USF-CUTR I-4 FRAME Project “Before” Study: Data Collection and Analysis of Safety and Mobility Conditions Prior to Implementation

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16. Abstract

The Florida Department of Transportation (FDOT) created the Interstate 4 (I-4) Florida’s Regional Advanced Mobility Elements (FRAME) project to address safety and mobility issues on I-4 between Tampa and Orlando. The I-4 FRAME project aims to deploy an advanced integrated corridor management system consisting of advanced next-generation technologies. As part of U.S. Department of Transportation (USDOT) Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) grant obligations, FDOT will conduct a before-after analysis of the emerging technologies. The Center for Urban Transportation Research (CUTR) is one of the universities participating in the before-after evaluation of the project. In this USF-CUTR I-4 FRAME project “before” study, the research team successfully achieved the project objectives and associated tasks: (1) identified mobility challenges on the project corridor and documented how the I-4 FRAME project is addressing the goals set out by FDOT, (2) conducted “before” data collection and data analysis on 15 selected transportation systems and services, (3) developed methodologies for evaluating the safety and mobility performance and benefits of the I-4 FRAME project, (4) studied On-Board Unit (OBU) technology and compared various aspects of both dedicated short-range communication (DSRC) and Cellular Vehicle-To-Everything (C-V2X) On-Board Units (OBUs), (5) performed a comparative study on various use cases of FL511 application and deployed OBUs, and (6) assisted FDOT in developing a Data Management Plan (DMP) and a Project Evaluation Plan (PEP) for the I-4 FRAME project to submit to the Federal Highway Administration (FHWA). This report includes a summary of results and findings from all tasks performed for Phase 1 of the project, which includes data collection and analysis for the “before” period of the project.

17. Key Words
I-4 FRAME, ATCMTD, data analysis, RITIS, mobility analysis, safety analysis, baseline conditions, CV applications, connected vehicles, DSRC, C-V2X, RSU, OBU, CARMA, SCMS

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LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
ºF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	ºC

Executive Summary

The Florida Department of Transportation (FDOT) created the Interstate 4 (I-4) Florida's Regional Advanced Mobility Elements (FRAME) project to address safety and mobility issues on I-4 between Tampa and Orlando. The I-4 FRAME project aims to deploy an advanced integrated corridor management system consisting of next-generation traffic incident management, work zone traffic management, road weather alerts, freeway back-of-queue warnings, wrong-way driving alerts, and speed harmonization message systems using Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) technologies. The U.S. Department of Transportation (USDOT) selected the I-4 FRAME project for its Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) grant. As part of grant obligations, FDOT is conducting a before-after analysis of the emerging technologies. The University of South Florida (USF) Center for Urban Transportation Research (CUTR) is one of the universities participating in the before-after evaluation of the project.

To meet the goals set by FDOT, the CUTR team accomplished the following project objectives and associated tasks:

- Identified mobility challenges on the project corridor and documented how the I-4 FRAME project is addressing the goals set out by FDOT.
- Conducted "before" data collection and data analysis on 15 selected transportation systems and services from the I-4 FRAME project.
- Developed methodologies for evaluating the safety and mobility performance and benefits of the I-4 FRAME project and collect necessary data from FDOT and local data sources to support methodology development.
- Supported and assisted Florida Polytechnic University in evaluating the potential of communication technologies for preventing secondary crashes and developing microscopic simulation models to demonstrate and quantify the possible benefits of Connected Vehicles (CVs) for preventing primary and secondary crashes.
- Studied On-Board Unit (OBU) technology and compared various aspects of both dedicated short-range communication (DSRC) and Cellular Vehicle-To-Everything (C-V2X) OBUs and performed a comparative study on various use cases of FL511 application and deployed OBUs.
- Assisted FDOT in developing a Data Management Plan (DMP) and a Project Evaluation Plan (PEP) for the I-4 FRAME project to submit to the Federal Highway Administration (FHWA).

This report includes a summary of findings from all tasks performed for Phase 1 of the project, which included data collection and analysis for the "before" period of the project, characterized as prior to any deployment of Roadside Units (RSUs), OBUs, and CV applications on the I-4 FRAME project corridors. Detailed analysis and results are provided in each task deliverable.

Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

3GPP	3rd Generation Partnership Project
5GAA	5G Automotive Association
5GCroCo	5th Generation Cross-Border Control
ATCMTD	Advanced Transportation and Congestion Management Technologies Deployment
ATMS	Advanced Transportation Management System
ATIS	Advanced Traveler Information System
AASHTO	American Association of State Highway and Transportation Officials
AADT	Annual Average Daily Traffic
API	Application Programming Interface
ASTRI	Applied Science and Technology Research Institute
ARIB	Association of Radio Industries and Businesses
BSM	Basic Safety Message
BI	Buffer Index
CAR	Crash Analysis Reporting System
C-V2X	Cellular Vehicle-to-Everything
CATT	Center for Advanced Transportation Technology
CBD	Central Business District
CO	Central Office
CDOT	Colorado Department of Transportation
CAM	Connected and Automated Mobility
CAV	Connected Automated Vehicle
CVI-UTC	Connected Vehicle/Infrastructure University Transportation Center
CV	Connected Vehicles
CEF	Connecting Europe Facility
C-ADS	Cooperative Automated Driving System
CARMA	Cooperative Automation Research for Mobility Applications
CDA	Cooperative Driving Automation
CCAM	Cooperative, Connected, and Automated Mobility
C-ITS	Cooperative-Intelligent Transport Systems
CAMP LLC	Crash Avoidance Metrics Partners LLC
CAMP	Crash Avoidance Metrics Partnership
DMP	Data Management Plan
DSRC	Dedicated Short-Range Communication
DelDOT	Delaware Department of Transportation
DMS	Dynamic Message Sign
ECA	Enrollment Certificate Authority
CEN	European Committee for Standardization
ETSI	European Telecommunications Standards Institute
EU	European Union
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FL511	Florida 511
FDOT	Florida Department of Transportation

FL Poly	Florida Polytechnical University
FTE	Florida's Turnpike Enterprise
FRAME	Florida's Regional Advanced Mobility Elements
FSP	Freight Signal Priority
GTFS	General Transit Feed Specification
GTFS-RT	General Transit Feed Specification-Real Time
GIS	Geographical Information Systems
GDOT	Georgia Department of Transportation
BMVI	German Federal Ministry of Transport and Digital Infrastructure
GPS	Global Positioning System
HDOT	Hawaii Department of Transportation
HAR	Highway Advisory Radio
HSM	Highway Safety Manual
IT	Information Technology
IEEE	Institute of Electrical and Electronic Engineers
IEEE	Institute of Electrical and Electronics Engineers
ICM	Integrated Corridor Management
ITS	Intelligent Transportation System
ISTEA	Intermodal Surface Transportation Efficiency Act
IoV	Internet of Vehicles
I-275	Interstate 275
I-4	Interstate 4
I-75	Interstate 75
LCCF	Local Certificate Chain File
LTE	Long-Term Evolution
MCDOT	Maricopa County Department of Transportation
MAC	Medium Access Control
MVDS	Microwave Vehicles Detection System
MnDOT	Minnesota Department of Transportation
NTU	Nanyang Technological University
NPMRDS	National Performance Management Research Data Set
NTSB	National Transportation Safety Board
NB	Negative Binomial
NOFO	Notice of Funding Opportunity
OBU	On-Board Unit
OSS	Open-Source Software
OEM	Original Equipment Manufacturers
OOBE	Out-of-Band Emissions
POG	Percent Arrival on Green
PHY	Physical
PTI	Planning Time Index
PEP	Project Evaluation Plan
PCA	Pseudonym Certificate Authority
PKI	Public Key Infrastructure
R-ICMS	Regional Integrated Corridor Management System
RITIS	Regional Integrated Transportation Information System

RTMC	Regional Traffic Management Center
RTC	Regional Transportation Commission
REL	Reversible Express Lanes
RCI	Roadway Characteristics Inventory
RSU	Roadside Unit
SPF	Safety Performance Functions
SPMD	Safety Pilot Model Deployment
SCMS	Security Credential Management System
SPaT	Signal Phase and Timing
SAE	Society of Automotive Engineers
SSO	State Safety Office
THEA	Tampa-Hillsborough Expressway Authority
TLI	Traffic Light Information
TMC[1]	Traffic Message Channel
TSP	Transit Signal Priority
TSMO	Transportation System Management and Operations
TTI	Travel Time Index
TIM	Traveler Information Message
USDOT	U.S. Department of Transportation
UCF	University of Central Florida
UF	University of Florida
UMTRI	University of Michigan Transportation Research Institute
USF-CUTR	University of South Florida Center for Urban Transportation Research
V2X	Vehicle-to-Everything
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
WLAN	Wireless Local Area Network
WWD	Wrong Way Driving
WWVDS	Wrong-Way Vehicle Detection Systems

1 Introduction

1.1 Project Overview

The Florida Department of Transportation (FDOT) Interstate 4 (I-4) Florida's Regional Advanced Mobility Elements (FRAME) project is an extensive, interregional, Integrated Corridor Management (ICM) project running from the Central Business District (CBD) in Tampa to the southwest side of Orlando at Florida's Turnpike, as shown in Figure 1-1. The I-4 FRAME project covers 77 miles of I-4 roadway and over 200 miles of surrounding arterial networks with 381 signals. The project will deploy an advanced ICM system consisting of next-generation traffic incident management, work zone traffic management, road weather alerts, freeway back-of-queue warnings, and speed harmonization message systems with Vehicle-to-Infrastructure (V2I) technologies. This will be achieved by installing 689 Roadside Units (RSUs) with the dual capability of transmitting and receiving Connected Vehicle (CV) data using Dedicated Short-Range Communication (DSRC) and Cellular Vehicle-to-Everything (C-V2X) technologies. At the same time, FDOT will seek to procure and install vehicle On-Board Units (OBUs) that can communicate via this technology.

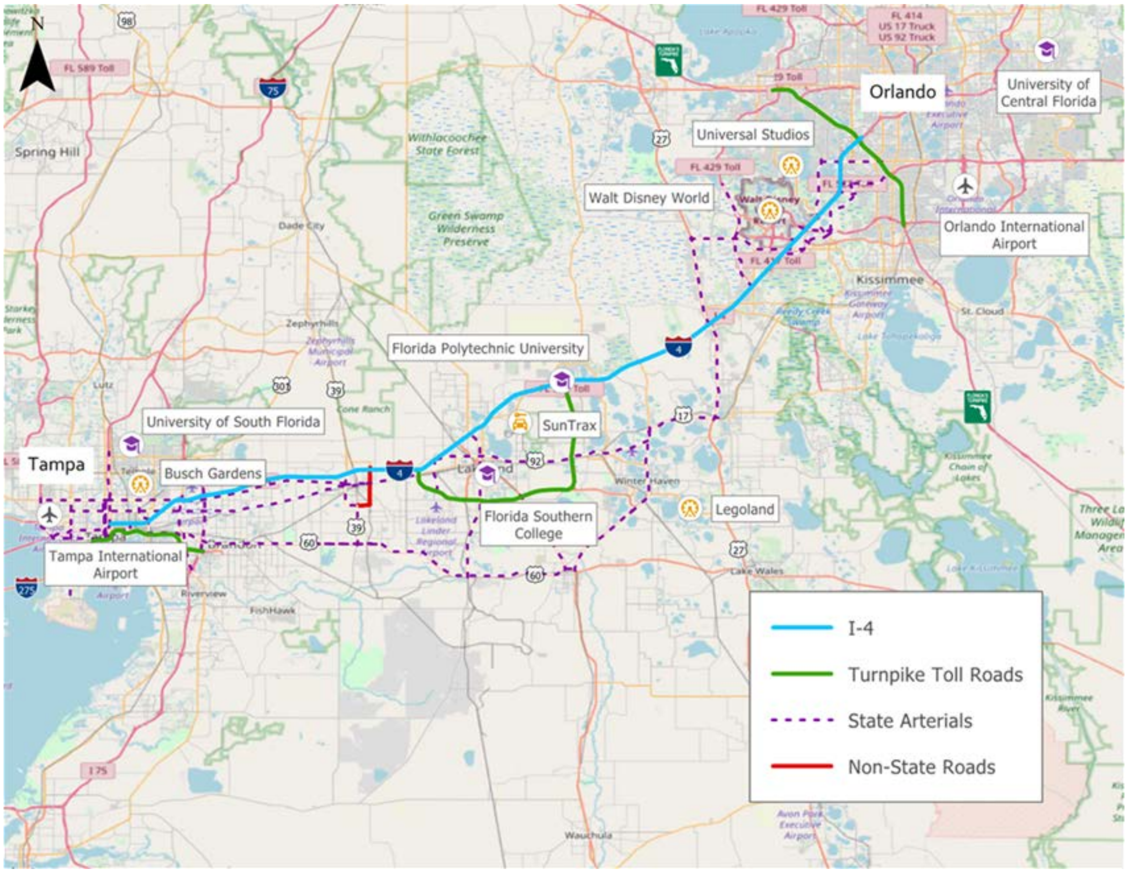


Figure 1-1. I-4 FRAME project map

Source: FDOT

The U.S. Department of Transportation (USDOT) selected the I-4 FRAME project for its Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) grant. As part of grant obligations, FDOT will conduct a before-after analysis on the emerging technologies. Because I-4 FRAME spans three FDOT Districts (1, 5, and 7), FDOT has partnered with universities in the study area to complete the evaluation. Teams from the Center for Urban Transportation Research (CUTR) at the University of South Florida (USF), the University of Central Florida (UCF), and Florida Polytechnic University (FL Poly) are contributing to data collection and collaborating on analyzing the "before" conditions in the research scope, and the University of Florida (UF) is performing project management and coordination with the universities to maintain consistency and data management with USF-CUTR.

1.2 Project Objectives and Associated Tasks

For this project, each research team from USF-CUTR, UCF, and FL Poly is performing allocated tasks and project transportation system applications and services for I-4 FRAME along with the data to be collected for each application. Each team is considering a comprehensive performance measurement framework for the use cases identified and providing a comprehensive evaluation of the "before" conditions for the study area.

Major project objectives and associated tasks for the USF-CUTR team included the following:

- Identify mobility challenges on the project corridor and document how the I-4 FRAME project is addressing the goals set out by FDOT.
- Conduct "before" data collection and data analysis on 15 selected transportation systems and services from the I-4 FRAME project.
- Develop methodologies for evaluating the safety and mobility performance and benefits of the I-4 FRAME project and collect necessary data from FDOT and local data sources to support methodology development.
- Support and assist FL Poly in evaluating the potential of communication technologies for preventing secondary crashes and developing microscopic simulation models to demonstrate and quantify the possible benefits of CVs for preventing primary and secondary crashes.
- Study OBU technology and compare various aspects of DSRC and C-V2X OBUs and perform a comparative study on use cases of FL511 application and deployed OBUs.
- Assist FDOT in developing a Data Management Plan (DMP) and a Project Evaluation Plan (PEP) for the I-4 FRAME project to submit to the Federal Highway Administration (FHWA).

This report includes a summary of findings from all tasks performed for Phase 1 of the project, which included data collection and analysis for the "before" period of the project, characterized as prior to any deployment of Roadside Units (RSUs), OBUs, and CV applications on the I-4 FRAME project corridors. Detailed analysis and results are provided in each task deliverable.

1.3 Study Limitations

The “before” study analysis had limitations stemming from data availability and deployment details not available to the evaluation team. Data were requested and acquired in cooperation with the FDOT Central Office, FDOT Districts, and Florida’s Turnpike Enterprise. As data became available or were obtained, the team modified its original plan to conduct analysis according to the availability of the data and the limited information on RSUs and specific application deployment for each location. The team conducted all analyses to the best of its ability with the data received.

1.4 Report Organization

The report is organized as follows: Section 2 provides an overview of CV technologies. Section 3 summarizes the DMP and PEP. Section 4 identifies and addresses mobility challenges on I-4 FRAME project corridors. Section 5 presents “before” data collection and analysis of selected individual I-4 FRAME project transportation systems and services. Section 6 describes the development of predictive analysis methodologies. Section 7 presents the future of Connected Automated Vehicle (CAV) deployments on transitioning to C-V2X. Section 8 provides comparative assessment of DSRC and C-V2X OBUs. Section 9 offers conclusions and lessons learned.

2 Overview of CV Technologies

Data transmitted in a Vehicle-to-Vehicle (V2V) exchange are valuable only if they are received promptly, are accurate, and are transmitted in a consistent manner [1]. Using a combination of DSRC, C-V2X, and hybrid protocols, vehicles in a V2V communications network exchange data with each another. Interoperability is the degree to which different devices equipped with V2V technologies from different Original Equipment Manufacturers (OEMs) and aftermarket vendors can interact with one another in a timely and reliable manner [1]. If components from various manufacturers are not compatible, the system will suffer from deficient performance and eventual failure due to lack of interoperability. The following sections introduce different CV technologies and their limitations. Thereafter, an overview of national and global C-V2X and DSRC programs is presented, and the impact of policies and regulations on the implementation of CV technologies in the U.S. is explored and discussed.

V2V systems are mobile nodes that directly connect one moving car with another. Vehicle-to-Infrastructure (V2I) and Vehicle-to-Pedestrian (V2P) systems are designed to connect moving automobiles to roadside infrastructure or pedestrians. When vehicles communicate with Information Technology (IT) networks and data hubs, the network type shifts to Vehicle-to-Network (V2N). Vehicle-to-Everything (V2X) communication refers to all these types of communication through linking vehicles to other recipients [2].

DSRC and C-V2X communication technologies are the data transfer technologies currently employed in V2X systems. The first DSRC deployment dates back to 1991, when USDOT conducted a national project after passage of the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991. The project aimed to integrate communications technology into the national ground infrastructure to improve traffic safety, save fuel, and reduce pollution [3]. However, the first significant moves toward the worldwide deployment of DSRC were made when various standards bodies, including the Society of Automotive Engineers (SAE) in the U.S., the European Committee for Standardization (CEN) and the European Telecommunications Standards Institute (ETSI) in Europe, and the Association of Radio Industries and Businesses (ARIB) in Japan, sought to standardize DSRC [4]. As standards evolved, several projects were carried out globally to test driving warning systems [4]. In 2010, the Institute of Electrical and Electronics Engineers (IEEE) introduced the IEEE 802.11p standard, an upgraded version of the IEEE 802.11a standard [5], which outlined the Physical (PHY) and Medium Access Control (MAC) layers for exchanging wireless broadcast messages in a vehicular setting [6]. Since then, the standard has been the primary protocol for DSRC deployments worldwide.

With the introduction of Long-Term Evolution (LTE), cellular networks with high capacity, low latency, and high reliability have been widely accessible. With the advent of the 5G network, these capabilities are anticipated to advance [4]. The 3rd Generation Partnership Project (3GPP) published Releases 14 and 16 for the LTE-V2X and 5GNR-V2X standards in 2016 and 2019, respectively [7]. Since then, C-V2X has been considered a viable alternative to DSRC worldwide in CV pilots globally.

2.1 Advantages and Disadvantages of DSRC

Local, low latency network connectivity is offered by DSRC, which enables almost instantaneous network connections and network-free broadcast messaging [1]. It is preferable to employ DSRC technology when there are only a few hundred meters between vehicles, inter-roadside infrastructure, and pedestrians [8]. Vehicle OBUs, RSUs, and pedestrian mobile devices all communicate data over the DSRC system. However, published data indicate that DSRC systems struggle with high traffic volumes in terms of dependability, efficiency, and productivity [9, 10]. In addition, DSRC communication technologies are not meant for massive data transfers or Internet access in automobiles [1]. Moreover, considering that video-sharing would take 82% of total bandwidth by 2022, this situation will become even more urgent and delicate [11]. Due to the limits of present DSRC technology, there is considerable interest in C-V2X communication technologies.

2.2 Advantages and Disadvantages of C-V2X

C-V2X is cheaper than DSRC [12], as LTE chipsets are less expensive than Wireless Local Area Network (WLAN) chipsets. Also, C-V2X has a higher growth potential than DSRC, as it provides a long-term path for continuous improvement [13]. C-V2X also is more reliable than DSRC for long distance communications [14, 15]. However, the main advantage of C-V2X over DSRC is that, unlike DSRC, which supports only direct communication, C-V2X can communicate both directly and indirectly. In the direct mode of C-V2X, like DSRC, vehicles communicate directly with other vehicles and RSUs, whereas under indirect C-V2X, vehicles communicate via a cellular network [13]. Indirect C-V2X is advantageous, as the cellular network can collect data from numerous vehicles, allowing more effective traffic management on a broader scale.

Despite the fact that a C-V2X connection provides better data stream coverage, cellular networks are not always available in all locations, and coverage might occasionally encounter dead patches [1]. Furthermore, each cellular station transmits information to all devices within its coverage area, and those devices communicate with the station through unicasting. Therefore, as the number of vehicles increases, so does the number of unicast streams, which places a strain on the network’s resources and makes it more difficult to send messages in a timely manner [1]. Delay in the transmission of data is one of the most crucial and controllable aspects of traffic safety. This is especially true when considering that the number of mobile users and the quantities of data transmission have been increasing steadily since 2017 and will continue to do so through 2022 [11].

2.3 DSRC Programs in the U.S. and World

2.3.1 DSRC Programs in the U.S.

In 2005, the first public CV testbed in the U.S. was created on El Camino Real (SR-82) in Palo Alto, California, between Stanford Avenue and W Charleston Avenue [16]. There are 11 consecutive intersections along this road, and more than 50,000 cars drive through this section between San Francisco and San Jose every day. The testbed's collaborators were Caltrans, the Metropolitan Transportation Commission, and the California PATH program at the University of California, Berkeley. CV standards were implemented in the previously planned California CV testbed in 2013 with the support of USDOT. This testbed focused on adopting multimodal intelligent traffic signal systems and environmentally-friendly transportation applications. The main goal was to improve the arterial network's overall performance by implementing transit and freight Traffic Signal Priority (TSP), emergency vehicle prevention, and pedestrian safety applications.

The Maricopa County Department of Transportation (MCDOT) and the University of Arizona started Arizona's Connected Vehicle Program in 2007 as a research effort to improve traffic signal operations, incident management, and traveler information. MCDOT established vehicle prioritizing at that time to protect emergency vehicles from colliding at signalized intersections. MCDOT's SMARTDrive Program^{SM} connects with numerous emergency vehicles at the same intersection to determine which vehicle has the right-of-way [17].

In 2016, the American Association of State Highway and Transportation Officials (AASHTO) challenged states to implement DSRC to broadcast real-time Signal Phase and Timing (SPaT) at signalized intersections on at least one road corridor in each state by January 2020 [18]. Several states and cities responded to the challenge:

- The Delaware DOT (DelDOT) equipped 13 intersections in Smyrna and Dover; the agency also intends to install devices at various spots along the beach. Vehicles equipped with OBUs can receive messages regarding signal timing information from RSUs, resulting in a safer and more efficient transportation network [19].
- In 2019, FHWA granted the Georgia DOT (GDOT) a $2.5 million grant for CV technology [20]. GDOT released RSU and OBU cost figures for the 2019 and 2020 Signal Phase and Timing (SPaT) Challenge [18] in Atlanta, noting that RSUs at 1,600 intersections cost $6,640,000 [21].
- The Hawaii DOT (HDOT) installed RSUs on 16 east Hawaii traffic signals. CV sensors discreetly capture data from Bluetooth-enabled devices in vehicles to determine trip durations. HDOT will use the data to enhance traffic signal timing [22].
- In Indiana, connected traffic signal equipment was installed in several places around the state. SPaT message deployment in the West Lafayette corridor used both DSRC and cellular communication; the research team successfully showed and tested use cases for

sending virtual vehicle detection calls to a traffic signal controller using Basic Safety Messages (BSMs) [23].

