Performance Evaluation of Connected Vehicle (CV) and Transportation Systems Management and Operations (TSM&O) Projects in Florida

Final Report

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DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

METRIC CONVERSION TABLE

U.S. UNITS TO SI* (MODERN METRIC) UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	25.400	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.610	kilometers	km
mm	millimeters	0.039	inches	in
m	meters	3.280	feet	ft
m	meters	1.090	yards	yd
km	kilometers	0.621	miles	mi

AREA

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in^2	square inches	645.200	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	2.590	square kilometers	km^2
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.470	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

VOLUME

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
fl oz	fluid ounces	29.570	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
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

NOTE: volumes greater than 1,000 L shall be shown in m^3.

*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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16. Abstract

Connected vehicle (CV) technologies and Transportation Systems Management and Operations (TSM&O) strategies are increasingly being considered by transportation agencies to improve the safety and mobility of the transportation network. To fully understand the potential benefits of CV and TSM&O initiatives, it is crucial to not only identify the performance measures used to evaluate the progress of each initiative, but also to estimate the benefit-to-cost (B/C) ratios to justify the funding requests associated with implementing these technologies and strategies.

The primary goal of this research was to assist the Florida Department of Transportation (FDOT) in developing approaches to evaluate the performance of CV projects and current TSM&O strategies being deployed, including the Rapid Incident Scene Clearance (RISC) program, the Road Ranger Service Patrol (RRSP) program, and the Smart Work Zone (SWZ) TSM&O strategies.

A comprehensive review of the existing body of literature was conducted to identify the quantitative and qualitative performance measures and metrics that are being considered in evaluating the performance of CV deployments and TSM&O strategies. B/C analyses were conducted to quantify the mobility and safety benefits associated with implementing the RISC and RRSP programs. Results indicate that for every dollar spent on the RISC program, $5.78 is returned in secondary crash savings, and $1.20 is returned in incident-related traffic delay savings. For every dollar spent on the RRSP program, $5.15 is returned in secondary crash savings, and $7.44 is returned in incident-related traffic delay savings. The study also discussed the potential safety and mobility benefits of Smart Work Zone (SWZ) technologies.

Performance criteria and evaluation metrics were also developed for the different stages of the CV project development process (i.e., pre-project phase, planning phase, design-deploy-test phase, and the operations & maintenance phase). The performance criteria of two CV deployments in Florida (Gainesville Signal Phase and Timing (SPaT) Project and I-4 Florida's Regional Advanced Mobility Elements (I-4 FRAME) Project) were also reviewed. Findings from this research offer guidance in evaluating the effectiveness of CV and TSM&O initiatives. Evaluation criteria and approaches presented in this report can better prepare FDOT for deployments.

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- Shawn Kinney, FDOT – TIM Road Ranger Program Manager
- Md Omar Faruk, FDOT GEC – CAV and TSM&O Engineer

EXECUTIVE SUMMARY

Connected vehicle (CV) technologies and Transportation Systems Management and Operations (TSM&O) strategies are increasingly being considered by transportation agencies to improve the safety and mobility of the transportation network. CV technologies focus on high-level technological advances to improve safety, mobility, and the environment. TSM&O, on the other hand, is a program based on actively managing the multimodal transportation network, measuring performance, and streamlining and improving the existing system to deliver favorable safety and mobility outcomes to the traveling public.

The goal of any CV or TSM&O deployment is to improve the transportation system by:

- improving safety,
- improving mobility,
- improving public agency efficiency, and/or
- reducing negative environmental impact.

The objective of this research was to assist the Florida Department of Transportation (FDOT) in developing approaches to evaluate the performance of CV projects and the Rapid Incident Scene Clearance (RISC), Road Ranger Service Patrol (RRSP), and Smart Work Zone (SWZ) TSM&O strategies. The tasks involved in the research effort included:

- identify both qualitative and quantitative performance measures that can be used to evaluate CV and TSM&O initiatives,
- identify and recommend performance metrics that could be used to estimate the benefit-to-cost (B/C) ratios in deploying CV initiatives,
- conduct benefit-cost analysis of RISC and RRSP programs,
- document the potential safety and mobility benefits of SWZ technologies, and
- develop criteria for evaluating the performance of CV deployments.

Findings from this research offer guidance in evaluating the effectiveness of CV and TSM&O initiatives. Evaluation criteria and approaches presented in this report can better prepare FDOT for deployments.

Safety and Mobility Benefits of CV and TSM&O Strategies

B/C analyses were conducted to quantify the safety and mobility benefits associated with implementing the RISC and RRSP programs. Results indicate that for every dollar spent on the RISC program, $5.78 is returned in secondary crash savings, and $1.20 is returned in incident-related delay savings. For every dollar spent on the RRSP program, $5.15 is returned in secondary crash savings, and $7.44 is returned in incident-related delay savings.

Most previous studies indicated that SWZ technologies improved safety and mobility in work zones. Performance evaluation in the CV project development process was also discussed. Although at different levels of evaluation, quantitative performance measures should be evaluated during the pre-project, planning, and operations & maintenance phases, while qualitative performance measures should be evaluated throughout the CV project development process.

Performance Measures for CV and TSM&O Strategies

Targeted improvement areas are project-specific. Therefore, it is essential to identify performance measures used to evaluate the progress of each CV and TSM&O initiative and estimate the B/C ratios not only to fully understand the potential benefits of these initiatives, but also to justify the funding requests associated with implementing these strategies.

To identify the quantitative and qualitative performance measures and metrics that are being considered in evaluating the performance of CV deployments and TSM&O strategies, a comprehensive review of the existing body of literature was conducted, including government reports, white papers, opinion pieces, presentations, etc. Table E.1 offers several examples of potential qualitative evaluation questions, as they relate to the CV project development process. Table E.2 provides a summary of the identified quantitative performance measures for CV and TSM&O strategies.

Table E.1: Qualitative Evaluation in the CV Project Development Process

CV Project Development Phase	Examples of Potential Evaluation Questions
Pre-Project**	What are the performance target areas?
	Does existing literature provide adequate expected performance information?
	Are there previous CV deployments with similar target criteria?
Planning	Will the proposed system technologies have future application capabilities?
	What are the anticipated challenges?
	Will stakeholders need additional support to achieve project roles and responsibilities?
Design-Deploy-Test	Were there challenges in addressing system requirements provided by the stakeholders?
	What challenges did the systems manager experience during the deployment?
	Were potential challenges identified during the planning phase effectively addressed?
	Any challenges in the collaboration process with local agencies?
	What were the lessons learned regarding policies, procedures, processes, etc., and are they documented for future deployments?
Operations & Maintenance	What were the lessons learned from training and testing the system, and are they documented for future deployments?
	Were the CAV Program's safety, mobility, and economic development (SME) goals realized?
	Are there challenges with maintaining the system?
	Are there recommendations for future deployments?

** Refer to the FDOT 2019 CAV Business Plan for complete project selection criteria.

Table E.2: Summary of Quantitative Performance Measures for CV and TSM&O Strategies

<table>
<tr><th rowspan="2">Application</th><th colspan="2">Identified Potential Performance Measures</th></tr>
<tr><th>CV Deployments</th><th>TSM&O Strategies</th></tr>
<tr><td>Transit-related</td><td>• Travel speed
• Delay
• Average wait time at stops
• Average travel time
• Average throughput at intersections
• Transit, auto, pedestrian conflicts
• Transit ridership
• Bus headway
• Bus tailpipe
• Surrogate safety measures
• On-time arrivals and departures</td><td>• Travel time
• Travel time reliability
• Delay
• Crash frequency
• Crash severity
• Surrogate safety measures
• On-time arrivals and departures</td></tr>
<tr><td>Ped/bike-related</td><td>• Transit, auto, pedestrian conflicts
• Number of pedestrian crossing violation reductions
• Pedestrian collision with transit buses
• Pedestrian behavior
• Surrogate safety measures</td><td>• Delay
• Crash frequency
• Crash severity
• Surrogate safety measures</td></tr>
<tr><td>Vehicle-related</td><td>• Travel speed
• Delay
• Average wait time at stops
• Average travel time
• Travel time reliability
• Average throughput at intersections
• Number of hard acceleration and decelerations
• Congestion impact
• Incident rates
• Waiting time at intersections for crossing
• Crashes at ramps
• Average speed at work zone and other zones compared to posted speeds
• Acceptance and driver interviews
• Surrogate safety measures
• Secondary crashes</td><td>• Incident response time
• Travel speed
• Travel time
• Travel time reliability
• Delay
• Buffer index
• Average clearance time
• Throughput
• Crash frequency
• Crash severity
• Surrogate safety measures
• Secondary crashes</td></tr>
<tr><td>Environment-related</td><td>• Emission
• Fuel consumption</td><td>• Emission
• Fuel consumption</td></tr>
</table>

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LIST OF ACRONYMS AND ABBREVIATIONS

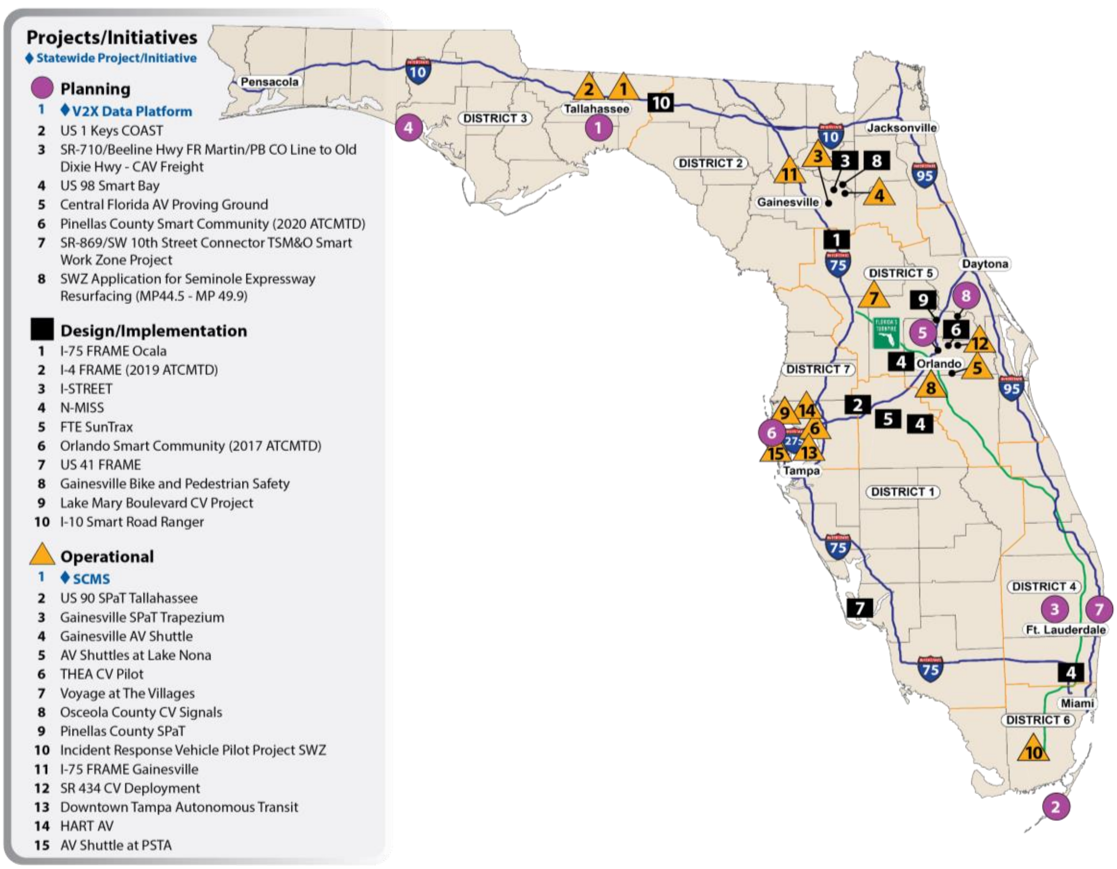
AADT	Annual Average Daily Traffic
ASCT	Adaptive Signal Control Technology
ATIS	Advanced Traveler Information System
ATM	Active Traffic Management
ATMS	Advanced Traffic Management System
ATSPM	Automated Traffic Signal Performance Measures
B/C	Benefit-cost
BI	Buffer Index
BSM	Basic Safety Message
BSW	Blind Spot Warning
CACC	Cooperative Adaptive Cruise Control
CARS	Crash Analysis Reporting System
CATT	Center for Advanced Transportation Technology
CAV	Connected and Automated Vehicle
CCTV	Closed-circuit Television
CEI	Construction Engineering & Inspection
CMF	Crash Modification Factor
CMM	Capability Maturity Model
ConOps	Concept of Operations
CSW	Curve Speed Warning
CTR	Cumulative Travel Time Responsive
CV	Connected Vehicle
CV2X	Connected Vehicle-to-Everything
CVO	Commercial Vehicle Operations
DMS	Dynamic Message Sign
DNPW	Do Not Pass Warning
DR	Deceleration Rate
DSFS	Dynamic Speed Feedback Sign
DSRC	Dedicated Short-Range Communications
EEBL	Emergency Electronic Brake Light
EL	Express Lane
EMS	Emergency Medical Service
EOQ	End-of-Queue
EPA	Environmental Protection Agency
ET	Encroachment Time
EVP	Emergency Vehicle Preemption
FCW	Forward Collision Warning
FDOT	Florida Department of Transportation
FFS	Free Flow Speed
FHP	Florida Highway Patrol
FHWA	Federal Highway Administration
FRAME	Florida's Regional Advanced Mobility Elements
FSP	Freeway Service Patrol
FTE	Florida's Turnpike Enterprise

GT	Gap Time
I2P	Infrastructure-to-Pedestrian
I2V	Infrastructure-to-Vehicle
IAPT	Initially Attempted Post-Encroachment Time
ICM	Integrated Corridor Management
IMA	Intersection Movement Assist
I-SIG	Intelligent Traffic Signal
IT	Information Technology
ITS	Intelligent Transportation Systems
KDOT	Kansas Department of Transportation
LCIS	Lane Closure Information System
LCW	Lane Change Warning
LED	Light-emitting Diode
LOS	Level of Service
LTA	Left Turn Assist
MoDOT	Missouri Department of Transportation
MM	Mile Marker
MMICM	Multimodal Integrated Corridor Management
MOE	Measure of Effectiveness
MOU	Memorandum of Understanding
NI	Normal Incident
NO	Number of Oscillations
NTP	Notice to Proceed
OBU	On-board Unit
PD&E	Project Development and Environment
PDMS	Portable Dynamic Message Sign
PET	Post-Encroachment Time
PI	Primary Incident
PSD	Proportion of Stopping Distance
PSL	Posted Speed Limit
PTI	Planning Time Index
R.E.S.C.U.M.E.	Response, Emergency Staging and Communications, Uniform Management and Evacuation
RCI	Roadway Characteristics Inventory
RISC	Rapid Incident Scene Clearance
RITIS	Regional Integrated Transportation Information System
RLVW	Red Light Violation Warning
RRSP	Road Ranger Service Patrol
RSE	Roadside Equipment
RSU	Roadside Units
RSWZ	Reduced Speed/Work Zone Warning
RTMC	Regional Transportation Management Center
RTMS	Remote Traffic Microwave Sensors
RWIS	Road Weather Information Systems
SC	Secondary Crash
SCATS	Sydney Coordinated Adaptive Traffic System

SDLMS	Simplified Dynamic Lane Merging Systems
SME	Safety, Mobility, and Economic Development
SPaT	Signal Phase and Timing
SPE	Speed Photo Enforcement
SR	State Road
SSGA	Stop Sign Gap Assist
SWIW	Spot Weather Impact Warning
SWZ	Smart Work Zone
TDM	Travel Demand Management
TERL	Traffic Engineering Research Laboratory
TET	Time Exposed Time-to-Collision
THEA	Tampa-Hillsborough Expressway Authority
TIM	Traffic Incident Management
TMC	Transportation Management Center
TOD	Time of Day
TSM&O	Transportation Systems Management and Operations
TSP	Transit Signal Priority
TTC	Time-to-Collision
UBR	Unified Basemap Repository
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VHT	Vehicle-Hours-Traveled
VISSIM	*Verkehr In Städten – Simulationsmodell*
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled

CHAPTER 1
INTRODUCTION

Transportation agencies have been increasingly considering connected vehicle (CV) technologies and Transportation Systems Management and Operations (TSM&O) strategies to improve the safety and mobility of the transportation network. Florida Department of Transportation (FDOT) has been at the forefront in deploying CV applications and TSM&O technologies across the state. As of November 2021, Florida's Connected and Automated Vehicle (CAV) Initiative currently has 33 projects, of which, 15 are operational, 12 are in the design and implementation phase, and six are in the planning phase. Figure 1.1 shows a map of the CV projects in Florida and the deployment phase of each project.



Note: Map as of November 2021.

Figure 1.1: Florida CV Project Map (FDOT, 2021a)

In 2019, FDOT developed a CAV Business Plan outlining the project selection criteria for future CAV deployments (FDOT, 2019). Ten categories were established to be self-scored on a scale of 1-10, as a pre-project evaluation process to meet the statewide CAV program's safety, mobility, and economic development (SME) goals. Of the ten categories, four categories (Safety, Mobility, Efficiency and Reliability, and Project Evaluation) directly relate to quantitative and qualitative performance measures, as shown in Table 1.1. Post-project evaluation is also required to assess the overall impact of the project (FDOT, 2019).

Table 1.1: Project Selection Criteria Presented in the 2019 FDOT CAV Business Plan (FDOT, 2019)

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) efficiencyand/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 (B/C)	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		

On a broader level, CV technologies focus on high-level technological advances to improve safety, mobility, and the environment. However, at the implementation stage, CV deployments constitute a wide array of new and emerging applications, including Pedestrian Collision Warning, Emergency Vehicle Preemption (EVP), CV Traffic Signal Systems, and vehicle-to-vehicle (V2V) Basic Safety Messages (BSMs). The CV Initiative in Florida includes several independent projects, such as the Gainesville Signal Phase and Timing (SPaT) Trapezium, and programs, such as the I-4 Florida’s Regional Advanced Mobility Elements (I-4 FRAME), as well as partnerships with several agencies and consortia, such as the Tampa Hillsborough Expressway Authority

(THEA). Accordingly, each CV deployment initiative is unique in its own right and has to be evaluated independently to document both the quantitative and qualitative impacts. Evaluating current CV deployment projects, programs, and partnerships in Florida would better prepare FDOT for future CV deployments.

In line with FDOT's CAV Business Plan and statewide TSM&O objectives, the United States Department of Transportation (USDOT) describes that the goal of any CV deployment is to improve the transportation system by (USDOT, 2016a):

- improving safety,
- improving mobility,
- improving public agency efficiency, and/or
- reducing negative environmental impact.

Targeted improvement areas are project-specific. Therefore, it is essential to identify performance measures that could be used to evaluate the progress of each CV deployment.

FDOT has also been a pioneer in adopting TSM&O strategies to improve the safety and operational performance of the roadway network. Several TSM&O strategies are currently being deployed in Florida, including the Rapid Incident Scene Clearance (RISC) program, the Road Ranger Service Patrol (RRSP) program, and Smart Work Zone (SWZ) strategies.

To fully understand the potential benefits of CV and TSM&O initiatives, it is crucial to estimate the benefit-to-cost (B/C) ratios to justify the funding requests associated with implementing these technologies and strategies. The validity of these estimations is dependent on the ability to accurately measure the quantitative and qualitative benefits of these deployments.

The goal of this research effort was to assist FDOT in developing approaches to evaluate the performance of CV and TSM&O projects. The efforts included identifying the quantitative and qualitative performance measures and metrics that are being considered in evaluating the performance of CV deployments and TSM&O strategies. In addition, the study estimated the safety and mobility B/C ratios of a few selected programs. A discussion on the performance evaluation process for CV deployments is also presented.

The report is organized as follows:

- Chapter 1: an introduction of the research topic.
- Chapter 2: a literature review of performance measures used in CV deployments and TSM&O strategies.
- Chapter 3: a benefit-cost analysis of the RISC program.
- Chapter 4: a benefit-cost analysis of the RRSP program.
- Chapter 5: a documentation of potential safety and mobility benefits of SWZ technologies.
- Chapter 6: a discussion of the performance evaluation criteria for CV projects.
- Chapter 7: summary and conclusions of this research effort.
- Appendix A: one-page summaries of RISC, RRSP, and SWZ technologies.

CHAPTER 2
LITERATURE REVIEW

This chapter discusses the review of existing literature to identify the quantitative and qualitative performance measures and metrics that are being considered in evaluating the performance of CV deployments and TSM&O strategies. The review encompasses information from different documents, including government reports, technical articles, white papers, opinion pieces, presentations, and books.

Performance measures provide a means to quantify the performance of a transportation system and/or to assess the impact of a specific transportation strategy. They can be classified as quantitative, such as volume, density, travel time, emissions, etc., or qualitative, such as user satisfaction, driver compliance, driver frustration, perception of agency operations, etc. (USDOT, 2016a). Based on target improvement goals, potential performance measures used for CV deployments and TSM&O strategies will vary.

Quantitative performance measures provide numerical estimates of the progress or regress in achieving performance targets (USDOT, 2016a). These measurements can be continuous (e.g., average travel time, average speeds, etc.) or discrete (e.g., average vehicle throughput, average person throughput, etc.) (USDOT, 2016a). A number of quantitative performance measures can be estimated using data obtained through existing technologies, such as closed-circuit television (CCTV), machine vision equipment, and sensors, including subsurface induction loop, acoustic, and radiofrequency sensors (Hadi et al., 2021).

In addition, quantitative performance measures can be classified as either macroscopic measures or microscopic measures. Macroscopic measures include, but are not limited to, mean speed, traffic flow rate, and occupancy (Hadi et al., 2021). Microscopic measures include measures of individual vehicles, such as location, speeds, acceleration and deceleration, standard deviations of speed between vehicles, and disturbance measures (Hadi et al., 2021). Disturbance measures refer to the number of oscillations representing stop-and-go operations and disturbance durations and measuring time-to-collision (TTC) (Hadi et al., 2021).

2.1 CV Deployments

Since CV deployments include site-tailored applications and technologies, performance measures selected for evaluation will vary, depending on available data and target improvement goals. For example, Table 2.1 lists the potential performance measures identified for the CV applications deployed in pilot projects located in New York, NY, and Tampa, FL.

Table 2.1: Performance Measures for CV Applications in New York and Tampa Pilots (Hadi et al., 2019)

Application	Identified Potential Performance Measures	
	New York	Tampa
Intelligent Traffic Signal System (I-SIG)	• Average speed • Average wait time at stops • Average travel time • Average throughput at intersections • Number of hard acceleration/decelerations	• Congestion impact • Incident rates • Travel time • Reliability of travel time • Emission • Fuel consumption
Transit Signal Priority	Not Applicable	• Transit ridership • Travel time • Travel time reliability • Bus headway • Bus tailpipe and emissions • Fuel consumption
Pedestrian in Signalized Crosswalk Warning	• Pedestrian collisions with transit buses • Number of warnings generated	• Transit/auto/pedestrian conflicts • Pedestrian behavior
Mobile Accessible Pedestrian Signal System	• Waiting time at intersections for crossing • Number of pedestrian crossing violation reductions	• Transit/auto/pedestrian conflicts • Pedestrian behavior
Curve Speed Warning	• Crashes at ramps • Number of warnings generated	• Incident rates
Reduced Speed/Work Zone Warning	• Average speed at work zone and other zones compared to posted speeds	Not Applicable
In-vehicle information	• Acceptance and driver interviews	
Intersection Movement Assist (IMA)		• Incident rate

In a recent study, Hadi et al. (2021) explored transportation performance measurement based on the availability of CV data. The study categorized measurement techniques into two groups: established performance measurement and emerging performance measurement. Emerging performance measurement, applicable to CV applications, was classified into two categories: planning performance measurements and operational performance measurements (Hadi et al., 2021). Tables 2.2 and 2.3 summarize the CV planning performance measures and operational performance measures, respectively, identified from previous publications reviewed in the study.

Table 2.2: Planning Performance Measures for CV Applications (Hadi et al., 2021)

Measure	Calculation Method
Roadway congestion index	$\dfrac{\frac{VMT_{Freeway}}{Lane{-}miles_{Freeway}}\ x\ VMT_{Freeway} + \frac{VMT_{Arterial}}{Lane{-}miles_{Aterial}}\ x\ VMT_{Arterial}}{13{,}000\ x\ VMT_{Freeway} + 5{,}000\ x\ VMT_{Arterial}}$
Travel rate index	$\dfrac{\dfrac{\frac{60}{Speed_{Freeway}}}{\frac{60}{Freeflowspeed_{Freeway}}}\ x\ VMT_{Freeway} + \dfrac{\frac{60}{Speed_{Arterial}}}{\frac{60}{Freeflowspeed_{Aterial}}}\ x\ VMT_{Arterial}}{VMT_{Freeway} + VMT_{Arterial}}$
Delay per eligible driver	Total delay (includes recurring and incident delay) per eligible driver
Delay per capita	Total delay (includes recurring and incident delay) per person
Wasted fuel per eligible driver	Difference between fuel consumption in existing conditions and fuel consumption based on free-flow speeds per driver
Wasted fuel per capita	Difference between fuel consumption in existing conditions and fuel consumption based on free-flow speeds per driver
Congestion cost per eligible driver	Costs in dollars of congestion based on comparison of existing conditions and free-flow conditions per eligible driver
Congestion cost per capita	Costs of congestion based on comparison of existing conditions and free-flow conditions per eligible driver
Annual person-hours of delay	$Daily\ vehicle\ hours\ of\ delay \times 250\ working\ days\ per\ year \times 1.25\ persons\ per\ vehicle$
Percent congested travel	$\dfrac{VMT\ under\ congested\ conditions}{Total\ VMT\ for\ the\ area}$
Travel rate index	$\dfrac{Travel\ time\ under\ congested\ conditions}{Travel\ time\ under\ uncongested\ conditions}$
Travel time percent variation	$\dfrac{Standard\ deviation}{Average\ travel\ time}\ x\ 100\%$
Travel time buffer index	$\dfrac{95\%\ confidence\ travel\ rate_{(minutes\ per\ mile)} - Average\ travel\ rate_{(minutes\ per\ mile)}}{Average\ travel\ rate_{(minutes\ per\ mile)}}\ x\ 100\%$
Travel time misery index	Average of the travel rates for the longest 20% of the trips − Average travel rates for all trips
Planning Time Index	$\dfrac{95th\ percentile\ travel\ time\ (minutes)}{FFS\ or\ PSL\ travel\ time\ (minutes)}$
Travel Time Index	$\dfrac{Actual\ travel\ rate\ (minutes\ per\ mile)}{FFS\ or\ PSL\ travel\ rate\ (minutes\ per\ mile)}$
Congested Roadway (miles)	$\sum Congested\ segment\ lengths\ (miles)$
Annual Hours of Truck Delay (AHTD)	$\dfrac{\sum\left(\frac{Freight\ VMT}{Travel\ speed} - \frac{Freight\ VMT}{Agency\ specified\ threshold\ speed}\right)\ x\ 7\ x\ 52}{\frac{80th\ percentile\ travel\ time}{Agency\ travel\ time}}$
Freight Reliability Index	$\dfrac{80th\ percentile\ travel\ time}{Agency\ travel\ time}$

Table 2.3: Operational Performance Measures for CV Applications (Hadi et al., 2021)

Performance Measures	Typical Definition
Commercial vehicle safety violations	Number of violations issued by law enforcement based on vehicle weight, size, or safety
Delay caused by incidents	Increase in travel time caused by incidents
Density	Passenger cars per hour per lane
Duration of congestion	Period of congestion
Evacuation clearance time	Reaction and travel time for evacuees to leave the area at risk
Incidents	Traffic interruption caused by a crash or another unscheduled event
Rail crossing incidents	Traffic crashes that occur at highway-rail grade crossings
Recurring delay	Travel time increases from congestion but does not consider incidents
Response time to weather-related incidents	Period required for an incident to be identified and verified and for an appropriate action to alleviate the interruption to the traffic to arrive at the scene
Roadway congestion index	Cars per road space
Security for highway and transit	Number of violations issued by law enforcement for acts of violence against travelers
Speed	Distance divided by travel time
Toll revenue	Dollars generated from tolls
Traffic volume	Annual average daily traffic, peak-hour traffic, or peak period traffic
Travel costs	Value of driver's time during a trip and any expenses incurred during the trip (vehicle ownership and operating expenses, tolls, or tariffs)
Travel time	Distance divided by speed
Vehicle occupancy	Persons per vehicle
Weather-related traffic incidents	Traffic interruptions caused by inclement weather

CV technologies focus on high-level technological advances to improve safety and mobility. Accordingly, available performance measures depend on the CV applications deployed. Table 2.4 provides a summary of potential performance measures that can be evaluated for various types of CV applications.

Table 2.4: Summary of Potential Performance Measures for CV Deployments

Application Type	Identified Potential Performance Measures for CV Deployments
Transit-related	• Travel speed • Delay • Average wait time at stops • Average travel time • Average throughput at intersections • Transit/Auto/Pedestrian Conflicts • Transit ridership • Bus headway • Bus tailpipe • Surrogate safety measures • On-time arrivals and departures
Ped/bike-related	• Transit/Auto/Pedestrian Conflicts • Number of pedestrian crossing violation reductions • Pedestrian collision with transit buses • Pedestrian behavior • Surrogate safety measures
Vehicle-related	• Travel speed • Delay • Average wait time at stops • Average travel time • Travel time reliability • Average throughput at intersections • Number of hard acceleration/decelerations • Congestion impact • Incident response time and duration • Waiting time at intersections for crossing • Crashes at ramps • Average speed in work zones and other zones compared to posted speeds • Acceptance and driver interviews • Surrogate safety measures • Primary crashes, frequency and severity • Secondary crashes, frequency and severity
Environment-related	• Emissions • Fuel consumption

Mobility and safety estimates constitute the majority of quantitative performance measures. Nevertheless, in recent years, a greater emphasis has been placed on measuring vehicle emissions to address environmental concerns. The following subsections discuss examples of these performance measures in greater detail.

2.1.1 Mobility Performance Measures for CV Applications

The following subsections discuss several key performance measures used in determining mobility improvements for CV deployments.

2.1.1.1 Travel Time

Travel time is one of the fundamental mobility performance measures used in studies that evaluated the mobility benefits of CV initiatives. Travel time is defined as the time required to traverse a route between any two points of interest. Khondaker & Kattan (2015) conducted a study on the variable speed limit in a CV environment using travel time as one of the performance measures. Similarly, travel time was used as a potential mobility performance measure for the Intelligent Traffic Signal (I-SIG) system and Transit Signal Priority (TSP) applications used in the New York and Tampa CV pilots.

2.1.1.2 Average Travel Speed

Travel speed over a specified section of highway is calculated as the distance divided by the travel time. Lee et al. (2013) evaluated the cumulative travel time responsive (CTR) real-time intersection control algorithm in the CV environment. Average travel speed was used as one of the performance measures in the study. The average speed was also used as one of the potential mobility performance measures for the I-SIG system application in the New York CV pilot, as indicated in Table 2.1.

2.1.1.3 Delay

Delay is a common and essential mobility performance measure for CV evaluation. Delay is the additional travel time experienced by a vehicle due to circumstances that impede the desirable movement of traffic. It is measured as the time difference between actual travel time and the free-flow travel time. Delay was used as one of the measures in a study that evaluated real-time adaptive signal control performance in a CV environment (Feng et al., 2015). Lee et al. (2013) also evaluated the CTR real-time intersection control algorithm in the CV environment using delay as the performance measure.

2.1.1.4 Additional CV Mobility Performance Measures

Hadi et al. (2019) stated that performance measures for a CV study may follow the "SMART" criteria. These criteria require the objectives to be:

- *Specific*: target a specific area for improvement,
- *Measurable*: quantify or at least suggest an indicator of progress,
- *Assignable*: assign who will do it,
- *Realistic*: state which results can realistically be achieved, given available resources, and
- *Time Related*: specify when the results can be achieved.

The performance metrics may be identified for each operational scenario or use case and may include output and outcome performance metrics (Hadi et al., 2019). For instance, the THEA CV Pilot, funded by the USDOT, developed performance metrics to evaluate issues that the project addresses.

In addition, the evaluation plan will also categorize the evaluation metrics and associated hypotheses into evaluation analysis areas related to the evaluation objectives (Hadi et al., 2019). For instance, the THEA evaluation metrics assess the effectiveness of the use cases in relation to the four "pillars": mobility, safety, environment, and agency efficiency. The identified performance indicators could be related to geographic and temporal extents, resolution, and frequency of the updates.

2.1.2 Safety Performance Measures for CV Applications

The following subsections discuss several key performance measures used in quantifying safety improvements for CV deployments.

2.1.2.1 Secondary Crashes

Once an incident has occurred, the longer it takes to disseminate the information to the public, the greater the likelihood of secondary crashes (Kitali et al., 2019; Yang et al., 2017). To effectively mitigate the risk of secondary crash occurrences, information about primary incidents must promptly be communicated to upstream drivers (Kitali et al., 2018). CV technologies have the potential of reducing the delay in relaying advance warning messages to upstream drivers by automating the incident detection process and instantly sending a message to upstream drivers after the incident has been verified by the Transportation Management Center (TMC).

The change in secondary crash frequency is an important measure to evaluate the safety performance of CV applications. Yang et al. (2017) investigated the impact of CVs on mitigating secondary crash risk through a simulation-based modeling framework that enables vehicle-to-vehicle (V2V) communication. The study concluded that CVs could be a viable way to reduce the risk of secondary crashes, and the benefits increased with increasing market penetration rates of CVs. In light of the potential benefits offered by CVs and the safety concerns associated with secondary crashes, Monyo et al. (2021) and Soloka (2019) quantified the potential benefits of CV technologies in mitigating secondary crashes.

