	3.38	4.824
Support of Un-Signalized Intersection Safety			
Non-CV-Based	0.50	0.72	1.89
CV-Based	1.79	2.26	3.31
Hazard Warning			
Non-CV-Based	0.12	0.35	1.63
CV-Based	1.00	1.18	1.86

In this study, the 15th and median percentiles of the B/Cs were used as inputs to the AHP. The other selecting criteria for the AHP were: accelerating the CAV program in Florida, improving performance, solution feasibility, and funding availability. Two decision-makers from the FDOT District 6 in Miami were asked to assign a score for each criterion relative to each other. The criteria were further decomposed into sub-criteria, and an assigned score was given for each sub-criteria. Table 5-16 shows the calculated weight for each criterion by both decision-makers. Based on Saaty (*1980*) method, the upper right corner cells only needed to be weighted as the lower-left corner are the reciprocal of the upper right corner. Noted, that the scores of the diagonal in the table are equal to 1, as it compares the criteria to itself. Decision Maker 1 assigned the highest score for improving performance and feasibility and gave both criteria 20% more than the importance of funding and maximizing the return on investment. Based on Decision Maker 1 assigned scores, the importance of accelerating the CAV program was about 20% less than improving the performance and approximately equal to the funding and ROI criteria.

Table 5-16 AHP Pairwise Comparison for Alternatives Selection Criteria

	Accelerate CAV Program	Improve Performance	Feasibility	Funding	Benefits / Costs
Decision Maker 1:					
Accelerate CAV Program	1.00	0.80	0.80	1.00	1.00
Improve Performance	1.25	1.00	1.00	1.25	1.25
Feasibility	1.25	1.00	1.00	1.25	1.25
Funding	1.00	0.80	0.80	1.00	1.00
Benefits / Costs	1.00	0.80	0.80	1.00	1.00
Decision Maker 2:					
Accelerate CAV Program	1.00	0.80	1.00	0.8	1.00
Improve Performance	1.25	1.00	1.25	1.00	1.25
Feasibility	1.25	1.00	1.00	0.8	1.00
Funding	1.25	1.00	1.25	1.00	1.00
Benefits / Costs	1.00	0.8	1.00	1.00	1.00

Table 5-17 shows the weight rating given by Decision Maker 1 for each sub-criterion relative to each other. With regard to improving the performance, safety is the priority criterion and 20% more important compared to mobility and reliability. With regard to the feasibility decision criteria, technology uncertainty, such as the decision to select between DSRC and Cellular technology, is the least important compared to the other sub-criteria.

Table 5-17 AHP Pairwise Comparison for Alternatives Selection Sub-Criteria

Improve Performance	**Safety**	**Mobility**	**Reliability**
Safety	1.00	1.25	1.25
Mobility	0.80	1.00	1.00
Reliability	0.80	1.00	1.00

Feasibility	**Ease of Implementation**	**Scalable to the rest of District 6**	**Lack of experience / Risks**	**Technology Certainty**
Ease of Implementation	1.00	1.25	1.25	2.50
Scalable to the rest of District 6	0.80	1.00	1.00	2.00
Lack of experience / Risks	0.80	1.00	1.00	2.00
Technology Certainty	0.40	0.50	0.50	1.00

Funding	**Federal Funds**	**DOT Funds**	**Local / Private Funds**
Federal Funds	1.00	0.9	1.00
DOT Funds	1.12	1.00	1.67
Local / Private Funds	1.00	0.6	1.00

Benefits / Costs	**15th Percentile NPV**	**Median NPV**
15th Percentile NPV	1.00	0.60
Median NPV	1.67	1.00

The AHP consistency index was calculated for each of the tables to check the consistency in rating the criteria relative to each other. The AHP analysis was conducted based on inputs from both decision-makers. However, the results shown in Figure 5-11 are only for Decision Maker 1, as an example. As can be inferred from this figure, utilizing CV-based technologies have a higher final score than existing alternatives. The AHP final scores for CV-based solutions and conventional solutions are 0.63 and 0.37, respectively. The AHP analysis results indicate that utilizing V2I applications is 41.3% more favorable than conventional solutions. This is because CV has a significantly better safety performance in reducing crash rates for both signalized and unsignalized intersections. Utilizing CV data has lower scores in the third criterion, which is feasibility, and this is due to the risks in the implementation and the technology uncertainty of CV deployment. More details of the AHP calculation process is shown in Appendix A.

Analytic Hierarchy Process

Goal	Criteria for Selection Between Different ITS Alternatives												
Critera	Accelerate CAV Program	Improve Performance			Feasibility				Funding			Benefits / Costs	
Priority	0.182	0.227			0.227				0.182			0.182	
Sub-Criteria	-	Safety	Mobility	Reliability	Ease of Implementation	Scalable to the rest of District 6	Lack of experience / Risks in implementatio	Technology Certainty	Fedral Funds	DOT Funds	Local / Private Funds	15th Percentile NPV	Median NPV
Priority	0.182	0.38	0.31	0.31	0.33	0.27	0.27	0.13	0.33	0.33	0.34	0.44	0.56
Final Score		CV- BASED SOLUTIONS				0.63	EXISTING SOLUTIONS					0.37	
CV- BASED SOLUTIONS	0.182	0.71	0.78	0.53	0.56	0.50	0.29	0.29	0.50	0.56	0.50	0.554	0.548
EXISTING SOLUTIONS		0.29	0.22	0.47	0.44	0.50	0.71	0.71	0.50	0.44	0.50	0.446	0.452

Figure 5-11 AHP Results and Final Score

5.4.3 Summary

This chapter of the study utilized a combination of stochastic return-on-investment analysis and a multi-criteria decision-making procedure to account for uncertainties and decision-maker priorities in the decisions to invest in CV-based applications. The results of the analysis show the ability of the developed method in confirming the cost-effectiveness of the CV-based applications as compared to conventional solutions. Based on the crash statistics of the case study, both the ROI and the MCDA analyses indicate that the CV-based applications for signalized intersection safety and unsignalized intersection safety are justified and are better options than conventional solutions. The cost-effectiveness of the midblock hazard warning applications at the midblocks was lower than those for signalized and unsignalized intersection applications. However, the CV-based midblock applications have higher cost-effectiveness than the considered conventional applications. The method developed in this study is recommended to be used by planners and TSM&O engineers when deciding to invest in CV-based applications.

5.5 FITSEVAL TOOL IMPLEMENTATION

A tool is needed to facilitate the pre-deployment return on investment described earlier in this document. The research team has already developed such a tool as part of another project funded by the FDOT research center. The project title is "Estimation of System Performance and Technology Impacts to Support Future Year Planning" and is funded under grant number BDV29-977-37. The tool can estimate the mobility, reliability, and safety impacts of advanced strategies on system performance and can perform the return on investment and MCDA analysis. The tool is an enhanced version of an existing tool referred to as the Florida ITS Evaluation Tool (FITSEVAL). The original version of the tool was developed within the Florida Standard Urban Transportation Modeling Structure (FSUTMS)/Cube environment for FDOT by Hadi et al. in 2008. This original tool can be used to assess the mobility, safety, environmental, and user-cost benefits, as well as the costs of the following ITS deployments:

- Ramp Metering
- Incident Management Systems
- Highway Advisory Radio (HAR) and Dynamic Message Signs (DMS)
- Advanced Travel Information Systems (ATIS)
- Managed Lane
- Signal Control
- Emergency Vehicle Signal Preemption
- Smart Work Zone
- Road Weather Information Systems
- Transit Vehicle Signal Preemption
- Transit Security Systems
- Transit Information Systems
- Transit Electronic Payment Systems

A different set of ITS implementations are included in the updated version of FITSEVAL to focus the development effort as it is implemented in a new platform. A strong focus in the updated version is on the impacts of connected vehicles (CV) and automated vehicles (AV). However, the assessment of additional applications can be added to the tool as needed. The following are the applications evaluated in the new version:

- Adaptive signal control with and without connected vehicle (CV) support
- Transit signal priority with and without CV support
- Freight signal priority with and without CV support
- Speed adjustment of CV to support arrival on green
- CV applications to support of signalized intersection safety
- CV applications to support unsignalized intersection safety
- CV applications to support hazard warning
- Vehicle automation

As stated earlier, the original version of FITSEVAL was produced utilizing the Script language of Cube. It works only as a processor to Cube-provided input and output files, in addition to analyst supplied parameters utilizing the user interface. The new version of FITSEVAL produced as part of Project BDV29-977-37 is a standalone desktop tool that reads files from multiple sources as long as it is provided in acceptable formats. The currently acceptable file formats are Cube files, Highway Capacity Software (HCS), and the Intelligent Transportation Systems Data Capture and Management (ITSDCAP) tool (also developed for FDOT by Florida International University). The source of the data can be any model (simulation or analytical models) or real-world data, as long as it is converted into one of these three formats. The software itself is coded in the C# language. The user does not need to use the C# language to utilize the tool since it is compiled and used in an executable form. The final FITSEVAL product is an executable file, which could be run on any windows platform. Thus, the user only needs to interface with the tool through the graphical user interface (GUI), and input and output files. Figure 5-12 is an example of the screens of the updated FITSEVAL showing a comparison of the assessed mobility of a corridor with and without connected vehicle (CV)-based adaptive signal control implementation. The upper half and lower half of Figure 5-12 present the mobility performance dashboard of the case study facility when utilizing the adaptive signal control without CV application and with CV applications, respectively. Figure 5-13 shows an example of the estimate reliability dashboard. Figure 5-13 shows that the reliability rating of the case study is 94% with a mean TTI of 1.87. Figure 5-14 shows an example of safety estimation dashboard. Figure 5-14 shows the safety performance dashboards showing the number of crashes by type for the facility.