- The Minnesota DOT (MnDOT) selected Highway 55 between downtown Minneapolis and I-494 to test CAVs. The initiative aims to broadcast SPaT information from traffic signals on the corridor to connected vehicles. MnDOT fleet cars were equipped to showcase the technology's potential [24].
- In Florida, several counties and cities have equipped intersections with CV technology. Four roadways around the University of Florida main campus in Gainesville use CV technology; the initiative aims to increase journey time, safety, throughput, and traveler information. In total, 27 traffic lights and 27 RSUs are included [25]. Osceola County deployed RSUs at two signalized crossings to further CV technologies; FHWA financed the deployment as a pilot project to test DSRC equipment and intersection processing technology [26]. Tallahassee is adopting CV technology for a large SPaT project; FDOT and Tallahassee will deploy roadside devices to broadcast SPaT information at 22 DSRC-equipped signalized intersections [27].

USDOT is leading the deployment project for CV testbeds in the U.S. as part of the Intelligent Transportation System (ITS) Strategic Plan [28]. Southeast Michigan is home to a USDOT-sponsored CV testbed, allowing CV developers to test any CV software. The testbed's construction began in 2009 and was completed in August 2017.

In 2012, the University of Michigan Transportation Research Institute (UMTRI) and USDOT launched a new initiative called Safety Pilot Model Deployment (SPMD) [29] to use CV technology to decrease roadway crashes. This $30 million project in Ann Arbor conducted from 2015–2018 featured approximately 2,800 cars and 73 lane miles. After the successful installation of SPMD, the Ann Arbor testbed was extended from northeast Ann Arbor to the entire city, covering a 27-square-mile region, with 45 streets and 12 interstate locations. The testbed's key goals were to ensure that model deployment would be transferable to an early operational deployment, the test equipment would continue to operate and maintain a robust test environment, and the testbed would be financially sustainable as a federally-supported program.

After the success of the SPMD project, USDOT set aside $45 million in September 2016 for sites in New York, Wyoming, and Florida to begin designing, deploying, and validating the CV Pilot Deployment Program:

- The goal of the pilot deployment in New York City is to improve vehicle and pedestrian safety [30]. This trial deployment includes 280 RSUs and 10,000 vehicles (cabs and buses) to investigate CV safety issues and benefits in an urban area. It also is researching pedestrian safety applications using 100 pedestrian-DSRC modules.

- Multiple regions along I-80 were selected as the Wyoming CV pilot deployment site [31]. DSRC OBUs were placed in 400 commercial vehicles (snowplows and heavy trucks) to offer safety alerts and route direction.
- In Florida, the Tampa-Hillsborough Expressway Authority (THEA) pilot project implemented multiple V2V and V2I applications [32] to reduce traffic congestion, vehicle conflicts, and motorists entering the Selmon Reversible Express Lanes (REL) the wrong way and to use CV techniques to enhance pedestrian safety and bus operation efficiency and reduce vehicle-pedestrian collisions. As part of the THEA program, about 1,000 vehicles, 10 buses, 10 trolleys, and 47 RSUs have been deployed.
- Virginia has two CV testbeds [33], one at the Virginia Smart Road in Blacksburg and one at Route 460 in Fairfax County along I-66 and routes 29 and 50. The Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC) selected two areas for its CV study due to traffic congestion, high crash rates, and poor air quality. In total, 40 RSUs and additional instrumented vehicles were stationed along both cities' highways.

2.3.2 DSRC Programs Outside the U.S.

Numerous other countries have established CV testbeds to evaluate DSRC communication:

- In South Korea, the Cooperative-Intelligent Transport Systems (C-ITS) pilot deployment project began in 2014 and was completed in 2017 [34]. The pilot began as a national initiative to validate C-ITS technology. Several safety warnings were evaluated in the pilot, including hazardous location warnings, road work zone warnings, signalized intersection violation warnings, pedestrian collision warnings, and forward collision warnings.
- German, Dutch, and Austrian authorities partnered with the automotive industry on the European C-ITS Corridor initiative [35] to develop Cooperative (V2X) Systems. A road-works safety trailer with Global Positioning System (GPS) and a communication system gave local hazard warnings and traffic information to approaching vehicles. The project aimed to increase safety for site workers and vehicles and gather real-time information regarding roadworks.
- In Australia, a collaboration among the University of Melbourne, Cisco, and Cohda conducted an experiment using the infrastructure for connected and automated vehicles [36]. The trial's purpose was to improve CAV response times to upcoming events and identify threats to both vulnerable road users and CAVs accurately. The program examined use cases such as collision warnings, road condition change warnings, and lower speed limit warnings.
- DIGINET-PS, an open test environment for CV technologies in Berlin, was established by the German Federal Ministry of Transport and Digital Infrastructure (BMVI) [37] to create a scalable and open testing platform for CVs and determine how much CV

technology can increase vehicle performance and make traffic safer, more efficient, and environmentally-friendly.

- Singapore's Nanyang Technological University (NTU) created the Smart Mobility Testbed as an innovation hub for safe connected vehicles and intelligent transportation systems [38] to accelerate the implementation of lifesaving V2V and V2I communication technologies. The $22 million program is exploring technology that will allow vehicles to "speak" to one another and RSUs. In total, 12 smart mobility use cases have been established to show how technology can improve road safety, traffic management, and travel experiences.

DSRC projects around the world are summarized in Table 2-1.

2.4 C-V2X Programs in the U.S. and World

2.4.1 C-V2X Programs in the U.S.

Multiple projects in the U.S. have focused on C-V2X technology and various use cases:

- To monitor the traffic network, the Colorado DOT (CDOT) and Panasonic constructed and tested V2X vehicle OBUs and roadside equipment in a real-world environment. Participants received real-time information regarding road conditions such as traffic delays, ice conditions, and accidents via continuous and automatic communications between automobiles and RSUs [39].
- The Regional Transportation Commission (RTC) of Southern Nevada and Qualcomm, Inc., installed C-V2X RSUs and aftermarket OBUs in Las Vegas in 2019 to study the benefits of C- V2X, including SPaT and traffic messaging [40].
- As part of a major Crash Avoidance Metrics Partners, LLC program, General Motors, Ford, Nissan, and Hyundai conducted a C-V2X road test in 2019 [41] that proved the viability of deploying C-V2X technologies.
- Caltrans conducted a pilot project in San Diego to investigate how C-V2X technology can aid in the widespread implementation of intelligent mobility solutions as part of a connected roadside infrastructure [42]. The pilot deployed vehicles equipped with OBUs and RSUs throughout a three-mile stretch of highway and at many key points along the I-805 freeway. During the trial, RSUs dispatched I2V messages alerting lower speed zones, construction zones, and disabled cars.
- USDOT considered a $9.9 million award for the UMTRI Smart Intersection project in 2021 that involved installation of a network of smart intersections around the city and a fleet of C-V2X-equipped vehicles. The project laid the basis for a national CAV deployment initiative by including C-V2X [43]. A connected smart infrastructure is being constructed on a highway by UMTRI to receive and aggregate traffic data via C-V2X technology, which will be used by heavy-duty vehicles transiting the corridor to improve their fuel economy while reducing trip time. [44].

Table 2-1. DSRC Projects Around The World

Project	Partners	Location	Start Year	V2X Tech	Objectives	Vendors
California Connected Vehicle Testbed	MTC and the UC Berkeley	El Camino Real, San Jose, CA	2017	DSRC	Implementing traffic signal priority for transit and freight, emergency vehicle preemption, pedestrian safety applications.	NA
MCDOT's SMARTDrive ProgramSM	MCDOT and the University of Arizona	Maricopa County, AZ	2007	DSRC	Improve traffic signal operations, incident management, traveler information	NA
Safety Pilot Model Deployment	UMTRI, MDOT, Parsons Brinckerhoff, Mixon-Hill, Leidos, Bosch	Ann Arbor, MI	2012	DSRC	Investigate effectiveness of CV safety applications	NA
NYC Connected Vehicle Project	USDOT, NYCDOT, and TransCore	New York, NY	2015	DSRC	Deploy CV technologies to enhance safety in urban area	Commsignia, Danlaw, Lear, Savari, Siemens, and Sirius XM
Tampa-Hillsborough Expressway Authority (THEA) Pilot, Phase 3	USDOT, COT, FDOT, Hillsborough Area Regional Transit (HART)	Tampa, FL	2015	DSRC	Evaluate deployment of CV technology to address mobility and safety issues	Siemens Mobility Inc., Savari, and Sirius XM
Wyoming DOT Connected Vehicle Pilot	USDOT, WYDOT, and the University of Wyoming	Wyoming	2015	DSRC	Use CV technology to reduce impact of adverse weather on truck trips	Sirius XM
Australian Integrated Multimodal EcoSystem (AIMES)	University of Melbourne, Cisco, Cohda, TAC, VicRoads, WSP	Melbourne, Australia	2019	DSRC	Faster CAV response to imminent events, analyze hazards to vulnerable road users and CAVs	Cohda and Cisco
South Korea C-ITS pilot	Korea Ministry of Land, Infrastructure and Transport	South Korea	2014	DSRC	Verify C-ITS technologies	NA
European C-ITS Corridor project	German, Dutch, and Austrian transport ministries and industrial partners	Germany, Austria, Netherlands	2016	DSRC	Increase safety and gather real-time information regarding roadworks.	NA

Project	Partners	Location	Start Year	V2X Tech	Objectives	Vendors
Digitally Connected Protocol Route	Berlin Senate Department for the Environment, Transport and Climate Protection, Cisco, Hella Aglaia, IAV GmbH	Berlin, Germany	2019	DSRC	Learn how CVs improve vehicle capabilities, making traffic safer, more efficient, environmentally friendly	Cisco
Smart Mobility Test Bed	NTU and NXP	Singapore	2015	DSRC	Demonstrate benefits of technology in terms of road safety, traffic management, improved travel experiences	Denso and Panasonic
Integrated Transportation Management Program	DelDOT	Smyrna and Dover, DE	2017	DSRC	Respond to AASHTO SPaT Challenge	NA
Georgia DOT SPaT Project	GDOT	Atlanta, GA	2019	DSRC	Respond to AASHTO SPaT Challenge	NA
Hawaii DSRC Deployment	Hawaii DOT (HDOT)	Hawaii	2020	DSRC	Respond to AASHTO SPaT Challenge	NA
Indiana Connected Vehicle Corridor Deployment Project	Indiana DOT (INDOT)	West Lafayette, IN	2019	DSRC	Respond to AASHTO SPaT Challenge	NA
Minnesota Connected Corridor Project	Minnesota DOT (MnDOT)	Minneapolis, MN	2017	DSRC	Respond to AASHTO SPaT Challenge	NA
Integrated Transportation Management Program	Delaware DOT (DelDOT)	Smyrna and Dover, DE	2017	DSRC	Respond to AASHTO SPaT Challenge	NA
Gainesville SPaT Trapezium	Florida DOT (FDOT)	Gainesville, FL	2019	DSRC	Respond to AASHTO SPaT Challenge	NA
Osceola County Connected Vehicle Signals	Florida DOT (FDOT)	Osceola, FL	2018	DSRC	Respond to AASHTO SPaT Challenge	NA
US 90 Signal Phase and Timing Tallahassee	Florida DOT (FDOT)	Tallahassee, FL	2018	DSRC	Respond to AASHTO SPaT Challenge	NA

The U.S. CV market has recently seen a shift from DSRC to C-V2X technology, which is expected to continue. Starting in 2022, Ford intends to use C-V2X in all of its new vehicles [45]. Virginia DOT and American Tower Corporation also announced deployment of C-V2X, which will provide state-of-the-art wireless infrastructure for Audi [46]. This project complements Audi's Traffic Light Information (TLI) service by warning motorists of the possibility of running red lights when traveling through signalized intersections; it also deployed vests equipped with C-V2X technology to increase the safety of maintenance staff who are vulnerable road users in construction areas. Additionally, Blue Bird, Fulton County Schools, and Audi are cooperating to deploy CVs with the goal of enhancing the safety of school buses and school zones [47].

2.4.2 C-V2X Programs in China

C-V2X technology is getting increased traction in China. In 2018, Shanghai launched the Three Layers Interoperability V2X Application Demonstration to showcase cross-communication modules, cross-terminals, and cross-vehicles LTE-V2X interoperability [48]. In total, 11 OEMs, eight terminal vendors, and three communication module providers participated. Demonstrations included use cases such as speed advisories, intersection collision warnings, emergency brake warnings, and forward collision warnings.

As part of a pilot project in Wuxi, Ford successfully tested C-V2X technology for the first time on Chinese public roads in 2018 [49]. The Ford team developed several use cases using direct and network modes of C-V2X technology in collaboration with regional partners such as Huawei and China Mobile. The technology sent drivers traffic light status messages, potential red-light violations, and recommended speed ranges for optimum fuel economy and traffic efficiency.

China also has developed a national framework for the Internet of Vehicles (IoV), and the Chinese automotive industry is introducing vehicles with this technology. After the Smart Vehicles Innovation Development Strategy was published in 2020, automakers began mass-producing smart vehicles incorporating C-V2X technology [50]. For example, Zhejiang Geely Holding Group, a Chinese automaker, partnered with Qualcomm Technologies and technology group Gosuncn to produce C-V2X and 5G-enabled vehicles in 2021 [51].

Numerous cities have collaborated with local wireless network providers to install thousands of RSUs. There are currently more than 10 C-V2X installations in China with a variety of applications, including information service, safety, and transportation efficiency [52]. Chinese authorities have also begun to plan for the 5G spectrum and regulations [53].

2.4.3 C-V2X Programs in Europe

Several European countries have launched CV use and testing:

- Germany was one of the first European countries to highlight the use of CVs equipped with C-V2X technology. Among the several use cases deployed in the program were emergency electronic brake lights, intersection collision warnings, pedestrian warnings, and traffic efficiency applications such as signal phase and timing [54].

- West Midlands, the automotive hub of the United Kingdom [55], is at the forefront of CV testing and trials there. About 300 kilometers of C-V2X infrastructure, including urban, rural, suburban, and interstate roads, have been constructed, where the region's automobile industry tests and implements technologies, such as using data to activate traffic and road hazard warnings.
- The Italian Ministry of Infrastructure and Transport is working with Anas Group on Italy's first CV pilot [56]. Over 80 kilometers of the highway are fitted with RSUs equipped with C-V2X technology, Europe's longest single-segment coverage. This smart road delivers vital information to road users, such as traffic flow deviation in the event of an accident, alternate route suggestions, access management, and parking.
- The CONCORDA project [57], a collaboration of 26 partners supported by the Connecting Europe Facility (EU CEF), is testing at six locations in Spain, France, Belgium, the Netherlands, and Germany. The testing will emphasize connected and automated driving and truck platooning using C-V2X technology. The project aims to show interoperability across test locations for technologies, applications, and implementations.
- The European Union (EU) is funding various 5G cross-border corridor trial projects to conduct a large-scale evaluation of 5G-enabled Connected and Automated Mobility (CAM) solutions. The 5G-CARMEN program (5G for Connected and Automated Road Mobility in the European Union) [58] is a 25-partner consortium demonstrating 5G technologies for Cooperative, Connected, and Automated Mobility (CCAM). The project seeks to have a global impact by conducting comprehensive testing throughout an important corridor stretching 600 kilometers from Bologna to Munich, Germany. Cross-border use cases addressed by 5G-CARMEN pilots include cooperative navigation, situation awareness, video streaming, and green driving.
- Fifth Generation Cross-Border Control (5GCroCo) is a European automobile and mobile communications collaboration funded by the EU [59] to develop a successful path to cross-border CCAM services and eliminate the uncertainties associated with a real 5G cross-border deployment. 5GCroCo tests 5G in a cross-border corridor in France, Germany, and Luxembourg. Tele-operated driving, high-definition maps for self-driving cars, and anticipated cooperative collision avoidance are some of the use cases validated in the program.
- The EU-funded 5G-MOBIX program [60] brings together 58 partners from 13 countries to test automated vehicle capabilities along two cross-border corridors. The experiments evaluate 5G benefits for connected and automated mobility applications such as cooperative overtaking, highway merging, truck platooning, and remote driving.
- 5G-ROUTES will conduct advanced field testing of the most innovative connected and automated mobility applications throughout a 5G cross-border corridor connecting Latvia, Estonia, and Finland [61]. The program validates the most recent 5G features and

3GPP specifications in real-world conditions. Among the use cases implemented by this initiative are dynamic vehicle platooning, cooperative lane change, and safe automated overtaking.

2.4.4 C-V2X Programs in Other Countries

C-V2X also is spreading outside the U.S., China, and Europe:

- In 2018, Japan conducted C-V2X field testing in partnership with Ericsson, Nissan, and Qualcomm to illustrate the advantages of C-V2X using direct communications using 3GP technology and network-based communications using LTE-advanced technology. Among the scenarios investigated were car-following, overtaking, hazardous sites, and pedestrian crossing [62].
- UD Trucks Corporation is currently involved in the Japanese government's highway platooning projects, in which C-V2X is used to transmit images taken by electronic mirrors and to support other communications [63]. Electronic mirrors can help improve visibility by correcting images while driving at night or in adverse weather.
- The Singaporean NTU and telecom provider M1 are collaborating to incorporate 5G technology into a C-V2X research testbed [64]. Participants can explore, create, and present 5G-connected mobility ideas on the NTU Smart Campus, a $24 million testbed. This will make it possible for business partners to roll out 5G connected mobility solutions in fields such as network security, real-time traffic routing, and collision avoidance.
- In South Korea, Hyundai Mobis and Korea Telecom created a proving ground to evaluate real-time communication between vehicles, infrastructure, and other vehicles. The traffic data collected by vehicles was forwarded to servers to be used for traffic signal timing and curve warning [65]. LG Electronics partnered with Qualcomm to develop CV solutions and a collaborative research center to explore 5G and C-V2X technology for autonomous vehicles [66].
- To study and test the technology's potential use cases on Hong Kong roads as well as the network and infrastructure needed for the application, the Hong Kong Applied Science and Technology Research Institute (ASTRI) initiated one of the largest C-V2X pilots in the world [67]. STRI's C-V2X system includes real-time communication between vehicles and pedestrians, roadside infrastructure, and networks, and instant information and warnings can be dispatched to improve driver assistance and road safety.
- Australia is looking to implement CVs using C-V2X technology. A CV system was built in collaboration with the Victoria Department of Transport, the Transport Accident Commission, Telstra, and Lexus Australia to investigate the potential safety advantages of connected vehicles, such as preventing accidents and lowering fatalities [68].

Table 2-2 provides a summary of the C-V2X projects around the world.

Table 2-2. C-V2X Projects Around The World

Project	Partners	Location	Start Year	V2X Tech	Objectives	Chipset Vendor	Module Vendor
Research on safety of work zones	VTTI, VDOT, Audi	VA	2020	C-V2X	Safety of maintenance workers	Qualcomm	Commsignia
Las Vegas C-V2X	RTC of Southern Nevada	Las Vegas, NV	2019	C-V2X	Demonstrate benefits of C-V2X technology, e.g., signal timing and traffic messaging	Qualcomm	Commsignia
San Diego AV Regional Proving Ground	USDOT, Caltrans	San Diego, CA	2020	C-V2X	Evaluate C-V2X technology	Qualcomm	Commsignia
Colorado Pilot Program	CDOT, Panasonic, Ford	CO	2018	C-V2X	Deploy C-V2X, real-time information about road conditions such as traffic delays, icy conditions, and crashes	Qualcomm	Panasonic, Kapsch
Improving efficiency of trucks via CV2X	CCAT, UMTRI	MI	2020	C-V2X	Maximize fuel economy of large without compromising travel time	NA	NA
Smart Intersections in Ann Arbor	USDOT, UMTRI	Ann Arbor, MI	2021	C-V2X	Trigger onboard warnings at intersections	NA	NA
C-V2X Performance Assessment Project	Ford, GM, Hyundai, Nissan	Detroit, MI	2019	C-V2X	Evaluate C-V2X communication technology	Qualcomm	NA
Europe's first live demo of C-V2X	5GAA, BMW, Ford, Peugeot Citroen	Germany	2018	C-V2X	Exhibit road safety and traffic efficiency benefits of using C-V2X	Qualcomm	Savari
Midlands Future Mobility project	Transport for West Midlands and Siemens	Coventry, Birmingham, Solihull, UK	2020	C-V2X	Improve air quality, reduce congestion, integrate ridesharing services into public transport	Qualcomm	Commsignia
Anas Program	Anas and Italy Ministry of Infrastructure and Transport	Italy	2021	C-V2X	Information services regarding deviation of traffic flow in event of accidents, management of accesses, parking, and supplies	NA	NA
5G-CARMEN	EU	Bologna-Munich	2018	C-V2X	Safer, greener, more intelligent transportation with goal of enabling self-driving cars	NA	NA

Project	Partners	Location	Start Year	V2X Tech	Objectives	Chipset Vendor	Module Vendor
CANCORDIA project	EU	Netherlands, Belgium, Spain, France, Germany	2017-2020	C-V2X	Improve interoperability of test sites	NA	NA
5GCroCo	EU	France, Germany, Luxembourg	2018	C-V2X	Develop way to cross-border CCAM services, alleviate 5G deployment uncertainties	NA	NA
5G-Mobix	EU	Spain, Portugal, Greece, Turkey, France, Finland, Germany, Netherlands	2018	C-V2X	Evaluate 5G benefits for connected and automated mobility applications	NA	NA
5G-ROUTES	EU	Latvia, Estonia, Finland	2018		Validate 5G features and 3GPP specifications in real-world conditions	NA	NA
Advanced Connected Vehicles Victoria (ACV2)	Dept. of Transport (Victoria), Transport Accident Commission, Telstra, Lexus Australia	Melbourne, AUS	2018	C-V2X	Test CV safety technologies for vulnerable road users such as emergency braking alerts, speed limit compliance, right-turn aid	NA	NA
C-V2X Trial in Japan	Continental, Ericsson, Nissan, NTT DOCOMO, OKI, Qualcomm	Japan	2018	C-V2X	Validate and demonstrate the benefits of C-V2X	Qualcomm	NA
Japanese government's highway platooning	UD Trucks Corporation, Government of Japan	Japan	2019	C-V2X	Improve visibility of platooning trucks	NA	NA
NTU C-V2X testbed	NTU and M1	Singapore	2019	C-V2X	Build C-V2X solutions for crash avoidance, traffic routing, network security	NA	M1
V2X Three-Layers Demonstration in Shanghai	11 OEMs, 8 vendors, 3 module providers	China	2018	C-V2X	Highlight LTE-V2X interoperability	Multiple providers	Multiple providers

Project	Partners	Location	Start Year	V2X Tech	Objectives	Chipset Vendor	Module Vendor
Wuxi's LTE-V2X pilot project	Ford, Huawei, China Mobile	China	2018	C-V2X	Test V2I, V2V, and V2P features using direct and network modes of C-V2X	NA	Huawei
China's C-V2X trial	Chinese government and transport ecosystem	China	2020	C-V2X	Show the benefits of connected and intelligent highways and urban roadways	Qualcomm	NA
Zhejiang C-V2X and 5G-enabled vehicles	Zhejiang Geely Holding Group, Qualcomm, Gosuncn	China	2019	C-V2X	Launch C-V2X and 5G-enabled card	Qualcomm	Gosuncn
Hong Kong C-V2X testbed	ASTRI and QTC Traffic Technology Limited	Hong Kong	2021	C-V2X	Improve driver assistance and road safety using instant information and safety warnings	NA	NA
South Korea C-V2X testbed	Hyundai Mobis, Korea Telecom	South Korea	2019	C-V2X	Demonstrate 5G Cellular C-V2X communications	NA	NA
Qualcomm, LG Electronics C-2VX Research Center	Qualcomm, LG Electronics	South Korea	2017	C-V2X	Develop CV solutions and collaborative research center	Qualcomm	NA

2.5 Regulation Impacts on CV Technology from Past to Present

C-V2X technology is at the vanguard of digital transformation, with the Federal Communications Commission (FCC) providing the operational spectrum, 5G Automotive Association (5GAA) members supplying the devices, and OEMs and road operators planning commercial releases. C-V2X supports both direct (PC5/Sidelink) and mobile network-based (Uu) connections. Although cellular networks are not required to provide data transmission services in the direct mode of C-V2X, they can be used to complement end-to-end use cases [69].