Since CVs are not yet widespread, researchers have been utilizing surrogate safety measures, in addition to secondary crashes, to quantify the safety benefits of CV deployments (Paikari et al., 2014; Rahman et al., 2018; Yang et al., 2017). Present changes in vehicle and road instrumentation influence safety at a rate that exceeds the efficiency of the traditional crash-based safety analysis methods. Accurate and quick measurement of safety with surrogate measures offers a viable solution. Also, surrogate safety measures are an alternative method for evaluating safety where the crash data is unavailable or insufficient. Compared to crashes, using surrogate safety measures is considered a proactive approach since the effectiveness of a roadway countermeasure can be quantified before actual crashes occur. Surrogate safety measures include time-to-collision (TTC), post-encroachment time (PET), and other CV safety performance measures. The following subsections describe these safety performance measures.

2.1.2.2 Time-to-Collision (TTC)

Among the surrogate measures proposed by the Federal Highway Administration (FHWA), time-to-collision (TTC) is the most well-known time-based safety indicator (Gettman & Head, 2003). TTC is defined as the time remaining before two vehicles collide, assuming both maintain their course and speed (Saffarzadeh et al., 2013). The TTC threshold (range 1.5 to 4.0 seconds) defines the potential traffic conflict and is effective for rear-end, head-on, and weaving conflicts (Mahmud et al., 2019).

Olia et al. (2015) conducted research to assess the potential impacts of CVs from a safety perspective, using TTC as one of the safety performance measures. The study indicated that CVs could avoid conflicts, take alternate routes, travel less congested routes within the network, and reduce sudden brakes and lane changes. The TTC safety indicator improved for CVs when the market penetration was up to 50%. The experiments suggest that any further increase in the proportion of CVs in the network beyond 50% market penetration appeared counterproductive. A possible contributing factor to this result could be that diverting too many vehicles (e.g., beyond 50%) to minor alternate routes causes excessive congestion in other parts of the network, and therefore, deteriorates the TTC.

Abdulsattar et al. (2018) presented an agent-based modeling and simulation framework to assess the safety performance effects of CV technologies in work zones under various CV market penetration rates and traffic demand levels. TTC and time exposed time-to-collision (TET) were used as surrogate safety measures for safety evaluation. The study concluded that the higher the traffic flow rate, the higher the CV market penetration level was needed to improve safety performance in work zones. Another study by Rahman et al. (2018) investigated the safety benefits of CVs on congested expressways with many lane-changing and merging maneuvers via microsimulation modeling. Five surrogate safety measures, including standard deviation of speed, TET, time-integrated TTC, time exposed rear-end crash risk index, and sideswipe crash risk, were employed as indicators for safety evaluation. Simulation results showed that CVs significantly improved traffic safety compared to the non-CV scenario. Monyo et al. (2021) and Soloka (2019) investigated how deploying CVs may mitigate secondary crashes on freeways. Both studies used TTC as one of the performance measures.

2.1.2.3 Post-Encroachment Time (PET)

PET is another commonly used surrogate measure and is more efficient for intersection conflicts (Mahmud et al., 2019). PET is defined as the time lapse between the commencement of encroachment by the turning vehicle plus the expected time for the vehicle to reach the point of collision and the completion time of encroachment by the turning vehicle.

2.1.2.4 Other CV Safety Performance Measures

- Gap Time (GT): The time lapse between commencement of encroachment by the turning vehicle plus the expected time for the through vehicle to reach the point of collision and the completion time of encroachment by turning vehicle.

- Encroachment Time (ET): Time duration during which the turning vehicle infringes upon the right-of-way of the through vehicle.

- Deceleration Rate (DR): The rate at which a crossing vehicle must decelerate to avoid a collision.

- Proportion of Stopping Distance (PSD): The ratio of distance available to maneuver to the distance remaining to the projected location of the collision.

- Initially Attempted Post-Encroachment Time (IAPT): Time lapse between commencement of encroachment by turning vehicle plus the expected time for the through vehicle to reach the point of collision and the completion time of encroachment by turning vehicle.

- Number of Oscillations (NO): An oscillation is defined as a deceleration phase followed by an acceleration phase. Stop-and-go traffic is the mechanism of traffic state transition to congestion and is related to traffic breakdown and instability.

2.1.3 Environmental Performance Measures for CV Applications

2.1.3.1 Emissions

Environmental performance measures primarily represent measurements of air quality in relation to the carbon intensity in a location or region. In the transportation industry, carbon intensity can be defined as the "CO_2 emissions per capita for all modes or individual modes of transportation" (Environmental Protection Agency [EPA], 2011). Examples of carbon intensity measures include (EPA, 2011):

- Total transportation CO_2 emissions per capita
- Passenger transportation CO_2 emissions per capita
- Heavy-duty vehicle CO_2 emissions per capita

Generally, CO_2 emissions can be estimated using vehicle miles traveled (VMT), average fuel economy, and the carbon content of the fuel. Depending on available data, estimates can be obtained for individual modes and vehicle classes (EPA, 2011).

A reduction in emissions can also be measured using a reduction in vehicle idle time and running time as performance measures. Instinctively, a reduction in emissions would be realized by a reduction in excess time spent by a vehicle in idle mode.

2.1.4 V2I and V2V Performance Measures for CV Applications

CV technology allows for the exchange of information between vehicles, drivers, bicyclists, pedestrians, and roadside infrastructure, i.e., roadside equipment (RSE). Communication and data transfer can occur in the form of vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), infrastructure-to-vehicle (I2V), infrastructure-to-pedestrian (I2P), or vehicle-to-everything (V2X). Tables 2.5 and 2.6 list potential performance measures associated with common V2I and V2V applications, respectively.

Table 2.5: Performance Measures for V2I Applications

Focus	V2I Application	Description	PMs	Source
Safety	Curve Speed Warning (CSW)	Alerts the driver if the current speed may be too high to safely traverse an approaching curve.	• Crash frequency/ severity	NOCoE, 2021
	Pedestrian in Signalized Crosswalk Warning	Alerts a transit bus operator when a pedestrian in the crosswalk of a signalized intersection is in the intended path of the bus.	• Pedestrian crashes	USDOT, 2021
	Red Light Violation Warning (RLVW)	Issues a warning to a driver who is about to run a red light.	• Crash frequency/ severity	NOCoE, 2021
	Speed Limit Warning	Provides in-vehicle safety alerts to drivers when the vehicle speed exceeds five miles-per-hour over the posted speed.	• Crash frequency/ severity	USDOT, 2021
	Stop Sign Gap Assist (SSGA)	Utilizes traffic information broadcasting from RSE to warn drivers of potential collisions at stop sign intersections.	• Crash frequency/ severity	NOCoE, 2021; USDOT, 2021
	Work Zone Warning	Notifies a driver to use caution when traveling through a work zone.	• Crash frequency/ severity	USDOT, 2021
	Reduced Speed/ Work Zone Warning (RSWZ)	Utilizes RSE to broadcast alerts to drivers to reduce speed, change lanes, or come to a stop within a work zone.	• Crash frequency/ severity	USDOT, 2021
	Wrong-way Entry Warning	Warns drivers that they may be driving the wrong way.	• Crash frequency/ severity	USDOT, 2021
	Spot Weather Impact Warning (SWIW)	Warns drivers of local hazardous weather conditions.	• Crash frequency/ severity	USDOT, 2021

Note: V2I = Vehicle-to-Infrastructure; PMs = Performance Measures; RSE = Roadside Equipment

Table 2.5 Performance Measures for V2I Applications (continued)

Focus	V2I Application	Description	PMs	Source
Mobility	Advanced Traveler Information System (ATIS)	Traveler information services that record or infer user decisions and other trip data used to improve system management.	• Travel time reliability	USDOT, 2021
	Integrated Corridor Management (ICM)	Operational coordination of multiple transportation networks mitigates the effect of incidents	• Delay • Travel time • Fuel consumption	USDOT, 2021
	Queue Warning	Provides drivers with timely warnings of existing and impending queues.	• Throughput • Travel time	USDOT, 2021
	Dynamic Speed Harmonization	Recommends target speed in response to congestion, incidents, and road conditions.	• Throughput • Travel time • Delay	USDOT, 2021
	Traffic Incident Management (TIM) messages	Provide location-based travel advisory information to drivers related to traffic information and incidents, major events, evacuations, etc.	• Travel time • Delay	USDOT, 2021
	Emergency Vehicle Preemption (EVP)	Provides signal preemption to emergency vehicles and accommodates multiple emergency requests.	• Incident response time/ duration	USDOT, 2021
	Transit Signal Priority (TSP)	Provides signal priority to transit vehicles at intersections and along arterial corridors.	• Schedule adherence • Travel time reliability	USDOT, 2021
	Signal Phase and Timing (SPaT) messages	Provides drivers with the current state of all lanes and signal phases at an intersection.	• Travel time	USDOT, 2021
Environment	Eco-Approach and Departure at Signalized Intersections	Determines vehicle's optimal speed to pass next signal on green or suggests decelerating to a stop in the most eco-friendly way possible.	• Time idling • Number of stops • Frequency of unnecessary accelerations/ decelerations • Traffic flow	USDOT, 2016b
	Eco-Traffic Signal Timing	Optimizes traffic network using the green time to serve traffic demands while minimizing the environmental impact.	• Emissions • Fuel consumption	USDOT, 2016b
	Eco-Traffic Signal Priority	Allows transit or freight vehicles to request signal priority.	• Emissions • Fuel consumption	USDOT, 2016b
	Connected Eco-Driving Environment	Provides customized real-time driving advice to drivers to adjust driving behavior to save fuel/reduce emissions.	• Emissions • Fuel consumption	USDOT, 2016b

Table 2.6: Performance Measures for V2V Applications

Focus	V2V Applications	Description	PMs	Source
Safety	Do Not Pass Warning (DNPW)	Warns the driver that it is not safe to pass a slower-moving vehicle if the passing lane is occupied by another vehicle.	• Crash frequency/ severity	NOCoE, 2021
	Emergency Electronic Brake Light (EEBL) Warning	Notifies a driver of a vehicle braking suddenly ahead.	• Crash frequency/ severity	NOCoE, 2021
	Forward Collision Warning (FCW)	Alerts a driver of a risk of a rear-end collision when cars ahead are stopped or traveling slowly.	• Crash frequency/ severity	NOCoE, 2021
	Intersection Movement Assist (IMA)	Warns a driver, when approaching an intersection, if another vehicle is running a red light or making a sudden turn.	• Crash frequency/ severity	NOCoE, 2021
	Left Turn Assist (LTA)	Alerts a driver when attempting to make an unprotected left turn across traffic.	• Crash frequency/ severity	NOCoE, 2021
	Blind Spot/ Lane Change Warning (BSW/LCW)	Alerts a driver of the presence of same-direction traffic in an adjacent lane. Alerts a driver of a potentially unsafe lane change.	• Crash frequency/ severity	NOCoE, 2021
	Vehicle Turning Right in Front of Bus Warning	Warns transit bus operators of the presence of vehicles attempting to go around the bus as the bus departs from a bus stop.	• Crash frequency/ severity	NOCoE, 2021
	Basic Safety Messages (BSMs)	Uses V2V communications to help determine immediate threats and alert drivers as necessary.	• Crash frequency severity	NOCoE, 2021
Mobility	Response, Emergency Staging and Communications, Uniform Management and Evacuation (R.E.S.C.U.M.E.)	Warns oncoming vehicle of lane closures and reduced speeds when approaching incident zones. Warns on-scene responders of vehicles approaching at speeds on in lanes that pose a high risk to their safety.	• Congestion • Travel time	USDOT, 2021
	Cooperative Adaptive Cruise Control (CACC)	Aims to dynamically adjust and coordinate cruise control speeds among platooning vehicles.	• Traffic flow • Throughput	USDOT, 2021

Note: V2V = Vehicle-to-Vehicle; PMs = Performance Measures

2.1.5 Qualitative Performance Measures for CV Applications

Qualitative performance measures can be used to evaluate perceptions and satisfaction levels. Although generally subjective in nature, qualitative performance measures can provide valuable information to transportation system managers when considering service and agency improvement strategies (USDOT, 2016a). Examples of qualitative performance measures include:

- User satisfaction (Hadi et al., 2021),
- Driver compliance (Hadi et al., 2021),
- Driver frustration (Hadi et al., 2021),

- Public perception of agency operations (USDOT, 2016a),
- Lessons learned, and
- Policies, procedures, and guidelines developed and adopted.

2.2 TSM&O Strategies

TSM&O is a program based on actively managing the multimodal transportation network, measuring performance, and streamlining and improving the existing system to deliver favorable safety and mobility outcomes to the traveling public. TSM&O comprises a set of strategies that focus on operational improvements that can maintain or restore the performance of the existing transportation system before additional capacity is needed. For successful implementation of the TSM&O strategies, quantifiable performance measures and metrics are crucial.

Existing studies used various performance measures to quantify the mobility and safety performance of TSM&O strategies. For example, most previous studies have used travel time, travel time reliability, travel speed, delays, level of service (LOS), and buffer index to quantify the mobility performance of TSM&O strategies. Similarly, the safety performance of TSM&O strategies is measured using crash frequency, crash severity, secondary crash occurrence, and surrogate safety measures.

2.2.1 Mobility Performance Measures for TSM&O Strategies

2.2.1.1 Incident Response Time

Incident response time is critical for incident management. The sooner an incident is responded to, the lower the negative impact from it. Some TSM&O strategies have used incident response time as the mobility performance measure. For instance, the incident response time was used to evaluate the operational benefits of the RISC program (Dougald et al., 2016). Another study focusing on the Freeway Service Patrol (FSP) program by Nee & Hallenbeck (2001) used the average incident response time as the performance measure. Sun et al. (2017) introduced a framework for designing and deploying the RRSP program on Florida's freeways. The study proposed incident response time as an important performance metric to evaluate the operational performance of RRSP. Another simulation model-based study by Wu et al. (2020) recommended a deployment plan for the RRSP program. The study suggested incident response time as an essential performance metric to determine the quickest response time.

2.2.1.2 Average Incident Clearance Time

Average incident clearance time is the time between the first recorded awareness of the incident by a responsible agency and the confirmation that the last responder has left the incident scene, as shown in Figure 2.1. The FDOT's RISC program and the Towing and Recovery Incentive Program (TRIP) are public-private partnerships that use incentive payments, and disincentive liquidated damages to ensure short clearance times for heavy vehicles wrecks. The program has significantly reduced the average incident clearance time (FHWA, 2012).

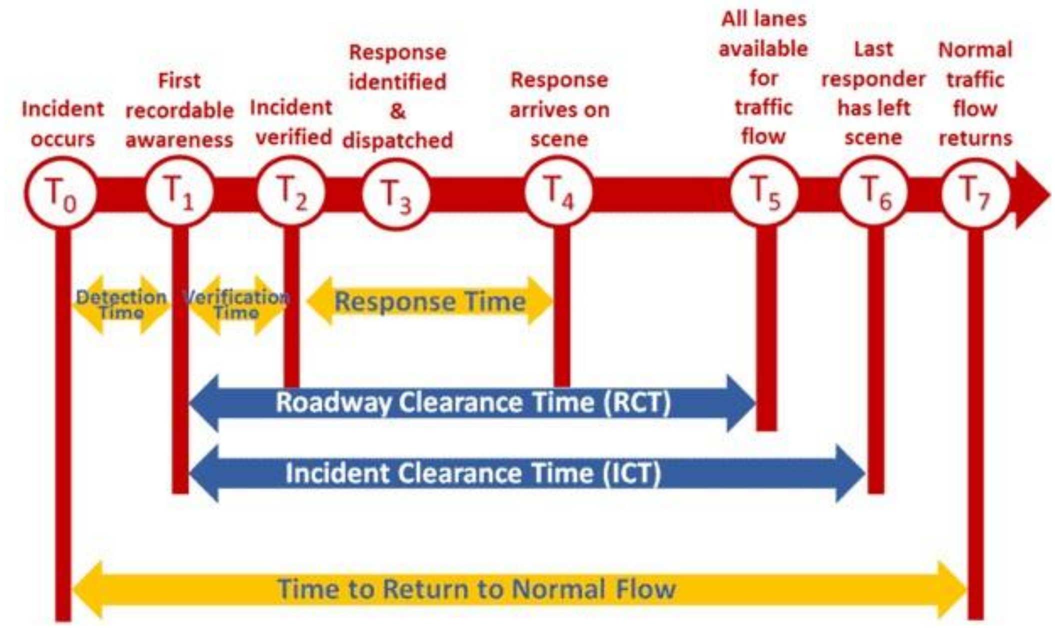


Figure 2.1: Incident Timeline Chart (FHWA, 2020)

2.2.1.3 Travel Time

Travel time is a common measure of effectiveness for mobility evaluation of TSM&O strategies. For example, Cohen et al. (2017) used the travel time to evaluate the performance of a study segment with and without ramp meters. Similarly, Karim (2015) explored the effectiveness of ramp metering on the operational efficiency of the freeway and used average travel time as one of the performance measures. Cambridge Systematics Inc. (2011) also indicated that many studies documented travel time as a quantifiable performance measure for evaluating the performance of express lanes (ELs) for general traffic and transit.

Several studies have also used the travel time to evaluate the mobility benefits of TSP (Cesme et al., 2015; Consoli et al., 2015; Shaaban & Ghanim, 2018; Skabardonis & Christofa, 2011; Zlatkovic et al., 2013; Ali et al., 2017). For instance, VISSIM modeling was used to evaluate the TSP's effectiveness in a study conducted along International Drive in Orlando, Florida (Consoli et al., 2015). The study compared the unconditional TSP and the conditional TSP (with bus 3 and 5 minutes behind schedule) with no TSP scenario. Several studies have also analyzed the mobility benefits of Adaptive Signal Control Technology (ASCT) using travel time (Martin, 2018; DKS Associates, 2010; Dutta & McAvoy, 2010; Hutton et al., 2010; Tian et al., 2011; Fontaine et al., 2015). For instance, a before and after study was conducted on an arterial segment with ten adaptive signalized intersections in Las Vegas to evaluate the safety performance of the Sydney Coordinated Adaptive Traffic System (SCATS) (Tian et al., 2011). The analysis was based on field data collected using a probe vehicle. The study adopted descriptive statistics to estimate the operational benefits of the SCATS.

2.2.1.4 Travel Speed

Travel speed is commonly used to evaluate the performance of several TSM&O strategies, including ELs, ASCT, RRSP, and Dynamic Message Signs (DMS). Alluri et al. (2020) used average speed to quantify the mobility benefits of DMS and ASCT strategies.

2.2.1.5 Travel Time Reliability

Travel time reliability measures the expected range in travel time and provides a quantitative measure of travel time predictability (Cambridge Systematics, Inc., 2001). It represents the consistency of one's travel time and reflects the user's experience in traveling rather than using average travel time as the performance measure. Travel time reliability has been used to assess various mobility performances of TSM&O strategies. A higher value is assigned to travel time reliability than to average travel time due to the usefulness of predictable travel times (Cambridge Systematics, Inc., 2001).

Some travel time reliability measures include coefficient of variation, buffer index (BI), planning time index (PTI), and 90th or 95th percentile travel time. The coefficient of variation of travel time represents the ratio of the standard deviation of the travel time to the mean travel time. It is a valuable statistic for comparing the degree of variation of travel time along the study corridor. It best quantifies the variation of travel times along the study corridor. PTI is computed as the 95th percentile travel time divided by the free-flow travel time. It represents how much total time a traveler needs to allow to ensure on-time arrival. BI is another essential performance measure used to evaluate the mobility performance of several TSM&O strategies. It represents the extra time cushion most travelers add to their average travel time when planning trips to ensure on-time arrival.

Several studies have used travel time reliability as the metric to evaluate the performance of ASCT (Martin, 2018; DKS Associates, 2010; Dutta & McAvoy, 2010; Hutton et al., 2010; Tian et al., 2011; Fontaine et al., 2015). Cohen et al. (2017) used travel time reliability to investigate the impact of ramp metering for traffic on the A25 roadway connecting Socx to Lille in France during morning peak hours (6:30 a.m. to 10:30 a.m.). The F-test was used to test the hypothesis of equal variances of travel time with and without ramp metering. Since travel time reliability helps understand the variability of the travel time, Mcleod et al. (2012) recommended using this measure to evaluate the performance of Smart Work Zones (SWZ). Alluri et al. (2020) used BI to quantify ramp metering and EL's operational performance. BI was used to capture the travel time variation at any time of day on facilities with ramp metering. The performance of ELs was evaluated where BI was again used as the performance measure (Alluri et al., 2020). The BIs for the ELs were compared with the BIs for the general-purpose lanes when the ELs were operational.

2.2.1.6 Delay

Delay is also one of the most common performance measures for evaluating TSM&O strategies. Sun et al. (2013) used the total vehicular delay to quantify the effectiveness of ramp metering by using simulation models at work zones in Columbia, Missouri. The total vehicular delay was considered the delay caused by both the mainline and ramp traffic. Simulation models provided the results in terms of total delay during under-capacity, at capacity, and over-capacity conditions. On average, the decrease in delay with low truck percentage and the decrease in delay with high truck percentage conditions resulted from metering ramps near work zones operating above capacity reduced significantly. On arterials, Alluri et al. (2020) quantified the mobility benefits of TSP using average vehicle delay.

2.2.1.7 Throughput

Throughput is another critical measure of effectiveness in the decision-making process. Throughput is the number of vehicles present at the start plus those attempting to enter and successfully enter the system during the analysis period. A study by Radwan et al. (2009) used throughput as an operational measure for SWZ, as roadway capacity where the work zone is located is lower than the normal operating conditions.

As a part of the TSM&O Capability Maturity Model (CMM) workshops, the FDOT Districts identified several performance measures. Each attendant of the workshop voted for each performance measure. As can be observed from Figure 2.2, the highest number of votes were received for improving travel time, travel time reliability, and throughput.

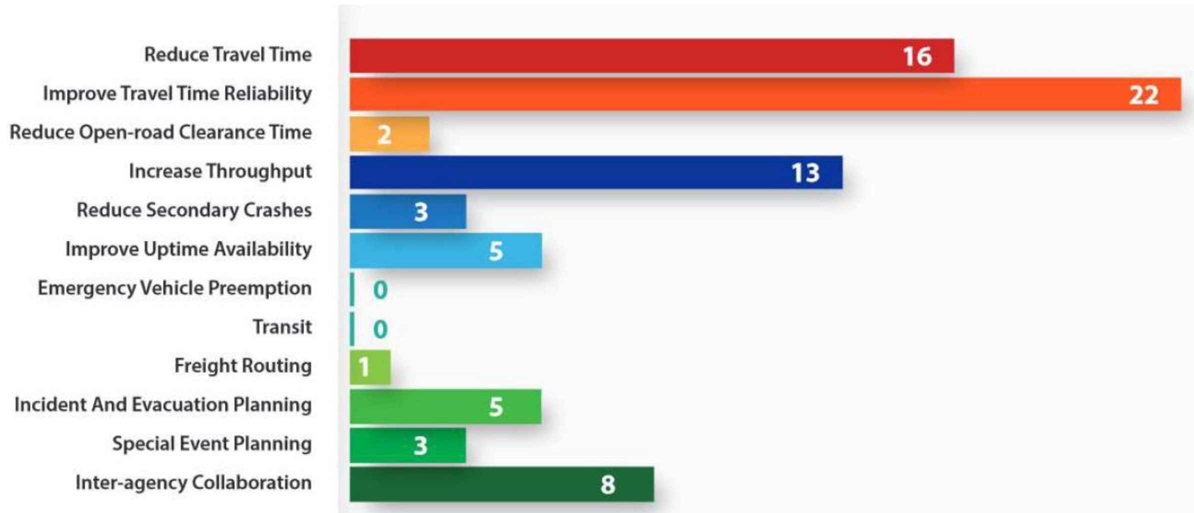


Figure 2.2: Performance Measure Votes Received from FDOT CMM Workshop Attendants (FDOT, 2018)

2.2.2 Safety Performance Measures for TSM&O Strategies

2.2.2.1 Crash Frequency / Crash Rate

Crash frequency is the number of crashes occurring in some geographical space, usually a roadway segment or intersection, over some specific time period. Crash frequency is usually normalized based on traffic volume, segment length and analysis period, commonly referred to as crash rate. Several studies have used crash frequency as one of their safety performance measures. Alluri et al. (2020) quantified the safety benefits of TSP using a full Bayesian method. The study used crash frequency as one of the safety performance measures. Goh et al. (2013) explored the road safety impacts of several bus priority treatments, including TSP. An empirical Bayes (EB) before-after study was used for an aggregate level analysis to determine the changes in expected crash frequency at intersections and roadway segments where TSP was deployed. Alluri et al. (2020) quantified the safety benefits of ASCT using the EB method. The study used crash frequency as one of the safety performance measures.

2.2.2.2 Crash Severity

Crash severity is another critical safety performance measure that is commonly used in traffic safety studies. Dutta & McAvoy (2010) evaluated the safety effectiveness of the SCATS over the time-of-day (TOD) signal plan. This study compared a section of M-59 (with SCATS) with a section on Dixie Highway (with a TOD system) to assess the safety effectiveness of the SCATS. The study revealed a shift in crash severity from A (incapacitating injury) and B (visible injury) to C (possible injury). However, the improvements were not statistically significant at a 95% confidence level. Alluri et al. (2020) quantified the safety benefits of TSP and ASCT using crash severity as one of the safety performance measures.

2.2.2.3 Secondary Crashes

Secondary crashes result from a change in traffic characteristics caused by primary incidents. The probability of occurrence of a secondary crash is a function of the duration of the primary incident. Several previous studies have used secondary crashes as a safety performance measure for TSM&O strategies. According to Guin et al. (2007), FSP deployment helped reduce incident duration time, thus reducing secondary crashes. The study assumed that 15% of crashes that occur on highways patrolled by FSPs were secondary crashes. Accordingly, a reduction in the primary incident duration from FSP response was found to result in a decrease in the probability of secondary crash occurrence. Another study by Alluri et al. (2020) evaluated the safety performance of the RRSP program. The study examined the benefits of the Road Ranger program in reducing the risk of secondary crash occurrence. Based on average incident duration reduction, the results suggest that the Road Ranger program may reduce the likelihood of secondary crashes. By controlling the traffic at an incident scene, the RRSP program reduces the probability of secondary crashes.

2.2.2.4 Surrogate Safety Measures

Surrogate measures have been used in several studies to evaluate the safety performance of TSM&O strategies where challenges existed with the collection of crash data and prediction of crash frequencies. For instance, safety analysis of DMSs was conducted using the coefficient of variation of vehicle speeds as a surrogate safety measure (Alluri et al., 2020). The variations were determined when the displayed messages on DMSs did not require drivers to take action (i.e., when the DMSs display advisory messages) versus when the DMSs displayed messages about downstream crashes. Overall, displaying crash messages on DMSs resulted in fewer crashes despite increasing speed variances. Another study by Sun et al. (2013) used surrogate measures to evaluate the performance of ramp meters that were temporarily deployed at work zones in Columbia, Missouri. Crash data could not be used since the ramp meters were deployed for a short period in the work zones. The surrogate measures used in this study included driver compliance rates, speed statistics along the mainline, ramp traffic, speed differences between merging and mainline vehicles, merging headways, lane changes, and braking events along the mainline (Sun et al., 2013).

2.2.3 Qualitative Performance Measures for TSM&O Strategies

An earlier primer released by the FHWA sought to provide guidelines for improving TSM&O activities on the state and local levels by presenting the capability maturity approach, a framework modified from the CMM concept established in the Information Technology (IT) industry and modified for the transportation industry (FHWA, 2012). The CMM approach identifies critical areas that affect the usefulness of a TSM&O program from the business processes, systems and technology, performance measurement, culture, organization and workforce, and collaboration (FHWA, 2012).

Realizing a growing need for improved mobility and safety on Florida roadways, the FDOT formed TSM&O Leadership and Task teams in 2010 and moved to a formal TSM&O program to develop a TSM&O Strategic Plan in 2013 (FDOT, 2013). Lately, a more comprehensive statewide TSM&O Strategic Plan has been established (FDOT, 2017a). The mission of the program is “to identify, prioritize, develop, implement, operate, maintain, and update TSM&O program strategies and measure their effectiveness for improved safety and mobility.”

Presently, TSM&O strategies are at numerous application levels in each of the FDOT’s seven Districts and the Florida’s Turnpike Enterprise (FTE). While Florida is moving with Active Traffic Management (ATM), Integrated Corridor Management (ICM), and CV initiatives, additional target TSM&O actions and strategies have been identified (FDOT, 2013). Traveler information systems, such as DMSs using integrated Intelligent Transportation System (ITS) technologies, have been a predominant management tool used statewide for many years. Significant efforts to mainstream TSM&O throughout all aspects of the project development process have occurred over the last year (FDOT, 2017a). These efforts aim to bridge the gap between planning and operations and promote FDOT policy and culture to provide efficient and safe travel for Florida motorists through TSM&O strategies.

To determine the extent to which TSM&O is being incorporated in FDOT projects, a survey was conducted to explore the current state-of-the-practice of TSM&O considerations, procedures, and practices at the District level in the FDOT (Sando et al., 2018a). Most project managers related to TSM&O activities generally perceive TSM&O leadership to be present at both the State and District levels in Florida. Eight out of eleven project managers chose both the Central and District office options. This suggests that while many facets of TSM&O activities are managed at the District level, TSM&O leadership in the Central Office is also desired or deemed beneficial. Project managers also usually consider TSM&O staff to primarily work in the traffic operations group and the ITS group within traffic operations. Only a few project managers perceive TSM&O staff to work in the planning group. These results indicate a range of perceptions, statewide, on when TSM&O activities are considered during the project development process and which office and workgroup TSM&O staff should reside. Mainstreaming TSM&O throughout the FDOT would require these elements to be better defined for all project managers involved in TSM&O activities.

Also, all prospective roadway projects are potential candidates for alternative capacity solutions involving TSM&O strategies. The future of congestion and safety management must include the most cost-effective measures to keep up with the growing number of road users depending on safe and reliable travel. To optimize roadway improvements to support maintenance and operation strategies, TSM&O considerations must occur early in the project development process.

Based on several prior research findings, successful mainstreaming of TSM&O will require TSM&O involvement in all phases of project development (Sando et al., 2018a). Key lessons learned to mainstream TSM&O in each discipline include:

- provide education and understanding of TSM&O in all disciplines,
- require communication and coordination with TSM&O staff in all project phases,
- develop a formalized process and procedure for TSM&O inclusion, and
- provide supportive TSM&O language in FDOT guidelines.

Other requirements for mainstreaming TSM&O include:

- improve the overall culture of TSM&O in the FDOT,
- place greater importance on TSM&O through policy and procedures,
- encourage the sharing of knowledge of TSM&O strategies and products,
- develop an outreach program for potential contractors and inspectors,
- consider a certification program for construction engineering & inspection (CEI) contractors,
- allow TSM&O staff to provide more input with accepting or rejecting construction work, and
- FDOT is also incorporating TSM&O into the FDOT PD&E Manual, the FDOT Design Manual, the FDOT Standard Plans, and FDOT Standard Specifications as key mainstreaming activities

2.3 Summary

CV technologies and TSM&O strategies are increasingly being considered by transportation agencies to improve the safety and mobility of the transportation network. CV technologies focus on high-level technological advances to improve safety and mobility. TSM&O, on the other hand, is a program based on actively managing the multimodal transportation network, measuring performance, and streamlining and improving the existing system to deliver positive safety and mobility outcomes to the traveling public. TSM&O comprises a set of strategies that focus on safety and operational improvements that can maintain or restore the performance of the existing transportation system before extra capacity is needed.

The main goal of this research was to assist FDOT in developing approaches to evaluate the performance of CV projects and the RISC, RRSP, and SWZ TSM&O strategies. Therefore, a comprehensive review of the existing body of literature was conducted, including government reports, white papers, opinion pieces, presentations, etc., to identify the quantitative and qualitative performance measures and metrics that are being considered in evaluating the performance of CV deployments and TSM&O strategies. Table 2.7 provides a summary of all identified performance measures for CV and TSM&O strategies.

Table 2.7: Summary of Performance Measures for CV Applications and TSM&O Strategies

Application	Identified Potential Performance Measures	
	CV Deployments	TSM&O Strategies
Transit-related	• Travel speed • Delay • Average wait time at stops • Average travel time • Average throughput at intersections • Transit, auto, pedestrian conflicts • Transit ridership • Bus headway • Bus tailpipe • Surrogate safety measures • On-time arrivals and departures	• Travel time • Travel time reliability • Delay • Crash frequency • Crash severity • Surrogate safety measures • On-time arrivals and departures
Ped/bike-related	• Transit, auto, pedestrian conflicts • Number of pedestrian crossing violation reductions • Pedestrian collision with transit buses • Pedestrian behavior • Surrogate safety measures	• Delay • Crash frequency • Crash severity • Surrogate safety measures
Vehicle-related	• Travel speed • Delay • Average wait time at stops • Average travel time • Travel time reliability • Average throughput at intersections • Number of hard acceleration and decelerations • Congestion impact • Incident rates • Waiting time at intersections for crossing • Crashes at ramps • Average speed at work zone and other zones compared to posted speeds • Acceptance and driver interviews • Surrogate safety measures • Secondary crashes	• Incident response time • Travel speed • Travel time • Travel time reliability • Delay • Buffer index • Average clearance time • Throughput • Crash frequency • Crash severity • Surrogate safety measures • Secondary crashes
Environment-related	• Emission • Fuel consumption	• Emission • Fuel consumption

CHAPTER 3
BENEFIT-COST ANALYSIS OF THE RAPID INCIDENT SCENE CLEARANCE (RISC) PROGRAM

This chapter discusses the second task in the research effort to evaluate the performance of CV and TSM&O projects in Florida. The task involved a benefit-cost (B/C) analysis of the Rapid Incident Scene Clearance (RISC) program from both safety and mobility perspectives. The safety B/C was estimated using a reduction in secondary crashes as the performance measure. A reduction in incident-related delay was used as the performance measure to quantify the mobility benefits of the RISC program.