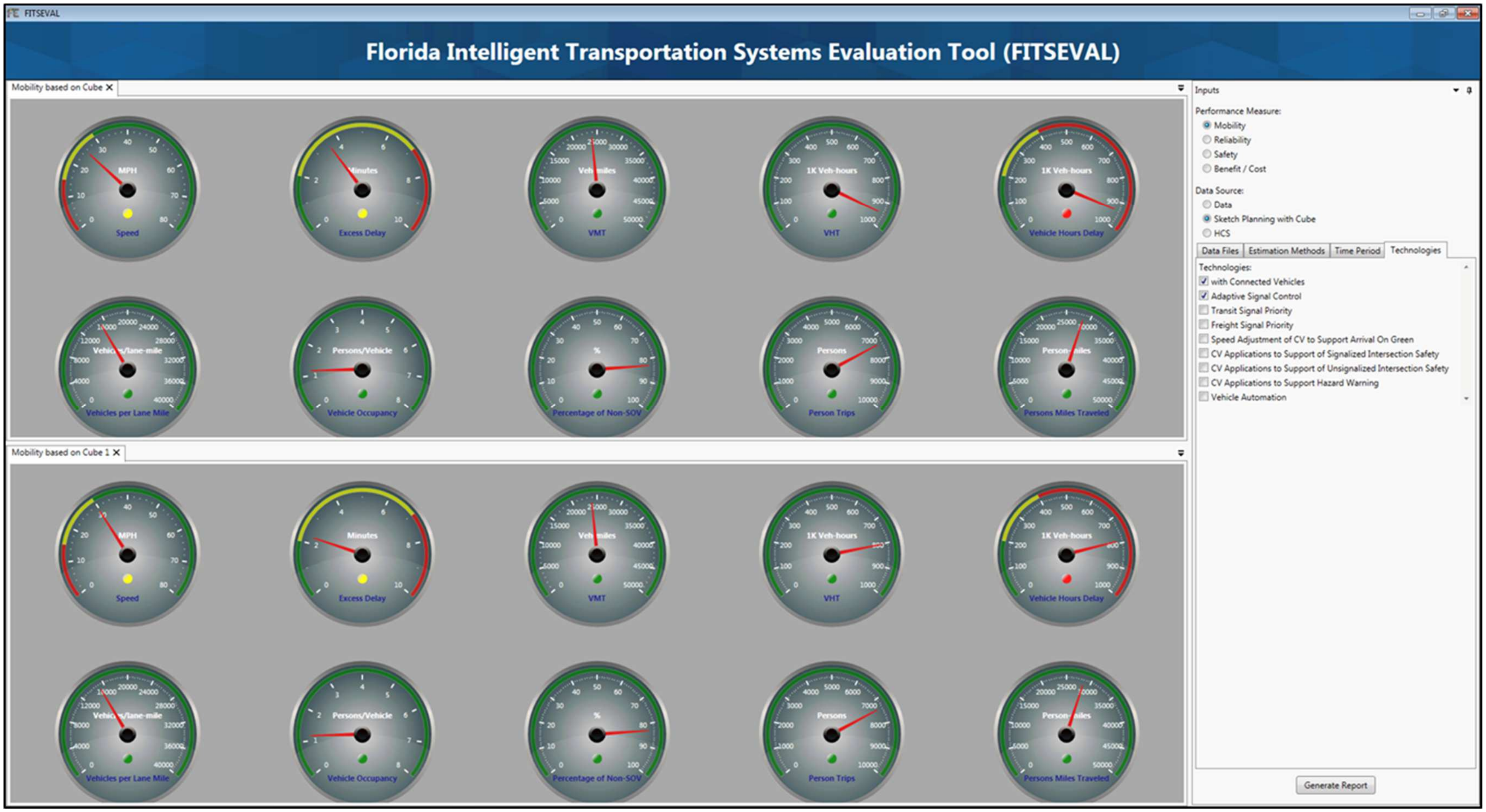


Figure 5-12 Comparison of Mobility with and without CV-Based Adaptive Signal Control

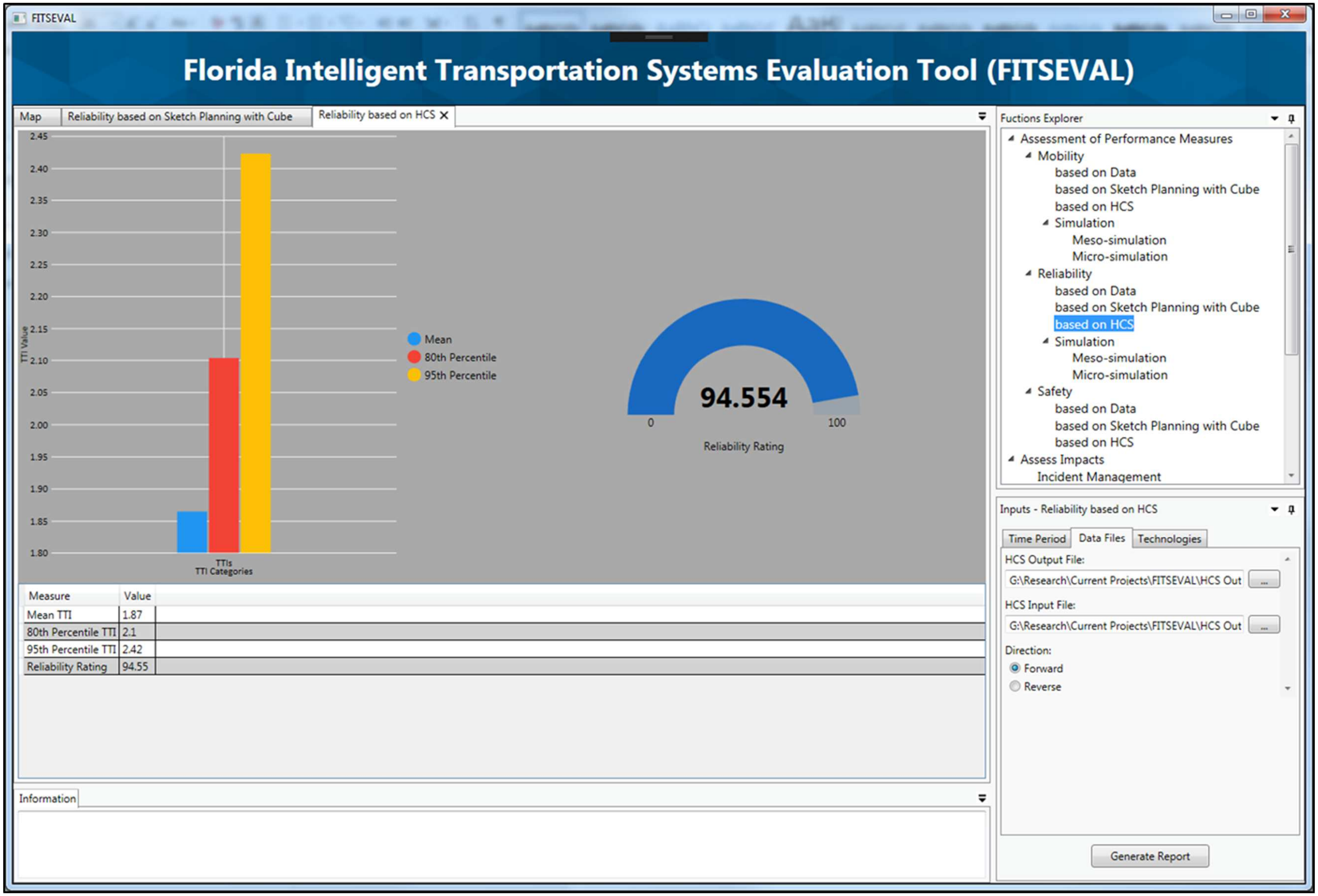


Figure 5-13 Reliability Dashboard Estimated Based on HCS Output

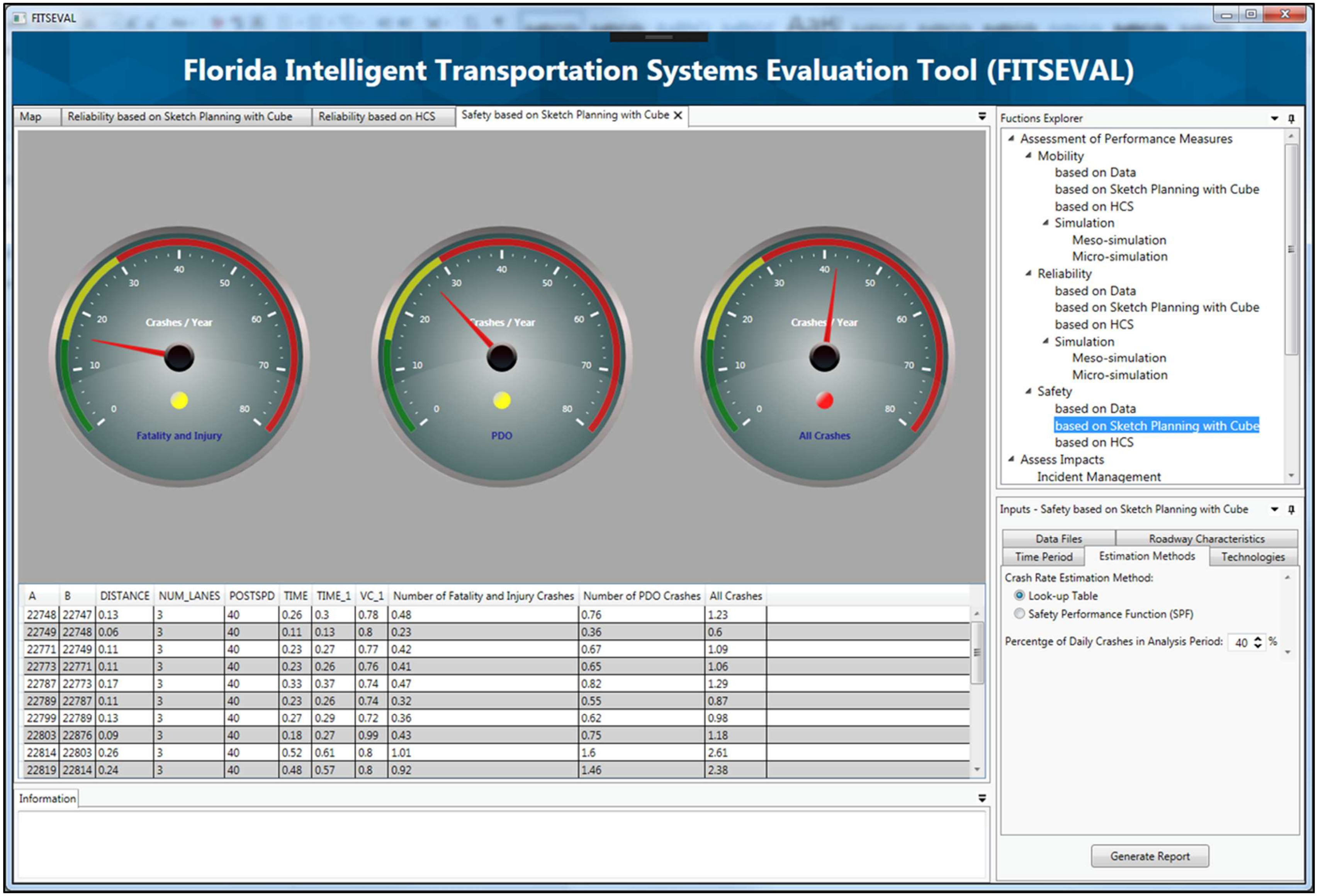


Figure 5-14 Safety Dashboard

5.6 SIMULATION APPLICATION

Simulation modeling can play a major role in supporting the pre-deployment and post-deployment assessment of CV-based applications, particularly given the limited deployment of these applications and the low market penetrations of CV that are expected in the near future. For instance, this section demonstrates the use of simulation modeling to assess the safety and mobility of one CV-based application, which is the Signalized Left Turn Assist (SLTA).

Utilizing permissive left-turn has been used as an effective solution to increase left-turn capacity and thus reduce intersection delays. With permissive left-turns, vehicles are allowed to make left-turns concurrently with the opposing through traffic once acceptable gaps are determined to be available by the turning drivers, with the left turners are supposed to yield to the conflicting traffic and pedestrians. Previous studies and research efforts done by the National Highway Traffic Safety Administration (NHTSA) reported that about 40% of the vehicle crashes in the United States occurs at intersections (Choi, 2010). More than 480,000 of the reported intersection crashes between 2005 and 2007 involved vehicles making left-turn maneuver on a permissive signal phase. Left-turn crashes have high probabilities of causing serious injuries or fatalities. The common reasons behind these types of crashes are failure to judge sufficient gap in the opposing traffic, misjudgment of the opposing vehicle's speed and location, and inadequate or obstructed sight distance.