Cellular network connectivity (Uu mode of C-V2X, also known as V2N) is extensively used in telematics services. Since 1996, when it initially appeared in automotive applications, its use has progressively increased across all vehicle brands and types. Over the previous three telematics design cycles, automakers have increased communication technology adoption and are rapidly reaching 100 percent attach rates [70]. Networked automobiles will provide features such as collision warnings, software updates, traffic and road condition updates [9]. The two modes of C-V2X function together seamlessly, as if they were on the same chipsets and platforms, which allows manufacturers to create new products with unified technology paths for improved performance and utility while also saving money [70].

In 1995, the National Transportation Safety Board (NTSB) proposed to the FCC [71] that CVs be given a dedicated spectrum, notably higher frequency bands, for transportation safety commutations. As a result, the FCC designated 75 MHz of the 5.9 GHz spectrum for intelligent transportation systems (ITS) and CV technologies in 1999 [72]. In 2020, the FCC designated the upper 30 MHz of the 5.9 GHz ITS band for C-V2X technology in a Report and Order [73]; as a result, the authorized spectrum for V2X was reduced from 75 to 30 MHz, leaving only two channels for V2X message distribution—10 MHz for DSRC and 20 MHz for C-V2x. Another factor to consider is the harmful interference of other competing technologies. Because of the new FCC spectrum limitations, the new U-NII-4 unlicensed Out-of-Band Emissions (OOBE) may cause interference with C-V2X transmission if they are too loud, especially from outside operations. This problem is compounded in busy city regions where Wi-Fi operations by vehicles, pedestrians, and other road users are expected.

The 5G Americas organization brings together top telecom service providers and manufacturers with the goal of promoting the advancement and full capabilities of LTE wireless technologies and their evolution to 5G. 5G Americas has requested 40 MHz of additional mid-band spectrum from the FCC to provide increased C-V2X capabilities and use cases. Meanwhile, the C-V2X spectrum allocation of 30 MHz will assist transportation stakeholders significantly in terms of safety [74]. To ensure C-V2X performance in the permitted frequencies, 5G Americas has recommended that the FCC limit U-NII-4 OOBE from fixed outdoor network nodes to a maximum of -27dBM/MHz at the 5895 MHz edge [9]. 5G Americas recommends that client-to-client and mobile hotspot use of the U-NII-4 spectrum be forbidden due to a lack of isolation to safeguard C-V2X OBU receivers [74].

3 Data Management Plan (DMP) and Project Evaluation Plan (PEP)

This section details Task 5 of the project scope, development of a DMP and PEP before the data were collected for the "before" analysis. Task 5 included developing draft iterations and finalizing the approved version. The final DMP and PEP address FHWA's comments on draft submittals. The DMP provides an overview of the data collected throughout the project and details all data elements, access policies, data sharing, storage, and archiving. The PEP describes project goals, evaluation methodology and design, performance measures, data collection procedures, and risks involved.

3.1 Minimum Requirements

Development of the DMP and PEP adhere to previously-established guidelines and minimum requirements as follows:

- The DMP is consistent with USDOT's recommended guidelines and includes the following sections:
    - Data description
    - Data access policies
    - Data storage and retention
    - Plan to update the DMP over the course of the project
- The PEP includes:
    - Statement of project objectives
    - List of evaluation criteria (quantitative performance metrics and/or qualitative assessments)
    - Description of data collection procedures tailored to the evaluation criteria
    - Outline of evaluation report

3.2 Data Management Plan (DMP)

CUTR led development of the DMP, which provides an overview of the data to be collected throughout I-4 FRAME deployment. The plan details all data elements, access policies, data sharing, storage, and archiving and is consistent with USDOT's recommended guidelines. Work under this task consisted of the following subtasks.

3.2.1 DMP Outline

CUTR prepared the DMP outline, which meets the original Notice of Funding Opportunity (NOFO) requirements and includes the following sections:

- Data description
- Data access policies
- Data storage and retention
- Plan to update DMP over course of project

The outline was shared with FDOT and all relevant research partner university task leads via USF's official storage platform. CUTR gathered input from FDOT to finalize the outline before proceedings with the project work.

3.2.2 Draft DMP

A draft DMP was developed by CUTR as follows:

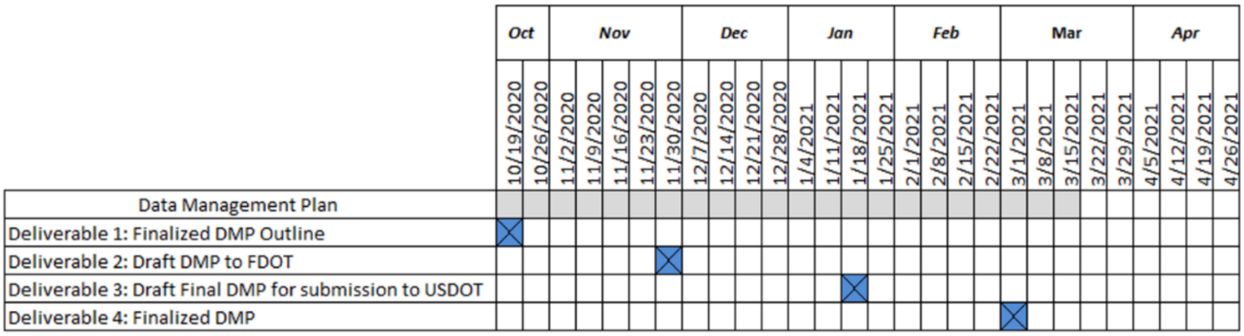
- Sought relevant data elements to be listed in the DMP outline from FDOT and other university partners involved in the collection of before-after data.
- Collaborated to identify and layout details of data access and storage and retention policies.
- Collaborated to identify data sources, data generation frequency, and format to be listed in the DMP.
- Laid out a plan to update the DMP at regular intervals during project deployment.

Following the initial drafts, CUTR finalized the DMP and prepared it for submission to USDOT for review.

3.2.3 Final DMP

Upon receipt of USDOT comments, CUTR finalized the DMP. The finalized and approved DMP can be found in the I-4 FRAME document archive.

3.2.4 Schedule of Deliverables



	Oct		Nov					Dec				Jan				Feb				Mar					Apr			
	10/19/2020	10/26/2020	11/2/2020	11/9/2020	11/16/2020	11/23/2020	11/30/2020	12/7/2020	12/14/2020	12/21/2020	12/28/2020	1/4/2021	1/11/2021	1/18/2021	1/25/2021	2/1/2021	2/8/2021	2/15/2021	2/22/2021	3/1/2021	3/8/2021	3/15/2021	3/22/2021	3/29/2021	4/5/2021	4/12/2021	4/19/2021	4/26/2021
Data Management Plan	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						
Deliverable 1: Finalized DMP Outline	☒																											
Deliverable 2: Draft DMP to FDOT							☒																					
Deliverable 3: Draft Final DMP for submission to USDOT														☒														
Deliverable 4: Finalized DMP																				☒								

Figure 3-1. Schedule and execution of DMP deliverables

3.3 Project Evaluation Plan (PEP)

The PEP describes project goals, evaluation methodology and design, performance measures, and data collections procedures and risks. The plan provides a consolidated method to benchmark and report project progress to the USDOT and relevant stakeholders.

3.3.1 PEP Outline

CUTR prepared the PEP, which includes:

- Statement of project objectives
- List of evaluation criteria (quantitative performance metrics and/or qualitative assessments)
- Description of data collection procedures tailored to the evaluation criteria
- Outline of evaluation report

3.3.2 Draft PEP

A draft PEP was developed by CUTR as follows:

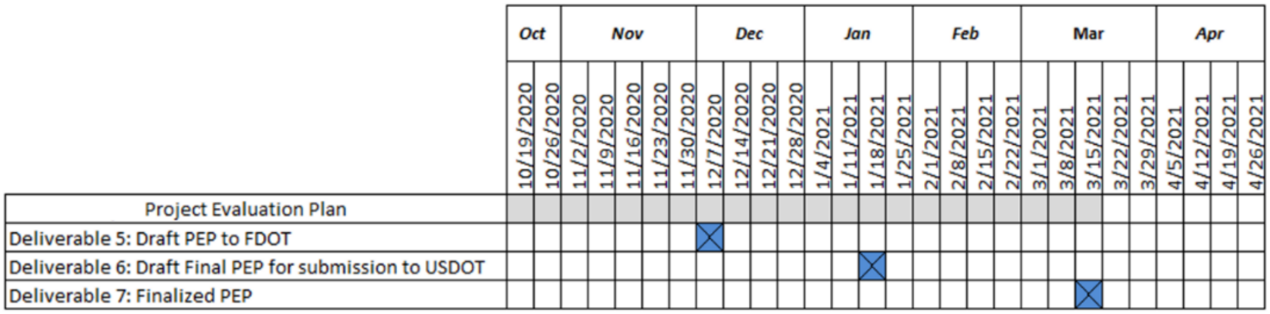
- Obtained from FDOT the statement of project objectives, which is also contained in the original project application (Volume I: Technical Application).
- In collaboration with all university partners engaged in the project evaluation effort, developed a list of quantitative and qualitative performance metrics that are consistent with the evaluation criteria identified in the previous step.
- In collaboration with all university partners engaged in the project evaluation effort, listed and describe the data collection procedures consistent with the overall evaluation effort.
- Prepared an outline of the evaluation report.

Following initial drafts, CUTR finalized the PEP and prepared it for submission to USDOT for review.

3.3.3 Final PEP

Upon receipt of USDOT comments, CUTR finalized the PEP. A copy of the finalized and approved PEP can be found on the I-4 FRAME document archive.

3.3.4 Schedule of Deliverables



	Oct		Nov					Dec				Jan				Feb				Mar					Apr			
	10/19/2020	10/26/2020	11/2/2020	11/9/2020	11/16/2020	11/23/2020	11/30/2020	12/7/2020	12/14/2020	12/21/2020	12/28/2020	1/4/2021	1/11/2021	1/18/2021	1/25/2021	2/1/2021	2/8/2021	2/15/2021	2/22/2021	3/1/2021	3/8/2021	3/15/2021	3/22/2021	3/29/2021	4/5/2021	4/12/2021	4/19/2021	4/26/2021
Project Evaluation Plan	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						
Deliverable 5: Draft PEP to FDOT								☒																				
Deliverable 6: Draft Final PEP for submission to USDOT														☒														
Deliverable 7: Finalized PEP																						☒						

Figure 3-2. Schedule and execution of PEP deliverables

4 Identifying and Addressing Mobility Challenges on I-4 FRAME Project Corridors

This section summarizes the findings and methods employed for analysis of the bottlenecks and mobility challenges along the I-4 FRAME corridors. Detailed analysis is presented in the Task 1 report. This section briefly explains Task 1, objectives of the task, and the methodology employed.

4.1 Task Definition

This project task aims to identify and address the mobility challenges of the I-4 FRAME project corridors. CUTR examined available data from existing point detectors and probe data and used this speed, volume, and density data to identify bottlenecks and their characteristics on a typical day. The identified bottlenecks were based on combined recurring and non-recurring traffic congestion. The findings of Task 1 pertain to the I-4 FRAME corridor including but not limited to major interstates, State roads, and arterials, as shown in Figure 1-1. Using this data-based analysis, insights into the mobility challenges faced on the I-4 FRAME corridor are summarized in this section.

4.2 Task Objectives

The primary objective of Task 1 was to identify the mobility challenges of the I-4 FRAME project. A data-based bottleneck analysis was conducted to identify locations and characteristics of bottlenecks. Main tasks were as follows:

- Examine available data from different databases and use speed and volume data to identify bottlenecks and their characteristics on a typical day.
- Use Annual Average Daily Traffic (AADT) information and expected growth rate to predict bottleneck characteristics in future years.
- Identify existing mobility challenges through detailed data-based analysis.
- Identify opportunities to use new technologies introduced in the I-4 FRAME project to overcome these mobility challenges.
- Compile associated data needs for a before-after study.

4.3 Methodology

To determine bottleneck locations and their characteristics, a data-based approach was used. Data from loop detectors such as speed, volume, and occupancy were extracted from the Regional Integrated Transportation Information System (RITIS), a database developed by the Center for Advanced Transportation Technology (CATT) Laboratory at the University of Maryland, which includes interstates and major arterials. Roadways can be selected and grouped for further analysis using the region explorer. The timeframe for the analysis was January 1 to December 31, 2021, selected to capture the latest mobility trends along the roadways. For mobility analysis, one year of data was considered sufficient. The resolution of the data was five minutes according to the DMP. Performance metrics used are provided later in this report.

RITIS has two suites available—a Probe Data Analytics suite and the National Performance Management Research Data Set (NPMRDS) Suite. There are also traditional loop detector data. NPMRDS deals with probe data from the HERE, INRIX, and TomTom databases, and covers most freeways, State roads, and arterials. The detector dataset outputs traditional loop detector and radar data and covers freeways using loop detectors and radar. RITIS–NPMRDS also has built-in tools that use this probe data to output results in the form of plots and bar charts, which enables easy analysis and data handling, as all analysis was conducted primarily using the built-in tools offered by RITIS. The set of tools primarily used for this analysis were congestion scans, performance charts, performance summaries, and bottleneck rankings, which provide metrics that can be used to quantify congestion and identify bottlenecks. HERE probe data and some INRIX data were used for the analysis.

The bottleneck ranking tool helps identify bottlenecks with the greatest impact. Data generated can be downloaded and further analyzed. For this analysis, the bottleneck locations were plotted using Tableau, which enabled visualizing the exact location of the head of the bottleneck.

4.4 Analysis and Results

The data were processed and cleaned in SAS, a statistical software suite, and a working dataset was imported into Tableau to visualize and analyze the data. Speed contour plots were plotted to visually inspect bottlenecks throughout the year. The bottlenecks were grouped by zone ID and duration at each location and were differentiated by weekday/weekend and by direction of travel — Eastbound (EB), Westbound (WB), Northbound (NB), and Southbound (SB). The road sections studied for this task (based on data availability) were the I-4 mainline freeway, Polk Parkway, and Florida's Turnpike for freeways and major arterials for each FDOT District.

A time-space plot was developed that provided the location and time period for each bottleneck location for EB, WB, NB, and SB headings for I-4, Polk Parkway, and Florida's Turnpike and the major arterials. Characteristics of these bottlenecks are presented in a separate section, and the bottlenecks are ranked based on these characteristics. This final report provides a high-level summary of the findings; detailed analysis is presented in the Task 1 report.

4.4.1 Bottleneck Ranking and Locations

This section presents bottleneck characteristics and ranks them based on their characteristics. Performance metrics such as total delay, Travel Time Index (TTI), and Planning Time Index (PTI) were used to characterize these bottlenecks. The bottlenecks were plotted on maps to visualize the exact location of each along I-4 FRAME area, and insights were drawn if the location had any bearing on the occurrence of the bottleneck.

4.4.2 Performance Measures for Bottlenecks

Numerous performance measures are available for analyzing bottlenecks. Travel time and volume data are required and used to compute these parameters. The following measures were used to characterize bottlenecks for the purpose of this task:

- Buffer Index (BI) – The buffer time's percentage value of the average travel time, where the buffer time is the extra time (or time cushion) that travelers must add to their average travel time when planning trips to ensure on-time arrival. The buffer index gets worse as reliability gets worse. For example, a buffer index of 0.4 (40 %) means that for a 20-minute average travel time, a traveler should budget an additional 8 minutes (20 min x 40% = 8 min) to ensure on-time arrival most of the time.

$$\boldsymbol{BI = \frac{95^{th} percentile\ Travel\ Time - Average\ Travel\ Time}{Average\ Travel\ Time}} \tag{1}$$

- Planning Time Index (PTI) – 95th percentile travel time for a highway segment divided by the reference travel time for the segment at ideal or free-flow speed. PTI differs from BI because it includes typical delay as well as unexpected delay. Thus, the PTI compares near-worst case travel time to a travel time in light or free-flow traffic. For example, a PTI of 1.60 means that for a 15-minute trip in light traffic, the total time that should be planned for the trip is 24 minutes (15 min x 1.60 = 24 min).

$$\boldsymbol{PTI = \frac{95^{th} percentile\ Travel\ Time}{Ref\ Travel\ Time}} \tag{2}$$

- Travel Time Index (TTI) – Travel time represented as a percentage of the ideal travel time, the mean travel time over the highway segment divided by reference travel time for the segment at ideal or free-flow speed.

$$\boldsymbol{TTI = \frac{Mean\ Travel\ Time}{Ref\ Travel\ Time}} \tag{3}$$

Using these performance measures, the bottlenecks were characterized and ranked, then categorized into EB and WB and weekdays and weekends.

4.4.3 Ranking Measures for Bottlenecks

Bottlenecks are characterized by a bottleneck profile and its base impact weighted by speed differential, congestion, and total delay:

- Bottleneck profile – provides summary information for each bottleneck, including average maximum queue length, average duration, and total duration.
- Base impact – calculated using the sum of queue lengths over the duration of the bottleneck in mile-minutes.

- Weighted base impact – base impact weighted by speed differential, congestion, or total delay, which will provide additional insight into the effects of bottlenecks on traffic in the selected area.
    - Speed differential – base impact weighted by the difference between free-flow speed and observed speed; basically, the raw speed drop weighted by queue lengths.
    - Congestion – base impact weighted by the measured speed as a percentage of free-flow speed. Congestion is defined as measured speed as a percent of free-flow speed; it is the speed drop adjusted by bottleneck activation threshold, weighted by queue length.
    - Total Delay – base impact weighted by the difference between free-flow travel time and observed travel time multiplied by the average daily volume (ADT), adjusted by a day-of-the-week factor; raw speed drop weighted by vehicle miles traveled (VMT) factor.
    - Average maximum queue length – length of queues in miles formed by congestion originating at each location.
    - Average daily duration – average amount of time per day that congestion is identified originating at each location.
    - Volume estimate – AADT weighted by queue length rounded to the nearest whole number.

The focus was checking and ranking bottlenecks from a corridor perspective. Hence, total delay was used to rank and compare bottlenecks, as the total delay metric is calculated from the total delay from all vehicles within the bottleneck.

4.5 Freeway Analysis

Four major roadways are part of the I-4 FRAME corridor analysis—I-4, Polk Parkway, Florida's Turnpike, and Selmon Expressway. Freeway analysis included depth analysis, performance measures derived from the analysis, and visualizations. The reported measures consist of a congestion scan, performance measures, ranking of bottlenecks on each respective freeway, and visualizing the location of the bottlenecks on a map. Bottlenecks are ranked based on total delay. A summary is provided in the following sections; individual findings of the analysis can be found in the Task 1 report.

4.5.1 Interstate 4

For the WB direction of I-4, there is congestion near Exit 7 during the PM peak hours of 3:00-7:00 PM. Congestion is also shown near exits 68 to 62 from 11:00 AM to 9:00 PM near Walt Disney World and Universal Studios Orlando, major tourist attractions. Congestion scans show similar congestion for the EB direction as well, with some congestion near the Tampa area close to US-92/Exit 7 for both the EB and WB directions.

EB and WB performance summaries are shown in Table 4-1 and Table 4-2, respectively, and include daily, weekly, weekday, and weekend performance measures. For all days (average of all days of week) for the EB direction, speed is 61.57 mph, BI is 0.54, PTI is 1.66, and TTI is 1.08. For the WB direction, for all days, speed is 61.49 mph, BI is 0.51, PTI is 1.61, and TTI is 1.07.

Table 4-1. 2021 EB Performance Summaries for I-4

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	62.44	0.47	1.54	1.06
Tuesday	63.61	0.40	1.48	1.04
Wednesday	62.47	0.47	1.57	1.06
Thursday	60.38	0.56	1.66	1.10
Friday	56.39	0.71	1.95	1.18
Weekdays	60.93	0.57	1.69	1.09
Saturday	61.21	0.45	1.61	1.08
Sunday	65.40	0.37	1.42	1.01
Weekends	63.24	0.45	1.55	1.05
All Days	61.57	0.54	1.66	1.08

Table 4-2. 2021 WB Performance Summaries for I-4

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	62.57	0.47	1.56	1.06
Tuesday	62.89	0.42	1.51	1.05
Wednesday	61.67	0.47	1.58	1.07
Thursday	60.43	0.53	1.65	1.09
Friday	58.04	0.62	1.82	1.14
Weekdays	61.06	0.52	1.64	1.08
Saturday	61.84	0.51	1.61	1.07
Sunday	63.38	0.48	1.54	1.04
Weekends	62.60	0.50	1.58	1.06
All Days	61.49	0.51	1.61	1.07

Daily performance metrics such as speed profile, BI, PTI, and TTI are listed in the Task 1 report. As noted, speed drops from 70 mph to almost 50 mph during the AM and PM peak hours, and the BI, PTI, and TTI also increase during these times.

Table 4-3 shows bottleneck rankings on I-4, with the top 10 ranked based on total delay weighted by VMT. Figure 4-1 plots these top 10 bottlenecks according to their geographic location, with bottlenecks marked with a “×” on the map and a number representing its rank. As shown, the majority of bottlenecks occur near Walt Disney World Resorts and Universal’s Orlando Resort; the other bottlenecks occur near Ybor City and Downtown Tampa.