3.1 RISC Program

The RISC program is one component of the traffic incident management team. It promotes coordination, communication, and cooperation between on-scene emergency responders, thereby streamlining the control and clearing of incident scenes. It is an incentive-based program that requires specialized equipment and trained operators to quickly remove wreckage from the roadway, especially where major crashes close most lanes or cause significant travel delays. Notably, proper equipment and qualified operators assist in maximizing the clearance efforts and minimizing the potential for additional delays. In Florida, the program supports the Open Roads Policy goal of safely clearing major highway incidents and truck crashes in 90 minutes or less.

The RISC program was first implemented on Florida's Turnpike Enterprise (FTE) roadways and is being expanded for statewide use, particularly on freeways. As of 2017, in addition to FTE, the RISC program is operational in six of the seven FDOT districts (see Table 3.1). Note that the program is operationally managed at the district level.

Table 3.1: RISC Program Deployment by District (FDOT, 2017b)

District	Number of RISC Vendors	Roadway Segments	Miles Covered
1	2	I-75, I-275	210
2	4	I-10, I-75, I-95, I-295, and J. Turner Butler Blvd.	280
3	1	I-10	165
4	5	I-75, I-95, I-595	193
6	3	I-75, I-95, I-195, I-395, SR 25, SR 826, SR 997, SR 970, and MacArthur Causeway	87
7	2	I-4*, I-75, I-275,	188
FTE	9	Mainline, Homestead Extension, Sawgrass Expressway, BeachLine West Expressway, Seminole Expressway/Toll 417, Western Beltway, Suncoast Parkway, Veterans Expressway, Poll Parkway, and Southern Connector Extension/Toll 417	460

Note: *District 7 manages the RISC program on I-4, not only in their own geographical area, but also in Polk County for District 1 as well; FTE = Florida's Turnpike Enterprise; SR = State Road.

The RISC contractor has the responsibility to respond to the incident within 60 minutes of the activation request. As part of the RISC contract, they must arrive on the incident scene with a 35- and 60-ton wrecker, one of which must contain a rotator. In addition, a third support vehicle is required, along with the wreckers that contain barrier tools and traffic control equipment. Once on scene and provided a *Notice to Proceed* (NTP) by the lead official on the scene, the vendor will have 90 minutes to open the travel lanes for traffic. If the proper equipment arrives on the scene within 60 minutes and the towing company clears the travel lanes within 90 minutes, they are eligible for a bonus from FDOT, in addition to the usual compensation for their services from the owner/insurance company.

The RISC program is an initiative that contracts with towing companies to provide quick and safe clearance of large vehicle crashes on major highways where the vehicles are overturned or damaged to the point that they cannot be towed by a smaller tow truck. Vehicle types that the RISC program responds to include tractor-trailers, box trucks, buses, lost loads, motor homes, and similar types of vehicles. Large commercial truck crashes can cause long traffic delays, secondary crashes, and jeopardize the safety of incident responders. Many times, during major commercial vehicle crashes, trailers loaded with cargo are damaged and spill their loads onto the highway or adjacent areas. The RISC contract requires the vendor to have specified extra equipment on hand or available 24 hours a day/7 days a week to respond to these major incidents. Note that the towing company can receive an extra incentive for the staging and/or use of this extra equipment in the incident clearance process.

The Florida Highway Patrol (FHP) is one of the key agencies during the RISC activation. They can activate RISC, give the notice to proceed, start and stop the RISC clock, and confirm all lanes cleared for the RISC contractors. They must work closely with the FDOT TMCs to ensure all the RISC log times are documented. Communication between the TMC personnel and the on-scene incident responder is critical. One important representative at the RISC event is the incidents response vehicle operator, i.e., FDOT incident commander, who serves as the FDOT on-scene incident commander and communicates all RISC benchmark times back to the TMC. When the RISC contractor arrives at the scene, they meet with the incident command team to determine the safest and most efficient method to clear the crash. The RISC clock is stopped to allow the recovery of the incident victims and under extenuating circumstances, such as a fatal crash investigation, cargo spills, or hazardous materials that are out of the control of the RISC contractor.

3.2 Potential Benefits of RISC Program

Traffic incidents often lead to capacity reduction and deterioration of the level of service. They account for more than half of all urban traffic delays and almost all rural traffic delays (Baykal-Gürsoy et al., 2009). The RISC program reduces the potential delays associated with the incident by clearing the incident as quickly as possible. Previous statistics indicate that the average travel lane clearance was 190 minutes before the RISC program was implemented. Since the implementation of the RISC program, travel lane clearance for the same incident types has been reduced to 68 minutes or by 179% (FDOT, 2017b). The significant benefits of the RISC program include incident-related delay savings, reduced fuel consumption and emissions, improved traffic flow, reduced potential for secondary crashes, reduced stress, and an increased sense of security.

In addition to affecting the operational quality of roadways, traffic incidents affect the safety of road users and incident responders. In the United States (U.S.), traffic-related incidents are the leading cause of death for emergency medical service (EMS) providers, law enforcement, and towing service providers. On average, one law enforcement officer is killed every month in the U.S., and one towing professional is killed every six days (Hagen, 2017). Traffic incidents also expose other vehicles to the risk of being involved in additional crashes called *secondary crashes* (Owens et al., 2010). These incidents tend to occur within the prior incident queue as vehicles encounter unexpected congestion and are unable to brake in time. They can also occur near a traffic incident as drivers become distracted by the incident scene (Goodall, 2017).

In an earlier study by Karlaftis et al. (1999), the likelihood of secondary crashes was observed to increase by 2.8 percent for each additional minute required to clear the initial crash. Other recent studies also associated an increase in incident clearance duration with a higher likelihood of secondary crashes (Goodall, 2017; Kitali et al., 2018, 2019; Sando et al., 2018b). Thus, besides the potential of reducing incident-related delays, the RISC program has the potential to improve the safety of road users and incident responders.

In this task, a B/C analysis was conducted to quantify the safety and mobility benefits associated with implementing the RISC program. The reduction in secondary crashes was used as the performance measure for estimating the safety benefits. The mobility benefits were quantified using incident-related delay as the performance measure. As a first step towards estimating the safety benefits of the RISC program, a readily implementable data-driven approach was developed to identify secondary crashes using high-resolution traffic data. The developed approach aims to better capture traffic flow characteristics, such as speed, that change over space and time and affect the queue formation caused by the primary incident.

The study also developed a data-driven approach to estimate delays for incidents attended to by RISC as one of the responding agencies and *control incidents* not attended to by RISC. The use of high-resolution traffic-related data eliminates the static limitation on the spatial and temporal extent of delays due to incidents. The proposed method for estimating the incident-related delays focused on identifying the spatial and temporal impact of an incident using speed and volume data. This method better captures the changes in the traffic demand and driver reaction to incident-related queues upstream of the incident location.

3.3 Data and Study Area

The study area, shown in Figure 3.1, includes the I-75 section in Florida. The section is about 144 miles in length, spanning from the junction between I-75 and Florida's Turnpike Mainline (SR-91) to the Florida-Georgia State line. The study corridor passes through FDOT Districts 2 and 5.

The following data types, collected between the years 2016 and 2019, were used:

- Traffic incidents from the SunGuide® database,
- RISC implementation logs,
- High-resolution traffic data from the Regional Integrated Transportation Information System (RITIS) platform, and
- Roadway geometric characteristics, i.e., on- and off- ramps from Google Maps and Google Earth Pro.

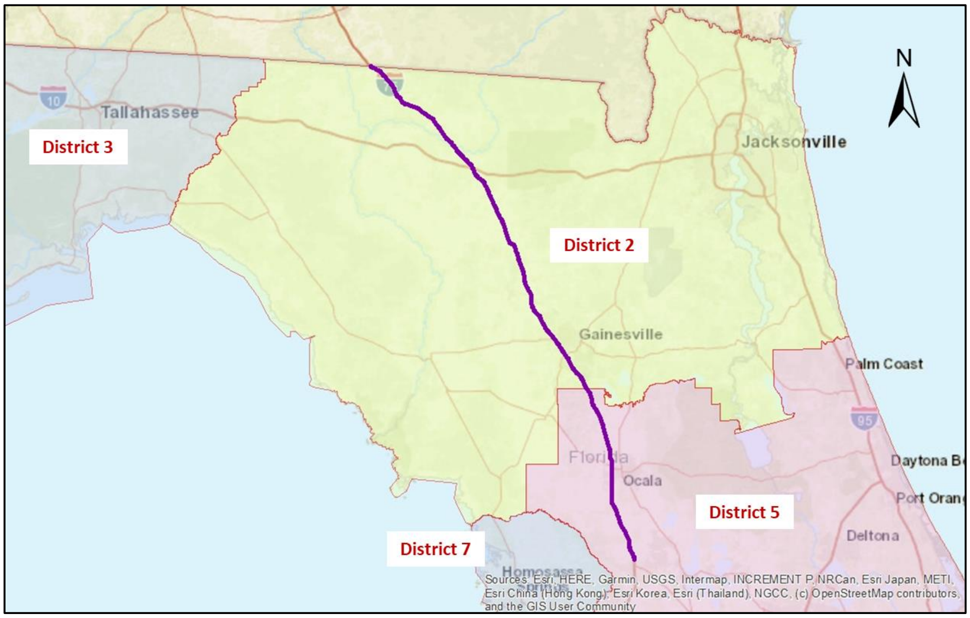


Figure 3.1: RISC Study Corridor

3.3.1 SunGuide® Data

The study used incident data retrieved from the SunGuide® database. During the study, the following information was worth using:

- event ID,
- latitude and longitude of the event location,
- incident notification date and time,
- event type, i.e., crash, flooding, disabled vehicle, debris on roadway, etc.,
- direction,
- county, and
- district.

Approximately 59,157 traffic incidents occurred along the study corridor between the years 2016 and 2019. After removing 15,600 incidents that lacked first notified date information, and 3,763 ramp-related incidents, the final dataset consisted of 39,794 incidents. As indicated in Figure 3.2, about half of the incidents were disabled vehicles. Crashes accounted for 31% of the total incidents along the study corridor during the study period.

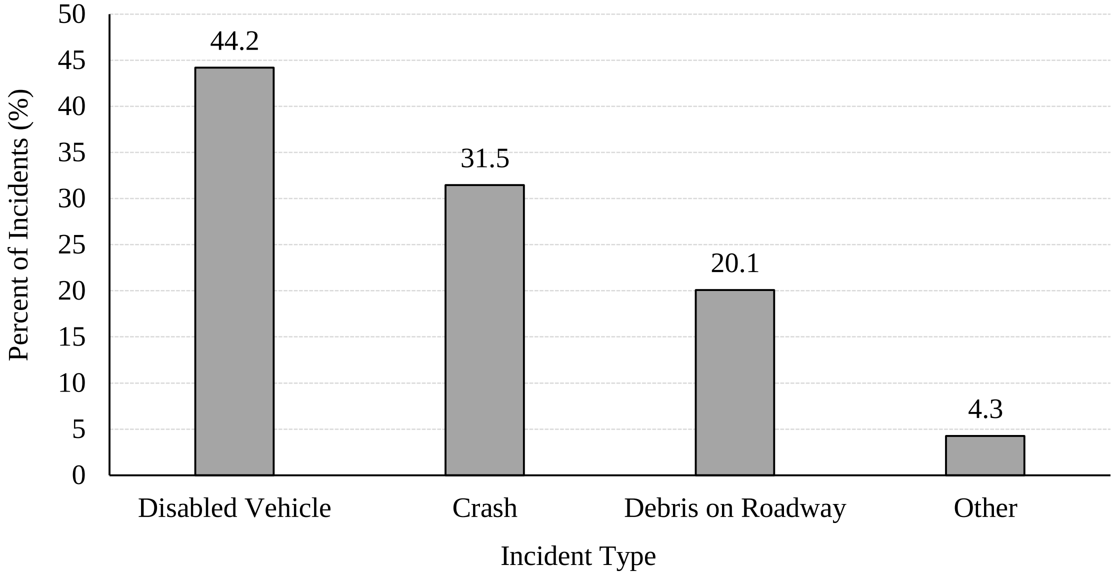


Figure 3.2: Distribution of Incidents by Incident Type

Figure 3.3 shows the distribution of the incidents by different time periods. More than three-quarters of the incidents (86%) occurred between 7 AM and 6 PM. About half (55%) of traffic incidents occurred during peak hours, i.e., morning peak, 6:00 AM to 10:00 AM, and evening peak, 3:00 PM to 7:00 PM. Specifically, 21% of incidents occurred during the morning peak, while the remaining 34% occurred during the evening peak.

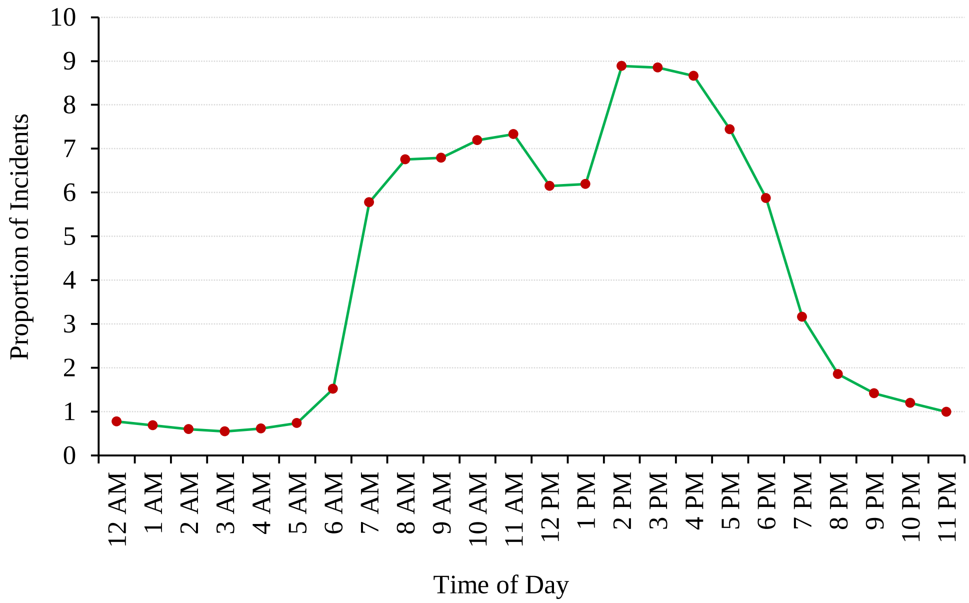


Figure 3.3: Distribution of Traffic Incidents by Time of Day

As indicated in Figure 3.4, the proportion of incidents that occurred on different days of the week did not vary significantly. Notably, the highest proportion of traffic incidents occurred on a Friday (17.3%).

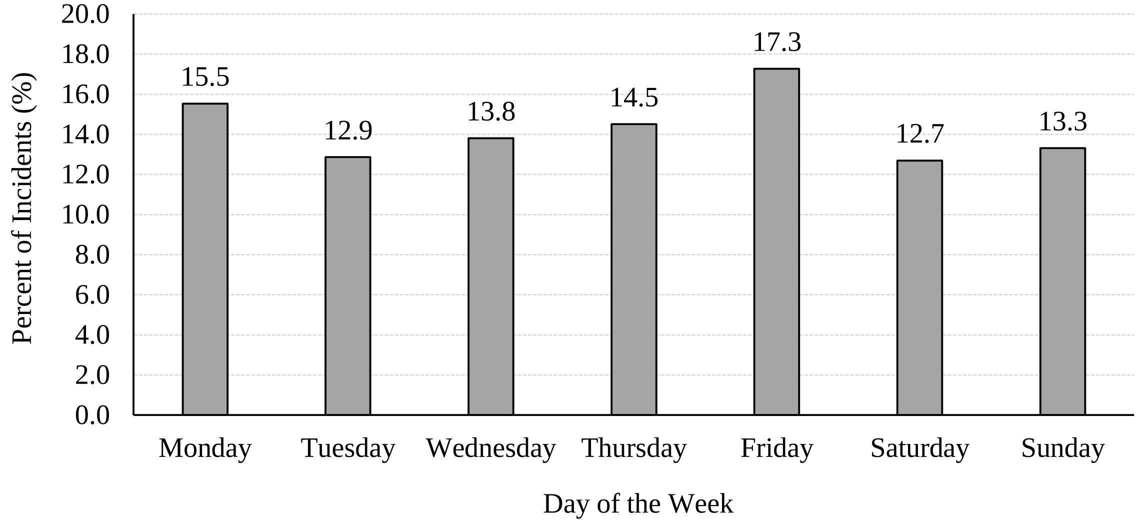


Figure 3.4: Distribution of Traffic Incidents by Day of the Week

As indicated in Figure 3.5, the proportion of incidents in different months increased between January and October, with September as the peak month.

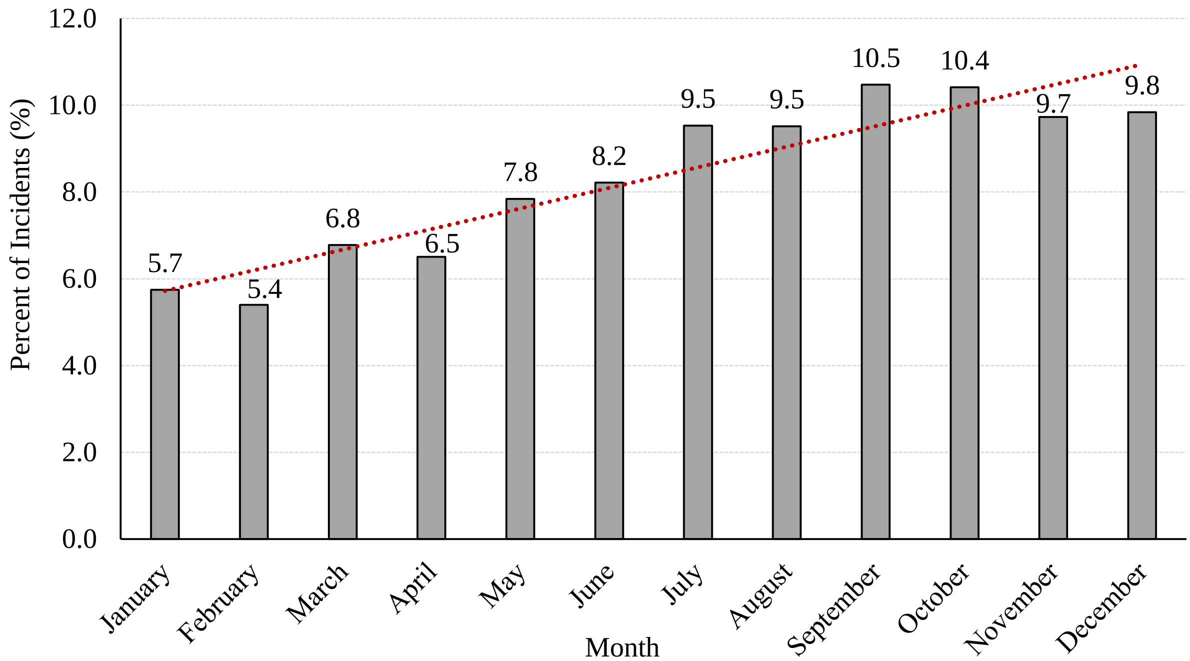


Figure 3.5: Distribution of Traffic Incidents by Month

3.3.2 RISC Implementation Logs

During the study period (2016 – 2019), RISC vendors attended to a total of 36 incidents that occurred along the study corridor. Of the 36 incidents:

- 33 were crashes, and the remaining three were vehicle fire;
- 13 occurred between 2016 and 2017, and the remaining 23 occurred in 2018 and 2019;
- 7 occurred at 2 AM;
- 26 had all lanes closed;
- 32 had a severe impact on traffic; and
- 28 were detected by the FHP.

As indicated in Table 3.2, the median duration of the RISC activation for the 36 incidents attended to by RISC vendors was 24 minutes. RISC vendors took about 47 minutes on average to arrive at the incident scene. The 36 incidents attended to by RISC Vendors had a median duration of 176 minutes. Figure 3.6 illustrates the durations presented in Table 3.2. Hereafter, the 36 incidents attended to by the RISC vendors will be referred to as *treatment incidents*.

Table 3.2: Duration of Incidents Attended To by RISC Vendors

Duration (Minutes)	Min	Mean	Median	SD	Max
RISC Activation	0	36.5	24	59.1	331
RISC Arrival	0	44.6	46.5	15.4	70
Notice to Proceed (NTP)	0	64.7	10	96.9	337
Overall RISC Clearance	21	157.4	76	212.4	1,020
Effective RISC Clearance	21	156.8	76	209.9	998
Incident Duration	64	300.1	176	272.8	1,218

Note: Min = Minimum; Max = Maximum; SD = Standard Deviation.

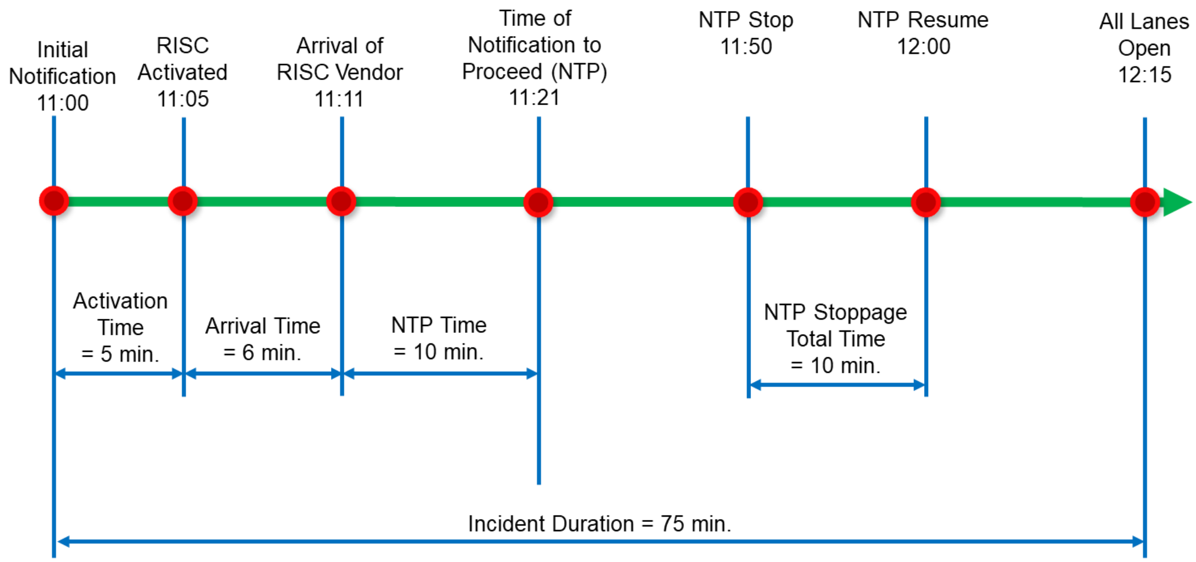


Figure 3.6: Sample Illustrative Timeline for Incidents Attended To by RISC Vendors

3.3.3 RITIS

High-resolution raw traffic data, such as speed in miles-per-hour (mph) and volume (vehicles/20 s), were extracted from RITIS, maintained by the Center for Advanced Transportation Technology (CATT) laboratory. The RITIS database contains traffic data, including speed, volume, and occupancy. There are about 422 RITIS detector stations along the selected freeway corridor (211 in the northbound direction and 211 in the southbound direction). The average spacing between detectors is approximately 0.7 miles. Speed data retrieved from the RITIS database were used to identify secondary crashes. Also, traffic speed and volume data were used to estimate the traffic delay during incidents. Note that, while real-time data could be retrieved from multiple sources, as indicated in Table 3.3, only data from RITIS were readily available during the study period, i.e., 2016-2019.

Table 3.3: Existing and Emerging Sources of Real-time Traffic Data

Data Type	Data Collected From	Data Source	Traffic Data Collected	Data Accessed From
Probe-based systems	• Bluetooth devices • Wi-Fi devices • Cellular devices • GPS	• BlueToad™ • HERE Technologies	• Travel time • Speed	Data could be accessed through the API available with the data providers
Crowdsourced Data	Mapping services	• Waze • Google Maps		
CV Data	OBUs	• From CV test vehicles	• Lane changing, deceleration rate, braking, speed, etc.	Data could be accessed through the RSUs

Note: API = Application Programming Interface; CV = Connected Vehicle; GPS = Global Positioning System; OBU = On-board Unit; RSU = Road Side Unit.

3.4 Methodology

This research conducted a B/C analysis to quantify the safety and mobility benefits of RISC. The B/C analysis was conducted, considering the safety and mobility benefits of the RISC separately. Two primary pieces of information are required to conduct the B/C analysis, i.e., anticipated benefits and costs associated with implementing the RISC program.

A critical element in estimating the safety and mobility benefits of the RISC program is the savings in secondary crashes and incident-related delay, respectively. However, it is challenging to estimate savings in secondary crashes and incident-related delays because such savings can only be concluded from crashes that did not occur and incident-related delay savings, which cannot be documented. To estimate such savings in secondary crashes and incident-related delays that would result from the RISC program, the research team identified incidents along the study corridor that occurred during the study period (i.e., 2016-2019) with similar characteristics as those attended to by RISC vendors, hereafter referred to as *control incidents*. The criteria considered included:

- incident direction,
- incident first notification time,
- presence of on- and off-ramps within a mile upstream and downstream of the incident location,

- incident severity, and
- number of lanes closed following the occurrence of the incident.

A total of 113 *control incidents* were paired with 22 of the 36 *treatment incidents*. Note that the remaining 14 *treatment incidents* were excluded from analysis due to missing high-resolution traffic data. Secondary crashes and incident-related delays associated with the *treatment incidents* and *control incidents* were next estimated. The difference in secondary crash count and incident-related delays associated with *treatment* and *control incidents* was then considered as the anticipated safety and mobility benefits of the RISC program.

3.4.1 Estimate Benefits of RISC Program

In this research, a data-driven approach was used to identify secondary crashes and estimate incident-related delays. This method focused on estimating the impact area of the incident using high-resolution speed data from RITIS detectors. The proposed approach aims to better capture the effects of traffic flow characteristics, such as speed, that change over space and time and affect the queue formation caused by the primary incident. As indicated in Figure 3.7, four main steps were in the proposed data-driven approach to identify secondary crashes and estimate incident-related delays. The following subsections discuss each of the steps in detail.

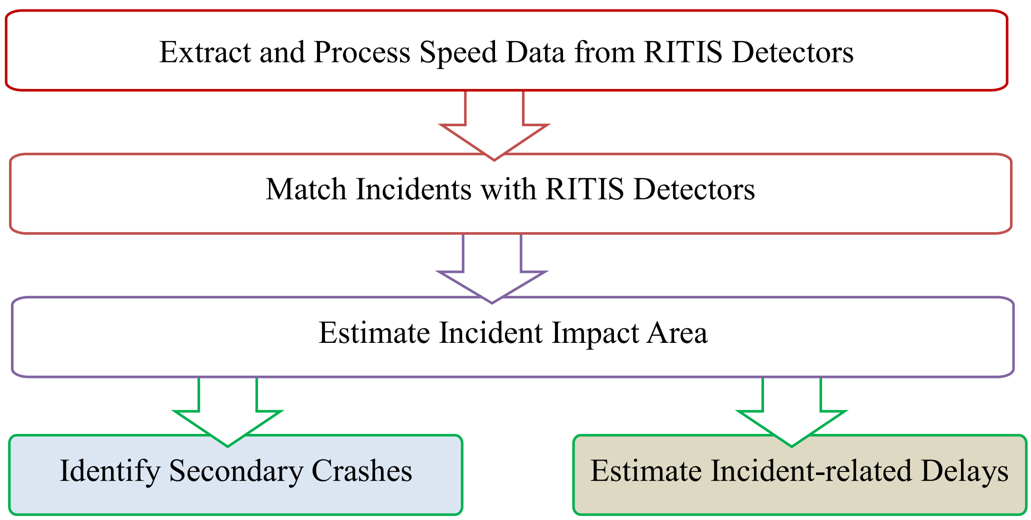


Figure 3.7: Data-driven Approach to Identify Secondary Crashes and Estimate Incident-related Delays

3.4.1.1 Extract and Process Speed Data from RITIS Detectors

High-resolution speed data (aggregated every 20 seconds) were retrieved from 422 RITIS detectors along the study corridor in 2016-2019. These data were used to establish the recurrent speed profile of the roadway segment under normal traffic conditions. The raw speed data were aggregated in a 5-min interval for individual days of the week, and its average was used to establish the recurrent speed profile. Before implementing this step, a boxplot was used to remove abnormal speeds in each 5-min interval dataset. This approach defines a speed as an outlier if a given speed value is outside the data interval (Park & Haghani, 2016). The abnormal speeds were removed because they were considered a result of rare events such as traffic incidents, inclement weather conditions, speeding drivers, detector measurement error, and/or other situations resulting in significant variation in traffic flow characteristics. Besides computing the average of the cleaned speed data, a confidence interval of two standard deviations was established to define the lower and upper bounds (i.e., speed bandwidth) of the speed profile to account for the variation in speeds on a roadway segment.

In summary, for each detector, seven speed profiles were created, one for each day of the week. Independent speed profiles for different days of the week and times of the day were established to account for the recurrent traffic congestion. Figure 3.8 shows a typical speed profile for 24 hours on a Monday. As expected, there is a significant drop in speed during the morning peak hours, while the average speeds were the highest between midnight and 5:00 AM.

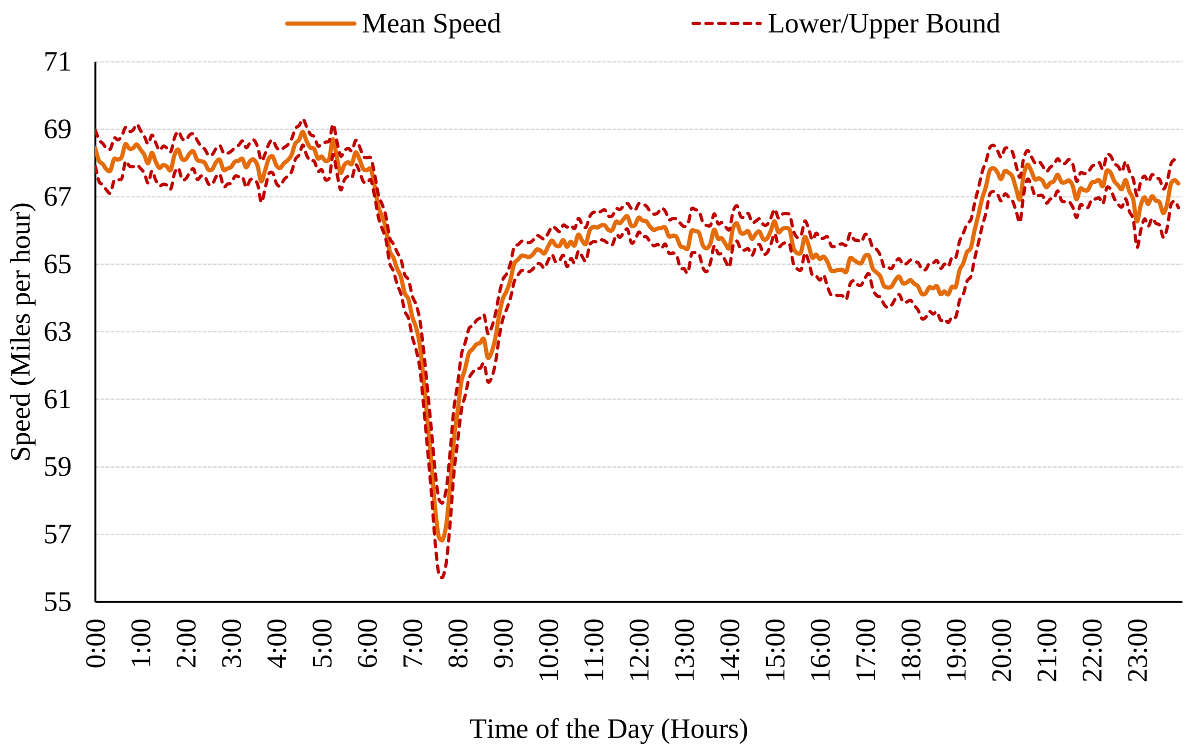


Figure 3.8: Sample Speed Profile on a Typical Monday

3.4.1.2 Match Incidents with RITIS Detectors

The geographic location of both the incidents and the detectors is the most critical information required for matching an incident with the detector. Mile markers (MMs) of incidents and detectors were used instead of the geographic coordinates, i.e., longitudes and latitudes. Through the ArcGIS tool, the Interstates Polyline shapefiles extracted from the FDOT Transportation Data and Analytics Office website were used to assign MMs to the incidents and the start and end of the roadway segments. This approach ensures that roadway alignment characteristics, especially on curved segments, do not affect the accurate computation of the spatial relationship between incidents and spacing between detectors. Using the assigned MMs, each incident was matched with the detector at the incident location.

3.4.1.3 Estimate Incident Impact Area

Traffic incidents and high-resolution traffic data were used to estimate the incident impact area. The impact area was computed for incidents that were successfully matched with the detectors, as discussed in the earlier section. This process was achieved by tracking the reported speeds at the segment where the incident occurred, from the time the incident was detected to the time when the traffic flow returned to normal. An incident was considered to have affected the traffic flow characteristics of the segment when the average speed along the segment was less than the lower boundary of the speed profile. The same procedure was repeated for all the upstream detectors affected by the incident. Next, the time taken for the traffic to return to normal, following the occurrence of an incident, was recorded for each affected detector. Since the incident impact duration along different detectors may differ, the incident impact area was defined for each detector individually. In summary, this process enabled the accurate estimation of the spatiotemporal impact area of the incident. That is, for each impacted detector, the temporal thresholds were defined by the incident impact duration, i.e., from the time the incident was first detected to the time traffic returned to normal.