Signalized Left Turn Assist (SLTA) is a connected vehicle application to address permissive left-turn safety concerns. An effort done at the University of California at Berkeley, California Partners for Advanced Transit and Highways (PATH), provided a comprehensive investigation of the SLTA (Misener et al., 2010). The study introduced the concept of operations of SLTA and developed SLTA alert algorithm. In addition, the researchers compared two decision support interfaces, the first is based on infrastructure and the second is based in-vehicle display. The results showed that both interfaces have their pros and cons and there was no evidence to eliminate the potential for either design. The SLTA application provides assistance for vehicles making left-turn during the unprotected left-turn signal phase at signalized intersections. SLTA supports left-turning drivers' decision in accepting a gap in the opposing traffic by computing the speeds and locations of the opposing vehicles and determining adequate and safe gaps for completing the maneuver. Thus, it improves the safety of the permissive left-turning traffic without the need to compromise the throughput and capacity of the left-turn lane by changing the left-turn phase to protected-only operation. Accordingly, the main role of SLTA application is to identify and alert the drivers about the safe gaps that would typically be accepted by the majority of drivers.

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This study investigates the use of micro-simulation to assess the benefits of CV-based SLTA applications considering both safety and mobility impacts. The benefits of SLTA are expected to include the reduction in left-turn crashes, improvement of left-lane capacity, and reduction in the left-turn vehicle delay. The mobility benefits are assessed based on the examination of the output of the utilized microscopic simulation model in this study, which is the PTV's Verkehr In Städten SIMulationsmodell (VISSIM). The safety benefits of SLTA are determined using surrogate safety measures through a combination of the VISSIM micro-simulation model and the Surrogate Safety Assessment Model (SSAM). A previous study reported that the combination of VISSIM and SSAM provides an appropriate tool to assess the safety impacts of connected vehicle applications (Fyfe, 2016). An important aspect of simulating CV-based applications is the need for more detailed calibration based on fine-grained data. The first objective in this chapter is to demonstrate how such calibration is performed to support the microsimulation-based modeling of SLTA. This calibration is based on a real-world gap acceptance distribution for a permissive left-turn phase at a signalized intersection. To simulate vehicle interactions appropriately at the microscopic level, researchers have proposed different methods for VISSIM calibration and model parameter validation. However, the calibration of drivers' gap acceptance behavior, especially of permissive left turns at signalized intersections, is yet to be explored. The second objective is to utilize the calibrated model to assess the potential impacts of SLTA on mobility and safety.

5.6.1 SLTA Research Review

Najm et al. (2010) estimated the safety benefits of intersection V2I applications in reducing the annual crash rates related to these applications. Findings showed that V2I systems address about 26%of vehicle-related crashes (Ragland et al., 2006). The most common crash type addressed by the SLTA countermeasure is head-on, left-turn, and angle crashes. These crashes involve left-turn vehicles, Subject Vehicle (SV), with a conflicting vehicle from the opposing traffic, Opposing Vehicle (OV). There are several reasons associated with these types of crashes, such as inadequate sight distance, inadequate surveillance, and failure to judge safe gaps in the opposing traffic. As described by Misener et al. (2010) and Richard et al. (2015a), the main role of the SLTA application is to provide assistance and support for the left-turning vehicle during permissive left-turn movements. The application deployment decision should be based on the geometric characteristics and the crash history of a particular intersection. SLTA is beneficial at intersections where there is a high traffic demand, limited sight distance, and high pedestrian and bicyclist volumes (Misener et al., 2010).

The SLTA messages and warnings can be communicated to drivers using Driver-Infrastructure Interface (DII) or Driver-Vehicle Interface (DVI) (Richard et al., 2015b). One of the design criteria of the application is the timing algorithm to determine when the SLTA will initiate the alerts to the SV driver. The key factors to be considered are the gap length in the opposing traffic and the SV driver's gap acceptance behavior. The SLTA system identifies the probability of a crash to occur between the SV and OV based on a pre-defined critical gap length. There is no available information in the literature regarding the safest gap length required for the system design. In general, based on previous research results, the drivers seem to comply with the application warnings when it matches their common sense in the accepted gap length. For example, a study by Richard et al. (2015a) emphasized the importance of using appropriate tuned gap lengths in the SLTA design to improve the driver's compliance with the system. The factors that potentially affect the drivers gap acceptance behavior and the SLTA time algorithm include the distribution of the gap sizes in the opposing traffic and the geometry of the intersection, such as the number of lanes and median size, in addition to other factors, such as queue presence, time of day, and signal timing.

Ogallo and Jha (2014) developed a methodology to analyze the critical gap for left-turn movements at signalized intersections. The study investigated the impact of intersection geometric sight obstructions for the left-turning vehicles on the accepted time gap length. Based on real-world data, two different scenarios were analyzed to compare the critical gaps with and without sight distance obstructions. The researchers introduced an adjustment factor for the critical gap when the line of sight of the SV drivers is obstructed. The results showed that the presence of a limited sight distance increases the left-turn gap size from 5 seconds to 6 seconds by adding extra lost time to the perception reaction time of the SV. Accordingly, the added extra lost time to the critical gap also reduces the potential capacity of the left-turn movement. An efficient SLTA application, which accounts for the intersection geometry and is designed with adequate gap size, is expected to provide a solution to this concern.

5.6.2 Methodology

This chapter presents a demonstration of the use of simulation for assessing CV-based intersection applications with the SLTA as an example of such applications. As stated earlier, a more detailed calibration of simulation based on microscopic parameter measurements is needed compared to traditional calibration methods that generally have been using macroscopic traffic parameter measurements.

The calibration of a microsimulation model is a process of traffic parameter adjustment to replicate real-world roadway network conditions (Fyfe, 2016). This iterative process compares the model outputs with ground truth data until real network conditions is properly presented. Huang et al. (2013) calibrated VISSIM by adjusting headway, flow, and speed parameters; and simulated traffic conflicts for signalized intersections using the SSAM. The calibrated models resulted in better conflict prediction when comparing the results from the calibrated and non-calibrated models with real world data. Researchers utilized microscopic trajectory data to improve the model's reliability when calibrating VISSIM for car-following parameters (Ragland et al., 2006). Kim et al. (2005) proposed a statistical method to assess the performance of the calibrated VISSIM models in terms of travel time distributions. A generic algorithm (GA) was employed to automate the process of determining the significant calibration parameters, including the number of the preceding vehicles observed, look-ahead distance, safety distance, and lane changing distance. The proposed approach was successful in identifying parameters that resulted in realistic travel time distributions. Lu et al. (2016) proposed an automated video processing methodology for VISSIM calibration. The method is based on collecting real-world vehicle trajectory data to determine the optimal values of car-following parameters related to the desired speed, acceleration, and safe following distance in VISSIM. Mathew and Radhakrishnan (2010) calibrated VISSIM considering heterogeneous traffic at signalized intersections in India. Heterogeneous traffic, including various vehicle type and size, non-uniformity of road geometric conditions, and non-lane-based flow posed additional challenge for simulation). A Genetic algorithm-based optimization resulted in a better calibrated VISSIM model (Mathew and Radhakrishnan, 2010).

The Highway Capacity Manual (HCM) defined the gap acceptance as "the process by which a minor street vehicle accepts an available gap to maneuver" (TRB, 2010). The gap is calculated in seconds when two successive vehicles pass the point of conflict. Ragland et al. (2006) described a method to identify the gap distribution presented to the driver as part of a California PATH investigation of permissive left-turn crashes. The method uses real-world data to assess the driver's behavior and to determine the distributions of accepted gaps in the oncoming traffic. This real-world gap acceptance distribution was used in our study to calibrate the VISSIM simulation model, and to compare the left-turn lane capacity and delay with and without SLTA. In practice, such distributions should be obtained to reflect the gap acceptance behavior for the analysis area when calibrating the simulation model. The proposed VISSIM calibration process for permissive left-turn gap acceptance is illustrated by modeling a four-leg signalized intersection. The calibration was conducted for an intersection located at NW 119th St and NW 17th Ave in Miami-Dade County, Florida, as depicted in Figure 5-15.