Table 4-3. Bottleneck Rankings for I-4

Rank	Average Max Queue Length (mi)	Average Daily Duration	Volume Estimate (veh/day)	Base Impact (mi-min)	Total Delay (veh-hrs)
1	7.3	6 h 26 m	45,716	954,456	1,255,287,685
2	4.48	5 h 8 m	50,128	484,734	1,049,372,363
3	3.25	5 h 30 m	67,786	376,013	756,797,041
4	5.4	2 h 29 m	52,059	275,726	576,645,457
5	2.69	4 h 12 m	77,056	222,638	466,461,143
6	1.34	8 h 31 m	55,998	226,809	407,318,592
7	9.85	38 m	45,244	135,420	198,466,631
8	2.93	1 h 27 m	67,931	87,930	163,079,253
9	6.39	37 m	65,305	80,444	148,229,014
10	7.3	6 h 26 m	56,634	89,883	125,160,491

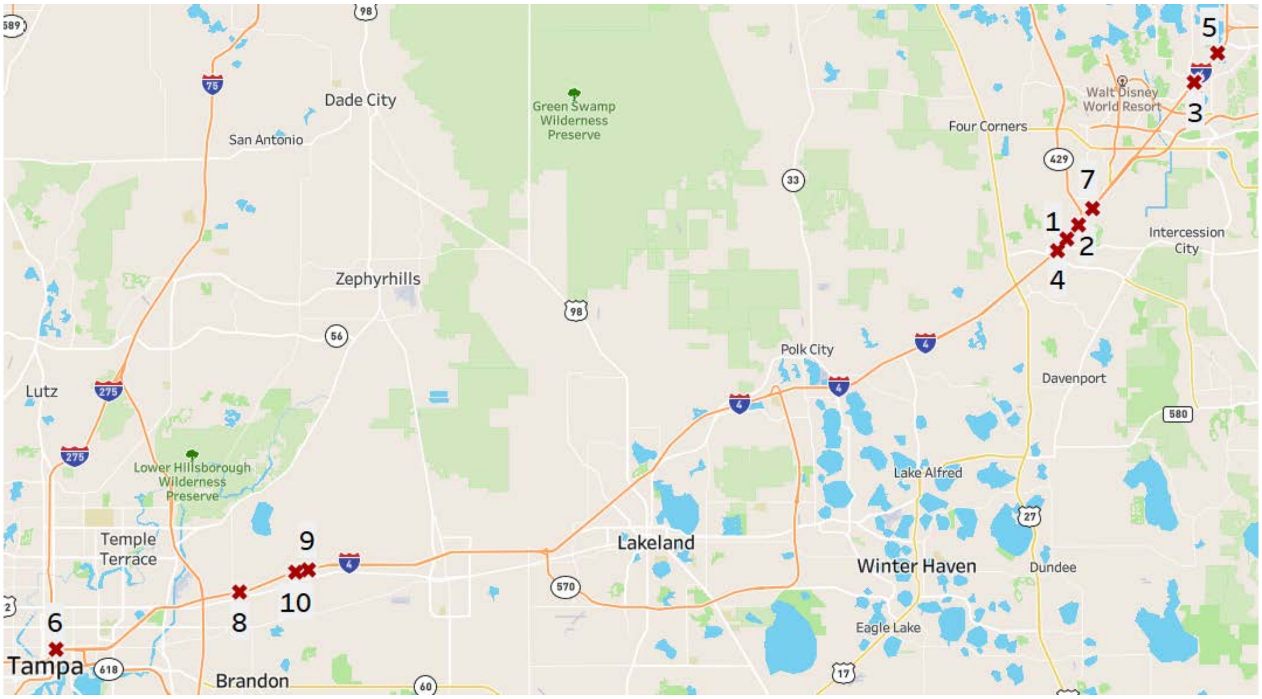


Figure 4-1. Bottleneck locations along I-4

4.5.2 Polk Parkway

There is no evident congestion on the Polk Parkway for both the EB and WB directions. However, further analysis of the performance summaries shows very slight congestion and occasional bottlenecks forming along the Polk Parkway.

Performance summaries are provided in Table 4-4 and Figure 4-4 for the EB and WB directions, respectively, including daily, weekly, weekday, and weekend performance measures. For all days (average of all days of week) for the EB direction, speed is 64.28 mph, BI is 0.06, PTI is

1.01, and TTI is 0.92. For the WB direction for all days, speed is 64.14 mph, BI is 0.06, PTI is 0.99, and TTI is 0.91. These performance measures suggest that there is little to no congestion other than occasional non-recurring bottlenecks along the Polk Parkway.

Table 4-4. EB Performance Summaries for Polk Parkway

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	64.01	0.05	1.02	0.93
Tuesday	63.82	0.06	1.02	0.93
Wednesday	63.90	0.05	1.02	0.93
Thursday	63.88	0.05	1.02	0.93
Friday	64.04	0.06	1.02	0.92
Weekdays	63.93	0.06	1.02	0.93
Saturday	65.16	0.05	1.00	0.91
Sunday	65.17	0.05	1.00	0.91
Weekends	65.16	0.05	1.00	0.91
All Days	64.28	0.06	1.01	0.92

Table 4-5. WB Performance Summaries for Polk Parkway

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	64.05	0.06	0.99	0.91
Tuesday	63.78	0.07	1.00	0.91
Wednesday	63.65	0.06	1.00	0.91
Thursday	63.70	0.06	1.00	0.91
Friday	63.98	0.07	1.00	0.91
Weekdays	63.83	0.06	1.00	0.91
Saturday	64.91	0.05	0.98	0.90
Sunday	64.94	0.05	0.98	0.90
Weekends	64.92	0.05	0.99	0.90
All Days	64.14	0.06	0.99	0.91

Daily performance metrics such as BI, PTI, speed profiles, and TTI are listed in the Task 1 report. As noted, there are no speed drops during the 24 hours shown. BI, PTI, and TTI also do not significantly vary during these times, which indicates very low levels of congestion on the Polk Parkway.

Table 4-6 shows bottleneck rankings on the Polk Parkway, which are ranked based on total delay weighted by VMT. Figure 4-2 plots these top 10 bottlenecks according to their geographic location. As shown, the majority of bottlenecks occur near the western portion of the Polk Parkway where it connects to I-4. However, based on average daily duration, these bottlenecks last for only a short time.

Table 4-6. Bottleneck Rankings for Polk Parkway

Bottleneck Rank	Average Max Queue Length (mi)	Average Daily Duration	Volume Estimate (veh/day)	Base Impact (mi-min)	Total Delay (veh-hrs)
1	2.26	3 m	14,046	2,354	1,590,648
2	1.59	1 m	13,459	880	1,424,878
3	1.41	3 m	15,051	1,988	1,382,062
4	2.27	2 m	12,944	1,804	1,352,646
5	1.57	3 m	15,028	1,465	1,327,528
6	2.11	1 m	13,150	1,172	1,072,863
7	1.97	1 m	13,407	1,331	1,047,604
8	1.79	2 m	13,110	1,164	833,838
9	2.02	1 m	13,552	926	721,042
10	0.71	2 m	13,040	754	625,605

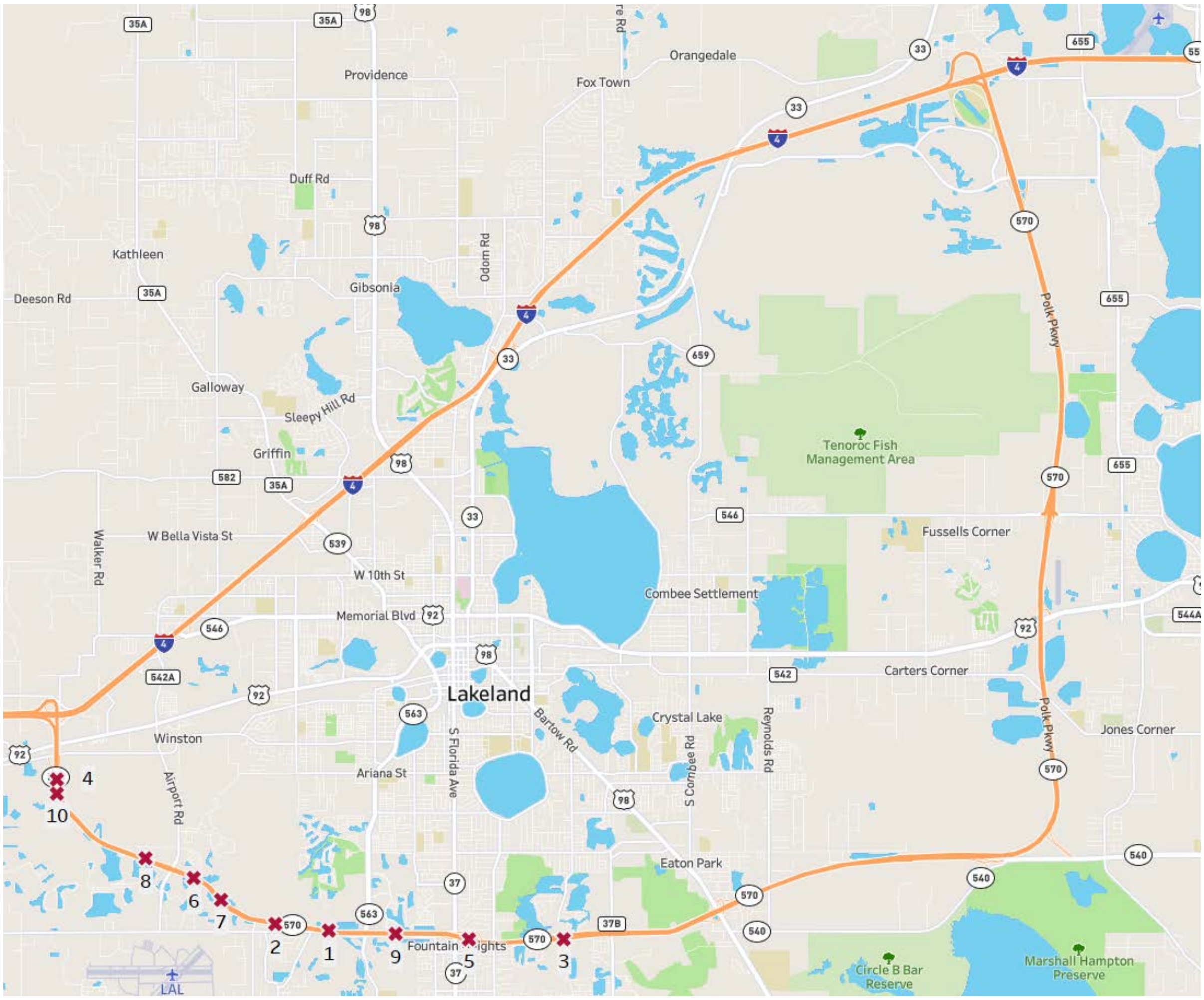


Figure 4-2. Polk Parkway bottleneck locations

4.5.3 Florida’s Turnpike

There is no evident congestion on the Turnpike for both the NB and SB directions. However, further analysis of the performance summaries indicates very slight congestion and occasional bottlenecks.

Performance summaries are shown in Table 4-7 and Table 4-8 for the NB and SB directions, respectively, including daily, weekly, weekday, and weekend performance measures. For all days (average of all days of week) for the NB direction, speed is 70.77 mph, BI is 0.04, PTI is 1.09, and TTI is 0.99. For the SB direction for all days, speed is 69.47 mph, BI is 0.06, PTI is 1.14, and TTI is 1.01. Speeds are almost near free-flow speeds, and indexes are near optimal. These performance measures suggest that there is little to no congestion other than occasional non-recurring bottlenecks along the Turnpike.

Table 4-7. NB Performance Summaries for Florida’s Turnpike

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	70.46	0.05	1.10	0.99
Tuesday	69.34	0.04	1.11	1.01
Wednesday	69.94	0.03	1.11	1.00
Thursday	70.24	0.03	1.10	1.00
Friday	70.04	0.04	1.12	1.00
Weekdays	70.00	0.04	1.11	1.00
Saturday	72.59	0.03	1.06	0.96
Sunday	72.92	0.04	1.06	0.96
Weekends	72.76	0.03	1.05	0.96
All Days	70.77	0.04	1.09	0.99

Table 4-8. SB Performance Summaries for Florida’s Turnpike

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	68.89	0.10	1.18	1.02
Tuesday	68.39	0.07	1.15	1.02
Wednesday	68.25	0.06	1.17	1.03
Thursday	68.13	0.13	1.24	1.03
Friday	67.93	0.27	1.40	1.03
Weekdays	68.31	0.12	1.22	1.02
Saturday	73.01	0.03	1.05	0.96
Sunday	72.07	0.06	1.10	0.97
Weekends	72.53	0.03	1.06	0.97
All Days	69.47	0.06	1.14	1.01

Daily performance metrics including BI, PTI, TTI, and speed profiles are shown in the Task 1 report. As noted, there are no speed drops during the 24 hours. BI, PTI, and TTI also do not significantly vary during these times, indicating very low levels of congestion on the Turnpike.

Table 4-9 shows the bottleneck rankings on the Turnpike, with the top 10 bottlenecks ranked based on total delay weighted by VMT. Figure 4-3 plots these top 10 bottlenecks according to their geographic location. As shown in Figure 4-3, the bottlenecks are spread out across the Turnpike but usually occur near the ramps connecting other major highways such as I-4, US-528, and US-417. However, based on average daily duration, these bottlenecks last for a short amount of time, except for the first one, which lasts around 45 minutes.

Table 4-9. Bottleneck Rankings for Florida's Turnpike

Bottleneck Rank	Average Max Queue Length (mi)	Average Daily Duration	Volume Estimate (veh/day)	Base Impact (mi-min)	Total Delay (veh-hrs)
1	4.95	46 m	35,109	78,173	78,399,588
2	4.3	8 m	36,271	12,350	16,856,698
3	4.77	6 m	36,792	10,978	11,868,285
4	5.24	3 m	37,119	7,677	11,493,926
5	4.64	5 m	37,745	8,718	11,413,350
6	2.87	13 m	29,485	13,574	9,109,025
7	2.43	6 m	37,617	5,499	8,455,248
8	2.88	1 m	38,075	2,291	5,496,961
9	4.45	3 m	33,376	5,390	4,227,023
10	3.12	2 m	31,766	1,980	3,091,016

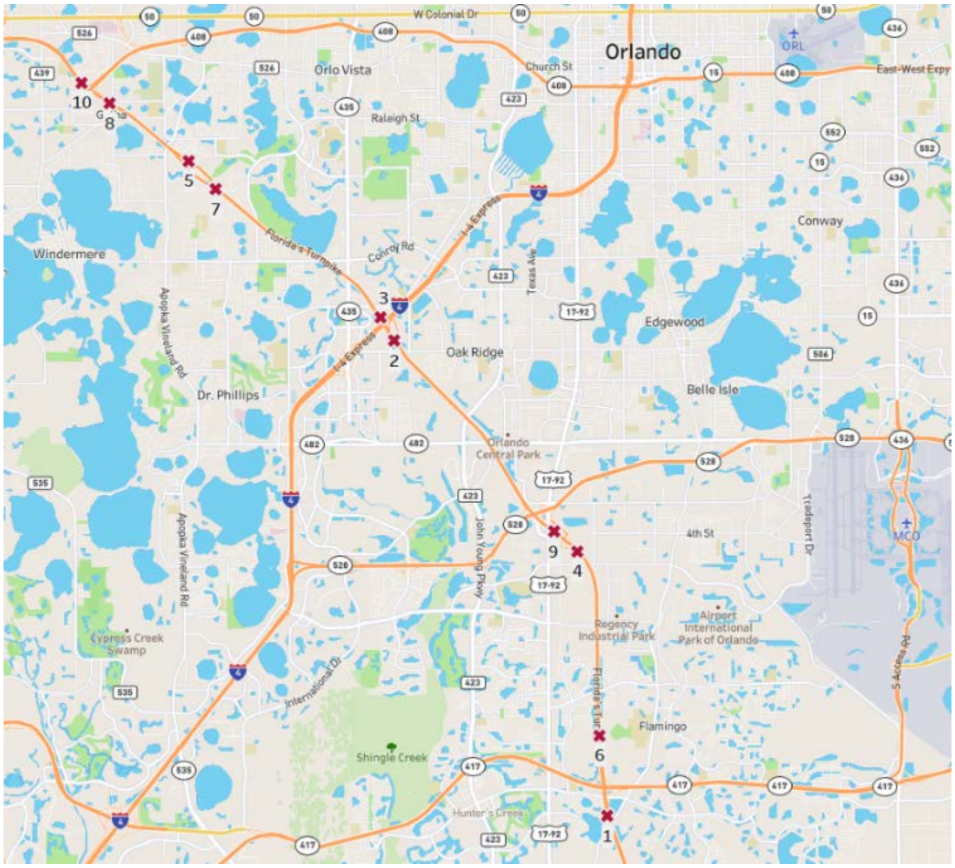


Figure 4-3. Bottleneck locations for Florida's Turnpike

4.5.4 Selmon Expressway

There is no evident congestion on the Selmon Expressway for both the EB and SB directions; there is some congestion from mile 3 to mile 7 in the later hours. However, further analysis of the performance summaries shows very slight congestion and occasional bottlenecks forming along the Expressway.

Performance summaries are listed in Table 4-10 and Table 4-11 for the EB and WB directions, respectively, including daily, weekly, weekday, and weekend performance measures. For all days (average of all days of week) for the EB direction, speed is 61.31 mph, BI is 0.07, PTI is 1.16, and TTI is 1.06. For the WB direction for all days, speed is 59.23 mph, BI is 0.14, PTI is 1.25, and TTI is 1.10. These performance measures suggest that there is little to no congestion other than occasional non-recurring bottlenecks along the Expressway.

Table 4-10. EB Performance Summaries for Selmon Expressway

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	61.03	0.09	1.18	1.06
Tuesday	59.37	0.08	1.18	1.09
Wednesday	59.02	0.08	1.17	1.10
Thursday	59.81	0.07	1.16	1.08
Friday	62.05	0.08	1.16	1.05
Weekdays	60.23	0.07	1.16	1.08
Saturday	63.93	0.03	1.10	1.01
Sunday	63.45	0.06	1.14	1.02
Weekends	63.69	0.05	1.13	1.02
All Days	61.31	0.07	1.16	1.06

Table 4-11. WB Performance Summaries for Selmon Expressway

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	58.99	0.14	1.27	1.10
Tuesday	59.04	0.17	1.28	1.10
Wednesday	57.66	0.23	1.35	1.13
Thursday	60.07	0.28	1.40	1.08
Friday	60.95	0.10	1.17	1.07
Weekdays	59.36	0.16	1.27	1.10
Saturday	56.02	0.02	1.12	1.16
Sunday	60.03	0.03	1.14	1.09
Weekends	57.95	0.02	1.13	1.12
All Days	59.23	0.14	1.25	1.10

Daily performance metrics such as BI, PTI, speed profiles, and TTI are shown in the Task 1 report. As noted, there are no significant speed drops during the 24 hours for the EB direction. BI, PTI, and TTI also do not significantly vary during these times for the EB direction. However, for the WB direction, there are similar results from the congestion scans, with fluctuations in the metrics during the later hours of the day.

Table 4-12 shows the bottleneck rankings on the Selmon Expressway, with the top 10 bottlenecks ranked based on total delay weighted by VMT. Figure 4-4 plots these top 10 bottlenecks according to their geographic location. As shown, the bottlenecks are spread out across the Expressway, with most occurring in pairs in opposite directions (EB and WB). However, looking at the average daily duration, these bottlenecks last for a short amount of time, except for the second one, which lasts around an hour.

Table 4-12. Bottleneck Ranking for Selmon Expressway

Bottleneck Rank	Average Max Queue Length (mi)	Average Daily Duration	Volume Estimate (veh/day)	Base Impact (mi-min)	Total Delay (veh-hrs)
1	3.51	13 m	10,507	16,655	17,944,231
2	3.45	1 h 3 m	10,328	11,764	8,252,484
3	2.12	1 m	9,258	1,375	687,293
4	1.54	0 m	5,057	481	231,468
5	2.38	14 m	9,410	806	199,439
6	0.03	22 m	8,971	213	96,000
7	2.52	0 m	5,858	405	76,462
8	2.17	0 m	6,063	199	64,046
9	2.54	0 m	5,864	91	63,620
10	0.02	18 m	6,039	34	8,384

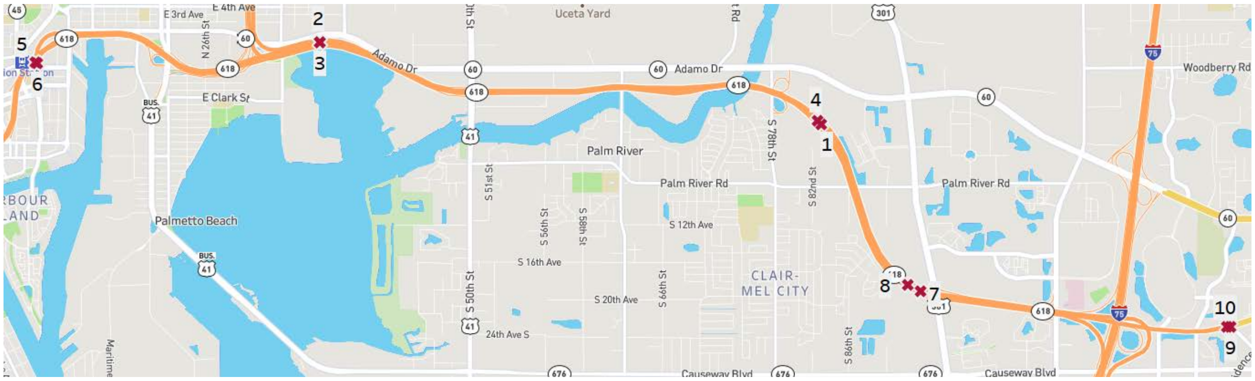


Figure 4-4. Bottleneck locations for Selmon Expressway

4.6 Arterials Analysis

Three FDOT Districts are part of the I-4 FRAME corridor analysis and have primary and secondary diversion routes. Of these major diversion routes, three span across FDOT Districts—SR-60, US-92, and US-98. These three major diversion routes were analyzed, followed by the primary diversion routes that connect to I-4 and the above-listed roadways. The latter group of diversion routes/arterials is a collection of roads. Generating congestion scans for each road was not feasible; performance summaries and bottleneck characteristics for these roads are listed, and the bottleneck locations were plotted.

Similar to the freeway analysis, arterials analysis includes in-depth analysis, performance measures derived from this analysis and visualizations. The reported measures consist of a congestion scan, performance measures, ranking of bottlenecks on each arterial or arterial group, and visualization of the location of the bottleneck on a map.

4.6.1 SR-60

There is evident congestion on SR-60 for both the EB and WB directions. There are several areas where the speed drops below 5 mph when averaged for every 5 minutes. Both the EB and WB roads show congestion patterns, indicating prominent bottlenecks along SR-60. The congestion patterns are similar for both directions.

Performance summaries are shown in Table 4-13 and Table 4-14 for the EB and WB directions, respectively, including daily, weekly, weekday, and weekend performance measures. For all days (average of all days of week) for the EB direction, speed is 34.76 mph, BI is 0.27, PTI is 1.31, and TTI is 0.95. For the WB direction for all days, speed is 36.65 mph, BI is 0.30, PTI is 1.31, and TTI is 0.96. These low speeds and high-performance measures suggest that there is congestion and bottlenecks along SR-60.

Table 4-13. EB Performance Summaries for SR-60

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	34.77	0.26	1.30	0.95
Tuesday	34.13	0.29	1.34	0.97
Wednesday	34.17	0.28	1.35	0.97
Thursday	33.94	0.30	1.37	0.97
Friday	33.36	0.32	1.43	0.99
Weekdays	34.07	0.29	1.36	0.97
Saturday	35.72	0.21	1.22	0.92
Sunday	37.61	0.17	1.14	0.88
Weekends	36.64	0.20	1.19	0.90
All Days	34.76	0.27	1.31	0.95

Table 4-14. WB Performance Summaries for SR-60

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	36.48	0.30	1.31	0.96
Tuesday	36.01	0.31	1.33	0.97
Wednesday	35.96	0.30	1.33	0.97
Thursday	35.88	0.31	1.35	0.98
Friday	35.42	0.33	1.37	0.99
Weekdays	35.95	0.31	1.34	0.97
Saturday	37.59	0.27	1.26	0.93
Sunday	39.59	0.21	1.14	0.88
Weekends	38.56	0.24	1.20	0.91
All Days	36.65	0.30	1.31	0.96

Daily performance metrics including BI, PTI, speed profiles, and TTI are shown in the Task 1 report. As noted, there are significant speed drops during the 24 hours for both directions, specifically during peak hours. BI, PTI, and TTI also vary significantly during these times for both directions.