Figure 3.9 shows an example of the impact area caused by an incident (**PI**) that occurred on January 13th, 2017, in the southbound direction at MM 380.4. In the figure, the x- and y-axes represent the time and length of the affected roadway segments, respectively. Note that each cell in Figure 3.9 represents a speed measurement by the detector at the t^{th} time interval, i.e., 5 minutes in this case. As indicated in Figure 3.9, the impact duration and impact length vary across the five detectors impacted by the incident. While the segment where the incident occurred, i.e., detector 0, has the most extended impact duration, the farthest segment impacted by incident **PI**, i.e., detector 4, has the shortest impact duration.

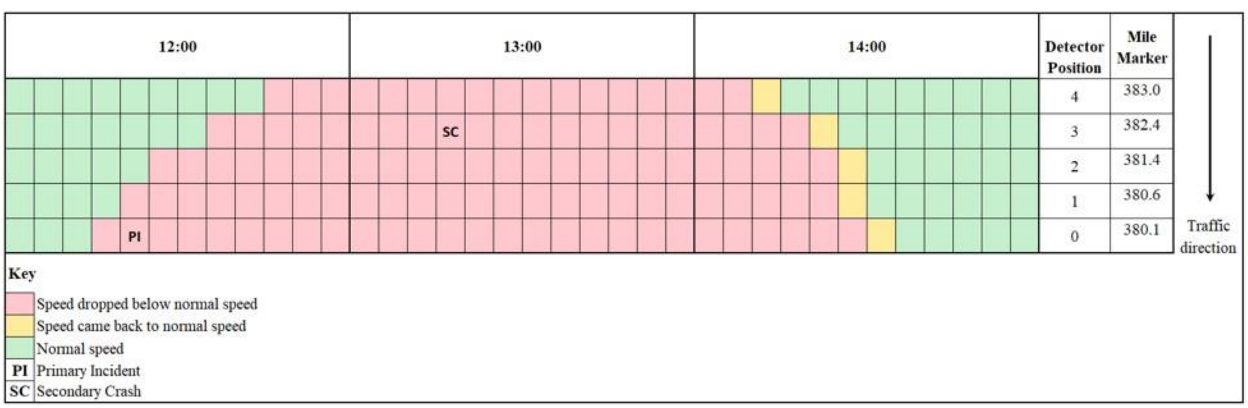


Figure 3.9: Illustration of the Approach to Estimate Incident Impact Area

3.4.1.4 Identify Secondary Crashes

Following the establishment of the area impacted by each incident, the last step was to identify secondary crashes. A traffic crash was considered a secondary crash if it occurred within the prior incident's spatiotemporal impact area. Considering the impact area in Figure 3.9, incident **SC** was considered a secondary crash to incident **PI** since it occurred within the spatiotemporal impact area of incident **PI**.

3.4.1.5 Estimate Incident-related Delays

Incident-related delays were estimated using traffic data from detectors within the incident impact area. A pair of consecutive detectors were used to define roadway segments within the incident impact area, as shown in Figure 3.10. The travel time along a segment was computed by dividing the distance between detectors by the average speed between detectors. Two types of travel times were estimated: (1) travel time during the incident and (2) normal travel time. The travel time during the incident was estimated from the real-time speed during the incident, while the normal travel time was estimated using the speed profiles discussed in Section 3.4.1.1. The difference between the two types of travel times was the extra travel time experienced by traffic passing through the segment during the incident. For each detector within the incident impact area, the traffic volume data were collected from when the incident occurred until the traffic speed returned to normal. The average of the traffic volume recorded on the pair of detectors defining a segment represented the amount of traffic affected by the incident. Estimating the traffic volume using average value accounted for the effect of the distance between detectors and the presence of entrance or exit ramps between the detectors. The incident-related delays were calculated as a product of the extra travel time and amount of traffic (i.e., traffic volume) passing along a segment during the incident. The summation of incident-related delays on all segments within the incident impact area was then recorded as the total traffic delay due to the incident.

Figure 3.10: Sample of Segments for Estimating Incident-related Delays

3.4.2 B/C Analysis

Both investment costs and benefits were converted to monetary values to conduct the benefit-to-cost analysis. The estimated benefits were calculated based on the estimated total secondary crash savings and incident-related delay savings.

3.4.2.1 RISC Program Investment Cost

The main cost component of the RISC program is incentives paid to RISC vendors following the criteria depicted in Figure 3.11.

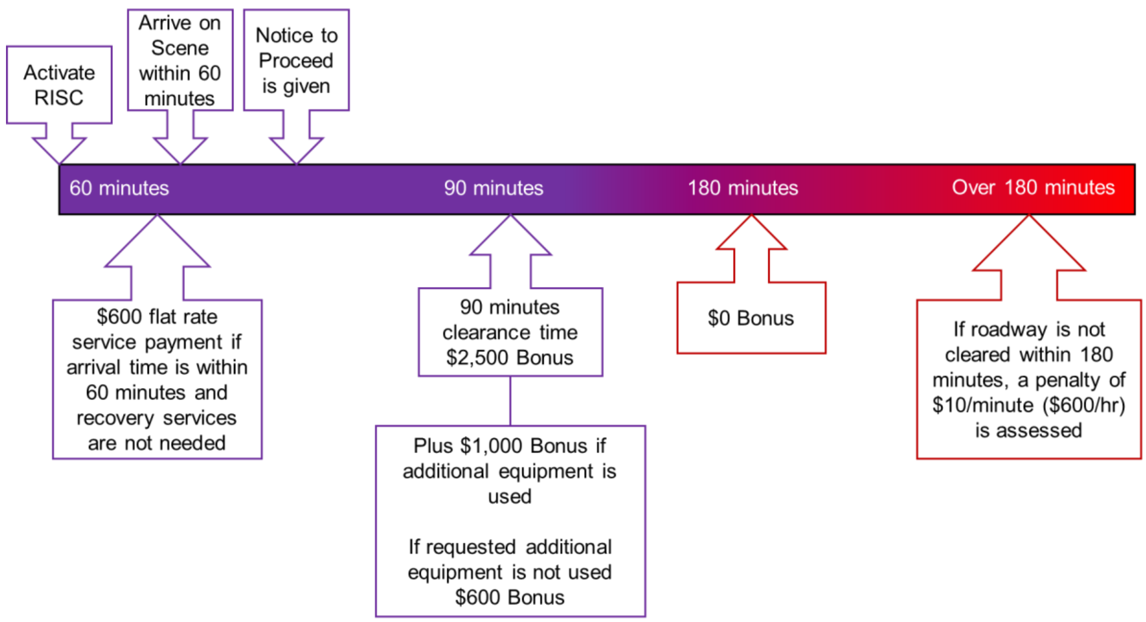


Figure 3.11: RISC Procedure Timeline (FDOT, 2017b)

Table 3.4 shows the total incentives paid to the RISC vendors who attended to the 22 incidents along the study corridor. As indicated in the table, seven RISC vendors received an incentive of $0; one received $600; six received $2,500; and five $3,500. It is unknown how much the RISC vendors received as an incentive for attending to the remaining three incidents. Similarly, as shown in Table 3.4, two vendors were paid the $600 flat-rate service payment. The vendors who attended to nine of the 22 incidents did not receive the $600 service payment. It is unknown whether the vendors who attended to the remaining 11 incidents received any service payments for arriving on the incident scene within 60 minutes.

For the sake of this research, $2,500 and $600 were assumed in cases where it was unknown whether the RISC vendors received the incentive and/or the $600 flat-rate service payment, respectively. After making this assumption, the total cost paid to the RISC vendors who attended to the 22 incidents was $47,800.This assumption provided the most conservative estimate of B/C ratios.

Table 3.4: Incentives Paid to RISC Vendors

Treatment Incident ID	Actual Incentives			Estimated Incentives		
	Incentive Paid	$600 Arrival Paid	Total Incentive	Incentive Paid	$600 Arrival Paid	Total Cost
T1	2,500	0	2,500	2,500	0	2,500
T2	0		0	0	**600**	600
T3	2,500		2,500	2,500	**600**	3,100
T4	2,500	0	2,500	2,500	0	2,500
T5	0		0	0	**600**	600
T6	0	0	0	0	0	0
T7	3,500	600	4,100	3,500	600	4,100
T8	3,500	600	4,100	3,500	600	4,100
T9	3,500		3,500	3,500	**600**	4,100
T10	0	0	0	0	0	0
T11			0	**2,500**	**600**	3,100
T12			0	**2,500**	**600**	3,100
T13			0	**2,500**	**600**	3,100
T14	0		0	0	**600**	600
T15	0		0	0	**600**	600
T16	2,500	0	2,500	2,500	0	2,500
T17	3,500	0	3,500	3,500	0	3,500
T18	3,500	0	3,500	3,500	0	3,500
T19	600	0	600	600	0	600
T20	0		0	0	0	0
T21	2,500		2,500	2,500	**600**	3,100
T22	2,500	0	2,500	2,500	0	2,500
	Total Cost		**$34,300.00**			**$47,800.00**

Note: A **$2,500** and **$600** were assumed in cases where it is unknown whether the RISC vendors received the incentive and/or the $600 flat rate service payment, respectively.

3.4.2.2 Monetary Safety Benefits

The monetary safety benefit was calculated by multiplying the reduction in secondary crashes following the implementation of the RISC program with the average crash cost (Equation 3.1). The average crash cost of $153,130 provided by the FDOT Design Manual was adopted (FDOT, 2020).

$$Total\ safety\ benefit = C_{cost} \times \sum_{i=1}^{n} \left(SC_i^C - SC_i^T \right) \tag{3.1}$$

where,

C_{cost} = average crash cost,

SC_i^C = number of secondary crashes that occurred within the impact area of the *control incidents* in a treatment-control incidents pair i, and

SC_i^T = number of secondary crashes that occurred within the impact area of the *treatment incident* in a treatment-control incidents pair i.

Table 3.5 provides the monetary safety benefits of clearing 22 incidents using RISC vendors as one of the responding agencies. As indicated in the table, the estimated benefit was $275,877.06.

Table 3.5: Monetary Safety Benefits of Implementing RISC Program

Treatment Incident	Average No. Secondary Crashes Caused by *Control Incidents*	No. Secondary Crashes Caused by *Treatment Incidents*	Difference in No. of Secondary Crashes Caused by *Control* and *Treatment Incidents*
T1	0.75	2	-1.25
T2	0.57	0	0.57
T3	1.00	0	1.00
T4	0.00	0	0.00
T5	0.11	0	0.11
T6	0.00	0	0.00
T7	2.33	2	0.33
T8	1.13	0	1.13
T9	0.48	0	0.48
T10	1.00	2	-1.00
T11	0.33	1	-0.67
T12	1.13	2	-0.88
T13	0.00	0	0.00
T14	0.00	0	0.00
T15	0.48	0	0.48
T16	0.50	0	0.50
T17	0.30	0	0.30
T18	0.50	0	0.50
T19	0.20	0	0.20
T20	0.00	0	0.00
T21	0.00	0	0.00
T22	0.00	0	0.00
Sum of Difference in Number of Secondary Crashes Caused by Control and Treatment Incidents			1.80
Total Safety Benefit			**$275,877.06**

3.4.2.3 Monetary Mobility Benefits

The monetary mobility benefits were calculated as a product of the incident-related delay savings due to the RISC program involvement in responding to incidents and the average cost of incident-related delay per vehicle. The incident-related delay savings per incident as a result of the RISC program was calculated using Equation 3.2 as follows:

$$DS = D - D_{RISC} \qquad (3.2)$$

where,

DS = delay savings per incident responded by the RISC program,

D = median delay caused by comparable incidents that were not responded by the RISC program, and

D_{RISC} = median delay caused by incidents that responded by the RISC program.

It is worth noting that the estimation of delay savings used median delays rather than average, minimum, or maximum delays. The average delay was not considered suitable in this case due to a significant small sample size, hence highly susceptible to outliers. The minimum and maximum values only show the extreme cases of the incidents that occurred along the study corridor. The mobility benefits were then estimated using Equation 3.3, as follows:

$$Mobility\ benefits = T_s \times DS \times n \tag{3.3}$$

where T_s is the value of delay time per traveler, n is the number of incidents responded by the RISC program in the study period, and DS is as defined in Equation 3.2. It was assumed that only one individual (driver) is in each delayed vehicle. Therefore, the study provides the absolute minimum benefits because of the RISC program. The cost of delay of $18.12 per person was adopted from Ellis & Glover (2019).

3.4.2.4 B/C Ratio

The B/C ratio was calculated as the ratio of the respective benefits to the corresponding costs. As discussed earlier, the main cost associated with the RISC program is incentives paid to the vendors depending on how early they arrive at the incident scene, how quickly they clear the scene, and the equipment used (Figure 3.11). Since the costs are contract-based and serviced as incentives, there exists no project useful life at the employer's side. For this reason, benefits and costs were not discounted, and the B/C ratios were calculated using all *treatment incidents* and *control incidents*.

3.5. Results and Discussion

3.5.1 Safety Benefits of RISC Program

A data-driven dynamic method was used to identify secondary crashes that occurred within the impact area of *treatment* and *control incidents*. This approach used incident data from the SunGuide® database and high-resolution speed data from RITIS. Overall, the 113 *control incidents* resulted in 52 secondary crashes. Meanwhile, the 22 treatment incidents resulted in nine secondary crashes.

As mentioned earlier in the report, the total cost paid to the RISC vendors who attended to the 22 incidents was $47,800. The estimated benefit of implementing this program was $275,877.06. Thus, the RISC program achieved a safety B/C ratio of 5.78. This implies that for every dollar spent on the RISC program, $5.78 is returned in secondary crash savings.

3.5.2 Mobility Benefits of RISC Program

The traffic delays caused by the *treatment* and *control* incidents were estimated using data collected within the incident impact area. The traffic data used were collected from RITIS. Traffic delays were estimated for the 12 incidents out of the 22 treatment incidents. The incident-related delays for the remaining incidents were not estimated due to lack of RITIS data. The median of traffic delays caused by the treatment incidents was approximately 22 vehicle-hours. Traffic delays were estimated for 65 incidents out of 113 control incidents. The median of traffic delays due to control incidents was approximately 183 vehicle-hours.

The estimated traffic delay savings per incident were approximately 161 vehicle-hours. Considering the cost of delays per vehicle was assumed to be $18.12 per person, the monetary value of the delay savings during the 12 treatment incidents was approximately $34,833. The cost of the RISC program for the 12 treatment incidents extracted from Table 3.4 was $29,000. Therefore, the B/C ratio of the RISC program on mobility was 1.20. This means that there is $1.20 return in incident-related traffic delay savings for every dollar invested in the RISC program.

3.6. Summary

The objective of this task was to conduct the B/C analysis of the RISC program. The B/C analysis was conducted, considering the safety and mobility benefits of the RRSP separately. The safety benefits were estimated based on the estimated reduction in secondary crashes. Secondary crashes occur within the spatiotemporal (impact area) ranges of the primary incidents. The current study used high-resolution speed data to define the impact area of the primary incidents. The proposed method would identify a crash as a secondary crash if it occurred within the impact range of the primary incident. The method aims to better capture the effects of traffic flow characteristics such as speed that change over distance and time and affect queue formation because of a prior incident.

The analysis was conducted using four years of data (2016-2019) collected along a 144-mile section of the I-75. Traffic incidents from the SunGuide® database, high-resolution speed and volume data from RITIS, and roadway geometric characteristics from Google Maps and Google Earth Pro were used to identify secondary crashes and estimate delays associated with incidents attended to by the RISC vendors (i.e., treatment incidents) and incidents not attended to by RISC vendors but with similar characteristics as treatment incidents (i.e., control incidents). The following criteria were used to select control incidents:

- incident direction,
- incident first notification time,
- presence of on- and off-ramps within a mile upstream and downstream of the incident location,
- incident severity, and
- number of lanes closed following the occurrence of the incident

Overall, 113 control incidents were identified and paired with 22 treatment incidents. The two incident categories resulted in 61 secondary crashes, i.e., 52 caused by control incidents and the remaining nine by treatment incidents. The RISC program achieved a B/C ratio of 5.78 when considering the safety benefits. This implies that for every dollar spent on the RISC program, $5.78 is returned in secondary crash savings. The RISC program was associated with a B/C ratio of 1.20 when considering mobility benefits. This indicates that for every dollar invested in the RISC program, there is a return of $1.20 in incident-related traffic delay savings.

CHAPTER 4
BENEFIT-COST ANALYSIS OF ROAD RANGER SERVICE PATROL (RRSP) PROGRAM

This chapter discusses the third task in the research effort to evaluate the performance of CV and TSM&O projects in Florida. It discusses the benefit-cost analysis of the Road Ranger Service Patrol (RRSP) program from both safety and mobility perspectives. The safety B/C was estimated using a reduction in secondary crashes as the performance measure. The mobility B/C was estimated using a reduction in incident-related delay as the performance measure.

4.1 RRSP Program

The RRSP program, also known as the Road Rangers, is a free service to motorists. The program is funded by the Florida Department of Transportation and its partners to help with traffic incident management (TIM). The program was initially used to manage vehicle incidents in construction zones. This program has since expanded to respond to all types of incidents and has become one of the most effective elements of the Department's incident management program. The RRSP program is typically assigned to work along major interstate corridors and within construction areas on interstates. The RRSP program provides traffic incident management response services and limited no-cost highway assistance to motorists to improve mobility and highway safety for emergency responders and the motoring public. The program offers services such as providing a limited amount of fuel, assisting with tire changes and other types of minor emergency repairs, and clearing incidents from travel lanes as quickly as possible. Some of the documented benefits of the program include:

- Increased safety at incident scenes
- Reduction of secondary crashes
- Reduction of incident duration by assisting the Florida Highway Patrol
- Assistance to disabled or stranded motorists
- Removal of road debris
- Reduction of congestion produced air pollutants

The current research estimated the safety B/C ratio using reduction in secondary crashes as the performance measure and the mobility B/C ratio using reduction in incident-related delay as the performance measure.

4.2 Data and Study Area

4.2.1 Safety

4.2.1.1 Study Area

The study area included the I-95 section in Florida. The section is 382 miles long, spanning from highway US-1 in Miami to the Florida-Georgia State line, as shown in Figure 4.1. Two main data types used are traffic incidents; and high-resolution traffic data. Incident data were collected from

January 2017 to June 2019, and speed data were collected from January 2017 through December 2019.

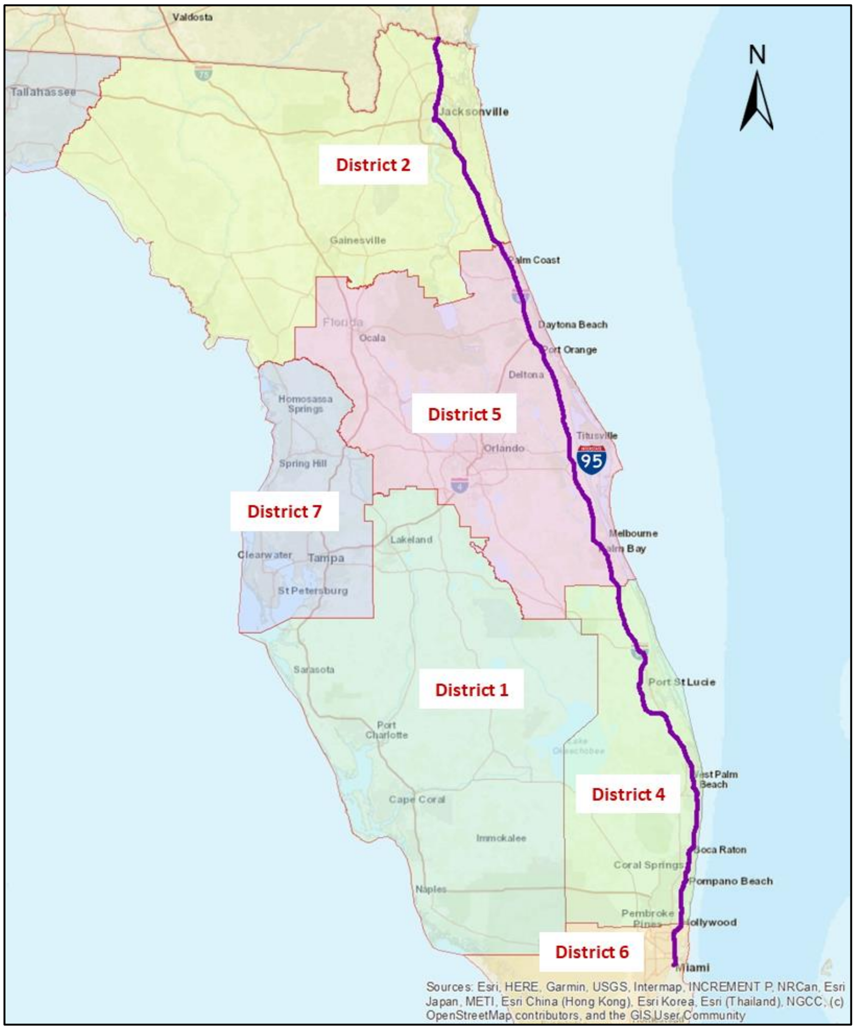


Figure 4.1: Study Corridor

The use of traffic data such as speed enables capturing the effects of traffic characteristics that change over time and space and affect queue formation as a result of the primary incident. As depicted in Table 3.3, traffic data can be collected from different sources, including probe-based systems, crowdsourced-based systems, and Connected Vehicles (CVs). In this research, HERE Technologies were explored. On the other hand, traffic incidents data were retrieved from the SunGuide® database.

4.2.1.2 HERE Technologies

The HERE Technologies record the speed for roadways by dividing them into traffic message channels. Generally, traffic message channels span a stretch from one exit or entrance ramp to the next. There are two types of traffic message channels: internal and external. An internal traffic message channel represents a stretch of road within an interchange, e.g., between an exit ramp and an entrance ramp. An external traffic message channel represents a stretch between interchanges. In this study, HERE Technologies speed data were collected from the RITIS platform. There are 639 traffic message channels along the study corridor. The average traffic message channel length along the study corridor is 1.3 miles (Figure 4.2). As depicted in Figure 4.3, 73% of the traffic message channels along the study corridor are less than a mile in length.

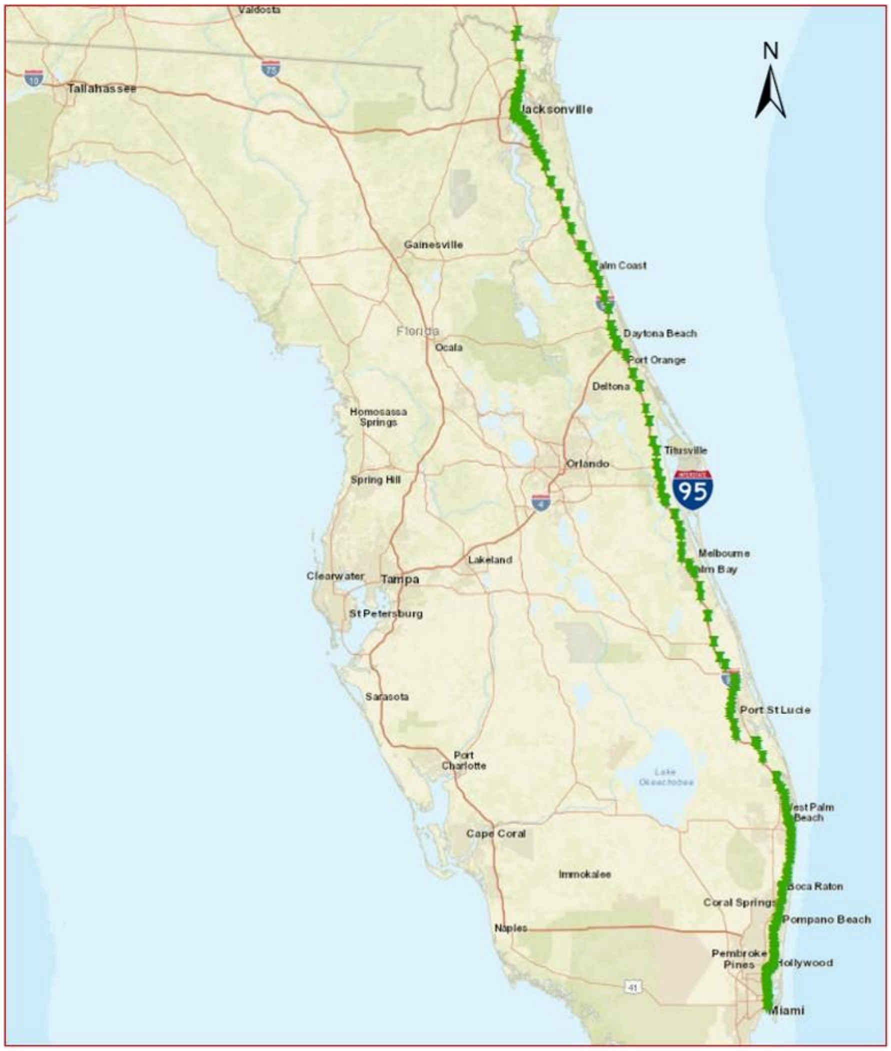


Figure 4.2: Network of HERE Traffic Message Channels along I-95

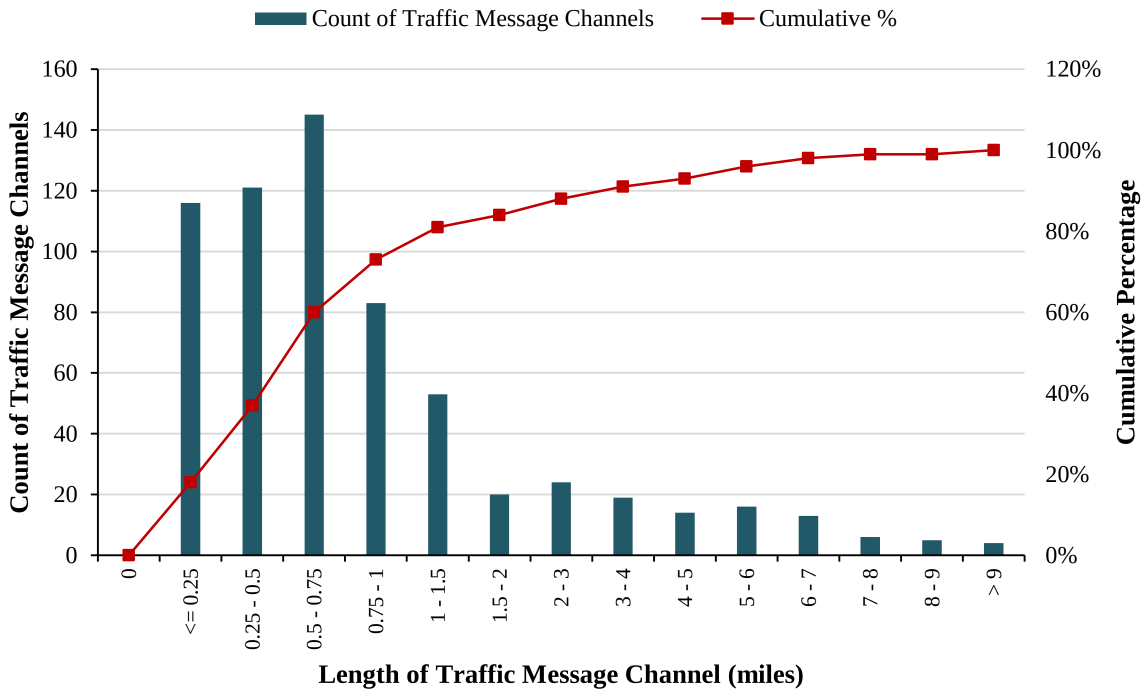


Figure 4.3: Distribution of Length of Traffic Message Channels along I-95

The length of the traffic message channel affects the estimation of the traffic dynamics caused by the incident, including queue formation and dissipation. The use of traffic data from overly long traffic message channels may result in an inaccurate estimation of the traffic flow characteristics changes. The current study limited the traffic message channel length to 8 miles (Table 4.1). Notably, 8.6% of the traffic message channels were more than 8 miles long. Thus, as depicted in Figure 4.4, the final study corridor has three main segments: 131.5-mile-long Segment 1, 129.2-mile-long Segment 2, and 33.5-mile-long Segment 3.

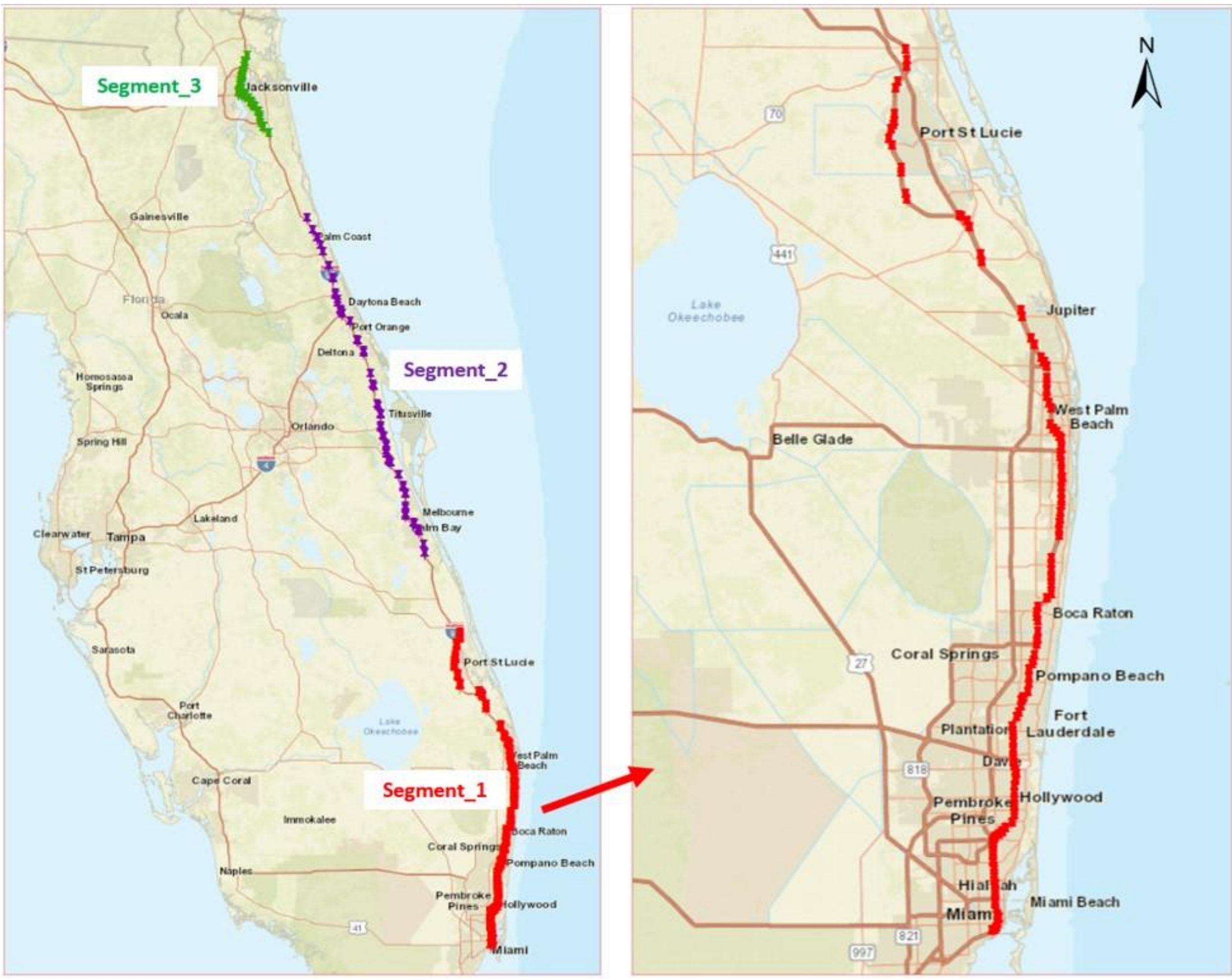


Figure 4.4: Selected Roadway Sections within the Study Corridor

Table 4.1 summarizes the information on Traffic Message Channels along the selected study corridors.

Table 4.1: Distribution of HERE Traffic Message Channels along the Study Corridors

Segment	From	To	Length (mi)	Direction	Number of traffic message channel	Minimum traffic message channel length (mi)	Average traffic message channel length (mi)	Maximum traffic message channel length (mi)
Segment 1	US 1	Orange Avenue	131.5	NB	160	0.01	0.83	7.42
				SB	161	0.01	0.82	7.42
Segment 2	Micco Rd	Matanzas Woods Pkwy	129.2	NB	62	0.06	2.31	7.98
				SB	60	0.06	2.32	7.98
Segment 3	Race Track Rd	Pecan Park Rd	33.5	NB	68	0.01	0.49	2.16
				SB	69	0.01	0.50	2.16
Overall			294.2		580	0.01	1.06	7.98

Note: NB = Northbound; SB = Southbound; mi = miles.

4.2.1.3 SunGuide®

SunGuide® is an Advanced Traffic Management System (ATMS) software used for incident management to process and archive incident data. For this study, the following information was retrieved from the SunGuide® database from January 2017 through June 2019.

- event ID,
- latitude and longitude of the event location,
- incident notification date and time,
- event type, i.e., crash, flooding, disabled vehicle, debris on roadway, etc.,
- direction,
- county, and
- district.

Most of the aforementioned variables are easy to understand. The categories of incident events included in the SunGuide® database are crash, disabled vehicles, debris on roadway, emergency vehicles, police activity, vehicle fire, flooding, pedestrian, abandoned vehicles, congestion, scheduled road work, wrong-way driver, and other. For this study, these categories are further summarized into four groups: crashes, vehicle problems, hazards, and other events. Crashes are self-explanatory. Vehicle problems include all events that are not crashes but are vehicle-related, e.g., disabled vehicles, abandoned vehicles, etc. Hazards include all objects on the roadway with the potential of causing crashes, e.g., debris on roadway, wildlife, etc. Other events encompass all other events that do not fit in the three aforementioned event categories, e.g., other, bridgework, amber alert, wrong-way driver, etc.