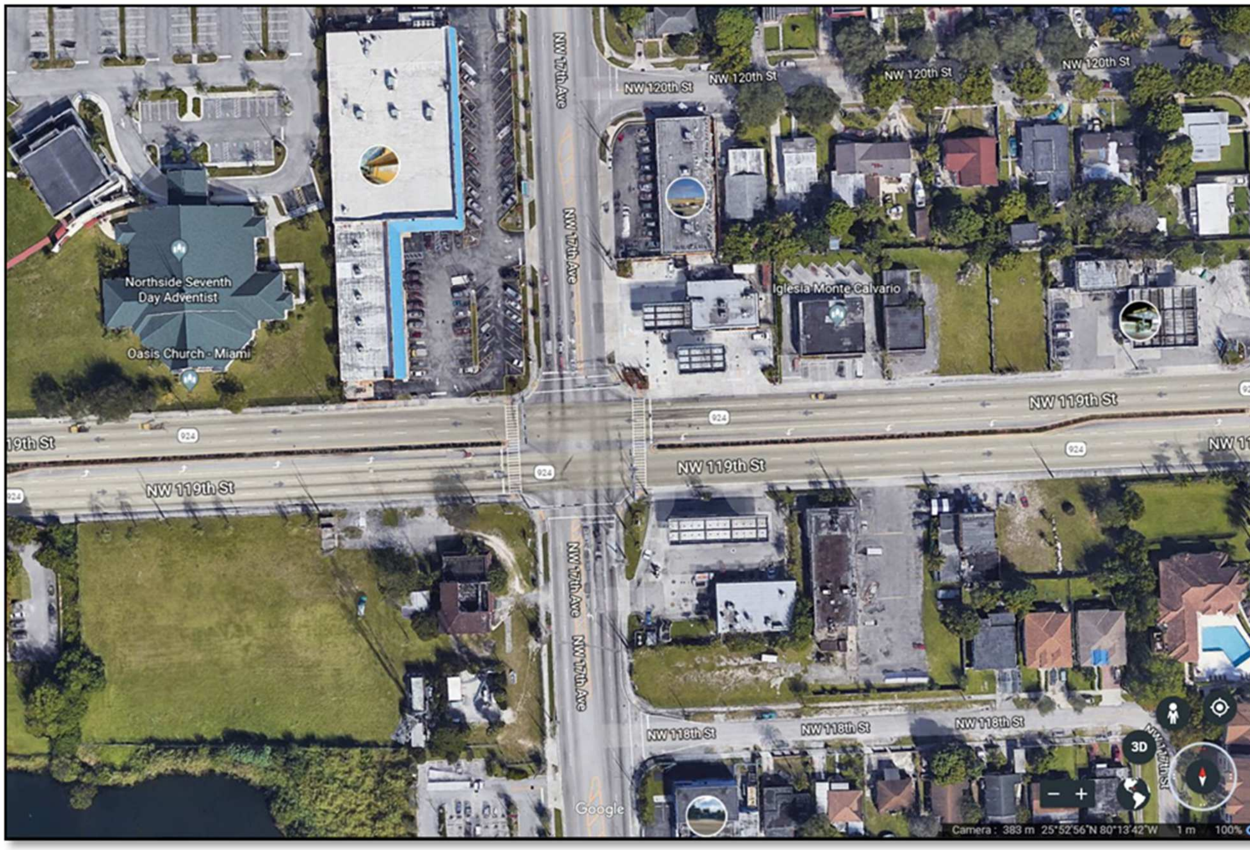

Figure 5-15 Study Location

Data required for the simulation were collected, including traffic volume, turning proportions, and signal timing plan. The morning peak hour (7:30 AM to 9:30 AM) was used in the calibration. The permissive left-turn was simulated in VISSIM using priority rules for the conflicting points between the left-turn traffic and the corresponding opposing through traffic. In VISSIM modeling, priority rules are used to simulate conflicting movements that cannot be controlled through signal controllers. Drivers' gap acceptance behavior can be adjusted in the priority rules using two parameters in VISSIM: minimum headway (feet) and minimum gap time (seconds) (PTV, 2018). These two parameters are illustrated in Figure 5-16. The minimum headway in VISSIM is defined as the distance from the start of the potential conflict area at the conflict marker (green bar in Figure 5-16) up to the first vehicle which is moving towards the conflict marker. If a vehicle reaches the conflict marker, then the headway is zero. The gap time is the time difference in seconds between the first opposing vehicle (OV) and the conflict marker. VISSIM provides the flexibility to use the headway and gap times in ways to simulate various gap acceptance perspectives. For example, gap time is usually used to set up the left-turn gap acceptance behavior for normal traffic flow conditions where left turning vehicles would yield for the opposing through traffic. However, during congestion, minimum headway in terms of distance is usually used to determine the gap (PTV, 2018). The data collection points for left turning vehicles in VISSIM are required to be placed in pairs. In this study, these points were placed towards the end of the left-turn bays, and at the beginning of the potential conflict area, i.e., on the links of the opposing through lanes. These points collect simulated vehicle information, such as the time when the vehicles pass the data collection points, and also provide simulated vehicle trajectories and traffic volumes.

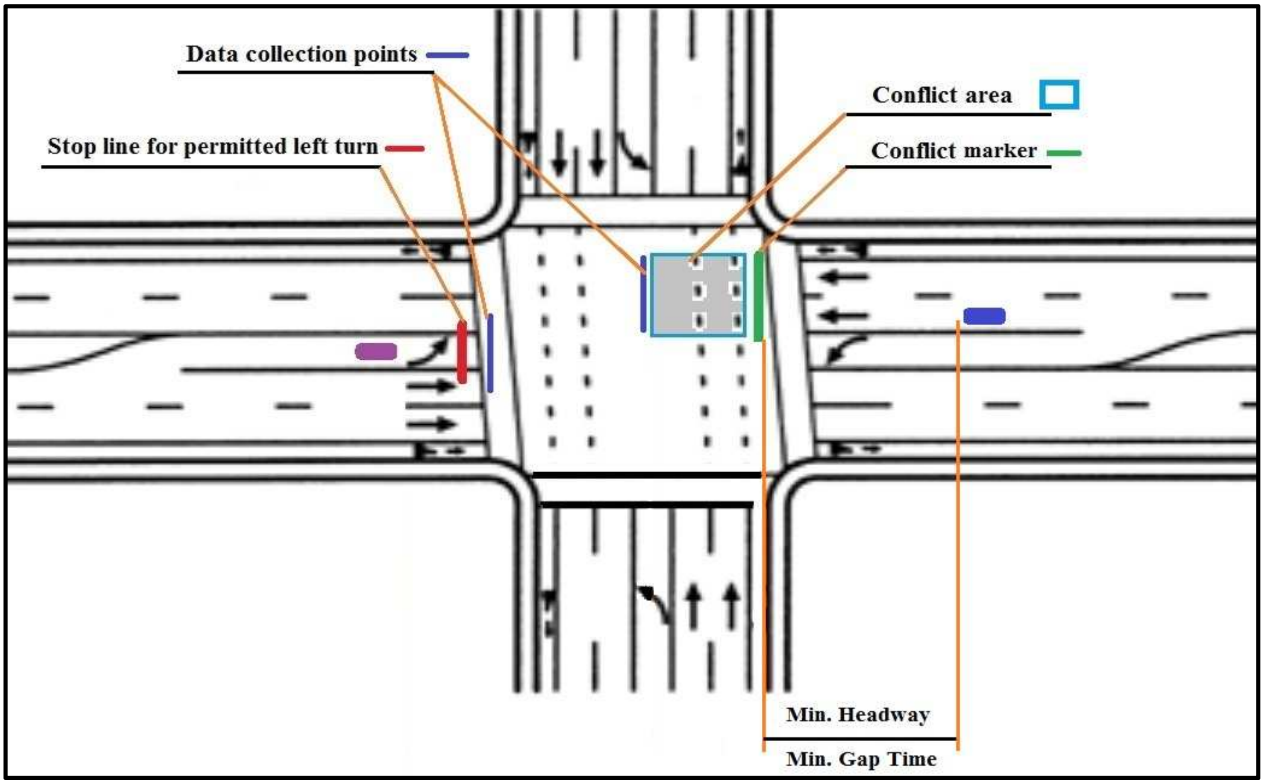

Figure 5-16 Priority Rule Application in VISSIM

The first objective of this part of the study was to calibrate VISSIM so that it can replicate real world left-turn gap acceptance scenario. The priority rules in VISSIM were used to simulate the real world gap acceptance. The objective was to replicate in the simulation the gap acceptance distribution obtained from the study conducted in Berkeley, California by Ragland et al. (2006) and reference earlier. Ragland et al. (2006) collected traffic data from five intersections using video surveillance and analyzed the available gap lengths and gap acceptance behaviors to develop a gap acceptance model. Figure 5-17 shows the gap acceptance distributions for each of the five intersections and for all intersections, referenced as the “Total” curve in the figure. The calibration procedure in the current study attempts to replicate the “Total” distribution in simulation to demonstrate how measured real-world gap acceptance distributions can be realized in simulation. As mentioned earlier, the gap acceptance calibration can also be done for the specific intersection under consideration. A logistic function was found appropriate to explain the real world gap acceptance distributions depicted in Figure 5-17.

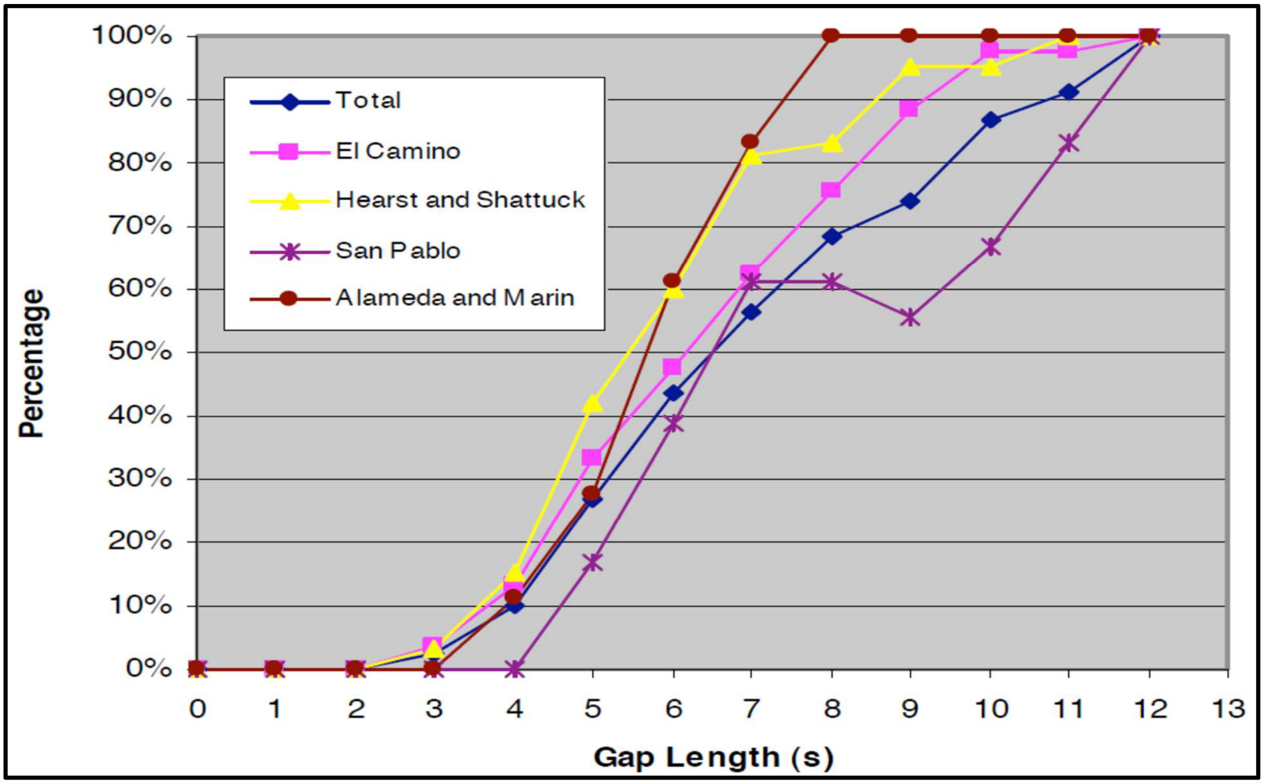

Figure 5-17 Gap Acceptance Behavior in the San Francisco Bay (Ragland et al., 2006).

There is no built-in distribution in VISSIM to simulate the real world gap acceptance behavior. If the minimum gap time and the minimum headway are both met for all conflict markers, the priority rule is satisfied and the subject vehicle is allowed to make the left-turn in the simulation without considering the variations in the gap acceptance behaviors of the drivers. Thus, another approach is needed to simulate the gap acceptance variations between vehicles according to a statistical distribution. It can be inferred from Figure 5-17 that the majority of the real world accepted gaps range from 3 seconds to 10 seconds. VISSIM by default assigns 3 seconds minimum gap time for all priority rules. To replicate the variations between drivers, it was necessary to create eight different priority rules with a minimum gap time ranging from 3 seconds to 10 seconds, at a 1 second interval. Eight vehicle classes were defined and each class is associated with one of the eight priority rules and thus has a unique minimum gap value. The percentage of the vehicles in each class was determined based on the distribution in Figure 5-17.

Once the model was calibrated, the next step was to analyze the influence of CV-based SLTA on the left-turn lane mobility and safety. The simulation of the CV SLTA application requires emulating CV messages advising the vehicles to accept gaps above a certain predefined safe gap. CV-equipped vehicles that receive these messages were coded as an additional class with a separate priority rule. Yan et al. (2008) reported that the critical gap accepted by left-turn drivers is 4.5 seconds, according to the HCM (TRB, 2010). Ogallo and Jha (2014) estimated that the critical gap for the left-turn movements at signalized intersections ranges from 5.4 seconds to 4.4

seconds with and without sight obstructions respectively. Richard et al. (2015a) reported that queue presence behind a left-turning vehicle can reduce the critical gap from 6.0 to 4.5 seconds, while rain intensity increased the gap acceptance from 6.5 to 13 seconds as the rain intensity increased from 0 to 0.39 inches/hr respectively. A gap length of 5 seconds was selected to be the pre-defined safe gap. The selection of the 5 seconds was based on the best estimated value from the literature. A varying SLTA utilization rate ranging from 10% to 100% were simulated and evaluated. The SLTA utilization rate is the multiplication of the CV market penetration and the associated compliance rate with the SLTA recommendations. If the messages are delivered using infrastructure displays, then the SLTA utilization rate reflects just the compliance rate. Please note that it is assumed that infrastructure-based sensors are available to measure the available gaps in the opposing traffic.