Table 4-15 shows the bottleneck rankings on SR-60, with the top 10 bottlenecks ranked based on total delay weighted by VMT. Figure 4-5 plots these top 10 bottlenecks according to their geographic location. As shown, the bottlenecks are spread out across SR-60 around key junctions such as the intersection with I-75 and in Downtown Tampa. The bottleneck characteristics also show significant bottleneck formations along SR-60. The average daily duration suggests recurring bottlenecks of at least one hour daily.

Table 4-15. Bottleneck Rankings for SR-60

Bottleneck Rank	Average Max Queue Length (mi)	Average Daily Duration	Volume Estimate (veh/day)	Base Impact (mi-min)	Total Delay (veh-hrs)
1	0.7	3 h 25 m	35,567	52,785	59,014,016
2	2.69	1 h 2 m	37,767	54,675	53,493,273
3	1.83	1 h 21 m	34,742	52,672	44,096,614
4	0.18	7 h 34 m	22,311	29,519	35,694,743
5	0.35	4 h	30,529	28,803	34,920,182
6	2.45	55 m	22,273	49,017	27,446,742
7	1.27	1 h 5 m	37,755	29,039	24,679,272
8	0.21	3 h 9 m	29,386	14,098	21,955,598
9	0.54	1 h 30 m	25,723	17,112	17,642,806
10	0.59	1 h 52 m	20,106	23,746	15,453,428

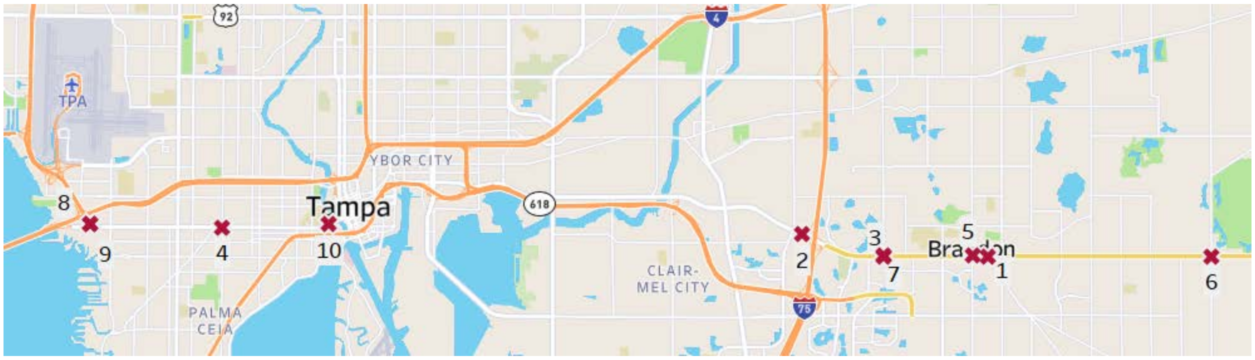


Figure 4-5. Bottleneck locations for SR-60

4.6.2 US-92

There is evident congestion on US-92 for both the NB and SB directions. The congestion patterns occur primarily during the AM and PM peak hours but also throughout the day. Further analysis of the performance summaries indicates congestion and recurring bottlenecks forming along US-92.

Performance summaries are listed in Table 4-16, Table 4-17, Table 4-18, and Table 4-19 for the NB, SB, EB, and WB directions, respectively, including daily, weekly, weekday, and weekend performance measures. For all days (average of all days of week) for the NB direction, speed is 29.80 mph, BI is 0.33, PTI is 1.41, and TTI is 0.95. For the SB direction for all days, speed is 29.80 mph, BI is 0.33, PTI is 1.41, and TTI is 0.95. These performance measures suggest that there is congestion and recurring bottlenecks along US-92.

Table 4-16. NB Performance Summaries for US-92

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	29.87	0.30	1.39	0.95
Tuesday	29.23	0.33	1.44	0.97
Wednesday	29.27	0.34	1.46	0.97
Thursday	28.78	0.33	1.46	0.98
Friday	28.65	0.35	1.49	0.99
Weekdays	29.15	0.31	1.43	0.97
Saturday	30.71	0.27	1.30	0.92
Sunday	32.50	0.23	1.20	0.87
Weekends	31.58	0.27	1.27	0.90
All Days	29.80	0.33	1.41	0.95

Table 4-17. SB Performance Summaries for US-92

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	30.26	0.28	1.36	0.95
Tuesday	29.57	0.30	1.41	0.97
Wednesday	29.71	0.29	1.41	0.97
Thursday	29.33	0.30	1.43	0.98
Friday	29.25	0.31	1.44	0.99
Weekdays	29.62	0.30	1.41	0.97
Saturday	31.24	0.27	1.28	0.92
Sunday	33.01	0.20	1.17	0.87
Weekends	32.10	0.26	1.24	0.90
All Days	29.80	0.33	1.41	0.95

For all days (average of all days of week) for the EB direction, speed is 36.62 mph, BI is 0.24, PTI is 1.22, and TTI is 0.92. For the WB direction for all days, speed is 36.92 mph, BI is 0.30, PTI is 1.27, and TTI is 0.93. These performance measures suggest that there is congestion and recurring bottlenecks along US-92.

Table 4-18. EB Performance Summaries for US-92

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	36.26	0.25	1.22	0.93
Tuesday	35.83	0.27	1.26	0.94
Wednesday	35.81	0.26	1.26	0.94
Thursday	35.76	0.26	1.26	0.94
Friday	35.35	0.28	1.30	0.95
Weekdays	35.80	0.26	1.26	0.94
Saturday	38.26	0.13	1.09	0.88
Sunday	39.44	0.11	1.04	0.85
Weekends	38.84	0.13	1.07	0.87
All Days	36.62	0.24	1.22	0.92

Table 4-19. WB Performance Summaries for US-92

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	36.51	0.32	1.29	0.94
Tuesday	36.10	0.32	1.30	0.95
Wednesday	36.14	0.32	1.30	0.95
Thursday	36.08	0.32	1.31	0.95
Friday	35.86	0.33	1.32	0.96
Weekdays	36.14	0.32	1.30	0.95
Saturday	38.42	0.22	1.17	0.90
Sunday	39.69	0.18	1.11	0.87
Weekends	39.05	0.20	1.14	0.88
All Days	36.92	0.30	1.27	0.93

Daily performance metrics BI, PTI, speed profiles, and TTI are shown in the individual report. Data were not available for the WB direction, so plots were not generated. As shown, there are significant speed drops during the 24 hours for all directions. BI, PTI, and TTI also significantly vary during these times.

Table 4-20 shows the bottleneck rankings on US-92, with the top 10 bottlenecks ranked based on total delay weighted by VMT. Figure 4-6 plots these top 10 bottlenecks according to their geographic location. As shown, the bottlenecks are spread out across US-92 but are located primarily near interchanges, Tampa International Airport, and Downtown Tampa. Based on average daily duration, these bottlenecks last for a significant amount of time, suggesting recurring bottlenecks.

Table 4-20. Bottleneck Rankings for US-92

Bottleneck Rank	Average Max Queue Length (mi)	Average Daily Duration	Volume Estimate (veh/day)	Base Impact (mi-min)	Total Delay (veh-hrs)
1	0.91	3 h 43 m	22,880	66,682	69,050,324
2	1.88	1 h 59 m	28,795	77,167	62,691,293
3	1.36	18 m	30,788	10,080	22,011,573
4	0.18	6 h 4 m	18,104	23,241	19,879,951
5	1.39	42 m	27,287	20,874	19,558,366
6	1.04	59 m	17,321	22,093	16,492,633
7	2.3	14 m	29,149	11,099	14,043,176
8	0.3	3 h 54 m	23,088	16,077	13,242,976
9	0.84	32 m	33,781	10,020	12,129,557
10	2.92	1 h 2 m	7,123	63,759	12,039,477

Figure 4-6. Bottleneck locations for US-92

4.6.3 US-98

There is evident congestion on US-98 for both the EB and WB directions. Congestion and low speeds are also evident throughout the day. Further analysis of the performance summaries indicates congestion and recurring bottlenecks forming along US-98.

Performance summaries are provided in Table 4-21 and Table 4-22 for the EB and WB directions, respectively, including daily, weekly, weekday, and weekend performance measures. For all days (average of all days of week) for the EB direction, speed is 31.56 mph, BI is 0.35, PTI is 1.37, and TTI is 0.96. For the WB direction for all days, speed is 31.13 mph, BI is 0.40, PTI is 1.43, and TTI is 0.98. These performance measures suggest that there is congestion and recurring bottlenecks along US-98.

Table 4-21. EB Performance Summaries for US-98

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	31.21	0.35	1.38	0.97
Tuesday	30.77	0.35	1.39	0.99
Wednesday	30.79	0.37	1.41	0.99
Thursday	30.71	0.36	1.41	0.99
Friday	30.41	0.36	1.42	1.00
Weekdays	30.77	0.37	1.41	0.99
Saturday	33.18	0.23	1.23	0.92
Sunday	34.31	0.24	1.18	0.89
Weekends	33.73	0.23	1.20	0.90
All Days	31.56	0.35	1.37	0.96

Table 4-22. WB Performance Summaries for US-98

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	30.79	0.40	1.43	0.99
Tuesday	30.33	0.41	1.47	1.01
Wednesday	30.27	0.38	1.44	1.01
Thursday	30.14	0.41	1.47	1.01
Friday	29.70	0.44	1.52	1.03
Weekdays	30.24	0.41	1.46	1.01
Saturday	32.87	0.27	1.27	0.93
Sunday	34.42	0.24	1.19	0.89
Weekends	33.63	0.25	1.23	0.91
All Days	31.13	0.40	1.43	0.98

Daily performance metrics for BI, PTI, speed profiles, and TTI are shown in the Task 1 report. As noted, there are significant speed drops during the 24 hours for both directions. Speeds start to drop during the AM peak hours ad remain low until 6:00 PM, after which there is a slight increase in speeds. BI, PTI, and TTI also significantly vary during these times for the EB and WB directions. These also increase during the AM peak hours (around 6:00 AM) and start dropping around 6:00 PM, indicating that there is congestion along the road.

Table 4-23 shows the bottleneck rankings on US-98, with the top 10 bottlenecks ranked based on total delay weighted by VMT. Figure 4-7 plots these top 10 bottlenecks according to their geographic location. As shown, bottlenecks are spread out across US-98 with most occurring in pairs in opposite directions (EB and WB). Looking at the average daily duration, some bottlenecks last for a significant amount of time and others for a smaller time.

Table 4-23. Bottleneck Rankings for US-98

Bottleneck Rank	Average Max Queue Length (mi)	Average Daily Duration	Volume Estimate (veh/day)	Base Impact (mi-min)	Total Delay (veh-hrs)
1	1.06	7 h 4 m	17,433	156,928	112,205,167
2	1.04	1 h	17,486	22,383	16,919,221
3	3.1	19 m	17,803	21,492	11,330,612
4	2.01	17 m	19,774	11,950	10,678,552
5	1.58	25 m	19,728	14,061	6,082,846
6	1.24	15 m	20,964	7,008	5,407,924
7	1.69	10 m	19,066	5,489	2,828,312
8	3.22	2 m	21,322	2,480	2,375,495
9	0.87	1 h 3 m	5,093	18,655	2,204,615
10	1.1	12 m	19,177	4,936	2,142,266

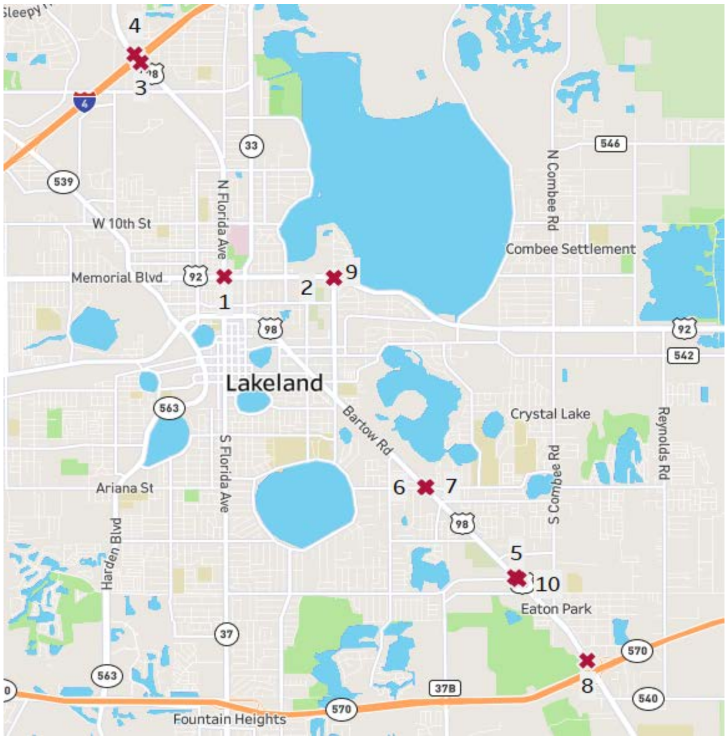


Figure 4-7. Bottleneck locations for US-98

4.6.4 FDOT District 7 Major Arterials

This section provides insights into the speed profiles, bottleneck characteristics, and locations for the major arterials in the study area (Figure 4-8). The primary diversion routes for FDOT District 7 and some secondary diversion routes were included in this set of major arterials, which was evaluated as a whole, as it was not feasible to conduct individual analysis for short connecting segments. Also, congestion scans can be performed on individual roadway segments and not on a group of segments. Therefore, for all FDOT District 1, District 5, and District 7 major roads, congestion scan analysis was not possible.

Figure 4-8. District 7 major arterials

Performance summaries are provided in Table 4-24, Table 4-25, and Table 4-26 for the WB (US-92 only), NB, and SB directions, respectively, including daily, weekly, weekday, and weekend performance measures. For all days (average of all days of week) for the WB direction, speed is 36.94 mph, BI is 0.45, PTI is 1.42, and TTI is 1.00. For the NB direction for all days, speed is 33.06 mph, BI is 0.25, PTI is 1.29, and TTI is 0.91. For the SB direction for all days, speed is 36.07 mph, BI is 0.24, PTI is 1.23, and PTI is 0.90. These performance measures suggest that there is congestion and bottlenecks along District 7 major arterials. The bottleneck rankings show the characteristics and locations of these bottlenecks.

Table 4-24. WB Performance Summaries for District 7 Major Arterials (US-92)

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	36.10	0.49	1.48	1.02
Tuesday	35.86	0.47	1.48	1.03
Wednesday	35.77	0.49	1.48	1.03
Thursday	36.41	0.43	1.42	1.02
Friday	36.63	0.44	1.42	1.01
Weekdays	36.15	0.49	1.48	1.02
Saturday	38.36	0.38	1.32	0.96
Sunday	39.82	0.22	1.12	0.93
Weekends	39.08	0.23	1.16	0.95
All Days	36.94	0.45	1.42	1.00

Table 4-25. NB Performance Summaries for District 7 Major Arterials

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	32.88	0.25	1.30	0.92
Tuesday	32.38	0.29	1.35	0.93
Wednesday	32.38	0.30	1.36	0.93
Thursday	32.22	0.29	1.37	0.94
Friday	31.93	0.32	1.39	0.95
Weekdays	32.35	0.28	1.35	0.93
Saturday	34.42	0.15	1.13	0.88
Sunday	35.58	0.11	1.07	0.85
Weekends	34.99	0.13	1.10	0.86
All Days	33.06	0.25	1.29	0.91

Table 4-26. SB Performance Summaries for District 7 Major Arterials

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	35.98	0.23	1.23	0.91
Tuesday	35.37	0.26	1.27	0.92
Wednesday	35.34	0.26	1.27	0.92
Thursday	35.32	0.26	1.28	0.92
Friday	34.93	0.27	1.29	0.93
Weekdays	35.38	0.26	1.27	0.92
Saturday	37.13	0.18	1.12	0.88
Sunday	38.77	0.10	1.02	0.84
Weekends	37.93	0.17	1.09	0.86
All Days	36.07	0.24	1.23	0.90

Table 4-27 shows the bottleneck rankings on the major arterials, with the top 10 bottlenecks listed and ranked based on total delay weighted by VMT. Figure 4-9 plots these top 10 bottlenecks according to their geographic location. As shown, the bottlenecks are spread out primarily across I-275. Also, looking at average daily duration, these bottlenecks last for a short amount of time, with a few exceptions such as the first and seventh bottlenecks, which last for over an hour.

Table 4-27. Bottleneck Rankings for District 7

Bottleneck Rank	Average Max Queue Length (mi)	Average Daily Duration	Volume Estimate (veh/day)	Base Impact (mi-min)	Total Delay (veh-hrs)
1	3.24	1 h 7 m	76,851	54,167	127,975,956
2	2.95	49 m	68,439	46,203	85,448,476
3	1.72	48 m	72,420	25,307	44,611,471
4	2.69	16 m	73,160	14,611	29,662,530
5	4.07	5 m	76,143	5,661	23,890,232
6	0.84	32 m	33,781	10,020	12,129,557
7	0.09	3 h	15,689	5,639	9,322,714
8	3.33	1 m	79,696	1,473	6,301,374
9	1.97	1 m	64,118	1,471	4,189,357
10	1.09	3 m	74,333	931	1,965,411

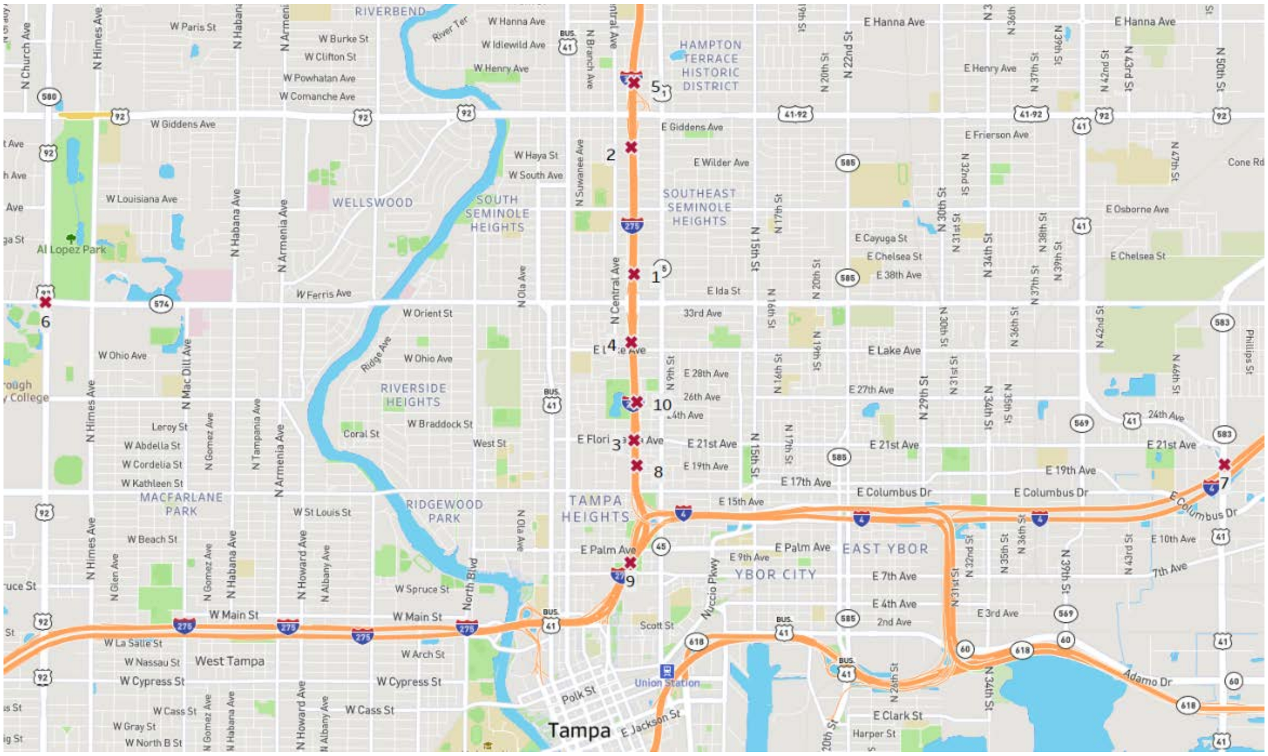


Figure 4-9. Bottleneck locations for District 7

4.6.5 FDOT District 5 Major Arterials

This section provides insights into the speed profiles, PTI, TTI, BI, bottleneck characteristics, and locations for the major arterials in FDOT District 5 (Figure 4-10). Performance summaries are listed in Table 4-28 through Table 4-35. FDOT District 5 arterials are split into four roadway sections—I-4 connectors along US-192 (EB and WB), SR-528-Beachline Expressway (EB, WB), and EB, WB, NB, and SB directions for the remainder of District 5 arterials.

Daily, weekly, weekday, and weekend performance measures are presented in Tables 28, 29, 30, and 31 for the I-4 connectors and SR-528 Beachline Expressway. For all days (average of all days of week) for the I-4 EB direction, speed is 53.98 mph, BI is 0.03, PTI is 1.09, and TTI is 0.91. For the WB direction for all days, speed is 47.77 mph, BI is 0.07, PTI is 1.39, and TTI is 1.05. For the SR-528 EB direction for all days, speed is 58.54 mph, BI suggests optimal conditions, PTI is 1.06, and TTI is 0.94. For the SR-528 WB direction for all days, speed is 49.49 mph, BI is 0.02, PTI is 1.14, and TTI is 0.99. These performance measures suggest that there is minimal congestion and bottlenecks along these four District 5 major arterials. Bottleneck rankings in the tables show the characteristics and locations of these bottlenecks.