Along the study corridor, the SunGuide® database included 361,431 incidents from January 2014 – June 2019. After excluding incidents with missing traffic message channels and other information, the remaining data consisted of a total of 331,599 incidents (Table 4.2).

Table 4.2: Distribution of Incidents by Event Type

General Term	Incident Type	Count	Percent (%)	Count	Percent (%)
Crash	Crash	52,727	15.90	52,727	15.90
Hazard	Debris on Roadway	14,167	4.27	15,613	4.71
	Pedestrian	1,446	0.44		
Vehicle Problems	Abandoned Vehicle	22,992	6.93	193,457	58.34
	Disabled Vehicle	166,104	50.09		
	Emergency Vehicles	2,445	0.74		
	Police Activity	1,358	0.41		
	Vehicle Fire	558	0.17		
Other	Amber Alert	29	0.01	69,802	21.06
	Bridge Work	5	< 0.01		
	Congestion	16,866	5.09		
	Emergency Road Work	221	0.07		
	Evacuation	5	< 0.01		
	Flooding	117	0.04		
	Interagency Coord	2,653	0.80		
	Off Ramp Backup	3,230	0.97		
	Other	35,570	10.73		
	PSA	17	0.01		
	Scheduled Road Work	9,573	2.89		
	Silver Alert	656	0.20		
	Special Event	178	0.05		
	Visibility	105	0.03		
	Weather	408	0.12		
	Wrong Way Driver	169	0.05		
Total		**331,599**	**100**	**331,599**	**100**

Furthermore, 69,802 incidents in the *other* group were excluded. Of the remaining incidents (261,797), 228,070 occurred along Segment 1, 13,550 occurred along Segment 2, and the remaining 20,177 incidents occurred along Segment 3. Table 4.3 presents a summary of incidents by event type. From this table, it can be inferred that nearly three-quarters of incidents (73.9%) reported to occur along the study corridor during the study period are vehicle problems. Crashes were the second most frequent category (20.1%), followed by hazards (6.0%).

Table 4.3: Distribution of Incidents by Event Type along the Different Segments

Event Type	Segment 1		Segment 2		Segment 3		Total Count	Total %
	Count	%	Count	%	Count	%		
Crash	36,749	14.0	7,313	2.8	8,665	3.3	52,727	20.1
Hazard	11,183	4.3	2,511	1.0	1,919	0.7	15,613	6.0
Vehicle Problems	180,138	68.8	3,726	1.4	9,593	3.7	193,457	73.9
Total	**228,070**	**87.1**	**13,550**	**5.2**	**20,177**	**7.7**	**261,797**	**100**

Figure 4.5 provides the distribution of incidents that occurred within the study area by type and time of day. As expected, most crashes occurred during peak hours – particularly during the evening period (34%) – accounting for more than half of all crashes (60%). Similarly, most of the incidents related to vehicle problems occurred during peak hours (57%), i.e., 26% during the

morning peak period and 31% during the evening peak period. Hazard-related incidents were proportionally and approximately equal (29%) during both morning and evening peak periods.

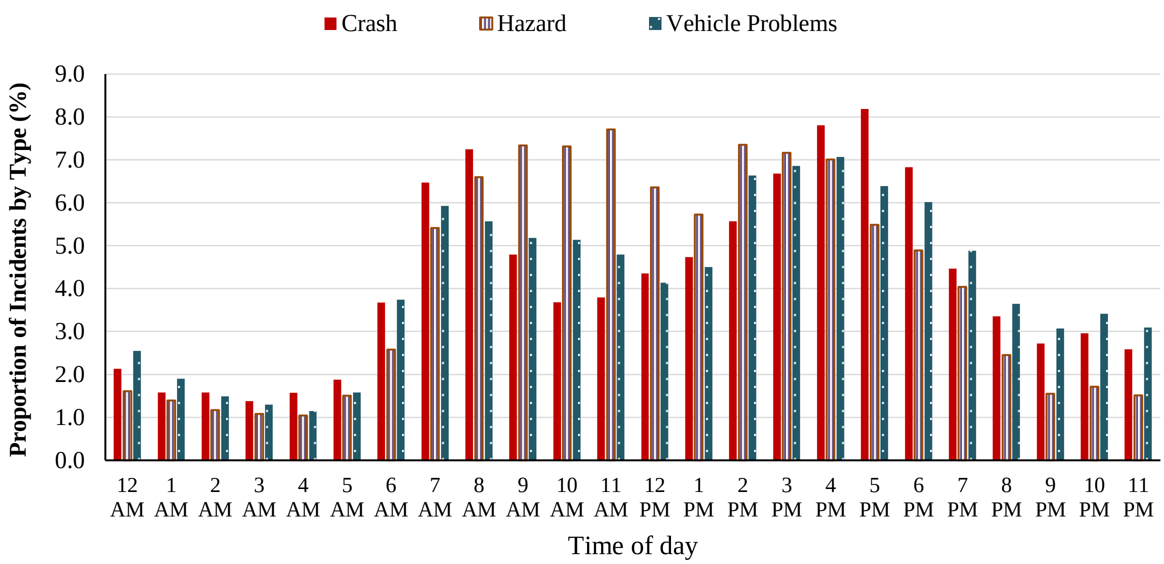


Figure 4.5: Distribution of Incidents by Event Type and Time of Day

Figure 4.6 indicates no significant difference in the number of incidents that occurred on different days of the week. The highest proportion of crashes occurred on Friday (16.7%), while the least proportion of crashes occurred on the weekend, i.e., Saturday (12%) and Sunday (11%).

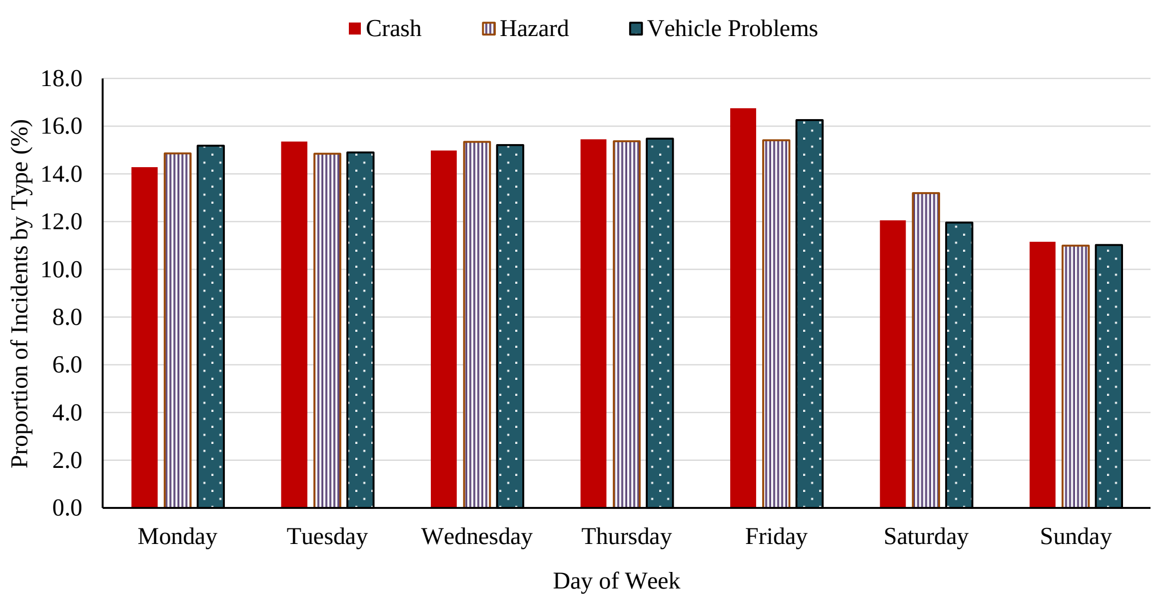


Figure 4.6: Distribution of Incidents by Event Type and Day of the Week

4.2.1.4 RRSP Operations

Along interstate 95 (I-95) in Districts 4, 5, and 6 in Florida, the program deployment and hours of operations are summarized in Table 4.4.

Table 4.4: RRSP Program Deployment and Hours of Operations

District	Contractor	Hours of Operations	Analysis Period
District 4 (113.8 mi)	Roy Jorgensen Associates	• Mon - Fri: 24 hours a day, 7 days a week, 365 days a year. • Sat - Sun: 24 hours a day, 7 days a week, 365 days a year.	• 2017 (Jan – Dec) • 2018 (Jan – Dec) • 2019 (Jan – Jun)
District 5 (129.2 mi)	AutoBase, Inc.	• Mon - Fri: 6:30 am - 8:30 pm • Sat - Sun: Not in operation	• 2019 (Apr – Jun)
District 6 (17.20 mi)	Sunshine Towing	• Mon - Fri: 24 hours a day, 7 days a week, 365 days a year. • Sat - Sun: 24 hours a day, 7 days a week, 365 days a year.	• 2017 (Jan – Dec) • 2018 (Jan – Dec) • 2019 (Jan – Jun)

Source: FDOT (2021c).

4.2.2 Mobility

4.2.2.1 Study Area

The study area included a network of Interstates, I-95, I-295, and I-10, in Jacksonville, Florida. The analysis was based on 3,383 incidents that occurred on the study corridors from 2015 to 2017. Figure 4.7 shows the network of the corridors included in the estimation of the mobility benefits of RRSP. The incident, speed, and volume data were extracted from SunGuide®, BlueTOAD™, and RITIS databases, respectively. The SunGuide® database was discussed in Section 3.3.1. The other data sources, including BlueTOAD™ and RITIS, are discussed in the next sections.

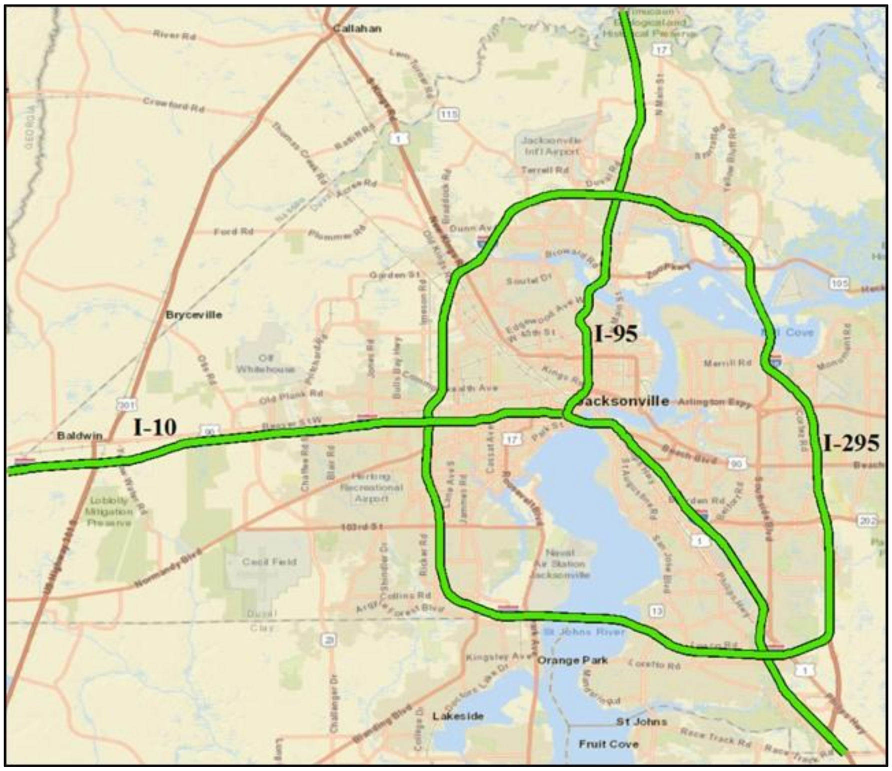


Figure 4.7: Interstates Considered in the Estimation of Mobility Benefits of RRSP

4.2.2.2 BlueTOAD™

The BlueTOAD™ devices act in pairs by matching the unique Media Access Control address (MAC ID) at two Bluetooth reader locations and measuring the travel time and travel speed of the vehicles between the two locations. The study locations have 135 BlueTOAD™ pair devices placed approximately every 1.7 miles on the mainline. BlueTOAD™ devices are Bluetooth signal receivers that read the media access control (MAC) addresses of active Bluetooth devices in vehicles passing through their area of influence. These devices act in pairs by recording the time when a vehicle passes both devices. This information is used to deduce the travel time of the vehicle between a pair of devices. The speed is calculated from the obtained travel time and a known path distance (not Euclidean distance) between the devices. For this research, the traffic speeds, travel time, the device location (latitude and longitude) were retrieved from the BlueTOAD™ database for the years 2015-2017. Figure 4.8 shows the BlueTOAD™ devices within the study area.

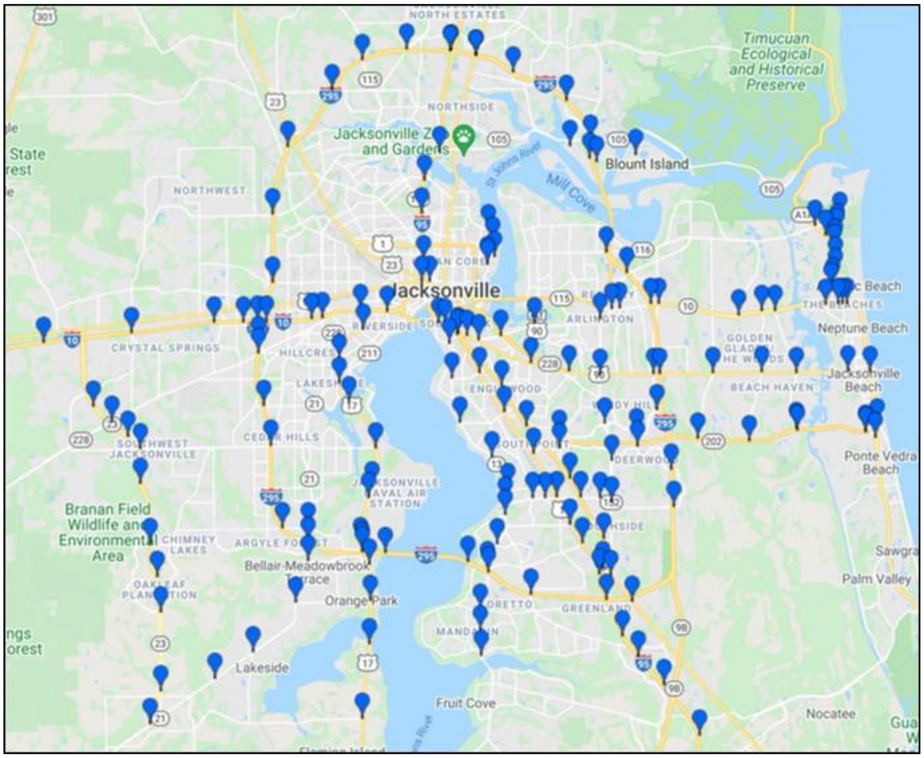


Figure 4.8: A Network of BlueTOAD™ Devices in the Study Area

4.2.2.3 RITIS

Traffic volume data were obtained from RITIS, a database maintained by the CATT laboratory. RITIS is an automated data sharing, dissemination, and archiving system that includes many performance measures, dashboards, and visual analytics tools. The traffic detectors in RITIS are maintained by the FDOT Districts responsible for the freeways in the location. The study area had 609 detectors placed approximately every 0.5 miles on the mainline, collecting traffic data available in RITIS. The following information retrieved from the RITIS database included: volume data aggregated at 15-min intervals and detector location (latitude and longitude).

4.3 Methodology

4.3.1 Estimate Safety Benefits of RRSP Program

A data-driven approach was used to identify secondary crashes in this study. This method focused on estimating the impact area of the primary incident using speed data from HERE Technologies. The proposed approach aims to better capture the effects of traffic flow characteristics, such as speed, that change over space and time and affect the queue formation caused by the primary incident. As indicated in Figure 4.9, four major steps were used to identify secondary crashes using the proposed data-driven approach. The following subsections discuss each of the steps in detail.

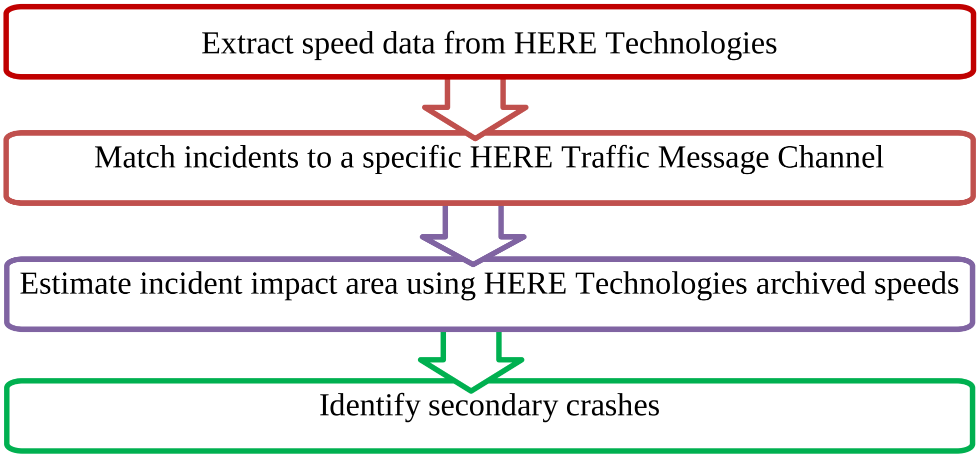


Figure 4.9: Data-driven Approach to Identify Secondary Crashes

4.3.1.1 Extract and Process Speed Data from HERE Technologies

The 5-min speed data from HERE Technologies were retrieved from 639 traffic message channels along the study corridor from January 2017 through December 2019. These data were used to establish the recurrent speed profiles of each traffic message channel under normal traffic conditions. Average speeds in 5-min intervals were used to establish the speed profiles. Additionally, confidence intervals of two standard deviations were established to define the lower and upper bounds of the speed profiles (i.e., speed bandwidth) to account for the variation in speeds on roadway segments. For each traffic message channel, a total of seven speed profiles were generated, one for each day of the week. Independent speed profiles for different days of the week and different times of the day were established to account for the recurrent traffic congestion. An example of a typical speed profile of an individual traffic message channel on a Monday is shown in Figure 3.8.

4.3.1.2 Match Incidents to a Traffic Message Channel

The geographic coordinates (i.e., longitudes and latitudes) of incidents and traffic message channels were converted to miles markers (MMs) to ensure that the spatial relationships between incidents and traffic message channels follow the roadway alignment characteristics, such as horizontal curves. Through the ArcGIS tool, the Interstates polyline shapefiles extracted from the FDOT Transportation Data and Analytics Office website were used to assign MMs to the incidents and the start and end of the traffic message channels.

Each incident was matched to a respective traffic message channel at the incident location using the assigned MMs. MMs increase in the northbound direction; thus, the MM of the incident in the northbound direction is supposed to be higher or equal to the MM of the start of the traffic message channel and lower than or equal to the MM of the end of the traffic message channel. On the other hand, MMs decrease in the southbound direction, and hence the MM of the incident is supposed to be greater than or equal to the MM of the start of the traffic message channel and less than or equal to the end of the traffic message channel. Figure 4.10 provides an example of a 0.25-mile-long traffic message channel on Segment 1.

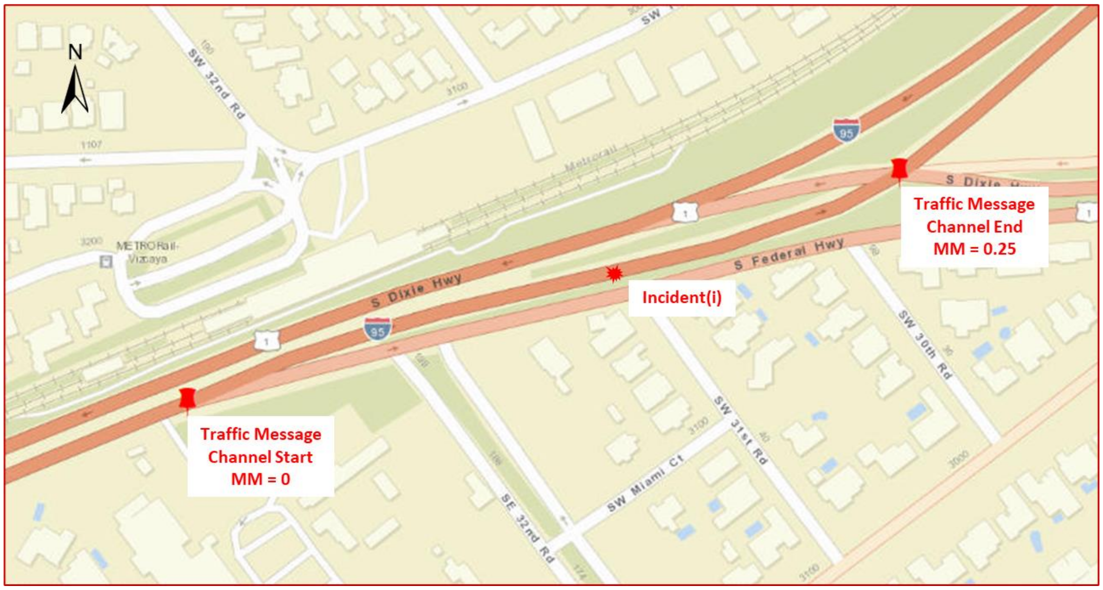


Figure 4.10: Assigning Incident to Traffic Message Channel

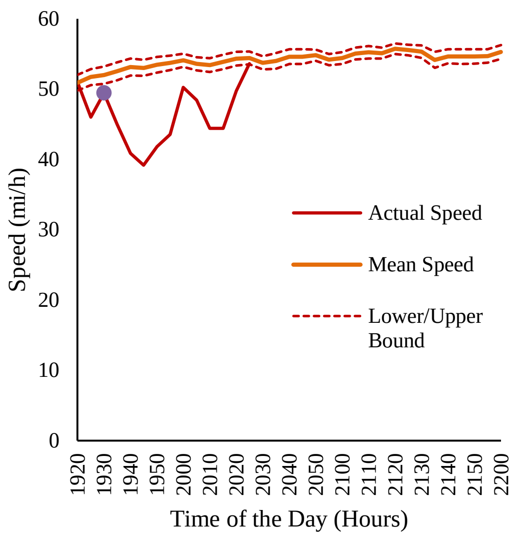
4.3.1.3 Estimate Incident Impact Area

An incident impact area is defined by two boundaries, i.e., spatial and temporal extents, herein referred to as *Incident Impact Length* and *Incident Impact Duration*, respectively. Incident impact duration refers to the time taken for the traffic to return to normal following the occurrence of an incident. On the other hand, the incident impact length refers to the total length of the segment where traffic flow speed was significantly below the normal speed at the 95% confidence interval. In other words, the incident impact area is defined by the length of the queue caused by the initial incident and the amount of time this queue lasts on the freeway. The incident impact area varies depending on the characteristics of the respective incident. As such, it is difficult to measure and hence not recorded in the SunGuide® database.

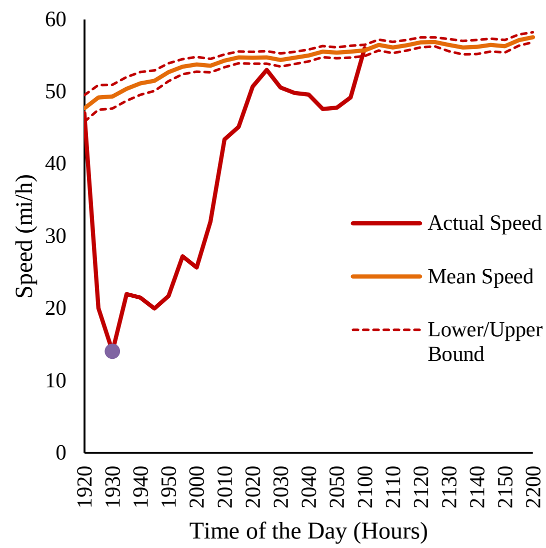
Traffic incidents and high-resolution traffic data were used to estimate the incident impact area. The impact area was computed for incidents that were successfully matched to the traffic message channels. This process was achieved by tracking the speed of the traffic message channel's reported speeds at the segment of the incident occurrence from the time of the incident detection to the time when the traffic flow returned to normal. An incident was considered to affect the traffic characteristics of the segment when the average speed along the segment was found below the lower speed profile boundary. The same procedure was repeated for all the upstream traffic message channels affected by the incident. Next, the time from when the incident occurred to the time when the speed during an incident returned to normal traffic speed for each affected traffic message channel was recorded.

Since the incident impact duration along different traffic message channels may be different, the incident impact area was defined for each traffic message channel. Figure 4.11 shows the typical speed profiles and the speeds of the traffic message channel segment during an incident. The information presented in Figure 4.11 refers to an incident that occurred on Wednesday (1/4/2017) at 07:28 PM along Segment 1 at MM 2.28, in the southbound direction. As can be inferred from

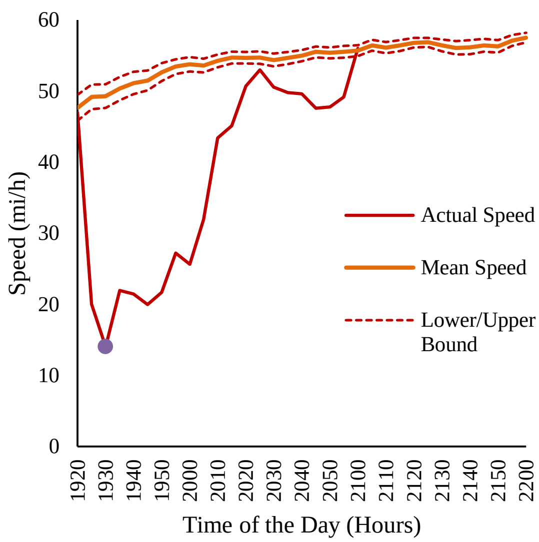
Figure 4.11, this incident impacted four traffic message channels, shown in Figure 4.12, including the one where the incident occurred (referred to as the Traffic Message Channel 0). The incident impact duration of the incident *(i)* varies along the four impacted traffic message channels. While the incident impact durations along the first four traffic message channels were approximately 95 minutes, the impact duration of the incident *(i)* along the first Traffic Message Channel #0 was approximately 60 minutes. The impact on the traffic message channel where the incident occurred started within a few minutes before the occurrence of the incident. It can be observed that the speed along the Traffic Message Channel #0 (location where the incident occurred) came back to normal much earlier than the rest of the traffic message channels.



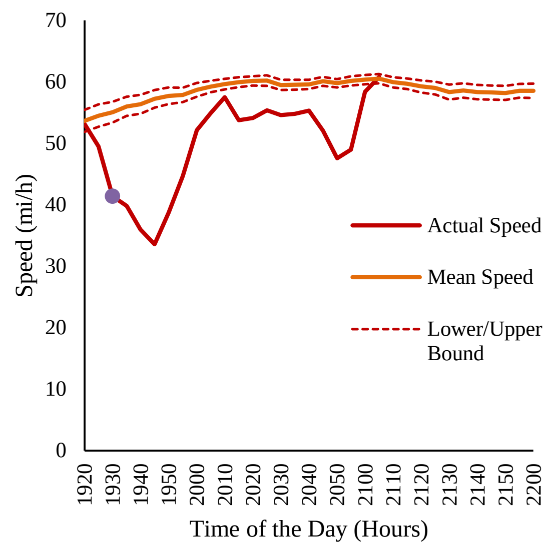
(a) Traffic Message Channel 0



(b) Traffic Message Channel 1



(c) Traffic Message Channel 2



(d) Traffic Message Channel 3

Note: Purple dot represents the first notification time of the incident.

Figure 4.11: Estimation of Incident Impact Duration from Speed Profiles

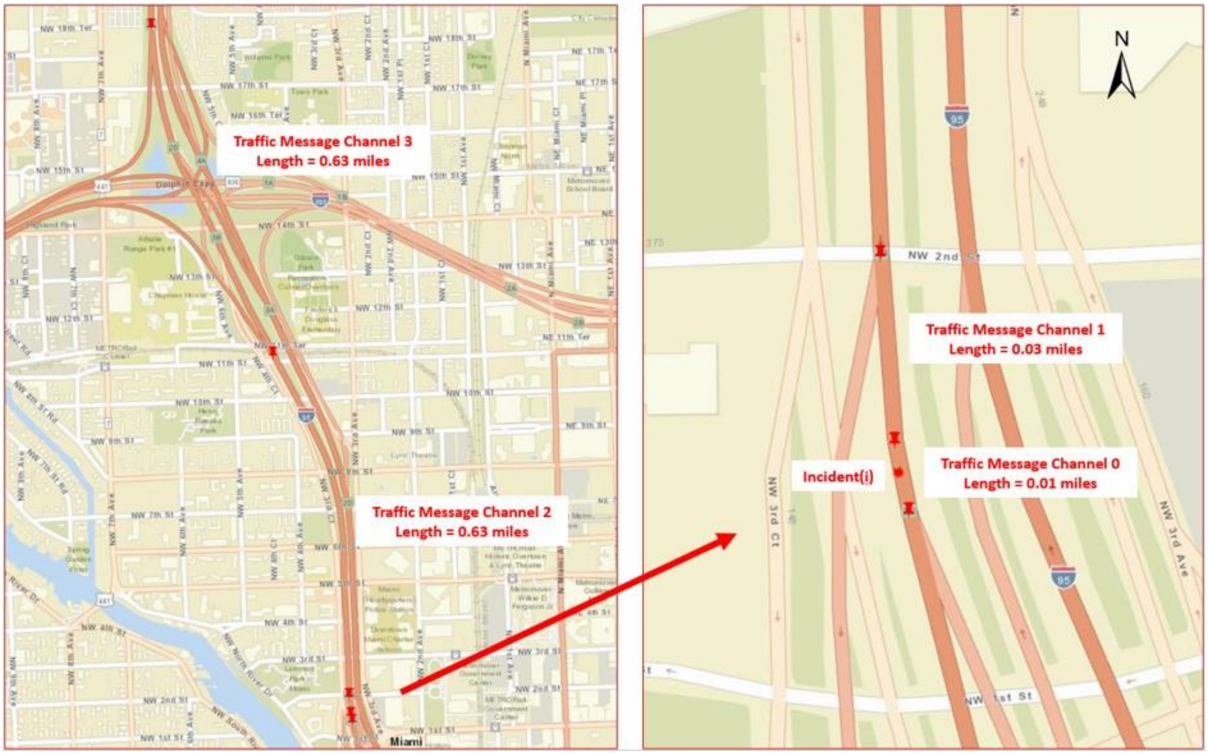
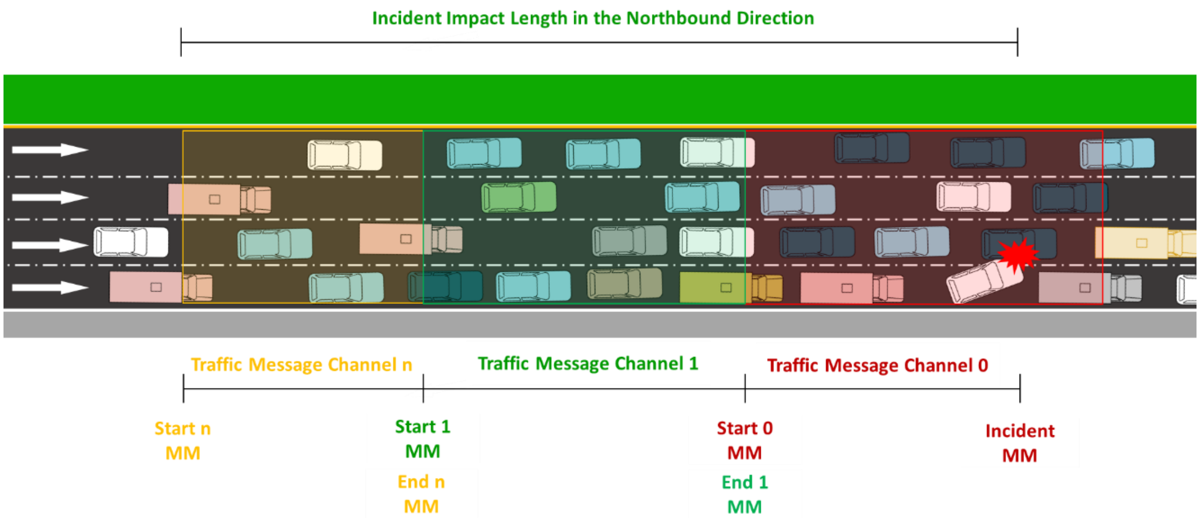
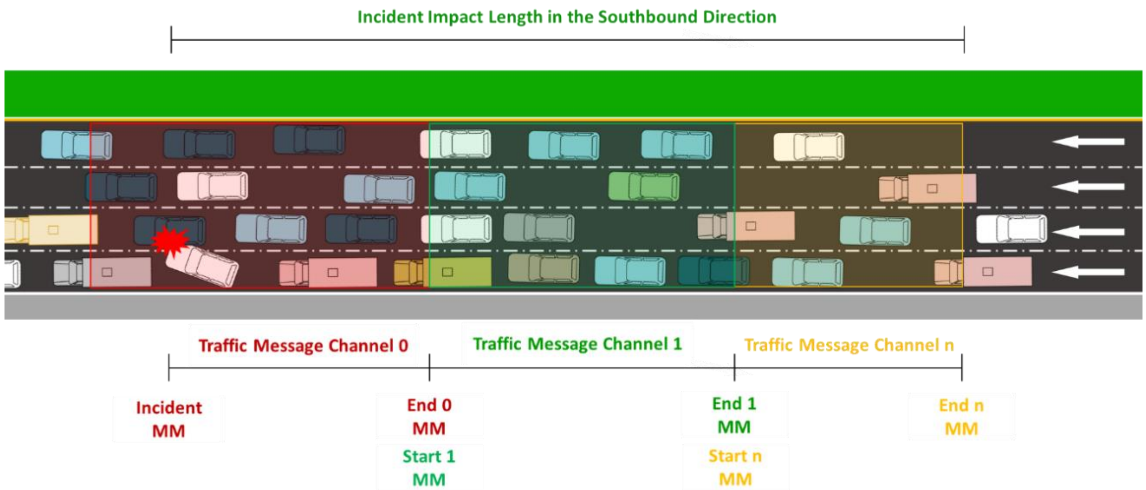


Figure 4.12: Incident Impact on Traffic Message Channels

In summary, this process enabled the estimation of the spatiotemporal impact area of the incident. That is, for each impacted traffic message channel, the temporal thresholds were defined by the incident impact duration, i.e., from the time the incident was first detected to the time the traffic came back to normal. As indicated in Figure 4.13(a), the incident impact length in the northbound direction is defined by the difference in distance between the location of the incident and the start of the last impacted traffic message channel (n). Meanwhile, the incident impact length in the southbound direction (Figure 4.13(b)) refers to the difference in distance between the location of the incident and the end of the last impacted traffic message channel (n).