As previously mentioned from the literature review, the SLTA application has the potential benefit of increasing the left-turn lane capacity as well as reducing the delay. The impact on capacity was assessed using simulation results and the impact on safety was assessed using the SSAM tool based on the vehicle trajectories output files from VISSIM. The SSAM is a software package that estimates the safety of traffic facilities by analyzing the traffic conflicts in simulation models. The SSAM quantifies the number of conflict points, which is then converted to Surrogate Safety Measures (SSM).

5.6.3 Analysis And Results

This section discusses the results of the calibration of the simulation model using the real-world gap acceptance distribution compared to using the deterministic minimum gap (3 seconds) in VISSIM and the results from assessment of the impacts of SLTA using simulation. Different opposing traffic volumes were used in the assessment ranging from 1,000 vehicles per hour to 1,900 vehicles per hour and the resulting capacity values for the permissive left-turn was assessed based on simulation. As a further validation, the resulting capacity from simulation with the default minimum gap and the capacity from simulation with the coded stochastic distribution were compared with the capacity estimated using the Highway Capacity Manual (HCM) procedure (TRB, 2010). The Highway Capacity Software (HCS) was used to determine the capacity of the left-turn lane under different opposing demand flow rates. The intersection geometric characteristics, traffic volumes and signal data were used as inputs to the HCS software to estimate the left-turn capacity. Figure 5-18 shows the left-turn capacity resulting from the calibrated simulation model with the real-world gap acceptance distribution, simulation with the default minimum gap in VISSIM (without calibration), simulation with single minimum gap of 5seconds (assigned to all vehicles), and the HCM procedure using HCS with minimum gap of 3 and 5 seconds. Figure 5-18 shows that using the defaults 3 second as deterministic gap acceptance in VISSIM and the HCS produced significantly higher capacity compared to those using VISSIM with the simulated stochastic distributions. Using 5 seconds, as the critical deterministic value, produced much lower capacity, close to that obtained using VISSIM with the stochastic gap acceptance distribution. From a capacity point of view, there was no significant difference between using only one minimum gap time of 5 seconds for all vehicles in VISSIM and the calibrated simulation model with the real-world gap acceptance distribution, especially during high opposing traffic volume. However, in case of low opposing traffic volumes the improvement in capacity came to be approximately 13.8% by utilizing the 5 seconds gap parameter for all vehicles. This percentage decreases gradually as shown in Figure 5-18 with the increase in the opposing traffic. The capacity results from assigning 5 seconds gap parameter for all vehicles are similar to the capacity results from utilizing SLTA with timing algorithm of 5 seconds and 100% market penetration. Although the percentage improvement in capacity is low, the main purpose of this analysis is the macroscopic behavior of drivers that will be influenced by the SLTA technology and its implications on safety assessment.

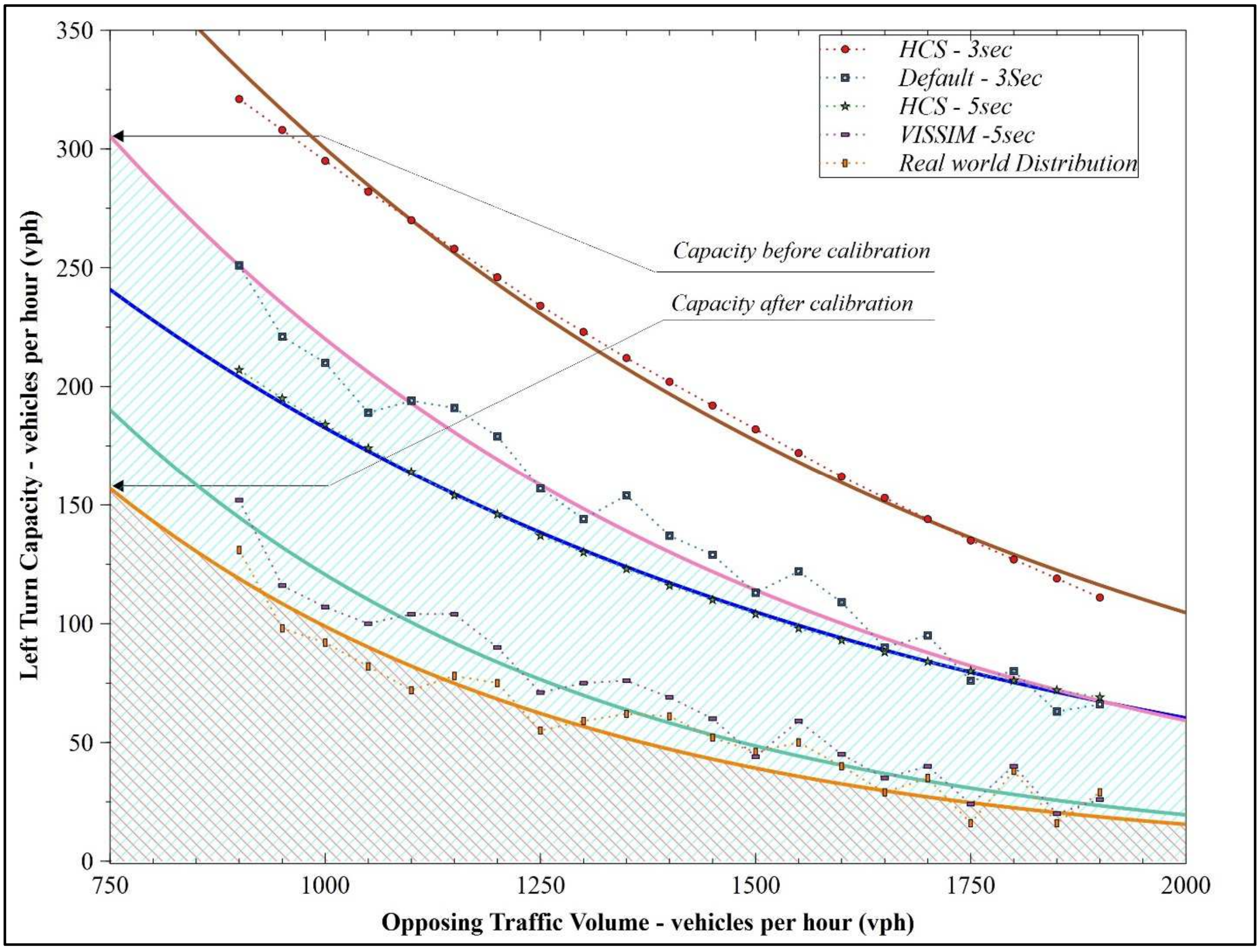

Figure 5-18 Relationship between Left-Turn Capacity and Opposing Traffic

For further validating the results, the capacity results from HCS were compared to the capacity output from VISSIM for the permitted left-turn using statistical Kolmogorov–Smirnov test (K-S test). The K-S test was specifically used to determine whether the estimated capacity using HCS and the simulated capacity using VISSIM resemble same distribution. The Kolmogorov–Smirnov is a nonparametric test which tests whether distributions from two samples are different. The two sample K-S test is considered very useful in comparing two distributions against each other, as it considers both the shape and the location of the cumulative distribution functions of the two data sets.

Based on K-S test tables and for the 95% confidence level, there was no sufficient evidence at 95% level of significance to conclude that VISSIM capacity results were different from HCS capacity distribution. The HCS is considered a deterministic approach in estimating the permitted left-turn capacity. However, by introducing the stochastic driver's gap acceptance behavior in VISSIM, the results showed that VISSIM default time gap parameter (3-seconds) and HCS (3-seconds) critical gap are under estimating the left-turn capacity by approximately 47.5%. In addition, the assigned time gap parameter (5-seconds) and HCS (5-seconds) are also under estimating the left-turn by approximately 13.8% and 30% respectively. The left-turn capacity is lower with the calibrated simulation model based on the real gap acceptance behavior by the left turners compared to the simulation with the default parameters. The resulting left-turn delay was then collected for the calibrated simulation model with the real-world gap acceptance distribution, simulation with the default minimum gap in VISSIM (without calibration), simulation with single minimum gap of 5 seconds, and the HCM procedure using HCS. Results showed that the delay with the calibrated model was higher among all due to the lower capacity.

The assessment of the impact of the SLTA with utilization rates of 10%, 20%, 50%, 80%, and 100% on capacity are plotted as shown in Figure 5-19. The results showed that SLTA could potentially improve the overall left-turn average capacity by approximately 42.6% with increasing the SLTA utilization from 10% to 100%. The impact of using the SLTA on left-turning vehicles delay is shown in Figure 5-20. It can be inferred that the SLTA reduced the average left-turn delay for all vehicles significantly as the utilization rate increases. In addition, by analyzing the left-turn delay with and without SLTA, the results show that with a 100% SLTA utilization (assuming 100% access to the information and 100% compliance rate), the average delay for all vehicles could be reduced by approximately 58%. These results indicate the potential operational benefits of SLTA in increasing the left-turn capacity and reducing the delays. In addition, results show the importance of calibrating VISSIM for driver's gap acceptance behavior. This critical time gap parameter could be tuned and also calibrated based on local driver's behaviors.