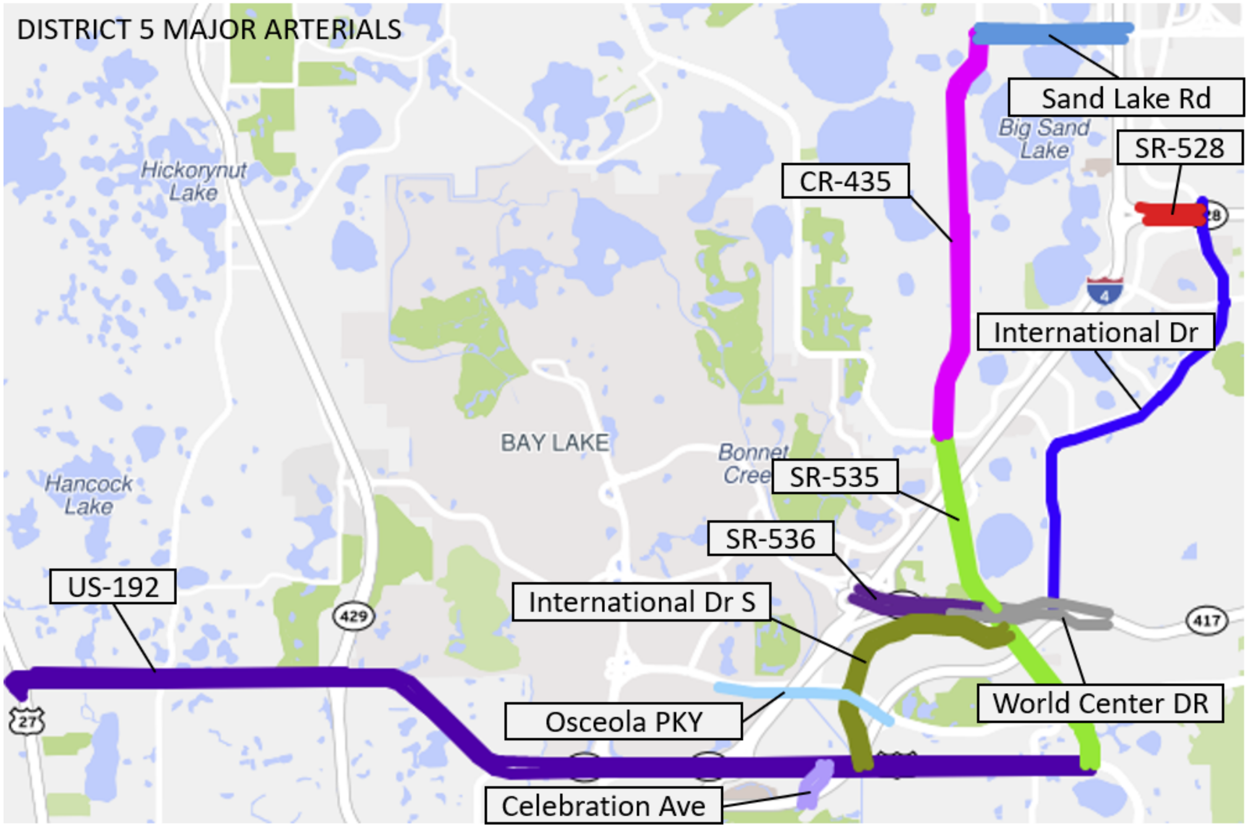


Figure 4-10. District 5 major arterials

Table 4-28. I-4 EB Connector Performance Summaries for US-192 between US-27 and SR-535

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	54.43	0.05	1.09	0.90
Tuesday	54.11	0.04	1.09	0.91
Wednesday	54.42	0.01	1.09	0.90
Thursday	54.11	0.02	1.09	0.91
Friday	53.08	0.00	1.09	0.92
Weekdays	54.02	0.02	1.09	0.91
Saturday	53.70	0.02	1.09	0.91
Sunday	54.07	0.06	1.09	0.91
Weekends	53.89	0.04	1.09	0.91
All Days	53.98	0.03	1.09	0.91

Table 4-29. I-4 WB Connector Performance Summaries for US-192 between US-27 and SR-535

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	49.28	0.07	1.25	1.01
Tuesday	48.89	0.05	1.28	1.02
Wednesday	49.03	0.03	1.32	1.02
Thursday	46.65	0.19	1.56	1.07

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Friday	41.52	0.67	2.63	1.20
Weekdays	46.85	0.15	1.52	1.07
Saturday	48.01	Optimal Conditions	1.39	1.04
Sunday	52.71	Optimal Conditions	1.09	0.95
Weekends	50.25	Optimal Conditions	1.25	1.00
All Days	47.77	0.07	1.39	1.05

Table 4-30. SR-528 – Toll/Beachline Expy EB Performance Summaries

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	58.66	Optimal conditions	1.04	0.94
Tuesday	58.51	Optimal conditions	1.06	0.94
Wednesday	58.80	Optimal conditions	1.06	0.94
Thursday	58.72	Optimal conditions	1.06	0.94
Friday	58.03	0.01	1.08	0.95
Weekdays	58.54	Optimal conditions	1.06	0.94
Saturday	58.30	0.02	1.06	0.94
Sunday	58.79	0.01	1.04	0.94
Weekends	58.54	0.02	1.06	0.94
All Days	58.54	Optimal conditions	1.06	0.94

Table 4-31. SR-528 – Toll/Beachline Expy WB Performance Summaries

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	49.81	Optimal conditions	1.11	0.98
Tuesday	49.66	Optimal conditions	1.11	0.99
Wednesday	49.77	Optimal conditions	1.14	0.98
Thursday	49.46	Optimal conditions	1.14	0.99
Friday	48.74	0.07	1.17	1.01
Weekdays	49.48	Optimal conditions	1.14	0.99
Saturday	48.96	0.09	1.17	1.00
Sunday	50.09	0.05	1.09	0.98
Weekends	49.52	0.08	1.14	0.99
All Days	49.49	0.02	1.14	0.99

Daily, weekly, weekday, and weekend performance measures are presented in Table 4-32 through Table 4-35 for the District 5 arterials. For all days (average of all days of week) for the NB direction, speed is 33.92 mph, BI is 0.29, PTI is 1.31, and TTI is 0.96. For the SB direction for all days, speed is 34.60 mph, BI is 0.27, PTI is 1.31, and TTI is 0.98. For the EB direction for all days, speed is 35.99 mph, BI is 0.29, PTI is 1.29, and TTI is 0.94. For the WB direction for all days, speed is 34.76 mph, BI is 0.43, PTI is 1.46, and TTI is 0.98. These performance measures suggest that there is some congestion and bottlenecks along these four District 5 major arterials. Table 4-36 shows the characteristics and locations of these bottlenecks.

Table 4-32. SR-528 – Performance Summaries for US-192 between US-27 and SR-535 NB

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	34.36	0.23	1.24	0.95
Tuesday	34.25	0.23	1.24	0.95
Wednesday	34.35	0.23	1.25	0.95
Thursday	34.05	0.24	1.26	0.96
Friday	33.36	0.28	1.33	0.98
Weekdays	34.07	0.24	1.26	0.96
Saturday	33.43	0.29	1.33	0.97
Sunday	34.43	0.26	1.26	0.95
Weekends	33.92	0.29	1.31	0.96
All Days	34.02	0.25	1.27	0.96

Table 4-33. SR-528 – Performance Summaries for US-192 between US-27 and SR-535 SB

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	34.90	0.26	1.28	0.97
Tuesday	34.73	0.27	1.31	0.98
Wednesday	34.74	0.27	1.31	0.98
Thursday	34.48	0.29	1.34	0.99
Friday	33.82	0.30	1.38	1.01
Weekdays	34.53	0.27	1.32	0.98
Saturday	34.33	0.30	1.34	0.99
Sunday	35.24	0.24	1.26	0.96
Weekends	34.78	0.28	1.31	0.98
All Days	34.60	0.27	1.31	0.98

Table 4-34. SR-528 – Performance Summaries for US-192 between US-27 and SR-535 EB

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	36.56	0.26	1.25	0.92
Tuesday	36.48	0.26	1.26	0.93
Wednesday	36.54	0.25	1.25	0.92
Thursday	35.85	0.30	1.31	0.94
Friday	34.71	0.33	1.38	0.97
Weekdays	36.01	0.29	1.30	0.94
Saturday	35.26	0.32	1.33	0.96
Sunday	36.62	0.27	1.25	0.92
Weekends	35.93	0.29	1.28	0.94
All Days	35.99	0.29	1.29	0.94

Table 4-35. SR-528 –Performance Summaries for US-192 between US-27 and SR-535 WB

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	35.48	0.38	1.39	0.96
Tuesday	35.40	0.38	1.39	0.96
Wednesday	35.35	0.37	1.40	0.96
Thursday	34.42	0.47	1.50	0.99
Friday	32.89	0.50	1.60	1.03
Weekdays	34.67	0.43	1.47	0.98
Saturday	34.24	0.42	1.46	0.99
Sunday	35.74	0.38	1.36	0.95
Weekends	34.97	0.41	1.42	0.97
All Days	34.76	0.43	1.46	0.98

Daily performance metrics for BI, PTI, speed profiles, and TTI are shown in the individual report. As shown, there are significant speed drops during the 24 hours for all directions. Speed fluctuates between 6:00 AM and 6:00 PM and fluctuates more on the I-4 connectors during the PM peak hours, indicating congestion. BI, PTI, and TTI also significantly vary during these times for all directions, with major fluctuations for the I-4 connectors for these metrics.

Table 4-36 shows the bottleneck rankings for District 5, with the top 10 bottlenecks ranked based on total delay weighted by VMT. Figure 4-9 plots these top 10 bottlenecks according to their geographic location. As shown, the bottlenecks are spread out across the District, with most occurring in pairs in opposite directions of travel. Bottlenecks also are located near key intersections with major roadways and near Orlando SeaWorld. Also, looking at average daily duration, these bottlenecks last for a significant amount of time, indicating recurrent bottlenecks in these locations.

Table 4-36. Bottleneck Rankings for FDOT District 5

Bottleneck Rank	Average Max Queue Length (mi)	Average Daily Duration	Volume Estimate (veh/day)	Base Impact (mi-min)	Total Delay (veh-hrs)
1	1.09	5 h 56 m	31,256	175,035	251,344,956
2	1.61	2 h 2 m	24,907	67,694	57,727,312
3	2.22	1 h 12 m	28,835	56,787	47,774,104
4	0.59	3 h 29 m	17,674	42,954	32,234,700
5	0.84	56 m	20,284	17,027	31,679,868
6	0.95	53 m	27,113	18,109	27,059,424
7	2.57	18 m	24,834	15,147	14,694,714
8	0.85	1 h 7 m	19,073	20,648	14,360,560
9	0.74	1 h 4 m	18,683	18,877	14,188,052
10	1.36	58 m	17,819	28,854	10,025,683

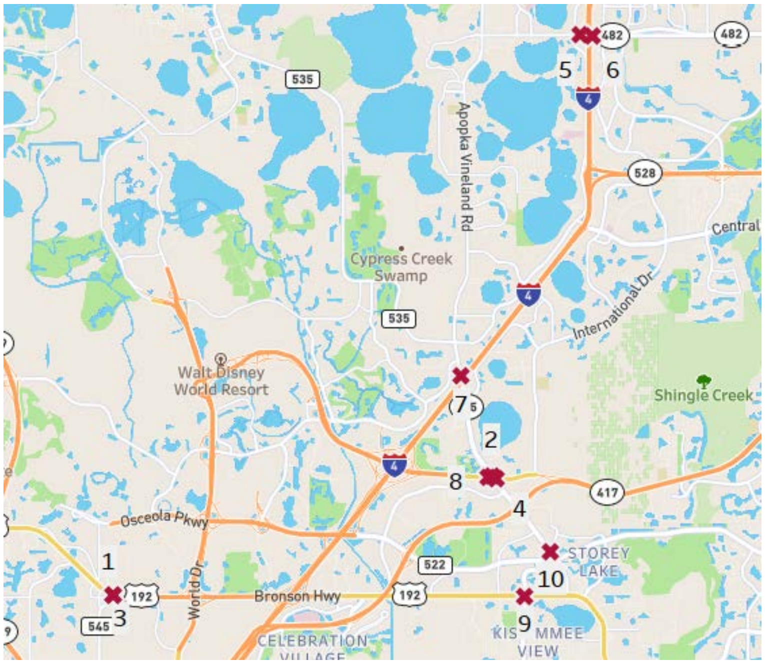


Figure 4-11. Bottleneck locations for District 5

4.6.6 FDOT District 1 Major Arterials

This section provides insights into the speed profiles, PTI, TTI, BI, bottleneck characteristics, and locations for the major arterials in FDOT District 1 (Figure 4-12).

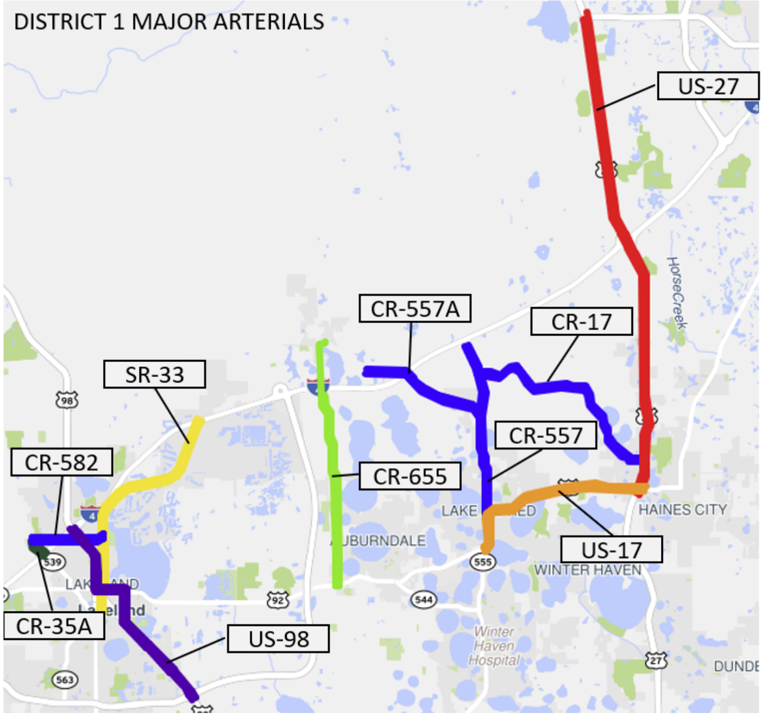


Figure 4-12. District 1 major arterials

Performance summaries are listed in Table 4-37, Table 4-38, Table 4-39, and Table 4-40 for the NB, SB, EB, and WB directions, respectively, including daily, weekly, weekday, and weekend performance measures. For all days (average of all days of week) for the NB direction, speed is 41.72 mph, BI is 0.22, PTI is 1.19 and TTI is 0.96. For the SB direction for all days, speed is 43.47 mph, BI is 0.15, PTI is 1.09, and TTI is 0.92. For the EB direction for all days, speed is 39.33 mph, BI is 0.21, PTI is 1.24, and TTI is 0.98. For the WB direction for all days, speed is 40.37 mph, BI is 0.16, PTI is 1.17, and TTI is 0.96. These performance measures suggest that there is congestion and bottlenecks along the District 1 major arterials. The bottleneck rankings show the characteristics and locations of these bottlenecks.

Table 4-37. NB Performance Summaries for District 1 Major Arterials

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	41.55	0.21	1.20	0.97
Tuesday	41.35	0.22	1.21	0.97
Wednesday	41.33	0.22	1.21	0.97
Thursday	41.19	0.23	1.22	0.98
Friday	40.34	0.30	1.30	1.00
Weekdays	41.14	0.24	1.23	0.98
Saturday	42.66	0.19	1.15	0.94
Sunday	43.87	0.14	1.08	0.92
Weekends	43.26	0.16	1.11	0.93
All Days	41.72	0.22	1.19	0.96

Table 4-38. SB Performance Summaries for District 1 Major Arterials

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	41.40	0.24	1.22	0.97
Tuesday	41.07	0.26	1.24	0.97
Wednesday	41.08	0.27	1.25	0.97
Thursday	41.00	0.27	1.25	0.97
Friday	40.77	0.27	1.25	0.98
Weekdays	41.06	0.26	1.24	0.97
Saturday	42.99	0.15	1.10	0.93
Sunday	43.96	0.13	1.06	0.91
Weekends	43.47	0.15	1.09	0.92
All Days	41.72	0.23	1.20	0.96

Table 4-39. EB Performance Summaries for District 1 Major Arterials

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	39.09	0.21	1.24	0.98
Tuesday	38.77	0.22	1.25	0.99
Wednesday	38.73	0.22	1.26	0.99
Thursday	38.70	0.21	1.26	0.99
Friday	38.29	0.23	1.28	1.00
Weekdays	38.71	0.22	1.26	0.99
Saturday	40.55	0.15	1.15	0.95
Sunday	41.41	0.15	1.12	0.93
Weekends	40.97	0.15	1.13	0.94
All Days	39.33	0.21	1.24	0.98

Table 4-40. WB Performance Summaries for District 1 Major Arterials

Day	Speed (mph)	Buffer Index	Planning Time Index	Travel Time Index
Monday	38.92	0.23	1.26	0.99
Tuesday	38.57	0.24	1.29	1.00
Wednesday	38.55	0.23	1.28	1.00
Thursday	38.48	0.24	1.29	1.00
Friday	38.14	0.25	1.31	1.01
Weekdays	38.53	0.24	1.29	1.00
Saturday	40.37	0.16	1.17	0.96
Sunday	41.47	0.14	1.12	0.93
Weekends	40.91	0.15	1.15	0.94
All Days	39.18	0.23	1.26	0.98

Table 4-41 shows the bottleneck rankings for District 1, with the top 10 bottlenecks ranked based on total delay weighted by VMT. Figure 4-13 plots these top 10 bottlenecks according to their geographic location. As shown in Figure 4-13, the bottlenecks are spread out across the District, with most occurring in pairs in opposite directions and near key intersections such as I-4 and Downtown Lakeland. Looking at average daily duration, some bottlenecks last for a short amount of time, but most last for a significant amount of time, indicating recurrent bottlenecks.

Table 4-41. Bottleneck Rankings for FDOT District 1

Bottleneck Rank	Average Max Queue Length (mi)	Average Daily Duration	Volume Estimate (veh/day)	Base Impact (mi-min)	Total Delay (veh-hrs)
1	1.06	7 h 4 m	17,433	156,928	112,205,167
2	8.9	17 m	24,037	57,313	33,630,220
3	2.1	1 h 21 m	13,475	56,718	32,674,407
4	0.96	1 h 11 m	23,905	24,766	24,627,731
5	8.92	14 m	21,518	43,157	23,160,995
6	0.06	8 h 17 m	14,420	10,355	19,613,098
7	1.04	1 h	17,486	22,383	16,919,221
8	3.1	19 m	17,803	21,492	11,330,612
9	2.01	17 m	19,774	11,950	10,678,552
10	0.11	6 h 36 m	10,138	14,995	9,982,358

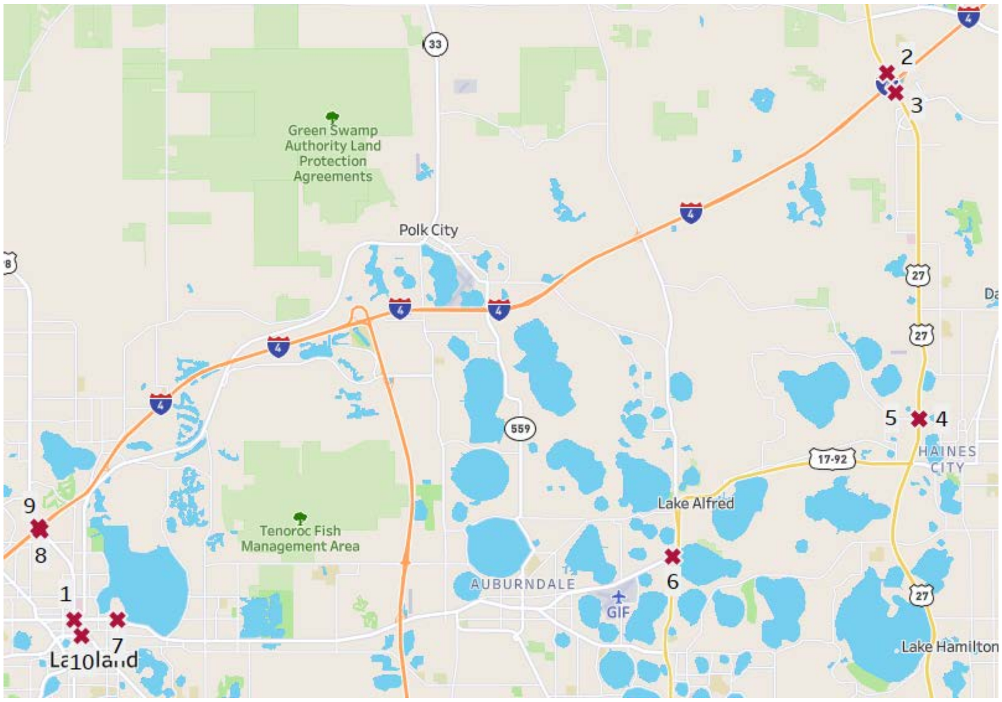


Figure 4-13. Bottleneck locations for District 1

4.7 Bottleneck Characteristics Prediction

This section explains the procedure adopted to predict future bottleneck characteristics. Historic AADT was extracted from previous databases, and future AADT was predicted. These future volumes were used to calculate growth rates, which were used to predict future volumes. Using these volumes, bottleneck characteristics were calculated and plotted. For more information on bottleneck characteristics and predictions, refer to the Task 1 report appendix.

4.7.1 Mobility Challenges

Using a data-based analysis, mobility challenges along I-4 FRAME corridors were identified. Bottleneck locations and durations are based on combined recurring and non-recurring traffic congestion.

4.7.2 Current Challenges and Insights

Most bottlenecks caused by recurring traffic congestion occur at specific points of interest on segments that are heavily traveled due to their proximity to popular attractions such as Walt Disney World and Universal Orlando. Also, I-4 is used to get to and from two busy airports, Tampa International Airport (TPA) and Orlando International Airport (MCO). As a result, I-4 has a high volume of vehicular movement. Significant delays occur along particular sections of I-4 due to traffic related to these popular attractions. Orlando is a primary tourist destination, and vehicular traffic patterns are similar on weekdays and weekends, with lower speeds and more delays on the weekends.

In addition to capacity issues and mobility challenges, effectively communicating real-time traveler information and warnings to drivers leading to efficient operation and use of existing capacity is important. For non-recurring traffic congestion, advance warning of traffic and roadway conditions to drivers to reduce crash risks and quick response from incident responders to traffic incidents to reduce vehicle delay are essential.

Along major arterials, the scenario is similar, with more recurring traffic congestion occurring at key intersections and along the ramps connecting major roadways. Better signal timing and planning and implementing advanced information exchange between vehicles and infrastructure will provide users with better opportunities to ward off congestion and eventually improve roadway conditions.

Prediction of future volumes indicates that delays will increase unless these existing mobility challenges are addressed and solutions are implemented to increase efficient use of existing capacity, reduce traffic-related crashes, and inform drivers with real-time traffic and roadway conditions.

4.7.3 Measures and Technologies for Congestion Mitigation

The noted capacity problems and mobility challenges from the data-based analysis can be addressed by implementing the I-4 FRAME project to meet the following goals set by FDOT:

- Enhanced use of existing capacity
- Real-time transportation information
- Reduced delays
- Acceleration of V2I technologies
- Reproducibility of technology transfer
- Evaluation of technologies and strategies in before-after analyses

Futuristic technologies and applications can help improve current congestion patterns and help drivers gain knowledge of suitable driving behavior. Also, efforts towards work zone and traffic incident management could improve traffic patterns, reduce non-recurring traffic congestion, warn drivers to expect delays, and provide or suggest alternate routes.

The applications that will be deployed along the I-4 FRAME corridor will potentially improve traffic conditions, reduce congestion, and eventually improve safety and mobility. The CV traffic signal system will enable vehicles to arrive at optimal times at intersections and also reduce queues, thus reducing accidents and non-recurring congestion. The Incident Scene Safety Monitoring application and CV applications can deliver messages to drivers of oncoming vehicles, alerting them of the situation ahead. This could potentially lead drivers to find alternate routes with lower travel times and, hence, improve mobility. The system deployed at Traffic Management Centers (TMCs) can monitor the conditions upstream of an incident to ensure that queue propagation is smooth and reduce or eliminate the conditions for secondary crashes. TSP will increase bus arrivals on schedule and the percentage of bus arrivals on green at CV-equipped intersections to improve mobility and potentially reduce crashes. The application of Intersection Safety Warning and Collision Avoidance can help reduce crash frequency and crash severity and help improve intersection safety and reduce non-recurring traffic congestion.