(a) Definition of Incident Impact Length in the Northbound Direction



(b) Definition of Incident Impact Length in the Southbound Direction

Figure 4.13: Definition of Incident Impact Length

4.3.1.4 Identify Secondary Crashes

The previous three steps in the proposed data-driven approach to identify secondary crashes enabled estimation of the incident impact area. Following the establishment of the area impacted by each incident, the last step was to identify secondary crashes. A traffic crash is considered a secondary crash if it occurred within the spatiotemporal impact area of the prior incident, conventionally referred to as a primary incident. Note that the current study focused on only secondary crashes that occurred in the upstream direction of the primary incidents.

Figure 4.14 describes the example of incidents that occurred on Wednesday, January 04th, 2017, at 7:28 PM, at MM 2.28 in the southbound direction. The primary incident (P1) resulted in significant congestion, i.e., average speeds dropped below the recurring speeds along this corridor. Fifteen minutes later, a secondary crash (SC) occurred at Traffic Message Channel #3, about 1-

mile upstream of the primary incident P1. This crash was considered secondary because it occurred within the incident impact duration and length of the primary incident (P1). Besides, a normal incident (NI) occurred fifteen minutes later but outside the impact length of the primary incident (P1). This incident is not a secondary crash.

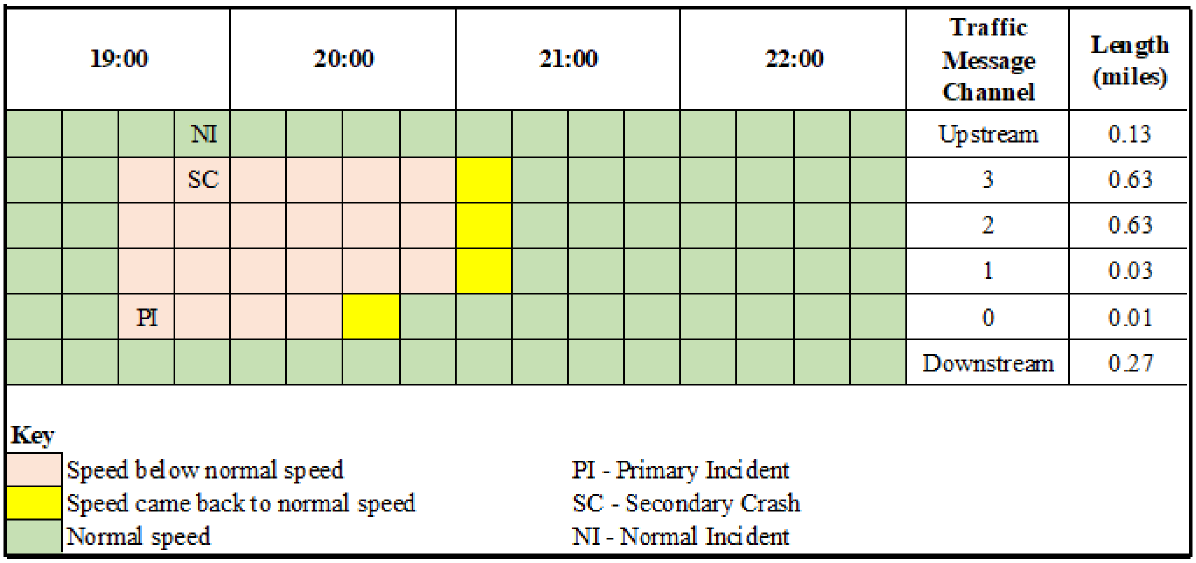


Figure 4.14: Detection of Secondary Crashes Using HERE Technologies Speed Data

4.3.1.5 Benefit-Cost Analysis of RRSP Program

The significant benefits of the RRSP program include incident-related delay savings, reduced fuel consumption and emissions, improved traffic flow, reduced potential for secondary crashes, reduced stress, and an increased sense of security. Previous studies have concentrated on quantifying delay savings and fuel consumption (Lin et al., 2012; Sun et al., 2017). These two aspects make up most of the benefits in terms of dollar value. Few studies were found to deal with the reduction in secondary crashes and other benefits that are difficult to quantify (Guin et al., 2007; Chou et al., 2010).

To conduct the benefit-to-cost analysis, both investment costs and benefits were converted to the monetary values in USD. The estimated benefits were calculated based on the estimated total secondary crash savings. The monetary benefit was calculated by multiplying the reduction in total crashes with the average crash cost.

The following steps discuss the approach used to estimate the benefits and costs:

Step 1: The main cost components of the RRSP program are capital, administrative, and operating costs. These costs depend upon the number of center-line miles covered, hours of operations, and the number of vehicles maintained and are generally included in contracts. In Florida, the RRSP program is managed at the local District level as a contracted service provided by private vendors (contractors). The Florida Department of Transportation (FDOT) is decentralized under legislative mandates known as Districts. Concerning the

RRSP program, the FDOT's Central Office TIM personnel facilitate program issues of statewide interest. As such, the costs of the RRSP program along the corridor differed as three Districts administratively managed it. Thus, the costs were requested from each District.

Step 2: A vital element in estimating the safety benefits of the RRSP program is the savings in secondary crashes. It is difficult, though, to estimate savings in secondary crashes, because such savings can only be concluded from crashes that did not occur, which cannot be documented. To estimate such savings in secondary crashes that would result from the RRSP program, Equations (4.1) and (4.2) were used. The crash modification factor was obtained from (Alluri et al. 2020). The crash savings for each of the service year Y was converted into monetary terms using Equation (4.3). The average crash cost of $153,130 provided by the Florida Design Manual was adopted (FDOT, 2020).

$$N_w = \frac{N_b}{CRF} \tag{4.1}$$

$$N_s = N_w - N_b \tag{4.2}$$

$$Benefit_Y = N_s * C_{cost} \tag{4.3}$$

where,

N_b : Number of secondary crashes found in the database, with the presence of RRSP program,

N_w : Estimated number of secondary crashes in the absence of RRSP program,

N_s : Number of secondary crashes saved,

CMF : Crash modification factor, CMF = 0.791, and

C_{cost} : Average crash cost.

Step 3: The B/C ratio was calculated as the ratio of the respective service year benefits to the corresponding service year costs. As discussed earlier, the costs of the RRSP program depend upon the number of center-line miles covered, hours of operations, and the number of vehicles maintained and are generally included in contracts. Since the costs are contract-based and serviced as rates, there exists no sense of project useful life at the employer's side. For this reason, benefits and costs were not discounted, and the B/C ratios were calculated solely per each service year.

4.3.2 Estimate Mobility Benefits of RRSP Program

This research used travel time and traffic volume on roadway segments with and without an incident to estimate the traffic delays due to an incident. The following sections discuss the procedure used to estimate the traffic delays caused by incidents. As indicated in Figure 4.15, five major steps were followed to estimate the traffic delays caused by incidents. The next subsections discuss each of the steps in detail.

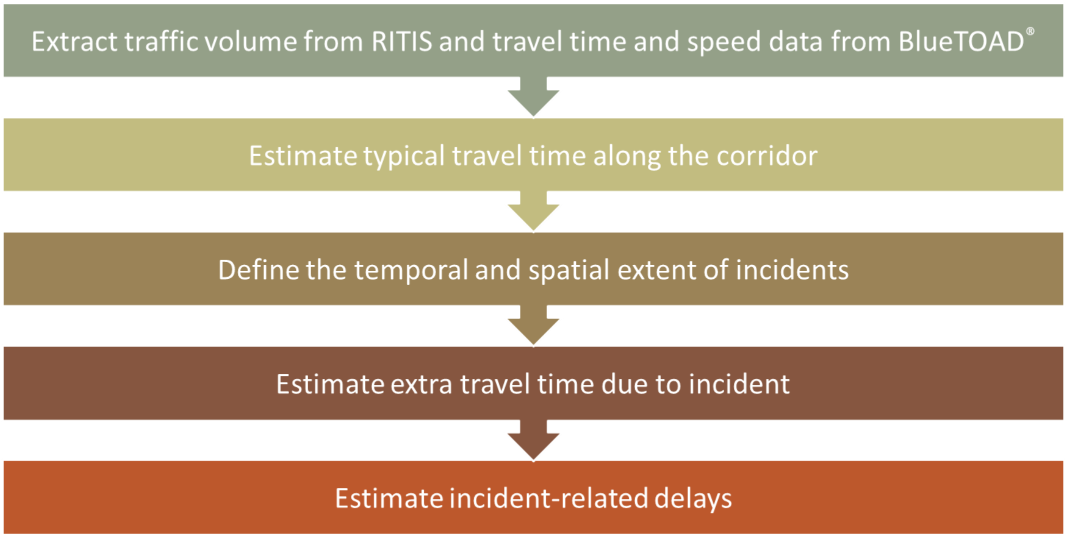


Figure 4.15: Data-driven Approach to Estimate Delays Due to Incidents

4.3.2.1 Establishing the Normal Travel Time Profile

Speed data aggregated in 15-minute intervals were collected from all the BlueTOAD™ pairs in the study network for the years 2015 - 2017. The data were aggregated in 15-minute intervals to obtain stable traffic flow rates. The speed data were used to establish the recurrent speed profile of each pair under normal traffic conditions. The speed profile was defined by the average 15-minute speed and the 95% confidence interval to define the upper and lower bounds of the profile and consider the variations in the recurrent speed.

4.3.2.2 Defining Temporal and Spatial Extent of Incidents

Every incident was mapped to the corresponding BlueTOAD™ pair using geographical coordinates of the incident and BlueTOAD™ devices. The date and time of the incidents were matched to the corresponding date and time in the speed data from the BlueTOAD™ pair to extract the speeds during an incident. The speeds during an incident were compared to the recurrent speed profile from the time an incident occurred. Traffic speeds below the lower boundary of the speed profile were tracked from the incident occurrence time to the time the speeds were above the lower boundary of the recurrent speed profile. The duration during which the speeds were below the normal profile was defined as the temporal extent of an incident (i.e., incident duration including recovery time).

The algorithm also checked for pairs upstream of the incident BlueTOAD™ pair that showed speeds that were below the lower boundary of the speed profile during the incident duration. The BlueTOAD™ pairs upstream of the incident pair that met the requirement had their speeds tracked in the same way to the BlueTOAD™ pair at the incident location. The number of the affected BlueTOAD™ pairs upstream of the incident defined the spatial extent of the incident.

4.3.2.3 Estimating Total Incident Delays

Speeds during the incident duration (i.e., time of occurrence of an incident to time when speeds return within the speed profile boundary) from all the affected BlueTOAD™ pairs and the distance between devices was used to calculate the travel time along the segment during an incident. The extra travel time for all the affected pairs was calculated as the difference between the profile travel time and the estimated travel time during an incident.

Traffic detectors in RITIS in the proximity of the affected BlueTOAD™ pairs were identified to obtain the volume data (aggregated in 15-minute intervals) related to the extra travel time. The traffic detectors in RITIS were limited by the lack of devices to monitor entry or exit ramps along some of the corridors. Therefore, for each segment, the average traffic volume was recorded by the detectors along the basic freeway segments. Traffic volumes were collected by matching the date and time during the incident duration to the date and time of volume data. The recorded volume was multiplied by the corresponding extra travel time delay to obtain the incident delay for each BlueTOAD™ pair for each 15-minute interval of the incident duration. The summation of all the estimated delays in each affected BlueTOAD™ pair was recorded as the total incident delay.

4.3.2.4 Benefit-Cost Analysis of RRSP Program

To conduct the benefit-to-cost analysis, the benefits were converted to the monetary values in USD and were compared to the costs of running the RRSP program. The estimated benefits were calculated based on the delay savings during traffic incidents. The procedure for estimating the benefits-to-cost ratio is summarized in the steps described below.

Step 1: The average delay of incidents that the RRSP program was the first responder at the incident scene in the study period (2015 – 2017) was estimated. Similarly, the average delay of incidents that the RRSP program was the first responder at the incident scene was calculated. The average delays were used to estimate the delay savings per incident using Equation 4.4:

$$DS = D - D_{rrsp} \tag{4.4}$$

where, DS is the delay savings per incident, D is the average delay of incidents that RRSP program was not the first responder at the incident scene, D_{rrsp} is the average delay of incidents that RRSP program was the first responder at the incident scene.

Step 2: The delay savings in the target year were estimated by multiplying the delay savings by the number of incidents in the target year. The delay savings in the target year were estimated using Equation 4.5:

$$DS_i = DS \times I_{rrsp} \tag{4.5}$$

where, DS_i is the delay savings due to RRSP in target year i (in this study, the target year was 2018), DS is the delay saving per incident in the study period, and I_{rrsp} is the number of incidents in which the RRSP program was the first responder at the incident scene in the target year.

Step 3: The benefits of RRSP in target year *i* were estimated by multiplying the total delay savings due to RRSP by the monetary value of a delay per traveler. It was assumed that each vehicle had one person, as such, the study estimated the minimum benefits of RRSP. The benefits were estimated using Equation 4.6:

$$Benefits_{rrsp} = DS_i \times T_s \tag{4.6}$$

where, $Benefits_{rrsp}$ are the benefits of RRSP in monetary value, DS_i is the delay savings due to RRSP in target year *i*, and T_s is the value of delay time per traveler. The value of T_s for this study was $18.12 per person per hour, adopted from Ellis & Glover (2019).

Step 4: The benefit-to-cost ratio (B/C) was estimated by dividing the benefits of RRSP in the target year by the cost of operating the RRSP in the same year. The operating cost of RRSP in the target year *i* was obtained from the agency managing the RRSP. In this study, the cost of RRSP in 2018 was estimated using monthly operating costs. Considering that the costs of RRSP from July 2018 to December 2018 included the RISC program, the operating costs for RRSP in these months were extrapolated from the operating costs in January 2018 to June 2018.

4.4 Results and Discussion

4.4.1 Safety Benefits of RRSP Program

A data-driven dynamic method was used to identify secondary crashes that occurred between January 2017 and June 2019. This approach used incident data from the SunGuide® database and high-resolution speed data from HERE Technologies. Because the high-resolution speed data are one of the input variables for the proposed approach, secondary crashes could only be identified along corridors with HERE traffic message channels. Overall, 3,906 secondary crashes were identified from 3,547 primary incidents. The identified secondary crashes in the upstream direction of the primary incidents accounted for 1.5% of the 261,797 incidents used in the analysis. The 3,547 primary incidents that induced secondary crashes represented 1.4% of all normal incidents (Table 4.5). These results indicate that approximately one in every 70 normal incidents was associated with a secondary crash in the upstream direction. Each primary incident caused an average of 1.1 secondary crashes. In Table 4.5, compared to other road segments, Segment 3 experienced the highest proportion of secondary crashes throughout the entire study period (3.0%). On the other hand, Segment 1 experienced the highest secondary crashes per mile (23.6 crashes per mile).

Table 4.5: Distribution of Secondary Crashes along the Study Segments

Segment	Segment Length (miles)	Normal Incidents	Primary Incidents	Secondary Crashes	All Incidents	Secondary Crashes per Unit Length	Proportion of Secondary Crashes (%)
Segment 1	131.5	225,222	2,848	3,097	228,070	23.6	1.4
Segment 2	129.2	13,372	178	203	13,550	1.6	1.5
Segment 3	33.5	19,656	521	606	20,177	18.1	3.0
Overall	294.2	258,250	3,547	3,906	261,797	13.3	1.5

As indicated earlier in this report, traffic incidents tend to result in additional incidents called secondary crashes. Traffic incidents that result in additional incidents are conventionally called primary incidents. Occasionally, secondary crashes tend to become primary incidents for other crashes conventionally referred to as tertiary crashes. In other words, there are some primary incidents that result in a series of cascading events, as indicated in Figure 4.16.

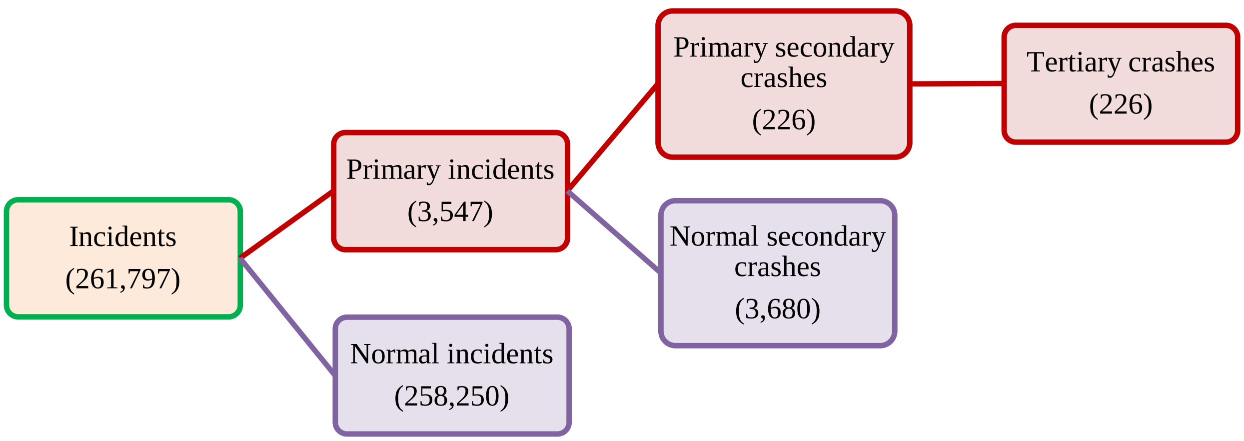
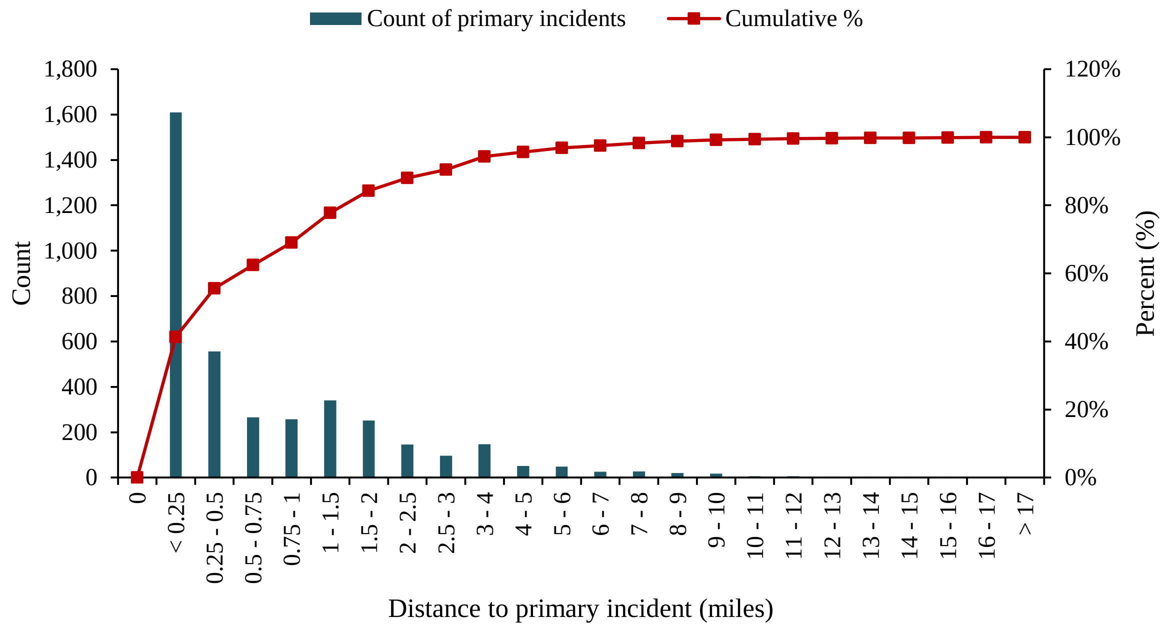


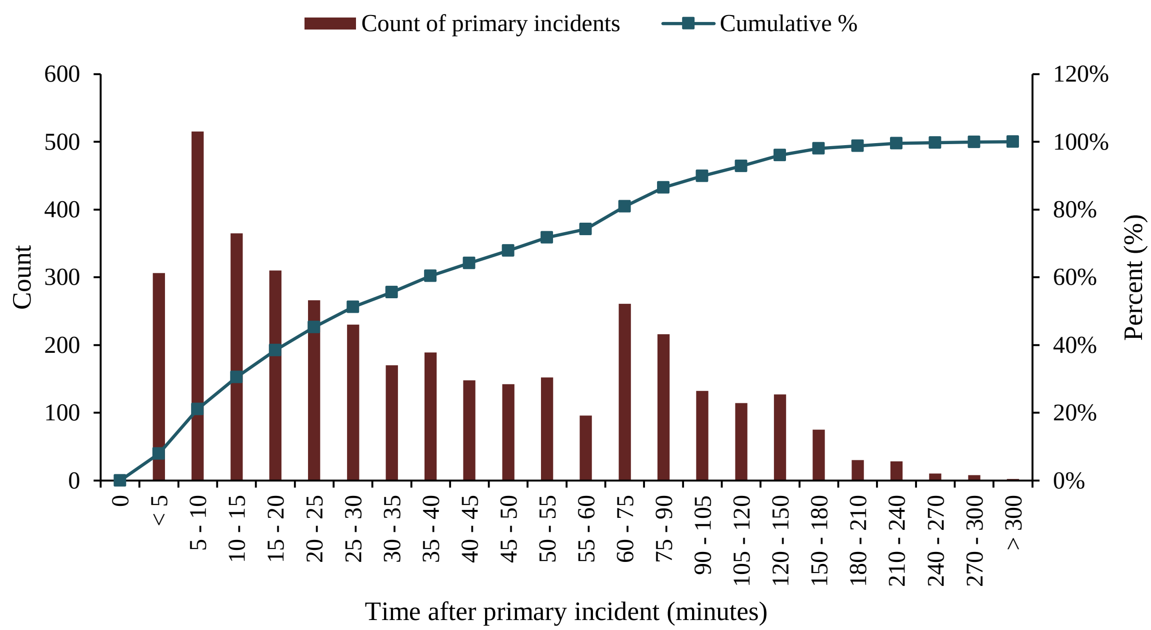
Figure 4.16: Occurrence of a Tertiary Crash

4.4.1.1 Spatiotemporal Distribution of Secondary Crashes

Figure 4.17 shows the spatial and temporal characteristics of secondary crashes in relation to primary incidents. The average incident impact length is 1.82 miles, and the median incident impact length is 0.6 miles. More than three-quarters of secondary crashes (84%) occurred within 2 miles upstream of the primary incident. On the other hand, the average incident impact duration is 42 minutes, and the median incident impact duration is 20 minutes. About 93% of secondary crashes occurred within 2 hours. Overall, 77.8% of secondary crashes occurred within 2 hours of the onset of primary incidents and within 2 miles upstream of the primary incidents.



(a) Spatial Distribution



(b) Temporal Distribution

Figure 4.17: Spatiotemporal Distribution of Secondary Crashes in Relation to Primary Incidents

4.4.1.2 Time of Day and Day of Week Distribution

Figure 4.18 shows the distribution of the 3,906 secondary crashes, 3,547 primary incidents, and 258,340 normal incidents by different periods. More than half of secondary crashes (69.1%) occurred during peak hours, i.e., morning, 6:00 AM to 10:00 AM, and evening, 3:00 PM, and 7:00 PM. More specifically, 25.8% of secondary crashes occurred during the morning peak, while the remaining 31.6% occurred during the evening peak. The highest proportion of secondary crashes occurred during the morning peak hours at 8:00 AM (10.4%), while the highest proportion of secondary crashes during the evening peak period occurred at 5:00 PM (9.4%).

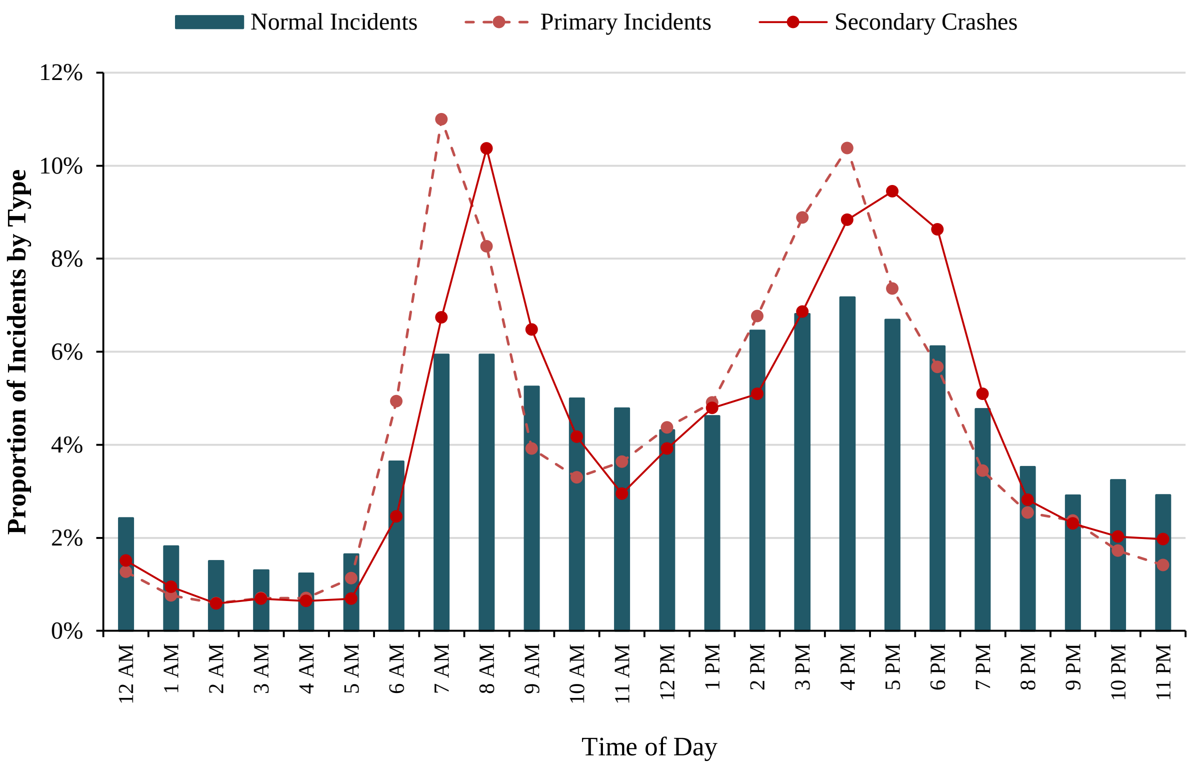


Figure 4.18: Distribution of Traffic Incidents by Time of Day

The highest proportion of primary incidents was observed during the morning peak period at 8:00 AM, accounting for 11% of all primary incidents. As can be inferred from Figure 4.18, the peaks of primary incidents and secondary crashes are one hour apart. Unlike primary incidents and secondary crashes, there is no significant distinction in the distribution of normal incidents during peak hours. More than three-quarters of normal incidents (81%) occurred between 6:00 AM and 8:00 PM. As can be observed from Table 4.6, more than half of normal incidents occurred during peak hours (57.3%), while the remaining occurred during off-peak hours.

Table 4.6: Distribution of Traffic Incidents by Time of Day

Incident Characteristic	Category	Incident Category (%)		
		Normal Incidents	Primary Incidents	Secondary Crashes
Time of Day	Peak hours	57.3	67.1	69.1
	Off-peak hours	42.7	32.9	30.9

Figure 4.19 presents the distribution of incidents by day of the week. It can be inferred from this figure that the proportion of normal incidents and secondary crashes is much higher on weekdays than on weekends. Compared to other days of the week, Friday was found to experience the highest proportion of secondary crashes (18%). Overall, 19 % of secondary crashes occurred on weekends.

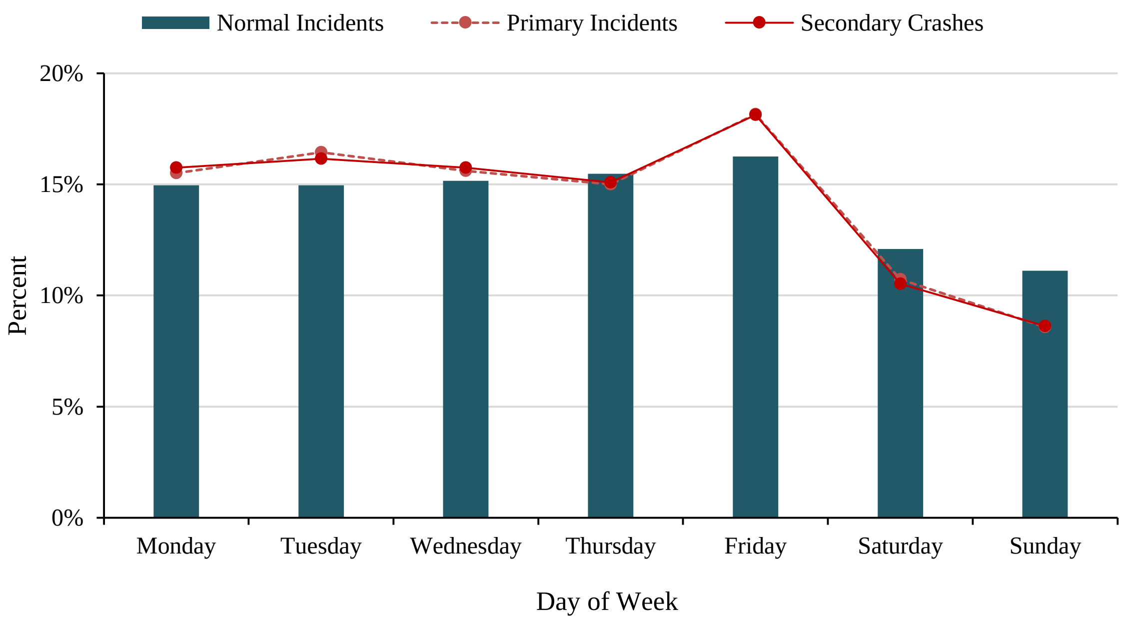


Figure 4.19: Distribution of Normal Incidents and Secondary Crashes by Day of Week

4.4.1.3 Incident Characteristics

As indicated in Figure 4.20, only 20% of normal incidents were crashes, a proportion similar to all incidents (20%), while more than half of the primary incidents were crashes (61%). In other words, the probability of secondary crashes was found to be higher when primary incidents were crashes. Similar findings were revealed by previous studies (Xu et al., 2016; Kitali et al., 2019).

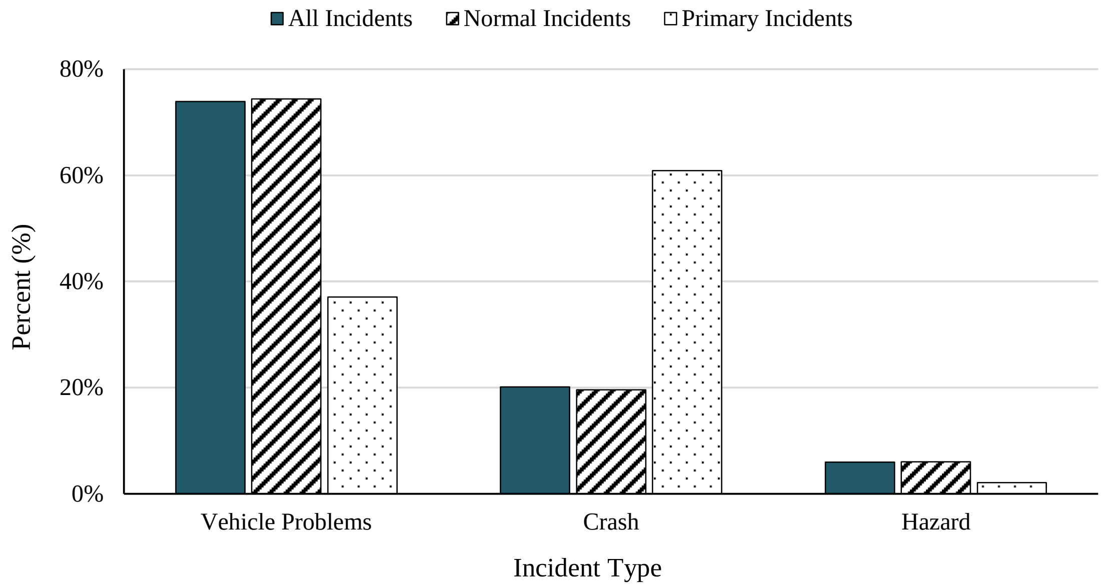


Figure 4.20: Distribution of Incidents by Incident Type

4.4.1.4 B/C ratio

The estimated B/C ratios of the RRSP program in each district are summarized in Table 4.7. The B/C ratios range between 3.05 and 6.75. Overall, the RRSP program achieved a combined B/C ratio of 5.15. This implies that for every dollar spent on the RRSP program, $5.15 is returned in secondary crash savings.