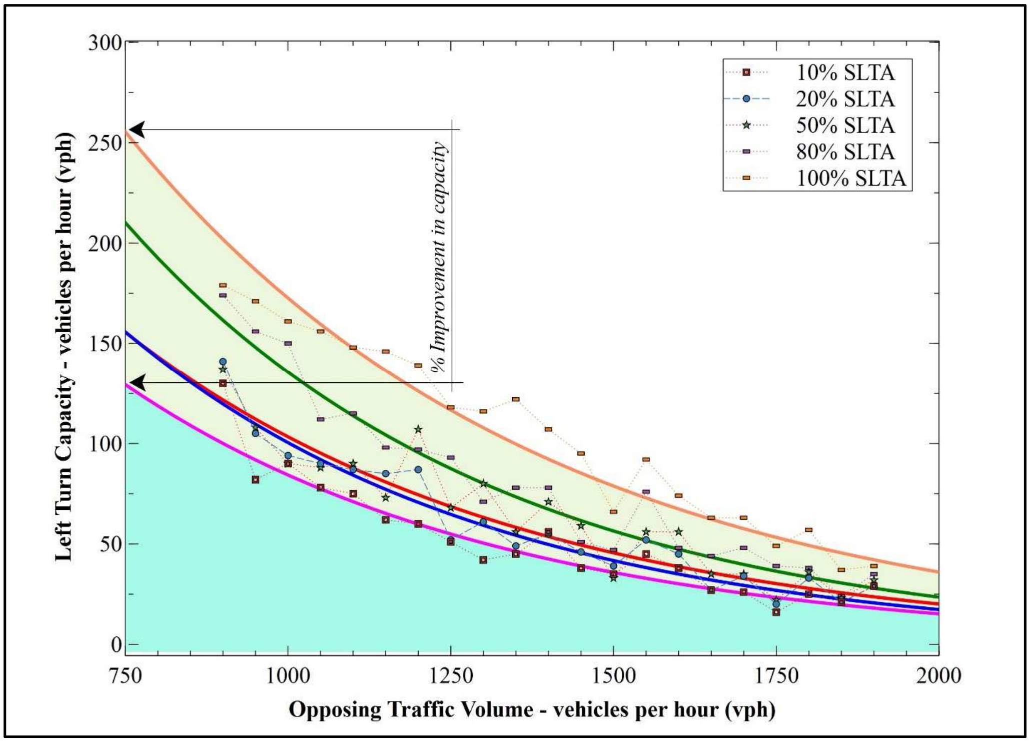

Figure 5-19 Impact of SLTA on Left-Turn Capacity

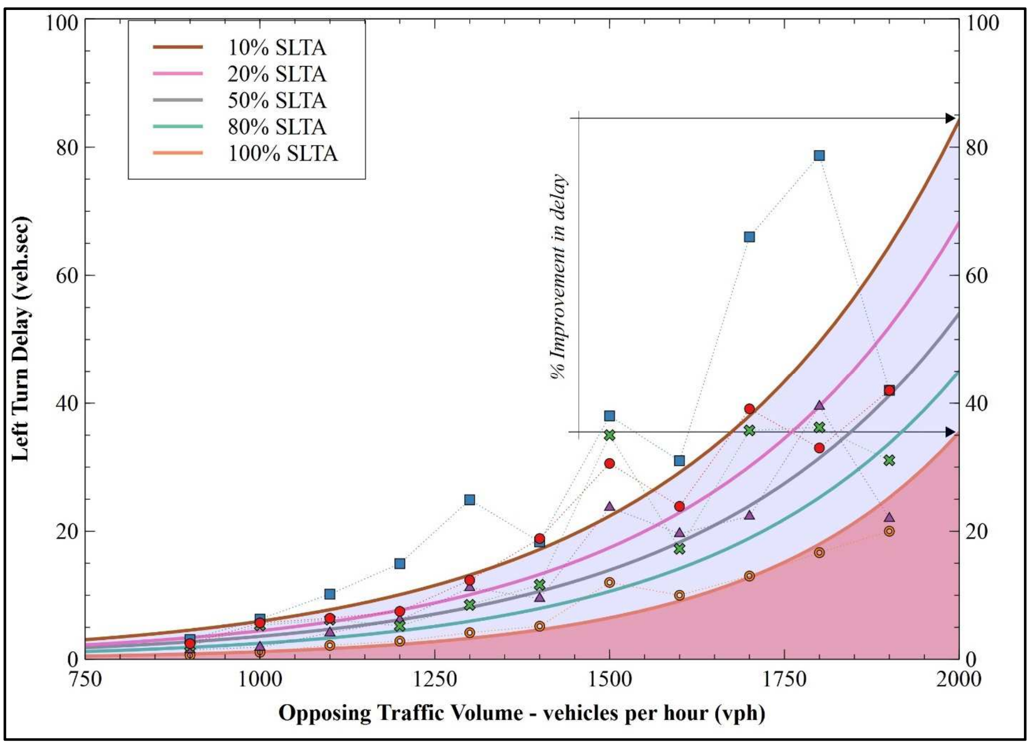

Figure 5-20 Relationship Between Left-Turn Delay and Opposing Traffic

5.6.4 Surrogate Safety Assessment

As stated earlier, the SSAM software package developed by the Federal Highway Administration Research and Technology of the United Stated Department of Transportation was used to provide safety assessment based on the simulation-based vehicle trajectories. Stamatiadis et al. (2016) developed a safety prediction tool that estimates the left-turn number of conflicts in signalized intersections. The researchers utilized VISSIM and SSAM to assess the impact of different variables, such as opposing traffic, green time, and intersection geometry on predicting the number of left-turn conflicts. The results showed that the number of conflicts is positive proportional with the opposing traffic. Accordingly, in the current study the impact of SLTA on improving the left-turn safety was assed under different opposing traffic volumes.

SSAM classifies a vehicle-to-vehicle interaction as a conflict by assigning threshold values to two surrogate measures of safety time-to-collision (TTC) and post-encroachment time (PET). When TTC = 0 and/or PET = 0, SSAM identifies these conditions as if a crash has occurred. By default, if $0 < TTC \leq 1.5$ s, and $PET \leq 5.0$ s, then SSAM marks the event as a conflict. In this Study, 1.5 seconds of TTC threshold and 5.0 sec of PET threshold were used in the SSAM software to investigate the number of conflicting points with and without CV conditions in the simulated network.

The purpose of this analysis was to examine the safety benefits with different SLTA utilization. VISSIM generates SSAM trajectories to file with extension (.trj). These files describe the course of all vehicle positions in the network. The SSAM trajectories were generated for different opposing traffic conditions ranging from 1000 to 1600 vehicles per hour. Figure 5-21 shows a reduction in the number of conflicts with increasing SLTA utilization. The statistical evaluation of the safety benefit of SLTA CV-based solution was further analyzed. The results showed that the intersection safety can be improved by approximately 33% with increasing the SLTA utilization from 10% to 100%.

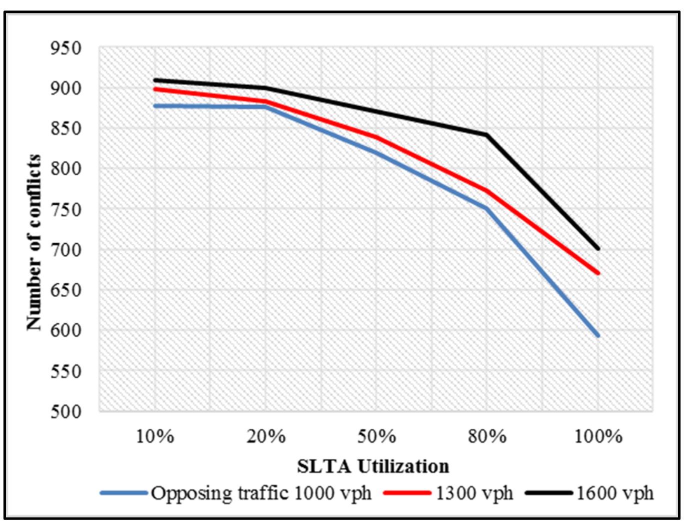

Figure 5-21 Surrogate Safety Analysis Results

5.7 POST-DEPLOYMENT EVALUATION

The previous sections of this document have addressed the pre-deployment assessment of CV-based applications based on return on investment and multi-criteria analysis. This section addresses post-deployment evaluation. The post-deployment evaluation is an important part of the systems engineering process used in intelligent transportation system (ITS) projects. The output from the evaluation can support the decisions made regarding changes and upgrades to the systems. In addition, post-deployment evaluation is important, because it helps decision makers understand the actual return on investment and whether the deployment objectives have been met. Results from the post-deployment evaluation of advanced strategies also provide critical inputs to the pre-deployment assessments of the types discussed earlier and the development and validation of sketch planning and modeling tools used to assess the advanced strategies.

The evaluation should be based on an evaluation plan that is developed with the project stakeholder involvement. The plan should include:

- Goal, Objectives, and Performance Metrics of the Evaluation
- Evaluation Targets and Hypothesis
- Threats and Challenges
- Evaluation Design
- Analysis Plan
- Data Plan and Data Collection
- Use of Modeling and Simulation in Post-Deployment Evaluation

5.7.1 Identification of Goal, Objectives, and Performance Metrics

The first step in the evaluation is to identify the evaluation goals and objectives and the associated performance metrics. This identification should be based on stakeholder inputs and related to the project objectives that in turn should be related to the strategic objectives and key performance indicators of the organization. The evaluation objectives should be such those presented in the following documents: the FDOT's 2017 Transportation System Management and Operations (TSM&O) Strategic Plan, 2019 Florida's Connected and Automated Vehicles (CAV) Business Plan, Statewide Arterial Management Program Action Plan (STAMP) (FDOT, 2018), individual districts' plans, and other relevant plans in the region. A stakeholder evaluation workshop should be conducted to ensure that the stakeholder's needs and interests are considered in the evaluation. The stakeholder engagement should continue throughout the evaluation process.

The defined performance metrics should follow the "SMART" criteria that require the objectives to be:

- **Specific:** Target a specific area for improvement.
- **Measurable:** Quantify or at least suggest an indicator of progress.
- **Assignable:** Specify who will do it.
- **Realistic:** State which results can realistically be achieved, given available resources.

- **Time Related:** Specify when the results can be achieved.

The metrics may be identified for each operational scenario or use case and can include output and outcome performance metrics. For example, the Tampa Hillsborough Expressway Authority (THEA) Connected Vehicle Pilot funded by the United States Department of Transportation (USDOT) developed performance metrics for the evaluation for each of the six Use Cases that describe the issues that the project will address.

The evaluation plan should also categorize the evaluation metrics and associated hypotheses into evaluation analysis areas that are related to the evaluation objectives. For example, the THEA evaluation metrics assess the effectiveness of the use cases in relation to four "pillars," which are: mobility, safety, environment, and agency efficiency. The identified performance indicators should be associated with geographic and temporal extents, resolution, and frequency of the updates.

5.7.2 Identification of Evaluation Targets and Hypothesis

Once the performance metrics are identified, then performance targets should be identified. The performance targets are sometimes referred to as impact hypotheses. The targets should be specific, time-bound, and can be quantified. The targets should be defined relative to internal benchmarks (e.g., exceeds the post-deployment performance) or external benchmarks that "perform better than national set values," or achieve global best practices (e.g., incident clearance time equal to or better than other districts in the state). The post-deployment assessment presented earlier in the report can also be used as the basis for setting the targets.

5.7.3 Identification of Threats and Challenges

The evaluation plan should identify challenges, constraints, and threats associated with the evaluation. Several factors or threats can affect the validity of evaluation. Thus, the evaluation plan should identify these factors, how they affect the evaluation, and how they are accounted for. For example, the findings and the results from post-deployment evaluations may be biased due to the influence of other causes (exogenous or confounding factors). The presence of these factors may result in changes in system performance that may not be due to the deployment, and if not accounted for, can bias the results. These exogenous factors may include, for example, seasonal variations, changes in the demands between years, more than usual adverse weather events, roadway construction, changes in vehicle mix, and so on. Another example of a threat to validity is what is referred to as "selection bias," in which there is a difference between the group receiving a treatment (e.g., CV technology) and the control or comparison group (e.g., not receiving the CV technology) that is not receiving the treatment. In this case, the selected group for the evaluation may have specific socioeconomic characteristics like age, income, education, gender, etc. that may not be representative of the whole population of drivers.

5.7.4 Evaluation Design

The evaluation plan should also include a description of the utilized experimental design. In general, the evaluation designs can be categorized as:

- ***Random Experimental Designs:*** In these design types, the test subjects are randomly assigned to a treatment (e.g., vehicles with onboard units) and control group (e.g., vehicles without onboard units).
- ***Quasi-Experimental Designs:*** These design types can be similar to the Random Design, depending on the specific selected design, in that they have a treatment group and a comparison group. However, they are different in that the assignment of treatment and control is not random. Typically, these designs attempt to control threats to validity via statistical analysis.
- ***Pre-Experiment Designs:*** These designs in general include simple comparisons. The most widely used type of these designs is the comparison between the before and after performance of the treatment group.

There are several design types within each of the three design categories listed above. The ability to address the threats to validity is the highest with the Random Experimental Designs and lowest with the Pre-Experimental Designs. When choosing the experimental design, several factors will need to be considered, including the ability to address potential threats to validity, data availability, budget, and time.