These I-4 FRAME applications will address the mobility challenges currently faced. Issues related to capacity utilization, traffic signal operations, intersection safety, and responses to traffic incidents can be resolved using these advanced CV technologies. The “after” analysis of this project will evaluate roads after these technologies have been deployed.

4.7.4 Data Needs

The RITIS database provided useful data and information for researchers to perform mobility analysis. Only some freeway and minor arterial data are incomplete or missing. For the “before” data collection and analysis on some CV applications, zone locations, lane closure data, and wrong-way crash locations, incident-related data and information was needed. These data could also be used during the after-data analysis in the future. With assistance from the FDOT Central Office, FDOT Districts 1, 5, and 7, and Florida's Turnpike Enterprise, the USF-CUTR research team obtained the “before” data and information for these CV applications.

4.8 Conclusion

This section identified bottlenecks along the I-4 FRAME project corridors and provided findings obtained through analyzing data from different data sources, including insights into bottleneck locations, their characteristics, and associated mobility challenges. Speed volume data were extracted from the RITIS database and processed and cleaned, and a working data set was created and used. Detailed data-based analysis identified recurrent bottlenecks around study area popular attractions and points of interest. Traffic patterns were analyzed for interstates and major arterials, and bottleneck locations were plotted on maps and ranked based on performance measures. Total delay, PTI, TTI, and average daily congestion were calculated, and bottlenecks were ranked according to these parameters. Corresponding data will be collected after completion of I-4 FRAME application deployment to evaluate how they help to address these challenges.

5 "Before" Study Data Collection and Analysis of Selected Individual I-4 FRAME Project Transportation Systems and Services

This section provides a summary of the analysis performed for each of the 10 CV applications and three services in the USF-CUTR scope of work. The applications and services for which findings are included in this section are:

1. Reduced Speed Zone Warning/Lane Closure
2. In-Vehicle Signage
3. Work Zone Management
4. Incident Scene Safety Monitoring
5. CV Wrong-Way Vehicle Detection Systems
6. CV Traffic Signal System
7. Transit Signal Priority (TSP)
8. Intersection Safety Warning and Collision Avoidance
9. Freight Signal Priority
10. Advanced Railroad Grade Crossing
11. OBU Penetration and Its Impact on Improving Safety and Mobility
12. SCMS Impact Analysis
13. Study Implications of Cooperative Automation Research for Mobility Applications (CARMA) and Impacts of Deployment in Project Corridor

Details for each of these applications and services can be found in the Task 2 report. A summary of each follows.

5.1 Reduced Speed Zone Warning/Lane Closure (VS09)

5.1.1 Application Description and Objectives

The Reduced Speed Zone Warning/Lane Closure application warns drivers via a Traffic Incident Management (TIM) advisory that there is a reduced speed zone or lane closure ahead for construction/work zones, school zones, or other areas of interest. This application is applied on freeways and is aimed at reducing crashes that occur due to high speed in these zones. The objectives of the task for this application were to 1) identify locations where reduced speed zones and lane closures occur, 2) collect incident and crash information per the PEP [75], 3) calculate performance measures for these locations and along the corridor, and 4) report findings.

5.1.2 Deployment Locations and Datasets

According to the I-4 FRAME deployment plan, locations at which this application will be functional includes the I-4 corridor and portions of I-275 and I-75 in Hillsborough County and several Turnpike roads. Table 5-1 lists these locations and the length of each segment. Deployment locations are shown in Figure 1-1.

Table 5-1. Deployment Locations for Reduced Speed Zone/Lane Closure Application

Road	Start Point (mm)	End Point (mm)	Segment Length (mi)
I-4	0	71.8	71.8
I-75	254.6	262	7.4
I-275	39.2	50.7	11.5
SR-60	17.7	19.1	1.4
SR-417	1	5.6	4.6
SR-429	0.7	5.4	4.7
SR-570	1.1	23.9	22.8
SR-589	2.6	3.6	1

The crash rate by route length for crashes is estimated according to Eq. 1:

$$\boldsymbol{R} = \frac{\boldsymbol{C}}{\boldsymbol{N} \times \boldsymbol{L}} \tag{4}$$

Where: R = Crashes per mile for the road segment, expressed as crashes per each one mile of roadway per year, C = Total number of crashes in study period, N = Number of years of data, and L = Length of roadway segment, in miles

Similarly, the incident rate by length is estimated according to Eq. 2:

$$\boldsymbol{R} = \frac{\boldsymbol{I}}{\boldsymbol{N} \times \boldsymbol{L}} \tag{5}$$

Where: R = Incidents per mile for road segment, expressed as incidents per each one mile of roadway per year, I = Total number of incidents in study period, N = Number of years of data and L = Length of roadway segment, in miles

Two datasets were used for this analysis. Crash data were gathered from Signal Four Analytics [76], a portal that provides up-to-date crash information with some limitations. Crash data covered January 2017–April 2022. The incident dataset was gathered primarily by the three FDOT District offices involved in the project (D1, D5, D7) and Florida's Turnpike Enterprise, which provided output from the SunGuide Regional Traffic Management Center (RTMC) system. Some missing incident information was collected from the Regional Integrated Transportation Information System (RITIS) [77].

5.1.3 Analysis and Results

All police-reported crashes (both long- and short-form) were collected for 2017 to April 2022 for all road segments in Table 5-1. Table 5-2 shows all crashes extracted from Signal Four for the study period for all road segments included in the study. Using Eq. 1, crash rates for all segments were calculated to normalize for the different segment lengths (shown in Table 5-1). According to this analysis, the 1.4 miles of SR-60 has the highest crash rate, followed by the I-4 section in D5. The segment with the lowest rate is SR-570, with 0.46.

Table 5-2. Crashes Reported on I-4 FRAME Corridors, 2017–2022

Road	2017	2018	2019	2020	2021	2022	Total	Crash Rate
I-275	368	453	516	550	503	159	2,549	41.59
I-4 D1	238	141	191	263	319	85	1,237	7.71
I-4 D5	1,768	1,615	1,613	866	1,356	293	7,511	99.94
I-4 D7	745	772	785	728	909	246	4,185	28.45
I-75	287	276	327	239	333	103	1,565	39.68
SR-417	40	39	42	41	30	5	197	8.03
SR-429	26	18	48	38	37	7	174	6.95
SR-570	10	11	8	8	16	3	56	0.46
SR-589	6	10	36	22	47	11	132	24.77
SR-60	72	136	305	105	213	101	932	124.90
Total	**3,560**	**3,471**	**3,871**	**2,860**	**3,763**	**1,013**	**18,538**	

The application will function when reduced speed zones or lane closures occur on I-4 segments. Crash data do not provide information on reduced speed zones; these are expected only in work zones where a planned activity takes place. Therefore, crash data were filtered to include crashes that occurred in work zones. The data show that the I-4 segment in D5 has the highest number of crashes (417) and the highest crash rate (5.55), with SR-570 having the lowest (0.02).

To evaluate the lane closure application, incidents with lane closures were obtained and used for analysis. To normalize for corridor length, an incident rate was calculated based on Eq. 2. Table 5-3 shows a summary of incidents with lane blockage and the calculated incident rate. For the segment of I-4 in D1, the data for 2021 and 2022 were missing, so the rate was adjusted for four years. With this analysis, the segment with highest rate was the one mile of SR-589 in Tampa. It is expected that CV applications will help to reduce incidents that follow unforeseen or unscheduled incidents and reduce secondary crashes, as reported in the previous section.

Table 5-3. Number of Incidents per I-4 FRAME Corridor

Year	I-275	I-4 D1	I-4 D5	I-4 D7	I-75	SR-417	SR-429	SR-570	SR-589	SR-60
2017	702	216	1297	663	315	54	78	92	165	60
2018	804	149	1541	809	358	86	132	147	181	63
2019	909	2392	1502	990	423	261	352	165	293	149
2020	1011	1661	989	1056	387	348	469	458	257	177
2021	1006	--	4784	1163	400	418	579	1850	413	92
2022	445	--	1923	389	102	126	245	522	139	75
Total	**4877**	**4418**	**12036**	**5070**	**1985**	**1293**	**1855**	**3234**	**1448**	**616**
Segment length	11.5	30.1	14.1	27.6	7.4	4.6	4.7	22.8	1.0	1.4
Incident rate	79.57	36.69	160.15	34.46	50.33	52.74	74.05	26.61	271.67	82.55

5.2 In-Vehicle Signage (TI07)

5.2.1 Objectives

In-vehicle signage technology will broadcast traffic signs and statuses through advanced sensors, which potentially could reduce crashes and improve safety and mobility. Mobility and safety metrics were studied near the deployment locations along the I-4 FRAME corridor. The "after" study will implement OBUs, which will export more performance metrics and could present a more in-depth analysis of the performance of this technology.

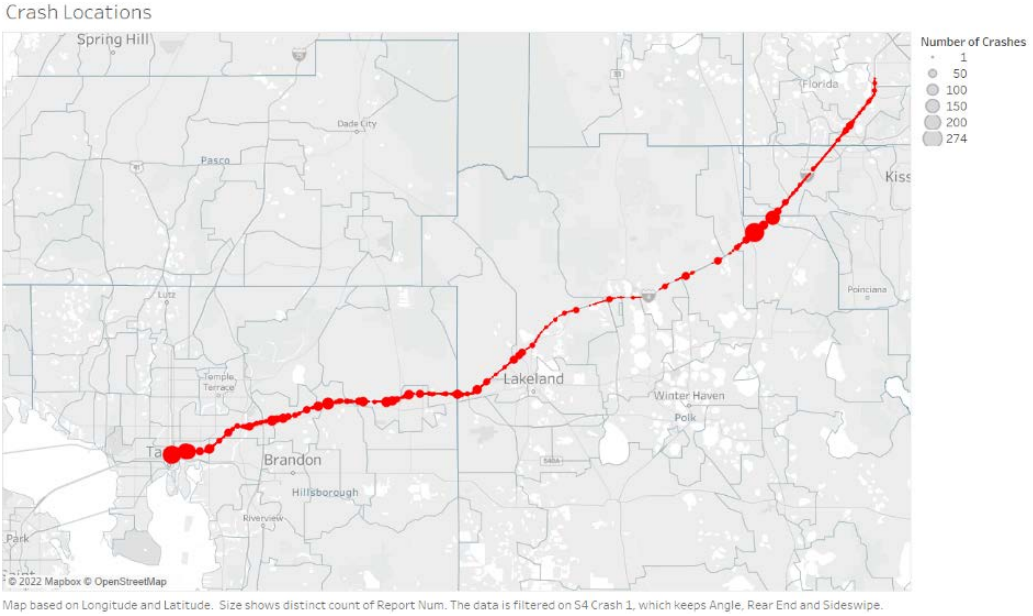
5.2.2 Deployment Locations and Datasets

This application will be deployed at all locations along the I-4 FRAME project—I-4 mainline, D1, D5, and D7 major arterials and intersections, as defined by FDOT. Crash data were collected from Signal Four and FDOT Open Data Hub and covered the period from January 2017 to October 2021. Mobility data were collected primarily from the Probe Data Analytics Suite of RITIS, and the period covered was April 2022 to June 2022.

5.2.3 Analysis

5.2.3.1 Safety Analysis

Crash locations are shown in Figure 5-1. Many crashes occurred in D5 and D7. For D7, crashes occurred primarily near Downtown Tampa and near the intersection with I-275. In 2017–2021, the largest number of crashes at a particular location was 274. According to the PEP, only angle, rear-end, and sideswipe crashes were to be considered in this analysis.



Map based on Longitude and Latitude. Size shows distinct count of Report Num. The data is filtered on S4 Crash 1, which keeps Angle, Rear End and Sideswipe.

Figure 5-1. Crash locations along I-4

Source: CUTR

Crashes over the years were plotted in Figure 5-2. Historically, D7 has had a greater number of crashes than D1 and D5. The crash trendline shows that the number of crashes decreased drastically in early 2020 due to the COVID-19 pandemic and the reduced number of people traveling. It increased to near pre-pandemic levels in late 2020, followed by an increasing trend. The number of accidents in D7 is higher than the pre-pandemic level after 2021.

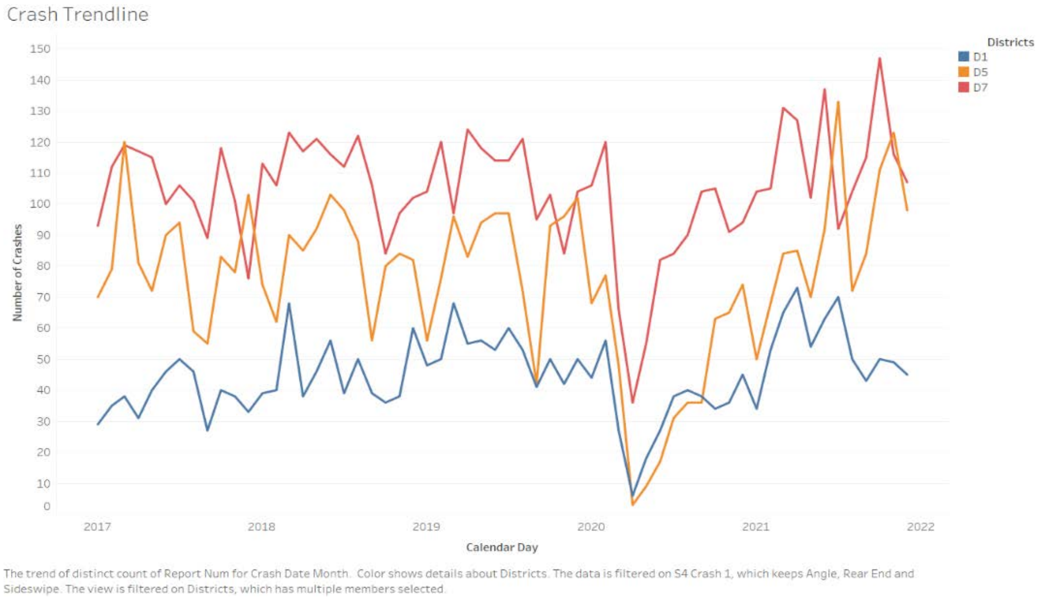


Figure 5-2. Crash trends per year by FDOT District, 2017–2022

Crash frequency by FDOT District is shown in Figure 5-3. Crash frequency normalizes crashes, as it averages them by number of years. The highest crash frequency was for D7, and the lowest was for D1. These performance metrics will be compared in the “after” study.

$$\boldsymbol{Crash\ Frequency} = \frac{\boldsymbol{Number\ of\ observed\ crashes}}{\boldsymbol{Number\ of\ years\ of\ data}} \qquad \textbf{(6)}$$

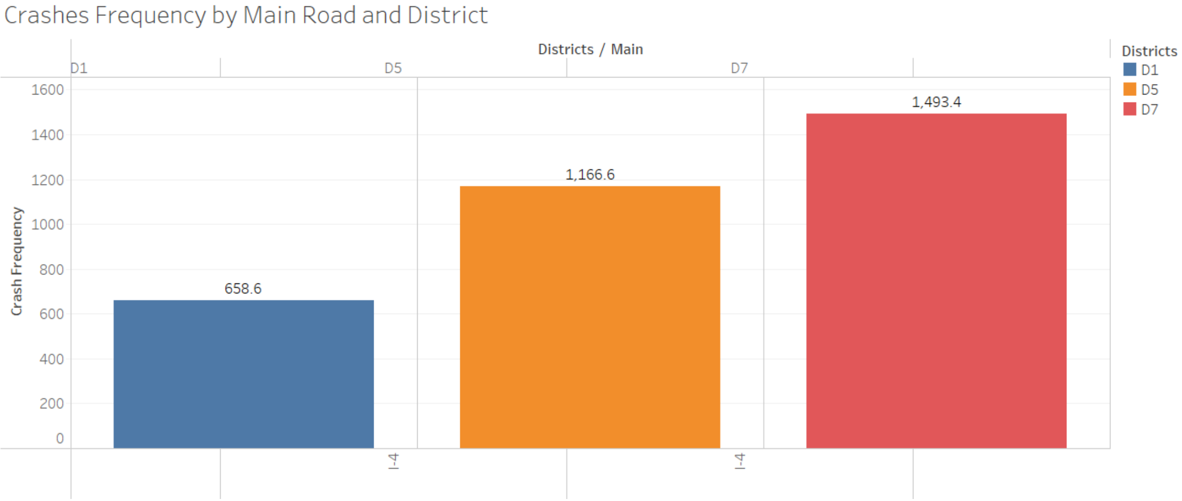


Figure 5-3. Crash frequency by main road and FDOT District

5.2.3.2 Mobility Analysis

I-4 performance metrics are shown in Table 5-4 and Table 5-5. AM peak-hour performance was better than PM peak-hour performance for the EB and WB directions. Weekends also had better TTI, PTI, BI, and speeds than weekdays for the EB and WB directions. The highest travel time index was 1.41 for the WB direction during PM peak hours on Friday. These tables present peak-hour aggregates of the performance metrics for the six-month period from January to June 2022 and were plotted for I-4 EB and I-4 WB and averaged every five minutes for April–June 2022.

Table 5-4. Performance Metrics for I-4 EB

	Speed (MPH)		BI		PTI		TTI	
	AM Peak	*PM Peak*	*AM Peak*	*PM Peak*	*AM Peak*	*PM Peak*	*AM Peak*	*PM Peak*
Mon	55	56	0.49	0.57	1.57	1.65	1.15	1.12
Tue	53	57	0.47	0.45	1.55	1.53	1.18	1.1
Wed	56	55	0.41	0.45	1.47	1.58	1.12	1.15
Thu	54	53	0.45	0.55	1.49	1.7	1.16	1.18
Fri	59	45	0.34	0.54	1.38	1.97	1.07	1.4
Weekday	55	53	0.43	0.61	1.49	1.79	1.14	1.19
Sat	66	53	0.16	0.49	1.12	1.72	0.95	1.2
Sun	71	59	0.05	0.45	1	1.5	0.89	1.07
Weekend	68	56	0.12	0.49	1.07	1.63	0.92	1.14
All Days	59	54	0.39	0.59	1.41	1.77	1.07	1.17

Table 5-5. Performance Metrics for I-4 WB

	Speed (mph)		BI		PTI		TTI	
	AM Peak	*PM Peak*	*AM Peak*	*PM Peak*	*AM Peak*	*PM Peak*	*AM Peak*	*PM Peak*
Mon	60	52	0.33	0.54	1.44	1.68	1.05	1.22
Tue	59	51	0.43	0.49	1.53	1.64	1.08	1.23
Wed	60	50	0.33	0.46	1.41	1.68	1.05	1.25
Thu	61	49	0.27	0.5	1.36	1.72	1.03	1.29
Fri	62	45	0.33	0.55	1.34	1.99	1.03	1.41
Weekdays	60	49	0.33	0.54	1.41	1.77	1.05	1.28
Sat	68	53	0.08	0.51	1.02	1.67	0.92	1.19
Sun	71	56	0.01	0.41	0.96	1.54	0.9	1.12
Weekends	69	55	0.03	0.46	0.98	1.6	0.91	1.15
All Days	63	51	0.31	0.57	1.34	1.78	1.01	1.25

5.3 Work Zone Management (MC06)

The Work Zone Management application broadcasts information to motorists in areas where maintenance, construction, and utility work are ongoing. Coordination and information exchange of work zone schedules and activities are required. Real-time roadway traffic conditions will be collected to support work zone scheduling and work zone management. Operational status may be monitored to provide driver information using surveillance (CCTV, etc.) for Dynamic Message Sign (DMS), Highway Advisory Radio (HAR), and TIM advisories relative to work zone speeds, and delays will be created from the respective RTMC via SunGuide for broadcast from RSUs to OBUs. Objectives of this task were:

- Identification of locations where Work Zone Management application will be deployed
- Collection of historical intersection crashes at MC06 locations
- Collection of historical time reliability data at MC06 locations
- Calculation of performance measures for these locations

5.3.1 Deployment Locations and Datasets

The Work Zone Management application will be deployed at 134 locations on I-4 FRAME freeways, as shown in Figure 5-4. Deployment segments include I-4, I-275, I-75, SR-589, SR-570, SR-417, and SR-429.

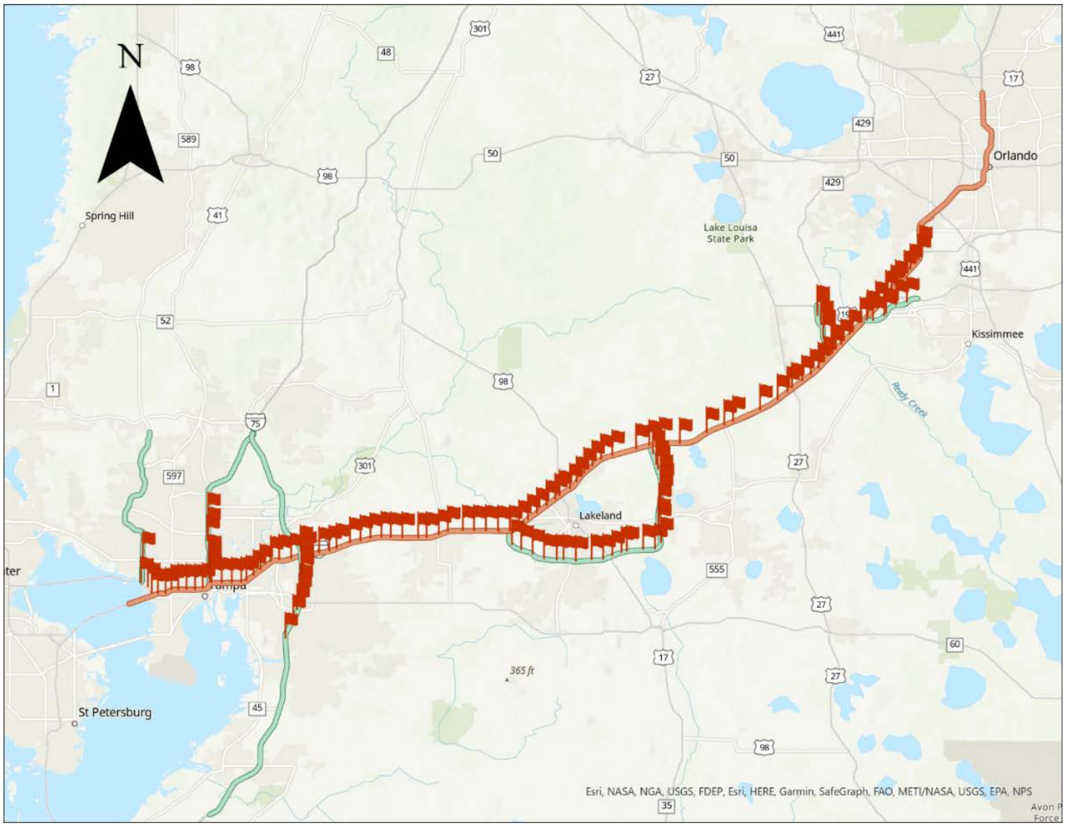


Figure 5-4. Deployment locations of Work Zone Management System (MC06)

Source: CUTR

To evaluate the safety performance of Work Zone Management System, historical crash data were collected from Signal Four Analytics. As the location of work zone projects may be changed in the "before" and "after" stages, data collection did not focus on specific Work Zone

Management System locations; work zone crash data were collected along seven corridors (I-4, I-275, I-75, SR-589, SR-570, SR-417, and SR-429) for five years (2017–2021).