Table 4.7: Benefit-to-Cost Ratio of Road Ranger Program in Each District

District	Year	Crashes	Secondary Crashes in Presence of RRSP	Secondary Crashes in Absence of RRSP	Secondary Crashes Difference	Crash Savings ($)	Cost ($)	B/C Ratio
District 4 (113.8 mi)	2017	9,957	759	960	201	$30,709,437.46	$4,960,836.84	6.19
	2018	10,695	853	1,078	225	$34,512,714.30	$5,110,402.20	6.75
	2019 (Jan - Jun)	5,204	360	455	95	$14,565,741.09	$2,608,473.95	5.58
	Overall	**25,856**	**1,972**	**2,493**	**521**	**$79,787,892.84**	**$12,679,712.99**	**6.29**
District 5 (129.2 mi)	2017	RRSP Program Not in Operation						
	2018	RRSP Program Not in Operation						
	2019 (Apr - Jun)	671	18	23	5	$728,287.05	$164,417.82	4.43
	Overall	**671**	**18**	**23**	**5**	**$728,287.05**	**$164,417.82**	**4.43**
District 6 (17.2 mi)	2017	4,053	415	525	110	$16,791,062.64	$3,833,241.72	4.38
	2018	3,940	289	365	76	$11,693,053.26	$3,833,241.72	3.05
	2019 (Jan - Jun)	2,103	159	201	42	$6,433,202.31	$1,910,822.78	3.37
	Overall	**10,096**	**863**	**1,091**	**228**	**$34,917,318.22**	**$9,577,306.22**	**3.65**
Overall		**36,623**	**2,853**	**3,607**	**754**	**$115,433,498.12**	**$22,421,437.03**	**5.15**

4.4.2 Mobility Benefits of RRSP Program

A data-driven approach was used to estimate delays caused by traffic incidents that occurred between 2015 and 2017 along Interstates in FDOT District 2. The approach used traffic incident data from SunGuide®, travel time and speed data from BlueTOAD™, and volume data from RITIS. About 1,747 incidents that the RRSP program was the first responder to arrive at the incident scene were analyzed. These were traffic incidents that occurred on the freeway mainline and did not have missing data in the traffic detectors upstream of the incident. The delays caused by incidents were estimated using the method described in Section 4.3.2. The following sections discuss the results of the analysis.

4.4.2.1 Time of Day and Day of Week Distribution

Figure 4.21 shows the traffic delays caused by incidents the RRSP program was the first responder to arrive at the incident scene. The delays in Figure 4.21 are distributed according to the time of day. The longest traffic delays were caused by incidents that occurred in the morning and evening peak hours. Specifically, the longest delays were associated with incidents that occurred between 6:00 AM and 7:00 AM, and around 5:00 PM. The average delays caused by incidents during peak and off-peak periods were 40.9 veh-hours and 113.8 veh-hours, respectively. Relatively longer delays during peak hours could be associated with higher traffic volumes than off-peak periods.

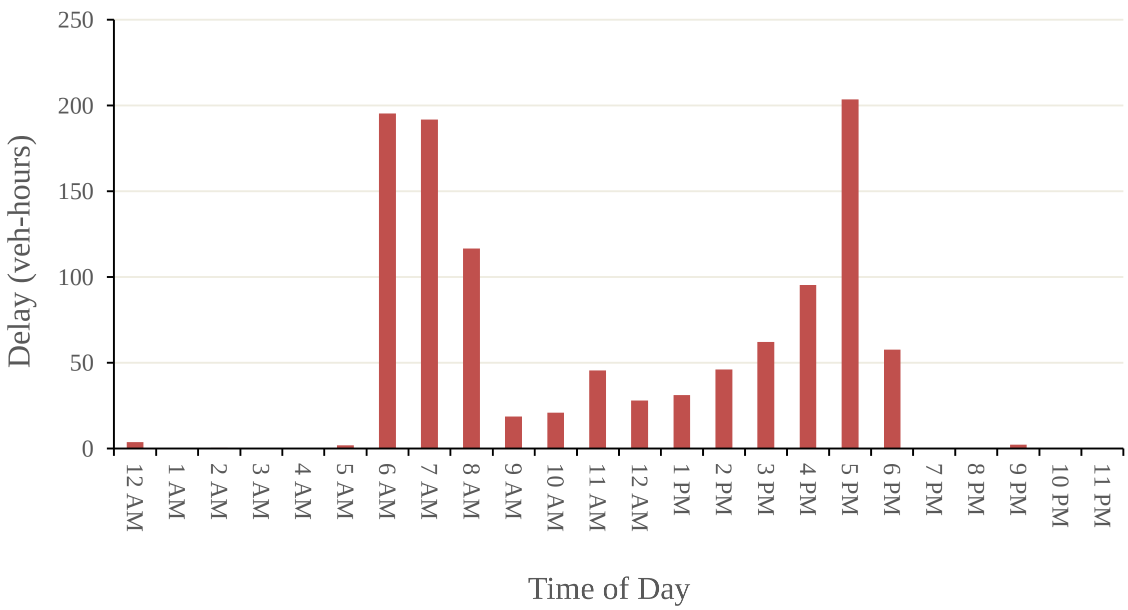


Figure 4.21: Delays due to Incidents according to Time of Day

Figure 4.22 shows the distribution of the delays caused by incidents that the RRSP program was the first responder to arrive at the incident scene according to the day of the week. The distribution does not include weekends because Roar Rangers in District 2 operate on weekdays only. It is indicated that longer delays occurred on Thursdays, which were approximately 112.7 veh-hours. The minimum delays (61.1 veh-hours) were observed on Mondays.

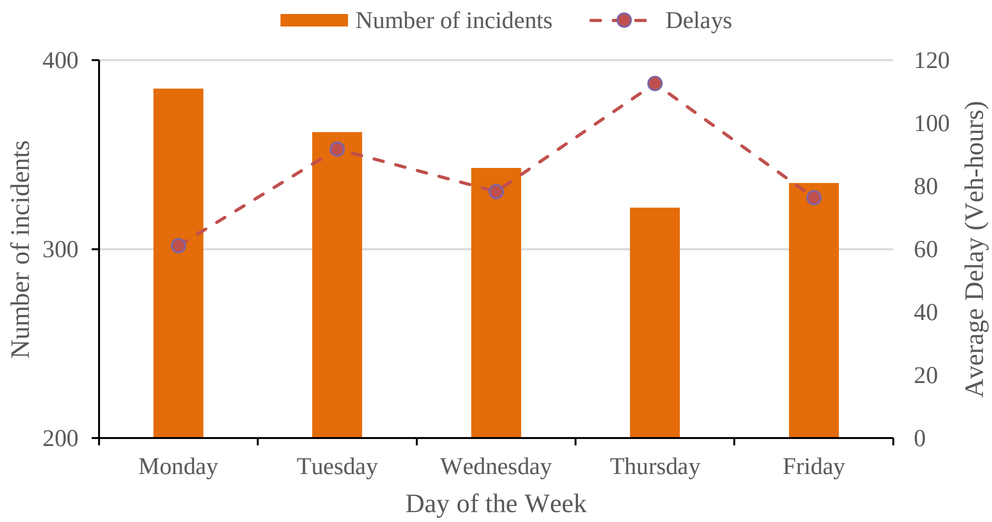


Figure 4.22: Delays due to Incidents according to the Day of Week

4.4.2.2 Incident Characteristics

Table 4.8 summarizes the traffic delays caused by incidents that the RRSP program was the first responder to arrive at the incident scene according to the incident type. Crashes comprised 8% of the incidents, with an average traffic delay of 221.7 veh-hours. The delays caused by crashes were the longest as compared to other incidents. The majority of the incidents were disabled vehicles with an average delay of 71.6 veh-hours. The average delays caused by debris on the roadway were similar to the average delays due to disabled vehicles but significantly lower than the average of delays caused by crashes.

Table 4.8: Traffic Delays Caused by Incidents According to Incident Type

Incident Type	Number of incidents	Percentage	Delay (veh-hours)
Crash	132	8%	221.7
Debris on Roadway	91	5%	72.9
Disabled Vehicle	1521	87%	71.6

4.4.2.3 Benefit-Cost Ratio of RRSP Program

Table 4.9 summarizes the calculation of the B/C of the RRSP in FDOT District 2 for the year 2018. Therefore, the B/C for the RRSP in 2018 was 7.44.

Table 4.9: Benefit-to-Cost Ratio of RRSP Program in FDOT District 2

Non-RRSP Incidents		RRSP Incidents					
Delay per incident in veh-hours	Number of incidents	Delay per incident in veh-hours	Number of incidents	Delay savings due to RRSP in veh-hours	Number of Incidents attended to by RRSP in 2018	Delay Savings due to RRSP in 2018 in veh-hours	Mobility Benefits of RRSP in 2018
159.1	2,038	83.3	1,747	75.8	10,849	822,681	$14,906,983
B/C Ratio							7.44

4.5 Summary

The objective of this task was to conduct the B/C analysis of the RRSP program. The B/C analysis was conducted, considering the safety and mobility benefits of the RRSP separately. The safety benefits were estimated based on the estimated reduction in secondary crashes. Secondary crashes occur within the spatiotemporal (impact area) ranges of the primary incidents. The current study used high-resolution speed data to define the impact area of the primary incidents. The proposed method would identify a crash as a secondary crash if it occurred within the impact range of the primary incident. The method aims to better capture the effects of traffic flow characteristics, such as speed that change over distance and time and affect queue formation because of a prior incident.

Traffic incidents from the SunGuide® database and high-resolution speed data from HERE Technologies were used to estimate the spatiotemporal thresholds of primary incidents. Incident data were collected from January 2017 to June 2019, and speed data were collected from January 2017 through December 2019. The study corridor included 294.2 miles along I-95 (section in Florida), divided into three analysis segments. The analysis was based on 261,797 traffic incidents that occurred along the study corridors between January 2017 and June 2019. Overall, 3,906 secondary crashes were identified from 3,547 primary incidents. The RRSP program achieved a B/C ratio of 5.15 when considering the safety benefits. This implies that for every dollar spent on the RRSP program, $5.15 is returned in secondary crash savings.

The mobility benefits were estimated based on the estimated incident-related traffic delays. Traffic delays introduced by incidents were estimated considering the spatial and temporal impact of the incidents. The study used incidents and traffic data (travel time, speed, and volume) collected on interstates in FDOT District 2 to estimate incident-related the delays. The proposed data-driven approach accounted for the dynamic characteristics of traffic demand during the incident duration. The estimated incident-related delays were based on 3,383 incidents that occurred between 2015 and 2017. The incident-related delay savings were calculated considering incidents that the RRSP program was the first responder at the incident scene. Using the costs for operating the RRSP in FDOT District 2, the RRSP had the B/C of 7.44. This implies that for every dollar spent operating the RRSP, $7.44 is returned in incident-related delay savings.

CHAPTER 5
SMART WORK ZONE (SWZ) TECHNOLOGIES

This chapter discusses the fourth task in the research effort to evaluate the performance of CV and TSM&O projects in Florida. It discusses the potential safety and mobility benefits of Smart Work Zone (SWZ) technologies.

5.1 SWZ Technologies

The SWZ technologies are ITS devices used in the work zones to improve mobility and safety of both motorists and workers (MassDOT, 2016; Pant, 2017). They are a collection of portable computers, communication channels, and sensor technologies. The SWZ technologies collect real-time data in work zones, make a logical decision locally or with coordination to a central system, and disseminate information to road users and/or workers (Venugopal et al., 2017). Permanent ITS equipment available in the work zone area can also retrofit the portable SWZ technologies (Edara et al., 2013). For example, the permanent Dynamic Message Signs (DMSs) can be a part of the system of portable dynamic message signs (PDMSs) installed in a work zone.

The primary objectives of SWZ technologies are to provide accurate information to road users regarding the travel time needed to pass the work zone, the extent of the expected delay due to the work zone, and downstream traffic and geometric conditions (Pant, 2017). The information from SWZ technologies also reduces motorist frustration, encourages road users to take alternate routes, alleviates work zone-related congestion, and improves safety.

FDOT is looking towards deploying SWZ technologies on Florida's freeways (FDOT, 2021b). These SWZ technologies could be applied in various projects' work zones, including resurfacing, construction, and widening projects. The SWZ technologies that the FDOT is currently considering include but are not limited to queue detection and warning systems; speed monitoring and management systems; and reduced speed alert systems (FDOT, 2021b).

5.2 Potential Benefits of SWZ Technologies

The main benefits of SWZ technologies include improving safety and enhancing mobility. These benefits are achieved by alerting motorists on the work zone conditions, reducing the frequency and severity of work zone crashes, decreasing the likelihood of secondary crashes, and minimizing congestion in the vicinity of work zones (FDOT, 2021b). Several studies have evaluated the benefits of SWZ technologies using a variety of measures of effectiveness (MOEs). These MOEs were selected based on a range of factors, including the goal of the SWZ technology, study area, location of application of the SWZ technology (i.e., entrance ramps), and data availability. Table 5.1 summarizes the SWZ technologies, where they have been applied, and their corresponding measures of the safety and mobility benefits.

Table 5.1: Potential SWZ Technologies and Their Measures of Effectiveness

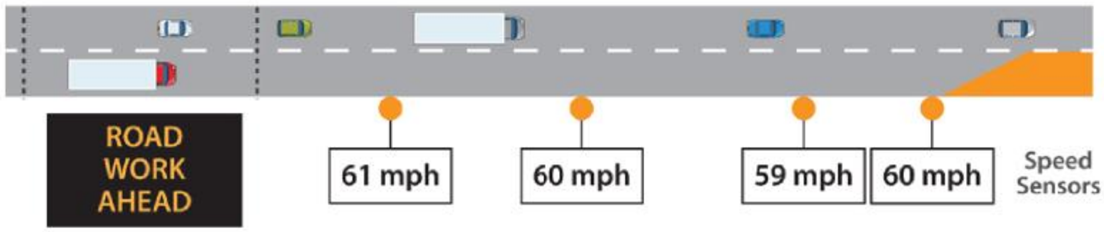
Category	SWZ Technology	State	Safety MOE	Mobility MOE
Queue detection and warning systems	End-of-Queue (EOQ) warning system	Texas	Crash frequency, severity and type	N/A
	Temporary DMS and queue warning trailers	Missouri	Crash frequency	Diversion rates, delays, and travel speeds
Speed monitoring and management systems	Automated speed photo enforcement (SPE)	Illinois	Driver compliance	N/A
	Temporary ramp metering	Missouri	Traffic flow parameters	N/A
	Simplified dynamic lane merging systems (SDLMS)	Florida	Capacity, travel time	N/A
	Dynamic speed feedback system	Texas, Nebraska	N/A	Travel speeds
Traveler information systems	In-vehicle message systems	N/A	Driver compliance	Diversion rates
	Lane closure information system	Florida	N/A	Diversion rates

5.2.1 Queue Warning Systems

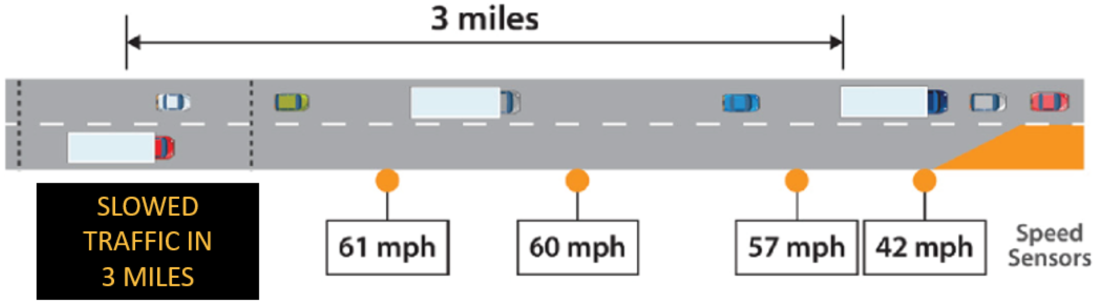
Queue warning systems include technologies that detect queue formation and alert road users using equipment for disseminating information, such as temporary and permanent DMSs. These systems are used to inform motorists about the conditions of the downstream work zones. Some of the queue warning systems include an End-of-Queue warning system, temporary DMSs and queue warning trailers, and an adaptive queue warning system using smart barrels. The operating principle of these systems is more or less the same, with the difference existing in the equipment for detecting queues and informing the motorists. The following sections discuss in detail some of the queue warning systems, their mode of operations, and their associated mobility and/or safety benefits.

5.2.1.1 End-of-Queue (EOQ) Warning System

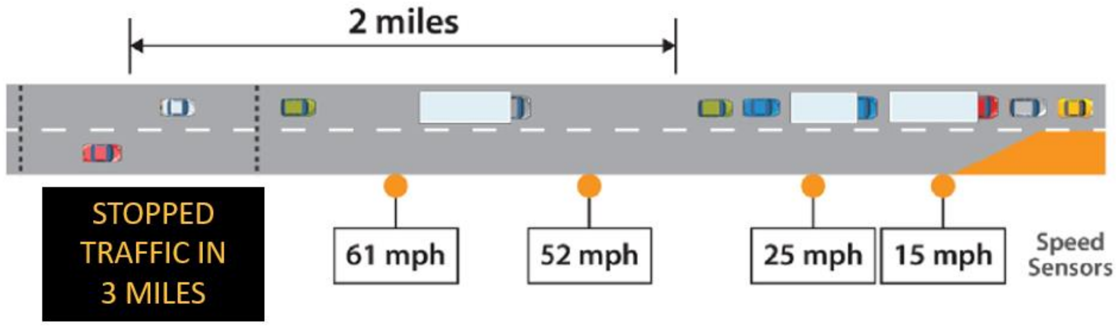
An end-of-queue (EOQ) warning system consists of a portable system of easily deployable radar speed sensors linked to one or more PDMS and portable transverse rumble strips (Ullman et al., 2016). The system was applied in a widening project along I-35 in Texas. The EOQ warning system operates by evaluating the speed of traffic passing near the sensors and automatically displaying appropriate queue warning messages based on the distance between the PDMS and the closest downstream sensor to detect slowed or stopped traffic. The traffic sensors were placed at multiple locations upstream of the work zone based on the expected queues. For example, in one location along I-35, the speed sensors were placed 3.5, 4.5, 5.5, and 6.5 miles from the taper, and a PDMS was placed 7.5 miles from the taper (Ullman et al., 2016). Moreover, the portable rumble strips were incorporated into the system to help get the attention of distracted drivers as they approach the work zones. Figure 5.1 shows the conceptual operation of the EOQ warning system with the PDMS displaying different messages to road users based on the traffic congestion immediately upstream of the active work zone.



(a) Without slowed or stopped downstream traffic



(b) With slowed downstream traffic



(c) With stopped downstream traffic

Figure 5.1: Conceptual Operation of Portable EOQ Warning System (Adapted from Ullman et al. 2016)

The safety benefits of the EOQ system were evaluated based on crashes that occurred at the end of the queue in work zones of a road-widening project during nighttime lane closures (Ullman et al., 2016). The analysis considered work zone locations where queues were expected to be generated during nighttime. It is important to note that the location and frequency of lane closures changed regularly based on activities of a widening project, such as milling and paving. The end-of-queue crashes were recorded as all crashes that occurred in the lane closure section and the queue section that extended five miles upstream of the beginning of the lane closure. By applying the with-and-without EOQ analysis approach, it was observed that the EOQ warning system reduced end-of-queue crashes in work zones during nighttime lane closures by 44% (Ullman et al., 2016). Further analysis showed that the proportion of severe crashes reduced from 58% to 41% due to the EOQ warning system. The system also reduced the percentage of rear-end crashes from 58% to 36%.

5.2.1.2 Temporary DMS and Queue Detection Trailers

A system comprising temporary DMSs and queue warning trailers is one of the queue warning systems that can be used in work zones. The system measures the traffic speed at a work zone and displays the information to motorists. The information given to road users is similar to that provided by the EOQ warning system. Agencies have deployed the temporary DMSs and queue detection trailer systems to improve traffic operations and safety in work zones. Information provided using this system upstream of work zones of a resurfacing project along I-44 in Missouri in 2012 included messages, such as "STAY ALERT. DO NOT TEXT AND DRIVE", "SLOWED TRAFFIC *XX* MILES AHEAD, *XX* MINS EXIT 109 TO EXIT 141" (Edara et al., 2013). In some work zone locations, the existing permanent DMSs were used instead of or in addition to the temporary DMSs. Using crash frequencies as an MOE, the temporary DMSs and queue warning trailers were observed to be associated with a 13.8% reduction in queue-related crashes at the work zones (Nemsky, 2015).

The effect of the information provided on the DMS on mobility was measured using diversion rates, delays, and reduction in traffic speed. Using surveys, it was observed that 52% of the drivers in the morning and evening peak used alternate routes due to the information provided on the DMS (Edara et al., 2013). It was observed that longer delays were observed when drivers were not aware of the work zones or were not influenced by the information provided on the DMSs. Furthermore, DMSs were found to have the most significant influence on drivers between 46 and 65 years. A study in Missouri estimated an average speed decrease of 3.64 mph and 1.25 mph along the two construction work zones included in the analysis (Edara et al., 2011).

5.2.2 Speed Monitoring and Management Systems

5.2.2.1 Temporary Ramp Metering

Ramp metering is a traffic management strategy utilizing traffic signals on the entrance ramp to control and regulate the number of vehicles joining the freeway mainline. Besides typical use in managing traffic on freeways, ramp metering can be used to improve traffic operations on work zones (Sun et al., 2013). Deployment of temporary ramp metering systems could positively affect the safety and mobility in work zones near entrance ramps. The temporary ramp metering system comprises battery-powered and remote-controlled two-head signal, ramp meter ahead or signal ahead sign, one vehicle per green sign, and stop here on red sign (Sun et al., 2013). Figure 5.2 shows a typical temporary ramp metering used in work zones on a freeway in Missouri.

The safety impact of ramp metering on work zones was evaluated using the following surrogate measures of safety: driver compliance, merging behavior, and speed differentials (Sun et al., 2013). Results suggested that lack of compliance could be a significant issue in the deployment of temporary ramp meters. Ramp meters decreased the number of merges involving vehicle platoons but increased the number of merges involving a lone vehicle. This meant the ramp metering's objective of breaking platoons translating to improved safety. Conversely, the speed differential between merging vehicles and mainline vehicles that are close to the merging vehicle increased when ramp meters were activated in the work zones.

Figure 5.2: Temporary Ramp Metering Application in Missouri
(Source: Sun et al., 2013)

While there are only a few studies evaluating the impact of ramp metering in work zones, several studies analyzed their effects on normal freeway corridors (Abdel-Aty & Gayah, 2010; Drakopoulos et al., 2004; Lee et al., 2006; Liu & Wang, 2013). Drakopoulos et al. (2004) observed a 13% reduction in crashes during ramp metering hours as an outcome of installing new ramp meters. Using the before-and-after approach, Liu & Wang (2013) analyzed the impact of 19 ramp meters in California while considering the effect of traffic volume near the entrance ramps. The authors observed about a 36% reduction in the crash rates, although most crashes were property damage only. Lee et al. (2006) quantified the safety benefits of local-traffic responsive ramp metering using a coefficient of variation of speed, the average speed difference between the upstream and downstream traffic at a specific location, and the average covariance of volume difference between adjacent lanes. Results showed that although ramp metering can benefit the road sections upstream of the ramp merge area, it could increase crash potential on the road sections downstream of the ramp merge area. Therefore, the overall safety benefit of ramp metering was a 5% to 37% reduction in total crash potential. Similarly, Abdel-Aty & Gayah (2010) used traffic regimes defined using traffic speeds and detector locations defined by Pande & Abdel-Aty (2006) to show that ramp metering can reduce the risk of rear-end and sideswipe crashes on congested freeways.

The mobility benefits of ramp metering are well documented. Table 5.2 summarizes studies on the mobility impact of ramp metering on freeway operations. The mobility benefits of ramp metering were evaluated using several MOEs, including travel time, travel time reliability, speed, delay, and traffic volume (Bertini et al., 2004; Cambridge Systematics Inc., 2001; KDOT & MoDOT, 2011; Levinson & Zhang, 2006; Trinh, 2000; Xie et al., 2012). It was observed that ramp metering improved travel time on freeways. However, there were conflicting results regarding the impact of ramp metering on travel time reliability.

Table 5.2: Mobility Benefits of Ramp Metering on Freeway Mainline Traffic

MOE	Reference	Findings
Travel Time	KDOT & MoDOT (2011)	Improved travel time
Travel Time Reliability	Levinson & Zhang (2006)	Reduced travel time variability
	KDOT & MoDOT (2011)	Improved travel time reliability
	Xie et al. (2012)	Improved travel time reliability
Traffic Speed	Trinh (2000)	Increased traffic speeds by 7 to 20 mph
	Cambridge Systematics, Inc. (2001)	Increased traffic speeds by 14%
Traffic Delay	Sun et al. (2013)	Decreased delays when traffic volume exceeded capacity
Traffic Volume	Cambridge Systematics, Inc. (2001)	Reduced traffic volume on freeways by 9% when deactivated
		Reduced vehicle-miles-traveled (VMT) by 14% when deactivated
	Bertini et al. (2004)	Increased vehicle-hours-traveled (VHT) by 5.8% when activated on a Saturday
		Increased vehicle-miles-traveled (VMT) by 0.7% when activated on a Saturday

5.2.2.2 Automated Speed Photo Enforcement (SPE)

The automated Speed Photo Enforcement (SPE) using radar can help reduce speeds and increase speed limit compliance in work zones (Benekohal et al., 2008). Figure 5.3 shows the automated SPE equipment used in the work zone projects in Chicago, IL. The automated SPE comprises two types of detection radars: down-the-road radar and across-the-road radar. It also includes a light-emitting diode (LED) display and a van for staging all the equipment. In Chicago, IL, the automated SPE vans were staffed with Illinois State Police officers (Benekohal et al., 2008). The speed measured on the down-the-road radar is displayed on the LED display to give drivers a last chance to decrease their speeds and comply with the speed limit. Across-the-road radar measures the speeds of vehicles 150 ft upstream of the radar. If the speed of the vehicle on the across-the-road radar is greater than a specified value, the radar activates the cameras to take pictures of the license plate of the violating vehicle. The cameras also record the date and time of the violation.

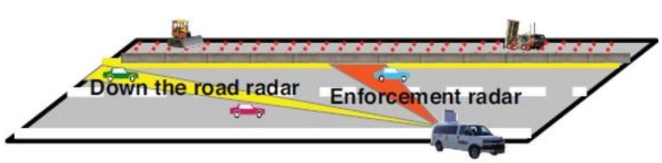


Figure 5.3: Automated Speed Photo Enforcement Equipment and Mode of Operations (Source: Benekohal et al., 2008)

Travel speed was used to show the impact of the automated SPE in work zones. It was observed that the automated SPE reduced the mean travel speed and increased compliance with the speed limit (Benekohal et al., 2008). The average speed of free-flowing and platooning vehicles was reduced below the speed limit of 55 mph regardless of the travel lane, i.e., median or shoulder lane. The reduction in the average speed ranged from 3.2 mph to 7.3 mph. Also, the percentage of vehicles exceeding the speed limit near SPE was reduced by approximately 20% and 24% for passenger cars and heavy vehicles not in platoons, respectively.

5.2.2.3 Simplified Dynamic Lane Merging Systems

Simplified dynamic lane merging systems (SDLMSs) are used to advise drivers on definite merging locations. Two types of SDLMSs include simplified early merge system (early SDLMS) and simplified late merge system (late SDLMS) (Radwan et al., 2009). The early SDLMS encourages earlier merging in advance of work zone lane closure to decrease the merging conflicts at the merge point of a lane closure. On the other hand, the late SDLMS allows drivers to use all the available traffic lanes to the merge point. Both SDLMSs are composed of multiple PDMSs, traffic detection stations, such as remote traffic microwave sensors (RTMSs), a central computer base station, and wireless communication links.

The operation of the SDLMSs is based on real-time speed data recorded by traffic detection stations. For the early SDLMS, the PDMSs display "DO NOT PASS" followed by "MERGE HERE". For the late SDLMS, the PDMS displays "STAY IN YOUR LANE" followed by "MERGE AHEAD". In one of the projects in Florida, the SDLMS was set to be activated when the average speed over 2-minute time drops below 50 mph and deactivated once the speed over the next timestamp goes over 50 mph (Radwan et al., 2009).

The effectiveness of the SDLMS was evaluated using work zone capacity (Radwan et al., 2009). The mean capacities at the work zone when using the conventional traffic control system, early SDLMS, and late SDLMS were 881 veh/hr, 970 veh/hr, and 896 veh/hr, respectively. The maximum capacities at the work zone when using the conventional traffic control system, early SDLMS, and late SDLMS were 1,092 veh/hr, 1,272 veh/hr, and 1,093 veh/hr, respectively. Also, the average travel time at a work zone when using the conventional traffic control system, early SDLMS, and late SDLMS were 3.97 minutes, 3.87 minutes, and 3.78 minutes, respectively. However, a statistical test indicated that there was no statistically significant change in the travel times.

5.2.2.4 Dynamic Speed Feedback Signs

The dynamic speed feedback sign (DSFS) system includes a displayed regulatory or advisory speed limit, a speed measuring device (i.e., loop detectors or radar), and a digital panel that displays the observed speed of the nearest vehicle (National Academies of Science, 2015). Figure 5.4 shows a typical DSFS setup that can be used in a work zone. The speeds that exceed the speed limit are displayed using red or flashing amber digits.

Figure 5.4: Dynamic Speed Feedback Trailer (Source: Dana Safety Supply, 2021)

Studies evaluated the safety effectiveness of DSFS on roadway segments that are not in work zones (Hallmark et al., 2015; Wu et al., 2020). Using a before-and-after approach, Wu et al. (2020) evaluated the safety effectiveness of DSFS on urban road segments in Alberta, Canada. Results showed a reduction of crashes ranging between 32.5% and 44.9%. A study based on the application of DSFS on rural two-lane roadways showed that the technology was associated with a crash reduction ranging between 5% and 7% (Hallmark et al., 2015). Few studies evaluated the effectiveness of DSFS in reducing speeds in work zones (Fontaine & Carlson, 2001; McCoy et al., 1995). The presence of DSFS reduced the average speed of vehicles entering a work zone by 4 to 5 mph (McCoy et al., 1995). It was also observed that DSFS reduced the number of drivers exceeding the posted speed limit by 20% to 40% (Fontaine & Carlson, 2001). The DSFS is, however, limited when used on multi-lanes during moderate or heavy congestion (National Academies of Science, 2015).

5.2.3 Traveler Information Systems

5.2.3.1 In-vehicle Work Zone Messages

Communicating work zone events to drivers through in-vehicle messages might improve traffic safety in work zones (Craig et al., 2017). In-vehicle messages would make drivers more aware of any risky work zone events and drive appropriately due to the immediacy of the in-vehicle message system. The in-vehicle messages could be provided through smartphones as an auditory message only or audio-visual messages. The in-vehicle messaging smartphone could either be mounted on the dashboard or placed on the passenger's seat. However, various factors are to be considered when designing messages to be sent to drivers using audio, including annoyance of messages, message appropriateness, urgency, and word choice. Factors that are to be considered during visual message design include display criteria/standards and reducing driver distraction. The visual messages also follow all the design criteria in audio messages. Figure 5.5 shows the potential in-vehicle work zone messages, their type, and the corresponding messages on the DMSs. Craig et al. (2017) evaluated the effectiveness of the in-vehicle message system in comparison to the PDMS using a driving simulator on measures including visual attention, driving performance, mental workload, and user-technology opinions.

Message Placement	Audio-Only Message	Audio-Visual Message (Icon)	DMS
Mile Marker 1.5 Start of Transition/ Advanced Warning Zone	"Slow Traffic Ahead" "Half Mile" "Reduce Speed"		CAUTION SLOW TRAFFIC AHEAD
Mile Marker 3 Near end of Transition/ Advanced Warning Zone	"Debris in Lane..." "Half Mile" "Use Caution"		CAUTION RIGHT LANE NARROWS
Mile Marker 4.5 Upstream in Activity Zone	"Trucks Entering Roadway" "Half Mile" "Use Left Lane"		CAUTION TRUCKS ENTERING ROADWAY

Figure 5.5: Examples of the In-vehicle Work Zone Messages (Adapted from Craig et al., 2017)

5.3 Summary

The objective of this task was to explore the possibility of estimating B/C ratios of the SWZ technologies. Several SWZ technologies with the potential to be used in work zones on Florida's freeways were reviewed. The following SWZ technologies were reviewed:

- EOQ warning system,
- temporary DMS and queue detection trailers,
- temporary ramp metering,
- automated speed photo enforcement (SPE),
- simplified dynamic lane merging system
- dynamic speed feedback signs, and
- traveler information systems.

The review was focused on describing the systems, identifying the MOEs, and summarizing the findings. The MOEs were categorized into safety and mobility measures. The safety MOEs explored were crash frequency, crash severity, crash type, and a number of surrogate safety measures, including speed differentials and variation in speed. The mobility MOEs included travel time, travel time reliability, and diversion rates. A majority of studies indicated that SWZ technologies improved safety and mobility in work zones.

CHAPTER 6
PERFORMANCE EVALUATION CRITERIA
FOR CONNECTED VEHICLE (CV) PROJECTS

This chapter focuses on developing detailed criteria for evaluating the performance of CV deployments. Different performance criteria and evaluation metrics were developed for different stages of CV deployments (i.e., pre-project phase, planning phase, design-deploy-test phase, and the operations and maintenance phase). The performance criteria of two CV deployments in Florida, the Gainesville SPaT Trapezium project and the I-4 FRAME project, were also reviewed.

6.1. Performance Evaluation Process for CV Projects

Whether quantitative, qualitative, or both, performance evaluation should occur throughout the CV project development process. Figure 6.1 offers guidance for performance evaluation tasks to be conducted during the pre-project, planning, design-deploy-test, and operations and maintenance phases of a CV project.