5.7.5 Analysis Plan

The analysis of the collected data should be based on an Analysis Plan that is included as part of the evaluation plan. The analysis plan will detail the methods and calculations used to assess the impacts of the deployment on system performance. The analysis plan will discuss the statistical methods used to describe, categorize, and cluster the data. In addition, the analysis plan will discuss the methods used to test the hypotheses of meeting the specified targets. Furthermore, the plan will specify statistical methods to address any identified threats or biases. Visualization techniques, such as graphs and dashboards, can be great tools to communicate the evaluation results.

More formal statistical hypothesis testing should be done in addition to the regularly used measures of deviation, such as mean percentage difference (MPD), mean percentage absolute difference (MPAD), and the standard deviation of percentage difference (SDPD). The type of statistical analysis will depend on the comparted parameters, the number of instances to compare, and the evaluation design. For example, for a before and after evaluation, a two sample or paired z-test or t-test is usually used for comparing the mean of pre- and post-deployment, depending on the collected data type. The F-test is used to compare variances, the z-test is used for the difference in proportions, and the Chi-Squared test is used to compare distributions. In some cases, ANOVA, multivariate ANOVA, regression, and/or non-parametric tests may be needed.

5.7.6 Data Plan and Collection

The evaluation will include data from multiple sources. The data for the evaluation needs to be collected and processed according to a Data Plan that ensures that the collected data are sufficient and do not add biases to the evaluation. The data requirement in the plan must be based on the evaluation performance metrics and evaluation design discussed in the previous sections. The Data Plan will include the data elements required to collect each performance metric; the data source(s) for each data element; nature and scale, and data resolution; spatial and temporal coverage; frequency; and data quality metrics, such as accuracy/validity, completeness, availability/accessibility, and timeliness.

Some of the data will come from existing sources, such as point sensor and probe vehicle archives in the Regional Integrated Transportation Information System (RITIS), national weather data bases, crash databases, and construction lane closure data. Other data will have to be collected using user surveys and/or newly installed technologies, such as connected vehicles, high resolution controller data, Bluetooth/Wi-Fi readers, and infrastructure sensors. Additional instrumentation may be needed for the purpose of the evaluation to collect all required data items at the required data quality.

The data collection will cover both pre-deployment (before) and post-deployment (after) conditions. Depending on the experimental design, the data may need to be collected for both the treatment and control or comparison groups.

The Data Plan should also include a Data Management Plan that describes how the data will be treated, archived, and preserved. The data management plan should identify data quality requirements to prevent biases. The plan should also describe how the data will be filtered and cleaned, aggregated, and archived for use in the analysis. An important aspect of the Data Management Plan is to ensure the protection of any collected Personally Identifiable Information (PII). In addition, if the field experiments use human participants, then the plan will need to specify the need to obtain Human Use Approval from an accredited Institutional Review Board (IRB). The management plan shall include the data format and metadata standards, in addition to policies for re-use, and redistribution of the data.

5.7.7 Use of Modeling and Simulation in Post-Deployment Evaluation

In some cases, it is difficult to estimate the impacts of real-world deployment. Particularly in the case of connected vehicles where the market penetration of these vehicles is small. In such cases, there is a potential for using analysis, modeling, and simulation (AMS) tools similar to those used in the pre-deployment evaluation to supplement the field evaluation. In these instances, the data collected during the evaluation is used to update the input parameters of the analysis, modeling, and simulation tools, and to produce better calibration and validation of the utilized tools and methods. This should result in a better post-deployment assessment using AMS post-deployment compared to pre-deployment.

5.8 CONCLUSIONS

CAV technologies will be a major consideration in the planning, design, and operations of ATM, as these technologies and applications that use technologies continue to advance and as the market penetrations and adoption of these technologies increase. With this recognition, transportation agencies will need methods to and information to support the required systems engineering process, including assessing the feasibility of these technologies to complement, supplement, or act as alternatives to existing solutions. To address this need, this project had identified applications, associated impacts, methods, and tools for use in support agency decisions to invest in CV-based solutions as part of the systems engineering process of ATM.

This project started with a review existing goals, objectives, and performance measures of TSM&O program and ATM program in Florida that can be used as a starting point to identify project specific criteria for the selection between development alternatives. In addition, the study review identifies CV-applications that can be used to support ATM. As part of this effort, this study reviewed the systems engineering process, national and state its architecture, planning for operations process, FDOT TSM&O Strategic Plan, STAMP Action Plan, Connected and Automated Vehicles Business Plan, FHWA ATDM applications, USDOT dynamic mobility applications, USDOT V2I safety applications, and Florida and USDOT pilot deployment applications. The study also reviewed previously developed methods and tools that can be used to support CV deployment decisions.

This study then Identified methods to support the decision to select between existing and CV-based applications to meet the goals and objectives of the TSM&O program. The method considers the needed functions, performance, risks and constraints, return-on-investment, and agency priority. The method consists of five steps: 1) identify performance metrics – selection criteria, 2) identify the needs, functions and alternative solutions, 3) identify the impacts of Existing and CV-based solutions utilizing simulation modeling or simple performance modification factors identified based on review of literature, 4) evaluate the return of investment of deployment alternatives considering uncertainty and stochastic distributions utilizing Monte Carlo simulation, and 5) conduct multi-criteria assessment of deployment alternatives, accounting for both qualitative and quantitative factors and for stakeholder priorities. Based on the results of applying the method to the project case study of this research (a segment of SR-924/NW 119th street in Miami, FL), CV-based applications can be more cost-effective than existing applications. However, they are associated with higher risks and constraints. It can be concluded that MCDA should be used in combination with stochastic return on investment in the decision to implement CV-based solutions to account for various factors, including uncertainty.

This study also provided agencies with a catalog of CV-based and alternative applications to meet needs, including impacts, risks, and uncertainties for use in identifying solutions to mobility and safety problems. In addition, the study provided information that can be used as part of ConOps development of CV-based application on urban arterials, information to support agency development of evaluation plans of post-deployment of CV-based projects in Florida, and information to support the simulation of CV-based applications utilizing existing microscopic simulation tools.

The developed method to assess deployment alternatives were implemented as part of the FITSEVAL tool developed by the research team as part of a separate FDOT research project. It is recommended that the developed method and associated tool is implemented by the FDOT as part of the considered CV-based projects.

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APPENDIX A

AHP CALCULATION PROCESS

Step 1: Develop the AHP Criteria and Assessment

The utilized objectives in the AHP analysis are selected based on the criteria presented in the Business Plan of the Florida Department of Transportation (FDOT) Connected and Automated Vehicle (CAV) program. The criteria for the AHP as shown in Figure A-1 were: accelerating the Connected Automated Vehicle program in Florida, improving performance, feasibility, funding, and benefit-cost ratios. Two transportation experts from the Florida Department of Transportation FDOT District 6 in Miami were asked to assign a score for each criterion relative to each other. The criteria were further decomposed into sub-criteria, and an assigned score was given for each sub-criteria.

	Score #		Score #		Score #
Extremely important	5	Very important	4	Not at all important	1
Moderately important	3	Slightly important	2		

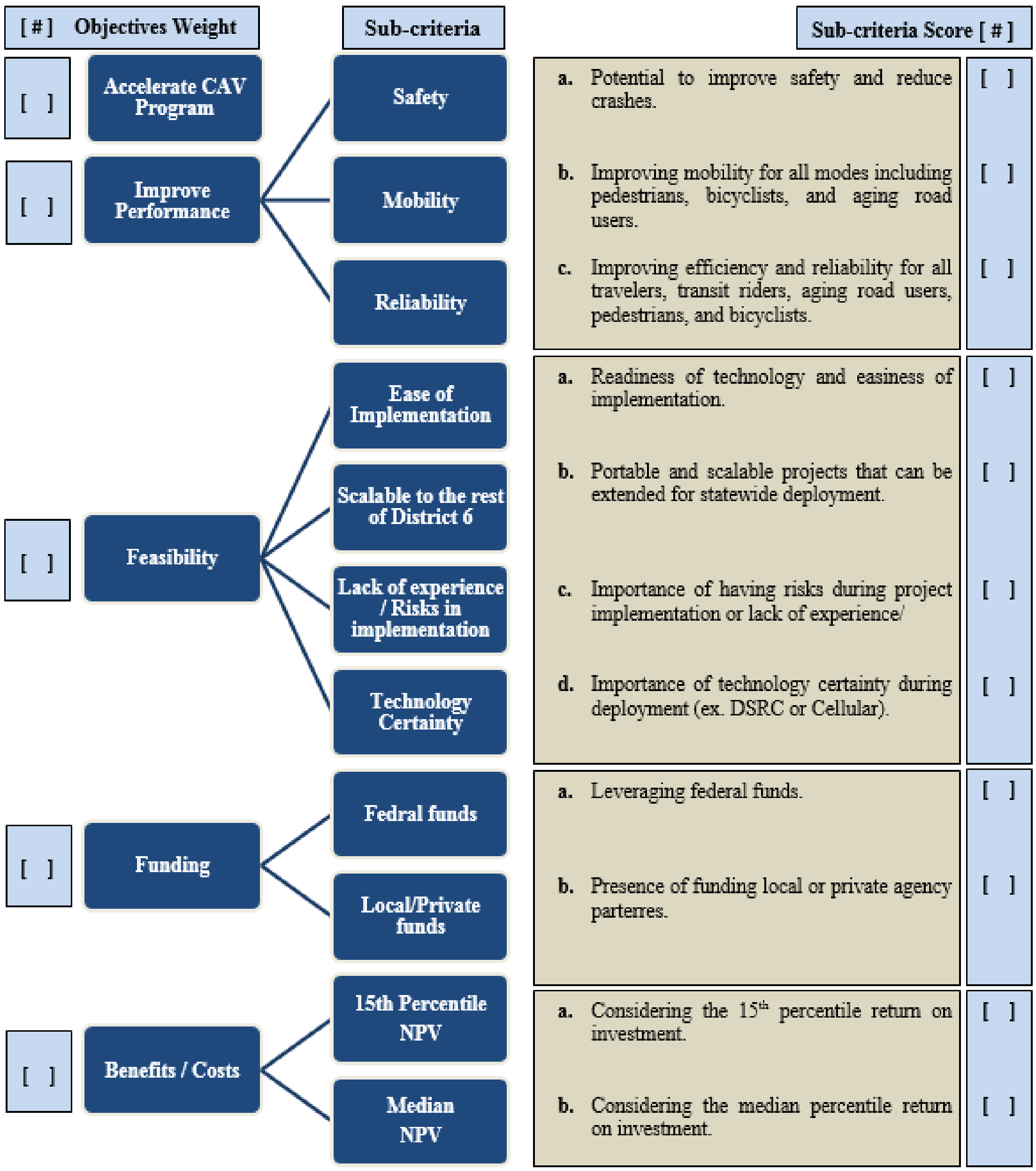

Figure A-1 AHP criteria and sub-criteria

Step 2: Develop the AHP Pairwise Matrices

In order to develop the weights for the hierarchy criteria, a pairwise comparison matrix was created. The first matrix is a n×n matrix, where n is the number criteria considered for evaluation as shown in Table A-1. Each entry a_{ij} (i is the row number and j is the column number) of the matrix represents the importance of the i^{th} criterion relative to the j^{th} criterion. If $a_{ij} < 1$, then the i^{th} criterion is less important than the j^{th} criterion. If a_{ij} is equal to 1, then the two criteria have the same importance or comparing the criteria to itself. For example, a_{11} entry is comparing Accelerate CAV program to itself so the value equal 1. While a_{12} entry is equal to 0.8, which means that Accelerate CAV program is 20% less important than Improve performance, and so on.

Step 3: Calculating the nth Root of Product

This step is used to normalize the entries in the matrix by multiplying the values in each row then getting the n^{th} root of this product. For example, the 5^{th} root of Accelerate CAV Program criterion is equal to 5^{th} root of $(1 \times 0.8 \times 0.8 \times 1 \times 1) = \sqrt[5]{0.64} = 0.9146$ as shown in Table A-1.

Step 4: Calculating the Priority Vector (PV)

The priority vector is calculated for each row by dividing the n^{th} root of each criterion by the summation of all the n^{th} root in the matrix. This mean that the summation of the priority vectors must be equal to 1. For example. Accelerate CAV Program has a value of 0.9146 for the 5^{th} root of product. The sum of all the 5^{th} root of the product is 5.0304. Therefore, the priority vector for Accelerate CAV Program is 0.9146/5.0304 = 0.182.

Table A-1. n×n Matrix Details

	Accelerate CAV Program	Improve Performance	Feasibility	Funding	Benefits / Costs	5^{th} root of product	Priority Vector (PV)
Accelerate CAV Program	1.00	0.80	0.80	1.00	1.00	0.9146	0.182
Improve Performance	1.25	1.00	1.00	1.25	1.25	1.1433	0.227
Feasibility	1.25	1.00	1.00	1.25	1.25	1.1433	0.227
Funding	1.00	0.80	0.80	1.00	1.00	0.9146	0.182
Benefits / Costs	1.00	0.80	0.80	1.00	1.00	0.9146	0.182
Sum	5.50	4.40	4.40	5.50	5.50	5.0304	1
Sum*PV	1.00	1.00	1.00	1.00	1.00		

Lambda max=	5.00
Consistency Index CI=	0.00
CR=	0.00

Step 5: Measuring the Degree of Consistency (CI)

As mentioned earlier in Chapter 5, Equation 5-3, a Consistency Index (CI) was calculated to measure the degree of AHP consistency. Lambda max was calculated as the summation of (Sum*PV) then the value was divided by the number of assessment criteria minus one. A Consistency Ratio (CR) was then applied to compare the CI relative to the RI. The consistency ratio is considered acceptable, if the value is less than or equal 10%. It can be inferred from the Table A-1 that the decision maker was very consistent in his/her inputs.

Step 6: Develop the Weights for the Sub-criteria

A second pairwise comparison matrix was created for each sub-criteria as shown in Table A-2 same as the matrix developed in step 1. Each entry in the matrix describes the importance of each sub-criterion relative to each other. Then step 2 and 3 are then repeated to get n^{th} root of product and the priority vector (PV).

Table A-2. Second Pairwise Comparison Matrix Details

Improve Performance		Safety	Mobility	Reliability	3rd root of product	Priority Vector (PV)
	Safety	1.00	1.25	1.25	1.16	0.38
	Mobility	0.80	1.00	1.00	0.93	0.31
	Reliability	0.80	1.00	1.00	0.93	0.31
	Sum	2.60	3.25	3.25	3.02	1.00
	Sum*PV	1.00	1.00	1.00		

Feasibility		Ease of Implementation	Scalable to the rest of District 6	Lack of experience / Risks	Technology Certainty	4th root of product	Priority Vector (PV)
	Ease of Implementation	1.00	1.25	1.25	2.50	1.41	0.33
	Scalable to the rest of District 6	0.80	1.00	1.00	2.00	1.12	0.27
	Lack of experience / Risks	0.80	1.00	1.00	2.00	1.12	0.27
	Technology Certainty	0.40	0.50	0.50	1.00	0.56	0.13
	Sum	3.00	3.75	3.75	7.50	4.22	1.00
	Sum*PV	1.00	1.00	1.00	1.00		

Funding		Fedral Funds	Local / Private Funds	2nd root of product	Priority Vector (PV)
	Fedral Funds	1.00	1.00	1.00	0.50
	Local / Private Funds	1.00	1.00	1.00	0.50
	Sum	2.00	2.00	2.00	1.00
	Sum*PV	1.00	1.00		

Benefits / Costs		15th Percentile NPV	Median NPV	2nd root of product	Priority Vector (PV)
	15th Percentile NPV	1.00	0.80	0.89	0.44
	Median NPV	1.25	1.00	1.12	0.56
	Sum	2.25	1.80	2.01	1.00

Sum*PV	1.00	1.00		

Step 7: Develop the Ratings for Each Decision Alternative

The third matrix is called the matrix of alternative scores. Each entry m_{ij} represents the score of the Z_{th} option with respect to each sub-criterion. In order to derive such scores, a pairwise comparison matrix is first built for each of the sub-criteria, against the alternatives (CV-based and non-CV based) as shown in Table A-3. Each entry of the matrix represents the evaluation of the first option compared and the second option with respect to each criterion.

Table A-3. Matrix of Alternative Scores

Safety			2nd root	Priority Vector (PV)
	CV-Based	Existing		
CV-Based	1	2.5	1.581	0.714
Existing	0.4	1	0.632	0.286
Mobility			2nd root	Priority Vector (PV)
	CV-Based	Existing		
CV-Based	1	1.67	1.292	0.625
Existing	0.6	1	0.774	0.375
Reliability			2nd root	Priority Vector (PV)
	CV-Based	Existing		
CV-Based	1	1.25	1.118	0.556
Existing	0.8	1	0.894	0.444
Ease of Implementation			2nd root	Priority Vector (PV)
	CV-Based	Existing		
CV-Based	1	1.25	1.118	0.555
Existing	0.8	1	0.894	0.444
Scalable to the rest of District 6			2nd root	Priority Vector (PV)
	CV-Based	Existing		
CV-Based	1	1	1	0.500
Existing	1	1	1	0.500
Lack of experience / Risks			2nd root	Priority Vector (PV)
	CV-Based	Existing		
CV-Based	1	0.4	0.632	0.286
Existing	2.5	1	1.581	0.714
Technology Certainty			2nd root	Priority Vector (PV)

	CV-Based	Existing		
CV-Based	1	0.4	0.632	0.286
Existing	2.5	1	1.581	0.714

Table A-3. Matrix of Alternative Scores (Continue)

Fedral Funds			2nd root	Priority Vector (PV)
	CV-Based	Existing		
CV-Based	1	1	1.000	0.500
Existing	1.00	1	1.000	0.500
Local / Private Funds			2nd root	Priority Vector (PV)
	CV-Based	Existing		
CV-Based	1	1	1.000	0.500
Existing	1	1	1.000	0.500
DOT Funds			2nd root	Priority Vector (PV)
	CV-Based	Existing		
CV-Based	1	1.25	1.118	0.556
Existing	0.80	1	0.894	0.444
15th Percentile NPV			2nd root	Priority Vector (PV)
	CV-Based	Existing		
CV-Based	1	1.24	1.114	0.554
Existing	0.806	1	0.898	0.446
Median NPV			2nd root	Priority Vector (PV)
	CV-Based	Existing		
CV-Based	1	1.21	1.100	0.548
Existing	0.826	1	0.909	0.452

Step 8: Calculating the Global Scores

Once the priority vector (PV) and the score matrix (S) have been computed, the AHP obtains global scores by multiplying S and PV as shown in Figure A-2. For example, the global score assigned for "Safety" sub-criterion is equal to the PV of "Improve Performance" in Table A-1 which is 0.227, multiplied by the PV of "Safety" in Table A-2 which is 0.38, and then multiplied by the PV of "CV-Based" in Table A-3 which is 0.714. Then the global score will be 0.06 as shown in Figure A-2, and so on.

Analytic Hierarchy Process													
Goal	Criteria for Selection Between Different ITS Alternatives												
Critera	Accelerate CAV Program	Improve Performance			Feasibility				Funding			Benefits / Costs	
Priority	0.182	0.227			0.227				0.182			0.182	
Sub-Criteria	-	Safety	Mobility	Reliability	Ease of Implementation	Scalable to the rest of District 6	Lack of experience / Risks in implementation	Technology Certainty	Fedral Funds	DOT Funds	Local / Private Funds	15th Percentile NPV	Median NPV
Priority	0.182	0.38	0.31	0.31	0.33	0.27	0.27	0.13	0.33	0.33	0.34	0.44	0.56
Final Score		CV- BASED SOLUTIONS					EXISTING SOLUTIONS						
CV- BASED SOLUTIONS	0.182	0.71	0.78	0.53	0.56	0.50	0.29	0.29	0.50	0.56	0.50	0.554	0.548
EXISTING SOLUTIONS		0.29	0.22	0.47	0.44	0.50	0.71	0.71	0.50	0.44	0.50	0.446	0.452
CV- BASED SOLUTIONS	0.18	0.06	0.05	0.04	0.04	0.03	0.02	0.01	0.03	0.03	0.03	0.04	0.06
EXISTING SOLUTIONS		0.02	0.02	0.03	0.03	0.03	0.04	0.02	0.03	0.03	0.03	0.04	0.05

Figure A-2: Global Scores

Step 9: Final Scores and Alternatives Ranking

The final score is calculated as the summation of all values in both alternatives (CV-Based and Existing Solutions) in Figure A-2. For example, the CV-Based alternative score = (0.18+0.06+0.05+0.04+0.04+0.03+0.02+0.01+0.03+0.03+0.03+0.02+0.06) = 0.63

As the final step, the option ranking is accomplished by ordering the global scores in decreasing order as shown in Figure A-3.

Analytic Hierarchy Process													
Goal	**Criteria for Selection Between Different ITS Alternatives**												
Critera	**Accelerate CAV Program**	**Improve Performance**			**Feasibility**				**Funding**			**Benefits / Costs**	
Priority	0.182	0.227			0.227				0.182			0.182	
Sub-Criteria	-	Safety	Mobility	Reliability	Ease of Implementation	Scalable to the rest of District 6	Lack of experience / Risks in implementation	Technology Certainty	Fedral Funds	DOT Funds	Local / Private Funds	15th Percentile NPV	Median NPV
Priority	0.182	0.38	0.31	0.31	0.33	0.27	0.27	0.13	0.33	0.33	0.34	0.44	0.56
Final Score		**CV- BASED SOLUTIONS**				**0.63**	**EXISTING SOLUTIONS**					**0.37**	
CV- BASED SOLUTIONS	0.182	0.71	0.78	0.53	0.56	0.50	0.29	0.29	0.50	0.56	0.50	0.554	0.548
EXISTING SOLUTIONS		0.29	0.22	0.47	0.44	0.50	0.71	0.71	0.50	0.44	0.50	0.446	0.452
CV- BASED SOLUTIONS	0.18	0.06	0.05	0.04	0.04	0.03	0.02	0.01	0.03	0.03	0.03	0.04	0.06
EXISTING SOLUTIONS		0.02	0.02	0.03	0.03	0.03	0.04	0.02	0.03	0.03	0.03	0.04	0.05

Figure A-3: AHP Results and Final Score