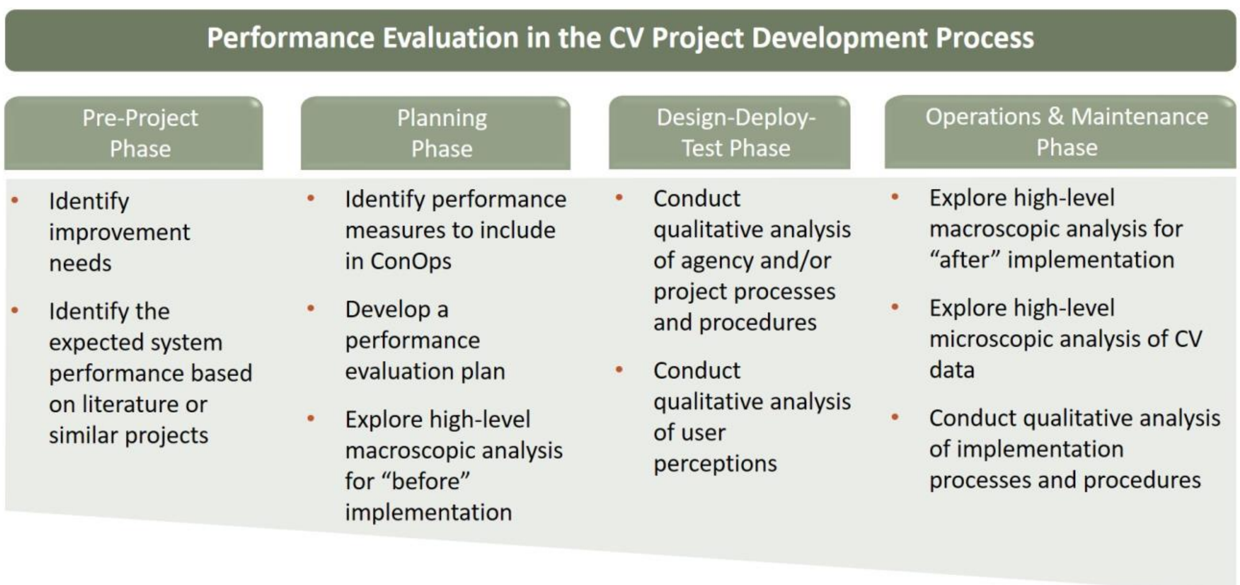


Figure 6.1: Performance Evaluation Process for CV Projects

6.1.1 Pre-Project Phase

During the pre-project phase of the CV development process, potential CV projects are evaluated for viability and best use of public funds following the FDOT CAV Business Plan (see Table 1.1, Chapter 1). For a CV project to be considered, the need for safety, mobility, or environmental improvement must first be established. Expected performance from the CV deployment can then be determined from literature or similar projects, if available. Suppose the project is deemed beneficial and meets the overall statewide CAV Program's Safety, Mobility, and Economic development (SME) goals. In that case, the planning phase can be initiated once funding has been approved. Proposed CV projects can be evaluated qualitatively using the questions presented in Table 6.1.

6.1.2 Planning Phase

In the planning phase, performance measures for the project are identified and included in the Concept of Operations (ConOps) plan. Since CV projects are often multifaceted and may involve multiple agencies, all stakeholders must be involved in the selection of performance measures. A performance measure evaluation plan should also be developed during this phase. Key elements discussed in the ConOps include:

- High-level system overview
- Stakeholders and project roles
- Current system situation
- Justification for project
- Stakeholder/user (i.e., operator) needs
- Description of the proposed system
- Modes of operation (i.e., TSM&O operations, incident operations, maintenance operations, and emergency/evacuation operations)
- User involvement and interaction
- Analysis of the proposed system
- Systems engineering plan
- Performance measurement of system

For many projects, a before-and-after analysis is performed to assess the progress of an implemented strategy. Therefore, to establish base values for comparison to post-deployment performance measure values, a high-level macroscopic analysis should be conducted. Qualitative evaluations of planning activities should also be considered. Examples of potential qualitative evaluation questions are presented in Table 6.1.

6.1.3 Design-Deploy-Test Phase

The proposed CV strategies are designed, implemented, and tested in the design-deploy-test phase of the project development process. Throughout this phase, qualitative assessment of each aspect of the project should be ongoing and documented as lessons learned and/or areas identified that could be improved for future CV deployments. Table 6.1 includes examples of potential qualitative evaluation questions.

6.1.4 Operations and Maintenance Phase

When a CV project enters the operations and maintenance phase, it is considered operational. Post-deployment data can be collected to conduct a macroscopic analysis of performance measures to determine the "after" implementation values. As indicated in Figure 6.1, a high-level microscopic analysis can also be conducted using the collected CV data. These quantitative evaluations can reveal whether the deployed CV strategy has provided an improvement in the target area(s).

Although qualitative evaluations should occur throughout the CV project development process, once operational, a comprehensive qualitative assessment of the planning and design-deploy-test phases of the project would be beneficial in preparing for future CV deployments. Table 6.1 offers several examples of potential qualitative evaluation questions that may be considered during the operations and maintenance phase of the project.

Table 6.1: Qualitative Evaluation in the CV Project Development Process

CV Project Development Phase	Potential Evaluation Question Examples
Pre-Project **	What are the performance target areas?
	Does existing literature provide adequate expected performance information?
	Are there previous CV deployments with similar target criteria?
Planning	Will the proposed system technologies have future application capabilities?
	What are the anticipated challenges?
	Will stakeholders need additional support to achieve project roles and responsibilities?
Design-Deploy-Test	Were there challenges in addressing system requirements provided by the stakeholders?
	What challenges did the systems manager experience during the deployment?
	Were potential challenges identified during the planning phase effectively addressed?
	Any challenges in the collaboration process with local agencies?
	What were the lessons learned regarding policies, procedures, processes, etc., and are they documented for future deployments?
Operations & Maintenance	What were the lessons learned from training and testing the system, and are they documented for future deployments?
	Were the CAV Program's safety, mobility, and economic development (SME) goals realized?
	Are there challenges with maintaining the system?
	Are there recommendations for future deployments?

** Refer to the FDOT 2019 CAV Business Plan (Table 1.1) for complete project selection criteria.

6.2 CV Case Studies

Two CV deployments in Florida were selected as case studies to determine the quantitative and qualitative performance measures used for each project. The projects selected for review included the Gainesville SPaT Trapezium (currently operational) and the I-4 FRAME project (currently in the design/implementation phase).

6.2.1 Gainesville SPaT Trapezium

The Gainesville SPaT trapezium became operational in 2019 and uses CV technologies and applications along four arterial corridors forming a trapezium surrounding the University of Florida main campus. The routes include SR 121 (SW 34th St), SR 26 (W University Ave), US 441 (SW 13th St), and SR 24 (SW Archer Rd). The project contains 27 signalized intersections, equipped with 27 RSUs broadcasting SPaT information using dedicated short range communications (DSRC), with the goal of improving travel time reliability, safety, throughput, and traveler information. The project will also deploy and test pedestrian and bicyclist safety CV and smartphone-based applications in the future (FDOT, 2021a). Figure 6.2 shows the project location map.

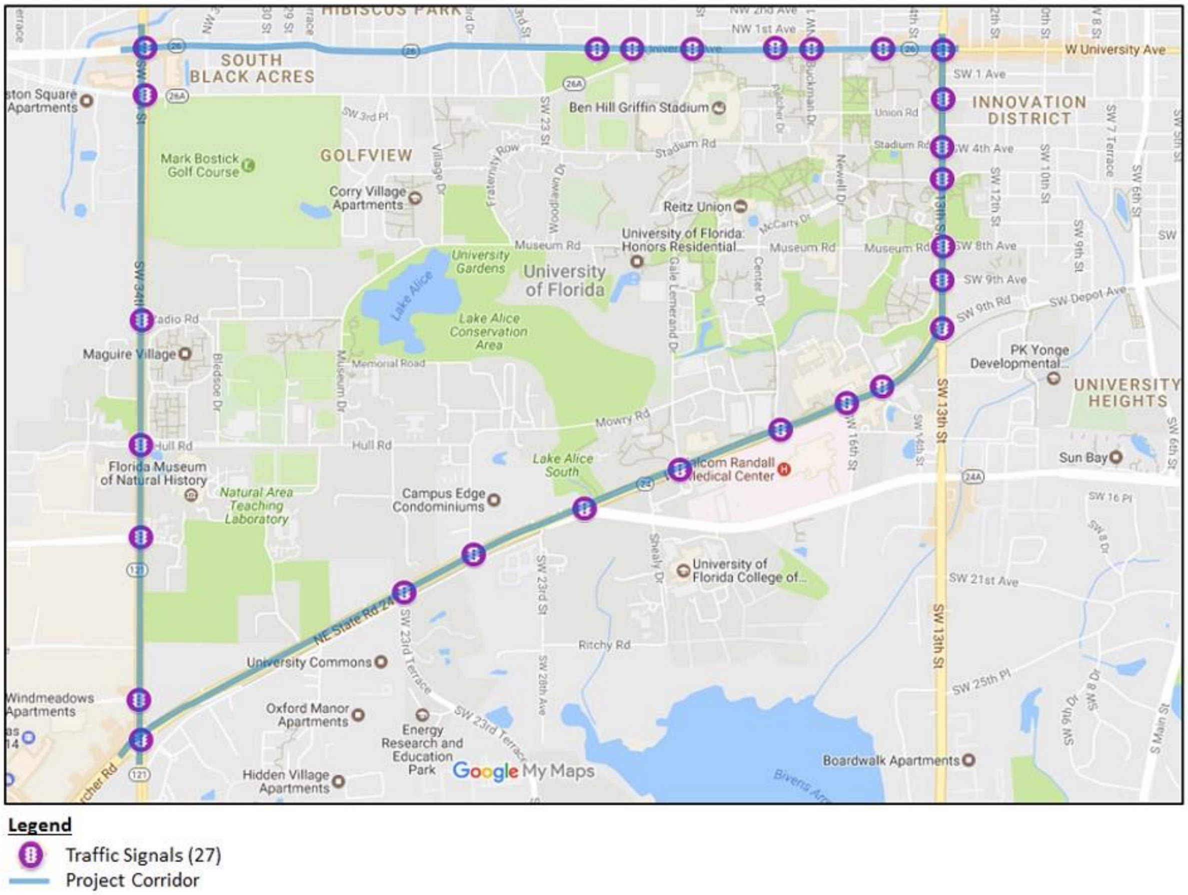


Figure 6.2: Gainesville SPaT Trapezium Location Map (FDOT, 2021a)

6.2.1.1 CV Application Packages

The project incorporated several CV application packages. These service packages include:

- Intersection Safety Warning and Collision Avoidance,
- Connected Vehicle Traffic Signal System,
- Pedestrian and Cyclist Safety,
- Security and Credentials Management,
- Device Certification and Enrollment, and
- Map Management.

6.2.1.2 Quantitative Performance Measures

Performance measures could be categorized into the following groups: transit-related, pedestrian/bike-related, vehicle-related, and environmental-related (refer to Table 2.4, Chapter 2). Some of these measures include (FDOT, 2020):

- vehicle crash frequency,
- pedestrian/bicycle crash frequency,
- traffic flow and volume,
- vehicle speed and speed changes,
- vehicle acceleration, starts and stops, and
- signal phase and timing parameters.

6.2.1.3 Qualitative Performance Measures

Evaluation of procedures and challenges throughout the project development process provided valuable information for future deployments of similar projects. Some of the lessons learned include:

- A revised procurement approach is needed for the inclusion of value-added (optional) services when the estimated cost for all intended services is not well known.
- Vendor-developed MAP is useful during testing at the Traffic Engineering Research Laboratory (TERL).
- Vendor presentations help to understand the potential deployment of safety and mobility applications.

6.2.2 I-4 FRAME

The Interstate 4 (I-4) Florida's Regional Advanced Mobility Elements (FRAME) project is a part of a Multimodal Integrated Corridor Management (MMICM) System, unifying several other projects in the region to improve safety and mobility along the I-4 corridor and adjacent arterials. The objectives of the project are to enhance data collection to support operations, the analysis of that data to enhance decision making by operators at Regional Transportation Management Centers (RTMCs), and the dissemination of that data to motorists along the corridor in real-time. The project spans from the Central Business District in Tampa to the southwest side of Orlando at the Florida Turnpike. The I-4 FRAME covers 77 miles of I-4, 122 miles of other limited-access routes, and signalized arterial roadways with a total of 491 traffic signal systems (FDOT, 2021a). Figure 6.3 shows the project location map.

The CV technologies deployed in the I-4 FRAME project support two focus areas: (1) CVs equipped with DSRC and cellular vehicle-to-everything (CV2X) devices, and (2) the enhancement of traffic signal operations on the diversion routes using an Automated Traffic Signal Performance Measures (ATSPM) System developed for the project.

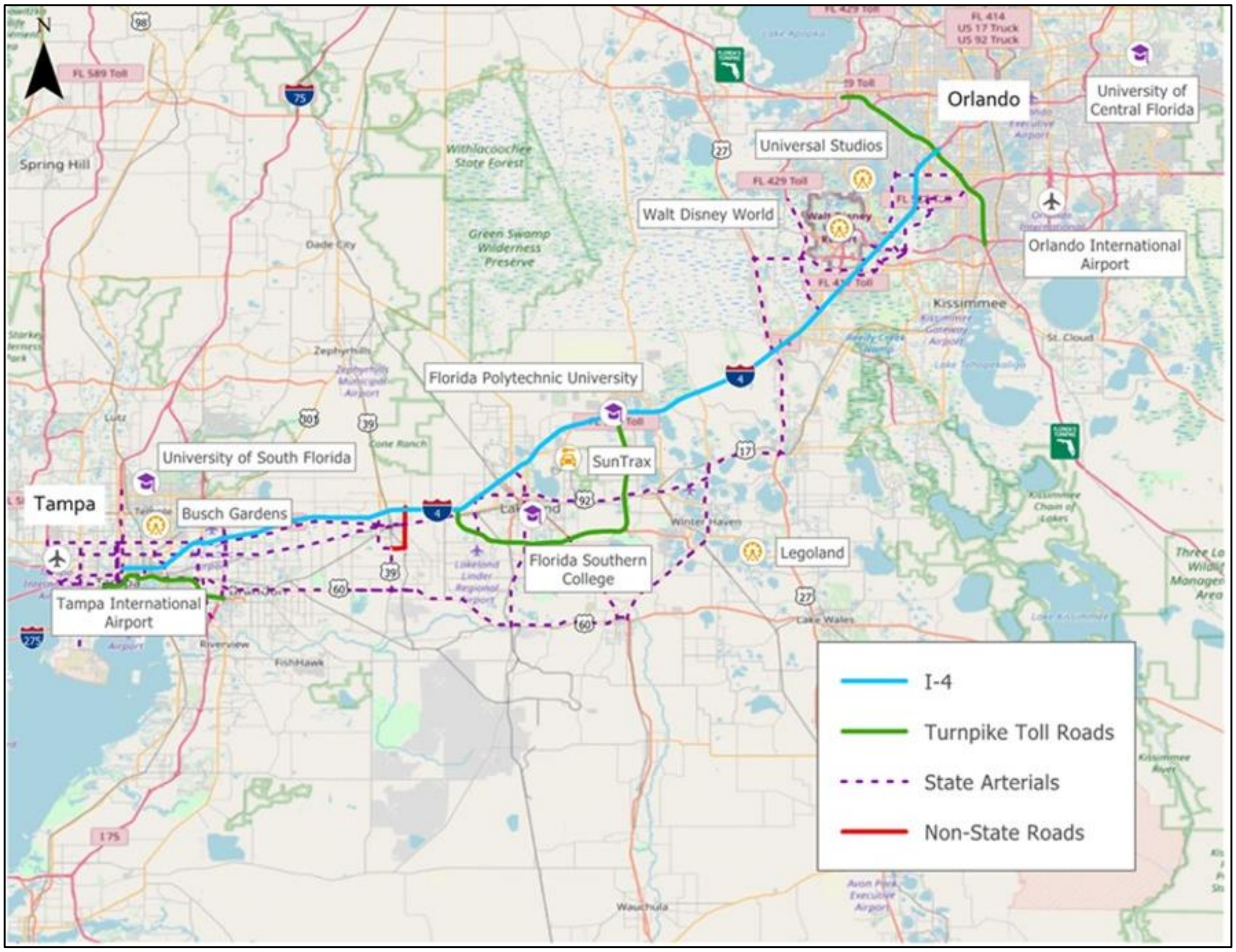


Figure 6.3: I-4 FRAME Project Location Map (FDOT, 2021a)

6.2.2.1 CV Application Packages

The I-4 FRAME project will incorporate a number of traditional ITS and CV technologies. Table 6.2 summarizes the anticipated benefits of each CV application to be implemented. The CV service packages to be implemented for freeway operations include:

- Dynamic Roadway Warning,
- Dynamic Route Guidance,
- Incident Scene Safety Monitoring,
- Queue Warning,
- Reduced Speed Zone Warning/Lane-Closure,
- Road Weather Motorist Alert and Warning,
- Speed Warning and Enforcement,
- Traffic Incident Management System,
- Work Zone Management, and
- Wrong Way Vehicle Detection and Warning.

CV application service packages to be implemented for arterial operations include:

- Advanced Railroad Grade Crossing,
- Connected Vehicle Traffic Signal System,
- Emergency Vehicle Preemption,
- Freight Signal Priority,
- Intersection Warning and Collision Avoidance,
- Pedestrian and Cyclist Safety, and
- Transit Signal Priority.

Table 6.2: CV Applications and Goals for I-4 FRAME

Category	CV Application Service Package	Anticipated Benefits
Safety	Dynamic Roadway Warning	Reduce crashes.
	Advanced Railroad Warning	Reduce crashes.
	Speed Warning and Enforcement	Reduce crashes.
	Wrong Way Vehicle Detection and Warning	Reduce crashes.
	Road Weather Motorist Alert and Warning	Reduce crashes.
	Queue Warning	Reduce crashes.
	Reduced Speed Zone Warning/Lane Closure	Reduce crashes.
	Pedestrian and Cyclist Safety	Reduce crashes.
	Intersection Warning and Collision Avoidance	Reduce crashes.
	Incident Scene Safety Monitoring	Provide guidance to motorists regarding incident zone operations.
Mobility	Connected Vehicle Traffic Signal System	Reduce travel time, fuel consumption, and emissions.
	Traffic Incident Management System	Reduce incident duration.
	Transit Signal Priority	Maintain transit schedule.
	Emergency Vehicle Preemption	Reduce incident response time.
	Freight Signal Priority	Reduce travel time, fuel consumption, and emissions.
	Dynamic Route Guidance	Reduce travel time
	Work Zone Management	Inform motorists of reduced speeds and potential delays.

6.2.2.2 Quantitative Performance Measures

Before-and-after studies will be conducted per the evaluation plan established in the ConOps. The performance of the I-4 FRAME will be evaluated based on the following performance measures:

- Primary crashes – frequency and rate by severity and location,
- Secondary crashes – frequency and rate by severity and location,
- Throughput – by time and location,
- Delay – by time and location,
- Average speed – by time and location,

- Average travel time – by time and location, and
- Incident response time and duration – by time and location.

6.2.2.3 Qualitative Performance Measures

Qualitative performance measures for the I-4 FRAME project relate to agency procedures and project challenges that may be improved upon to enhance the success of future CV deployments. The following aspects of the project that should be evaluated include, but are not limited to:

- Lessons learned,
- Challenges experienced by the Systems Manager,
- Recommendations for future deployments, and
- Reproducibility and technology transfer of deployed technologies.

6.3 Summary

This chapter discussed performance measures associated with CV deployments. Performance measures can be classified as quantitative or qualitative. Quantitative measures provide numerical estimates of the progress or regress made toward achieving performance targets, while qualitative measures, generally subjective in nature, provide other valuable information to evaluate perceptions and satisfaction, as well as lessons learned, policies, procedures, and guidelines developed and adopted.

Performance evaluation in the CV project development process was also discussed. Although at different degrees of evaluation, quantitative performance measures should be conducted during the pre-project, planning, and operations and maintenance phases, while qualitative performance measures should be evaluated throughout the CV project development process.

CHAPTER 7
CONCLUSIONS

Transportation agencies have increasingly been considering Connected Vehicle (CV) technologies and Transportation Systems Management and Operations (TSM&O) strategies to improve the safety and mobility of the transportation network. Florida Department of Transportation (FDOT) has been at the forefront in deploying CV applications and TSM&O technologies across the state. As of November 2021, Florida's Connected and Automated (CAV) Initiative currently has 33 projects, of which, 15 are operational, 12 are in the design and implementation phase, and six are in the planning phase. FDOT has also been a pioneer in adopting TSM&O strategies to improve the safety and operational performance of the roadway network. While FDOT is optimistic about the potential benefits of these technologies and strategies, it is crucial to estimate the benefit-to-cost (B/C) ratios to justify the funding requests associated with implementing these CV and TSM&O initiatives. The validity of these estimations is dependent on the ability to accurately measure the quantitative and qualitative benefits of these deployments.

On a broader level, CV technologies focus on high-level technological advances to improve safety, mobility, and the environment. However, at the implementation stage, CV deployments constitute a wide array of new and emerging applications, including Pedestrian Collision Warning, Emergency Vehicle Preemption (EVP), CV Traffic Signal Systems, and vehicle-to-vehicle (V2V) Basic Safety Messages (BSMs). The CV Initiative in Florida includes several independent projects, such as the Gainesville Signal Phase and Timing (SPaT) Trapezium, and programs, such as the I-4 Florida's Regional Advanced Mobility Elements (FRAME), as well as partnerships with several agencies and consortia, such as the Tampa Hillsborough Expressway Authority (THEA). Accordingly, each CV deployment initiative is unique and has to be evaluated independently to document both the quantitative and qualitative impacts. Evaluating current CV deployment projects, programs, and partnerships in Florida would better prepare FDOT for future CV deployments.

TSM&O, on the other hand, is a program based on actively managing the multimodal transportation network, measuring performance, and streamlining and improving the existing system to deliver positive safety and mobility outcomes to the traveling public. TSM&O comprises a set of strategies that focus on safety and operational improvements that can maintain or restore the performance of the existing transportation system before extra capacity is needed.

Several TSM&O strategies are currently being deployed to improve the safety and operational performance of our freeway network. The Rapid Incident Scene Clearance (RISC) program is an innovative program that supports Florida's Open Roads Policy of safely clearing major highway incidents and truck crashes in 90 minutes or less. This is an incentive-based program that requires specialized equipment and trained operators to quickly remove wreckage from the roadway, where major crashes close most lanes or cause significant travel delays. The Road Ranger Service Patrol (RRSP) program provides incident management response services and limited no-cost highway assistance to motorists to improve highway safety for emergency responders and the motoring public. Smart Work Zone (SWZ) TSM&O strategies are being implemented at several construction projects on the State Highway System for improving safety in and around work zones.

The goal of any CV and TSM&O deployment is to improve the transportation system by: (USDOT, 2016a):

- improving safety,
- improving mobility,
- improving public agency efficiency, and/or
- reducing negative environmental impact.

Targeted improvement areas are project-specific. Therefore, performance measures used to evaluate the progress of each CV and TSM&O deployments will vary.

The objective of this research was to assist FDOT in developing approaches to evaluate the performance of CV projects and the RISC, RRSP, and SWZ TSM&O strategies. The tasks involved in the research effort include:

- identify both qualitative and quantitative performance measures that can be used to evaluate CV and TSM&O initiatives;
- identify and recommend performance metrics that could be used to estimate the B/C ratios in deploying CV initiatives;
- conduct benefit-cost analyses of RISC and RRSP programs;
- document the potential safety and mobility benefits of SWZ technologies; and
- develop criteria for evaluating the performance of CV deployments.

7.1 Performance Measures for CV and TSM&O Strategies

Performance measures provide a means to quantify the performance of a transportation system and/or to assess the impact of a specific transportation strategy. They can be classified as quantitative or qualitative. Quantitative performance measures can be classified as either macroscopic measures or microscopic measures. Macroscopic measures include, but are not limited to, mean travel speed, traffic flow rate, and occupancy. Microscopic measures include measures of individual vehicles, such as location, speeds, acceleration and deceleration, standard deviations of speed between vehicles, and disturbance measures. Mobility and safety estimates constitute the majority of quantitative performance measures. Nevertheless, in recent years, a greater emphasis has been placed on measuring vehicle emissions to address environmental concerns.

To identify the quantitative and qualitative performance measures and metrics that are being considered in evaluating the performance of CV deployments and TSM&O strategies, a comprehensive review of the existing body of literature was conducted, including government reports, white papers, opinion pieces, presentations, etc.

Qualitative performance measures can be used to evaluate perceptions and satisfaction levels, such as public perception of agency operations, lessons learned, and policies, procedures, and guidelines developed and adopted. Although generally subjective in nature, qualitative performance measures can provide valuable information to transportation system managers when considering service and agency improvement strategies.

7.2 RISC Program

A B/C analysis was conducted to quantify the mobility and safety benefits associated with implementing the RISC program. The B/C analysis was conducted considering the safety and mobility benefits of the RISC program separately. The reduction in secondary crashes was used as the performance measure for estimating the safety benefits. The mobility benefits were quantified using incident-related traffic delay as the performance measure. A readily implementable data-driven approach was developed to identify secondary crashes and estimate incident-related traffic delay using high-resolution traffic data.

The data were collected for the period 2016-2019, along a 144-mile section of I-75, from the SunGuide® database, Regional Integrated Transportation Information System (RITIS), Google Maps, and Google Earth Pro. Incidents that were attended to by the RISC vendors were referred to as *treatment incidents*, while those that were not attended to by the RISC vendors were referred to as *control incidents*. Overall, 113 control incidents were identified and paired with 22 treatment incidents. The two incident categories resulted in 61 secondary crashes, i.e., 52 caused by control incidents and the remaining nine by treatment incidents. The RISC program achieved a B/C ratio of 5.78 when considering the safety benefits. This implies that for every dollar spent on the RISC program, $5.78 is returned in secondary crash savings. The RISC program was associated with a B/C ratio of 1.20 when considering mobility benefits. This indicates that for every dollar invested on the RISC program, there is a return of $1.20 in incident-related delay savings.

7.3 RRSP Program

A B/C analysis was conducted to quantify the mobility and safety benefits associated with implementing the RRSP program. The safety benefits were estimated based on the estimated reduction in secondary crashes. Incident data were collected from January 2017 to June 2019 from the SunGuide® database, and speed data were collected from January 2017 through December 2019 from HERE Technologies. The study corridor included 294.2 miles along I-95 (section in Florida), divided into three analysis segments. Overall, 3,906 secondary crashes were identified from 3,547 primary incidents. The RRSP program achieved a B/C ratio of 5.15 when considering the safety benefits. This implies that for every dollar spent on the RRSP program, $5.15 is returned in secondary crash savings.

The mobility benefits were estimated based on the estimated incident-related traffic delays. The study used incidents and traffic data (travel time, speed, and volume) collected on interstates in FDOT District 2 to estimate the incident-related delays. The proposed data-driven approach accounted for the dynamic characteristics of traffic demand within the incident duration. The estimated incident-related delays were based on 3,383 incidents that occurred between 2015 and 2017. The incident-related delay savings were calculated considering incidents that RRSP program was the first responder at the incident scene. Using the operating costs of the RRSP in FDOT District 2, the RRSP had a B/C of 7.44. This implies that for every dollar spent operating the RRSP, $7.44 is returned in incident-related delay savings.

7.4 SWZ Technologies

The study also documented the potential safety and mobility benefits of SWZ technologies. Several SWZ technologies with the potential to be used in work zones on Florida's freeways were reviewed. The following SWZ technologies were reviewed:

- End-of-Queue (EOQ) warning system,
- Temporary DMS and queue detection trailers,
- Temporary ramp metering,
- Automated speed photo enforcement (SPE),
- Simplified dynamic lane merging system,
- Dynamic speed feedback signs, and
- Traveler information systems.

The review was focused on describing the systems, identifying the measures of effectiveness (MOEs), categorized into safety and mobility measures, and summarizing the findings. Safety MOEs explored included crash frequency, crash severity, crash type, and a number of surrogate safety measures, including speed differentials and variation in speed. Mobility MOEs explored included average travel time, travel time reliability, and diversion rates.

7.5 Performance Evaluation Criteria for CV Projects

This task focused on developing detailed criteria for evaluating the performance of CV deployments. Different performance criteria and evaluation metrics were developed for different stages of CV deployments (i.e., pre-project phase, planning phase, design-deploy-test phase, and the operations & maintenance phase).

Performance evaluation, whether quantitative, qualitative, or both, should occur throughout the CV project development process. Suggested evaluation activities for each phase of the CV project development process include:

- Pre-Project Phase:
    - Identify improvement needs
    - Identify the expected system performance based on literature or similar projects
- Planning Phase:
    - Identify performance measures in the Concept of Operations (ConOps)
    - Develop a performance evaluation plan
    - Explore high-level macroscopic analysis for “before” implementation
- Design-Deploy-Test Phase:
    - Conduct qualitative analysis of agency and/or project processes and procedures
    - Conduct qualitative analysis of user perceptions
- Operations & Maintenance Phase:
    - Explore high-level macroscopic analysis for “after” implementation
    - Explore high-level microscopic analysis of CV data

- Conduct qualitative analysis of implementation processes and procedures

The performance criteria of two CV deployments in Florida (Gainesville SPaT Project and I-4 FRAME project) were also reviewed as case studies. Both quantitative and qualitative performance measures were identified for each project.

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APPENDIX A: ONE-PAGE SUMMARIES

Transportation Systems Management & Operations

TSM&O STRATEGIES

RISC Program

RISC program on scene

Rapid Incident Scene Clearance (RISC) program is an incentive-based program that utilizes specialized equipment and trained operators to quickly remove wreckage from the roadway, where major crashes close most lanes or cause significant travel delays.

RISC program coverage in Florida

RISC program is implemented on most freeways in Florida and supports the Open Roads Policy goal of safely clearing major highway incidents and truck crashes in 90 minutes or less.

Mobility Benefits

- Performance Measure: Incident-related traffic delay
- The RISC program achieved a B/C ratio of 1.20 when considering incident-related traffic delay savings.
- For every dollar spent on the RISC program, there is a return of $1.20 in traffic delay savings.

Safety Benefits

- Performance Measure: Secondary crashes
- The RISC program achieved a B/C ratio of 5.78 when considering secondary crash savings.
- For every dollar spent on the RISC program, there is a return of $5.78 in secondary crash savings.

Study Area & Data Needs

- Study Area: 144 Miles on I-75 (from the junction between I-75 and Florida's Turnpike Mainline (SR-91) to I-75 State line)
- Study Period: 2016-2019
- Data: Traffic incidents from the SunGuide® database
  RISC implementation logs
  Speed, volume, & occupancy from RITIS platform
  Roadway geometric characteristics (e.g., on- & off-ramps)
- The estimated benefits may be specific to the study corridors analyzed.

For more information, please refer to the report BDV29-977-64

TSM&O STRATEGIES

RRSP Program

RRSP on duty

Road Rangers Service Patrol (RRSP) program is a freeway service patrol on major roadways in Florida.
Road Rangers are often able to arrive at an incident scene quickly to enable advance safety protection, traffic control, and incident clearance.

RRSP program coverage in Florida

Mobility Benefits

- Performance Measure: Incident-related traffic delay
- The RRSP program achieved a B/C ratio of 7.44 when considering incident-related traffic delay savings.
- For every dollar spent on the RRSP program, there is a return of $7.44 in traffic delay savings.

Safety Benefits

- Performance Measure: Secondary crashes
- The RRSP program achieved a B/C ratio of 5.15 when considering secondary crash savings.
- For every dollar spent on the RRSP program, there is a return of $5.15 in secondary crash savings.

Study Area & Data Needs

- Study Areas: I-95 (35 mi), I-10 (21 mi), and I-295 (61 mi) in District 2
- Study Period: 2015-2017
- Data: Traffic incidents from the SunGuide® database
  Travel time, volume, & occupancy from RITIS platform
  Roadway geometric characteristics (e.g., on- & off-ramps)

- Study Areas: 382-mile I-95 in District 4, District 5, and District 6
- Study Period: 2017-2019
- Data: Traffic incidents from the SunGuide® database
  Speed, volume, & occupancy from RITIS platform
  Roadway geometric characteristics (e.g., on- & off-ramps)

For more information, please refer to the report BDV29-977-64

FDOT TSM&O
Transportation Systems Management & Operations

SMART WORK ZONE (SWZ) TECHNOLOGIES

SWZ Technologies

Dynamic travel time feedback trailer

SWZ technologies are Intelligent Transportation System (ITS) devices used in work zones to improve mobility and safety of both motorists and workers. They are a collection of portable computers, communication channels, and sensor technologies. Permanent ITS devices available in work zone areas can also retrofit the portable SWZ technologies.

Dynamic speed feedback trailer

Potential SWZ Technologies & Their Measures of Effectiveness (MOE)

Category	SWZ Technology	Safety MOE	Mobility MOE
Queue Detection and Warning Systems	End-of-Queue (EOQ) warning system	Crash frequency, severity, and type	N/A
	Temporary DMS and queue warning trailers	Crash frequency	Diversion rates, delays, and travel speeds
Speed Monitoring and Management Systems	Automated speed photo enforcement (SPE)	Driver compliance	N/A
	Temporary ramp metering	Crash risk	Traffic flow parameters
	Simplified Dynamic Lane Merging Systems (SDLMS)	Crash risk	Capacity, travel time
	Dynamic speed feedback system	N/A	Travel speeds
Traveler Information Systems	In-vehicle message systems	Driver compliance	Diversion rates
	Lane closure information system	N/A	Diversion rates

Data Needs

- Crash data from databases, such as CARS, Signal 4 Analytics, or SunGuide®
- Work zone data from the respective agencies (e.g., FDOT District Six Lane Closure Information System)
- Roadway geometric characteristics (e.g., on- & off-ramps)
- Traffic data from RITIS platform
- Cost of the SWZ technologies from vendors
- Crash modification factors (CMFs) of the SWZ technologies from literature

For more information, please refer to the report BDV29-977-64