To evaluate mobility performance, work zone projects were identified in FDOT Districts 1 and 7 for five years (2017–2021) on I-4 FRAME freeways. HERE data were matched to each identified work zone projects to calculate time reliability measures (BI, PTI, and TTI) in the "before" study.

5.3.2 Analysis Results

Work zone crashes on I-4 FRAME freeway segments are summarized in Figure 5-5.

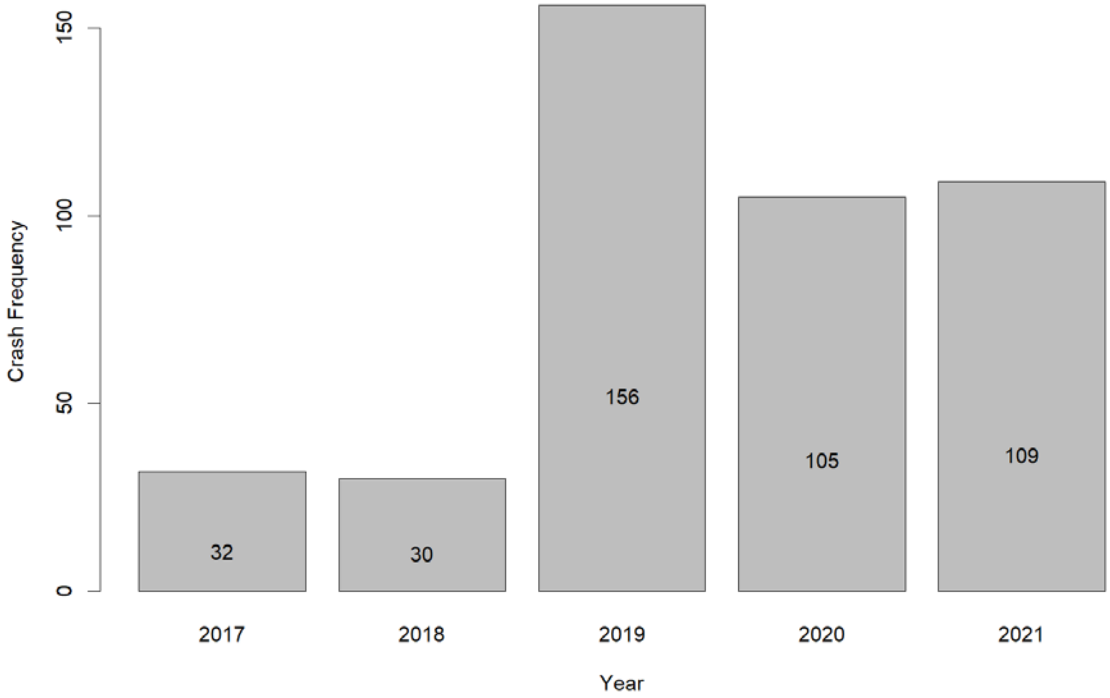


Figure 5-5. Distribution of I-4 FRAME work zone crashes (2017–2021)

Work zone lane closure events for I-4 D1 occurred during nighttime (8:00 PM–6:00 AM). Time reliability measures for the analysis time frame (8/17/2020–12/31/2021) are shown in Figure 5-6.

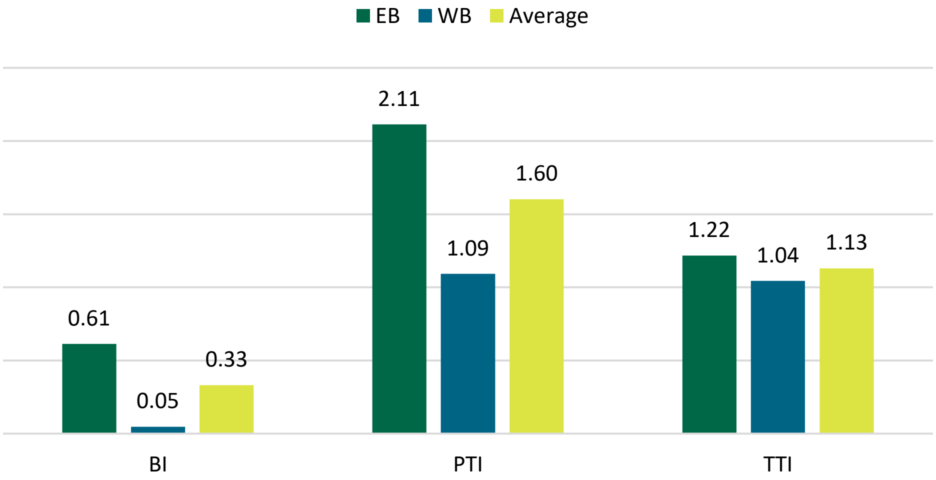


Figure 5-6. Time reliability of FDOT D1 work zone lane closures

Average time reliability measures for D7 work zone projects are shown in Figure 5-7. The values can be used to estimate the time reliability of work zone lane closure events given the lane closure duration.

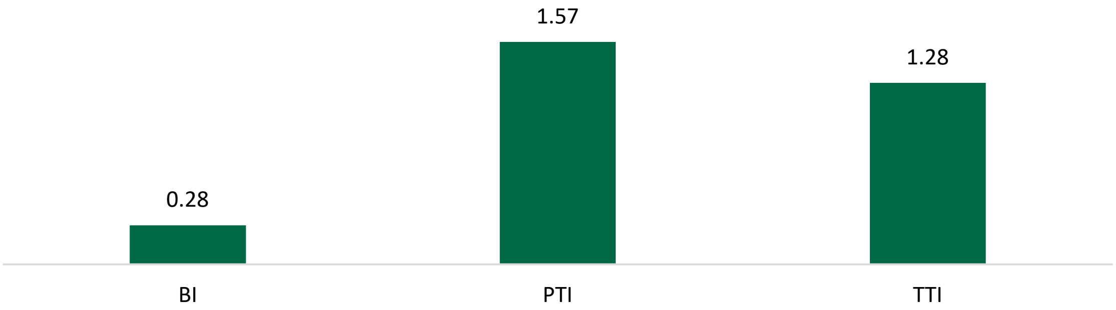


Figure 5-7. Average time reliability for FDOT D7 work zone lane closure events

"Before" data show increased work zone crashes on I-4 FRAME freeway segments after 2019, which may be caused by more work zone activities. The time reliability analysis indicates the impact of work zone activities on freeway mobility performance; "before" data will be compared to the "after" data to examine the performance of the work zone management system.

5.4 Incident Scene Safety Monitoring (PS07)

5.4.1 Application Description and Objectives

The Incident Scene Safety Monitoring application broadcasts information to alert drivers of incident zone operations. Operations assist motorists with advance notifications for merging and speed guidance around an incident and protect both motorists and emergency response personnel on scene. This application is applied on a freeway and is aimed at reducing crashes that occur due to high speed or inattention at these zones. Objectives of the task for this application were:

- Identification of locations at which incidents occur
- Collection of incidents and crash information per PEP
- Calculation of performance measures for these locations and along corridor
- Report findings

5.4.2 Deployment Locations and Datasets

The Incident Scene Safety Monitoring application will be deployed at the same locations as the Reduced Speed Zone/Lane Closure application and will cover the I-4 corridor along with the main diversion routes. This application, like most applications, is functional where there are RSUs to broadcast TIMs to vehicles passing in their coverage area. For this application, two datasets were used—crash data and incident data. Crash data and analysis were the same as in the Reduced Speed Zone Warning/Lane Closure application, so no additional crash analysis was performed. The incident analysis adds to the analysis presented for VS09 and adds clearance, response, and duration for the incidents.

5.4.2.1 Analysis and Results

Data collected from FDOT District offices and Florida's Turnpike Enterprise were not consistent in format; therefore, not all measures could be calculated to compare the difference between incidents with and without lane blockage. As shown in Table 5-6, clearance time (time taken to clear a roadway) is less for incidents without lane blockage than incidents with lane blockage. The difference in the two times was calculated for all roads, with the I-4 D1 segment having the largest difference (662 minutes, on average).

Table 5-6. Comparison of Incident Clearance and Duration Times

Road	Incidents with No Lane Blockage		Incidents with Lane Blockage		Clearance Time Diff (min)	Duration Time Diff (min)
	Mean Clearance Time (min)	*Mean Duration Time (min)*	*Mean Clearance Time (min)*	*Mean Duration Time (min)*		
I-275	168.7	356.35	382.95	462.89	214.25	106.54
I-4 D1	77.15	188.65	739.96	746.13	662.81	557.48
I-4 D5	22.19	42.74	105.06	98.68	82.87	55.94
I-4 D7	32.44	Not Avail.	40.31	Not Avail.	7.87	Not Avail.
I-75	59.88	237.82	462.49	498.28	402.61	260.46
SR-417	36.7	Not Avail.	281.25	Not Avail.	244.55	Not Avail.
SR-429	74.65	Not Avail.	248.806	Not Avail.	174.16	Not Avail.
SR-570	26.95	Not Avail.	188.2	Not Avail.	161.25	Not Avail.
SR-589	223.96	Not Avail.	484.73	Not Avail.	260.77	Not Avail.
SR-60	15.88	148.18	553.97	559.02	538.09	410.84

These numbers can be used as a baseline for improvement after the CV application is functional and will aid in the response and clearance time for incidents that occur on I-4 FRAME corridors.

FDOT D7 provided Road Ranger response times for the I-4 segment in D7. Figure 5-8 shows the response time for 6,026 traffic incidents logged in the SunGuide system for I-4 (mile marker 0.1 to mile marker 25). This shows an incident rate of 241 incidents per mile for January 2017 to May 2022. The annual average ranged from 8.2 minutes in 2017 (highest) to 4.7 minutes (lowest) in 2020; the overall average response time was 5.9 minutes.

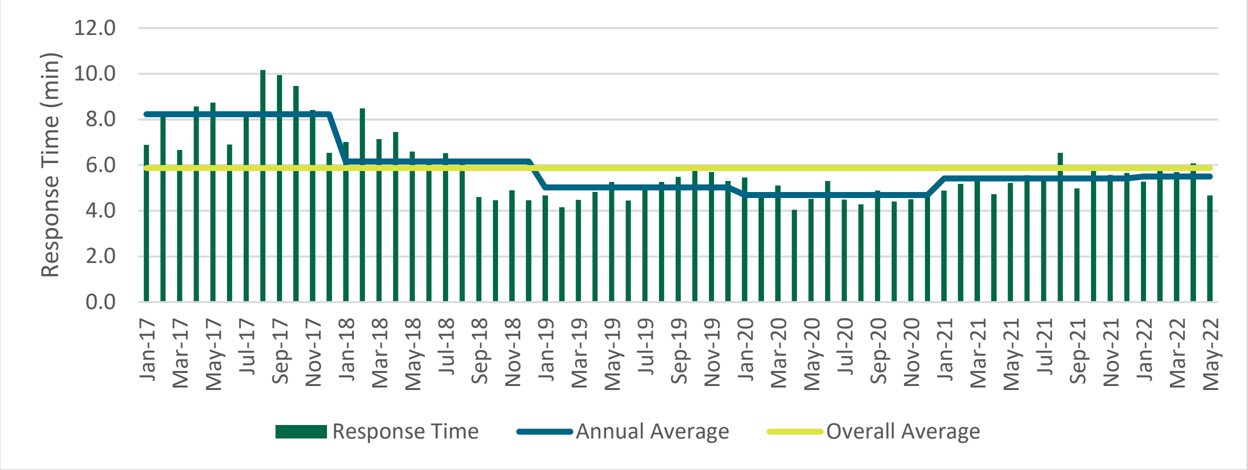


Figure 5-8. I-4 D7 incident response time, January 2017–May 2022

Similar data were provided by D5 for the I-4 segment included in the I-4 FRAME project. The monthly average response time for 12,036 incidents occurring on the segment ranged from 3.9 minutes (lowest) in 2017 to 7.5 minutes (highest) in 2021); the overall average response time was 6 minutes.

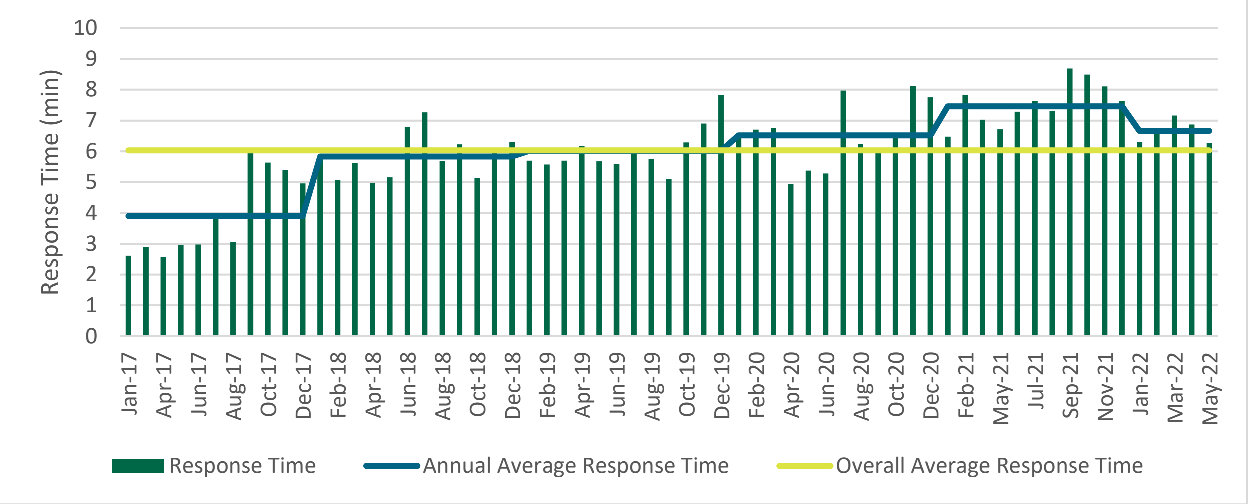


Figure 5-9. I-4 D5 incident response time, January 2017–May 2022

To assist FDOT in identification of where this application could have a larger impact, a heat map of all incidents from January 2017 to May 2022 was created for the I-4 corridor (Figure 5-10). This can be used to locate sections of I-4 that experience frequent incidents. The map can be dynamic and, when zoomed in to a specific area, more detailed.

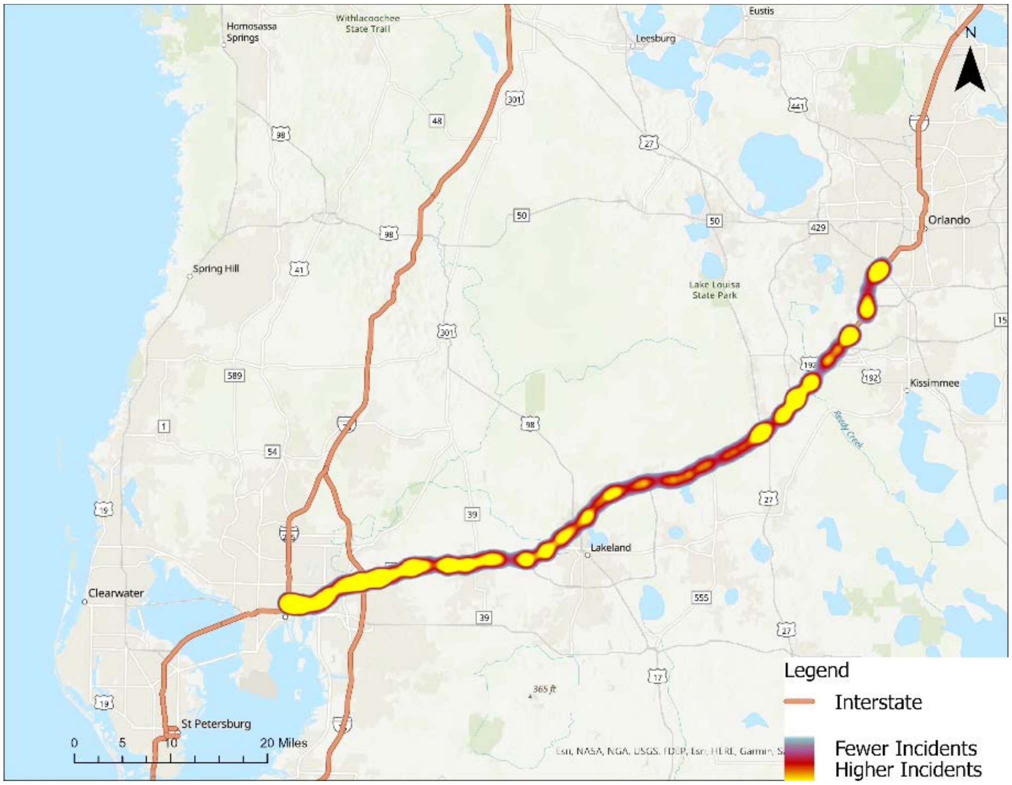


Figure 5-10. Heat map of all traffic incidents on I-4 corridor

5.5 Wrong-Way Vehicle Detection and Warning (TM25)

With the increase in wrong-way driving (WWD) crashes in Florida and to reduce WWD incidents, FDOT introduced Wrong-Way Vehicle Detection Systems (WWVDS) that assist motorists in properly identifying interstate exit ramps to avoid entering the wrong way. Wrong-way signage on exit ramps is equipped with radar to detect vehicles traveling the wrong way. Once the device detects a wrong-way driver, lights begin to flash to notify the driver that they are traveling in the wrong direction; if the driver continues in the wrong direction, radar detection sends alerts to FDOT traffic managers and law enforcement, and a wrong-way driver alert will appear on DMS to caution other motorists. The objectives of the Wrong Way Vehicle Detection and Warning application is to warn CV drivers when a vehicle has entered the interstate in the wrong direction and is traveling the wrong way towards them. Wrong way vehicles are detected via the WWVDS currently installed at ramps on I-4 and I-275.

5.5.1 Deployment Locations and Datasets

The WWD application is planned to be deployed in 20 selected ramps on I-4 and I-275—four along I-275 in D7 and eight on I-4. The other eight locations are in D1 on I-4, as shown in Figure 5-11. Some locations are opposite each other at the same location and are not easily identifiable on the map.

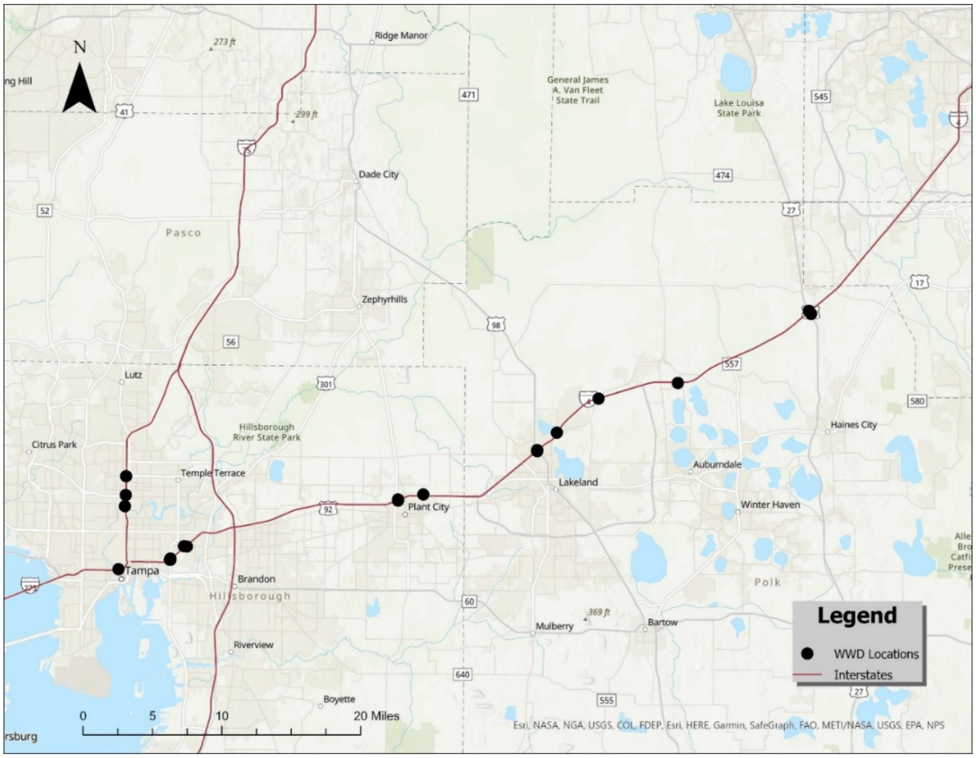


Figure 5-11. WWVDS deployment locations

Source: CUTR

Two datasets were used for this analysis—crash data provided by D7 Safety Office's Crash Analysis Reporting system (CAR) and WWD incident data reported in RITIS. The team collaborated with the D7 Safety Office to obtain confirmed WWD crashes that occurred during January 2017–April 2022. As these crashes are rare, it was necessary to use at least five years of data to include enough crashes in the analysis. In total, 17 wrong-way crashes were identified that occurred on I-275 in D7 and on I-4 throughout the project area. In addition, WWD incidents inside the I-4 FRAME area were identified in RITIS for the two corridors between January 2019 and April 2022. For incident analysis, a shorter period was used, as more incidents were logged into the system; 849 wrong-way incidents reported in RITIS and were filtered for the I-4 FRAME deployment locations.

5.5.2 Analysis and Results

Data showed 17 WWD crashes from January 2017 to April 2022 on I-275 and I-4, all but one during nighttime conditions with dry conditions. To identify the potential for WWD system deployment during the project, an RSU buffer of 1,000 meters was applied; only one WWD crash was within the boundaries of RSU on I-4. Crash rate by route length was calculated based on Eq. (1). According to the analysis, the I-275 segment is more prone to WWD crashes based on the most recent five years of data. As only one crash was within RSU boundary, the analysis could not be conducted for locations at which the application will be deployed.

As noted, all incidents reported to RITIS were extracted for the two corridors. The same buffer of 1,000 meters was applied to filter incidents that occurred within RSU boundaries. These are the relevant incidents to which the CV system will alert drivers. After filtering the WWD incidents, 186 were identified for I-4 and 292 for I-275. These incidents were reviewed to obtain information on the cause of the reporting. It was found that the system reports incidents for several reasons, including training and testing of the WWDS device, wrong/false alarms, lawnmowers collecting debris, presence of ATVs, duplicate events, backing of vehicles, and construction vehicles such as utility vans, construction vessels, work trucks, fire rescue vehicles, and others.

All incidents were reviewed to validate if they were true WWD incidents or false/erroneous alerts based on operator notes in the system. For each WWD incident activation, TMC operators review CCTV cameras to verify if a vehicle is traveling the wrong way. Based on the review, 29 WWD incidents (15.6%) were identified on I-4 and 16 (5.5%) on I-275.

Using Eq. 2, the incident rate was calculated, as shown Table 5-7. Note that these incidents were only the incidents that were true WWD incidents and were within RSU boundaries.

Table 5-7. WWD Incident Rate Calculation

Corridor	WWD Incidents (i)	Number of Years (n)	Segment Length (l)	CRASHES per Mile (r)
I-4	29	3.33	77	0.11
I-275	16	3.33	20	0.24

5.6 Connected Vehicle Traffic Signal System (TM04)

5.6.1 Objectives

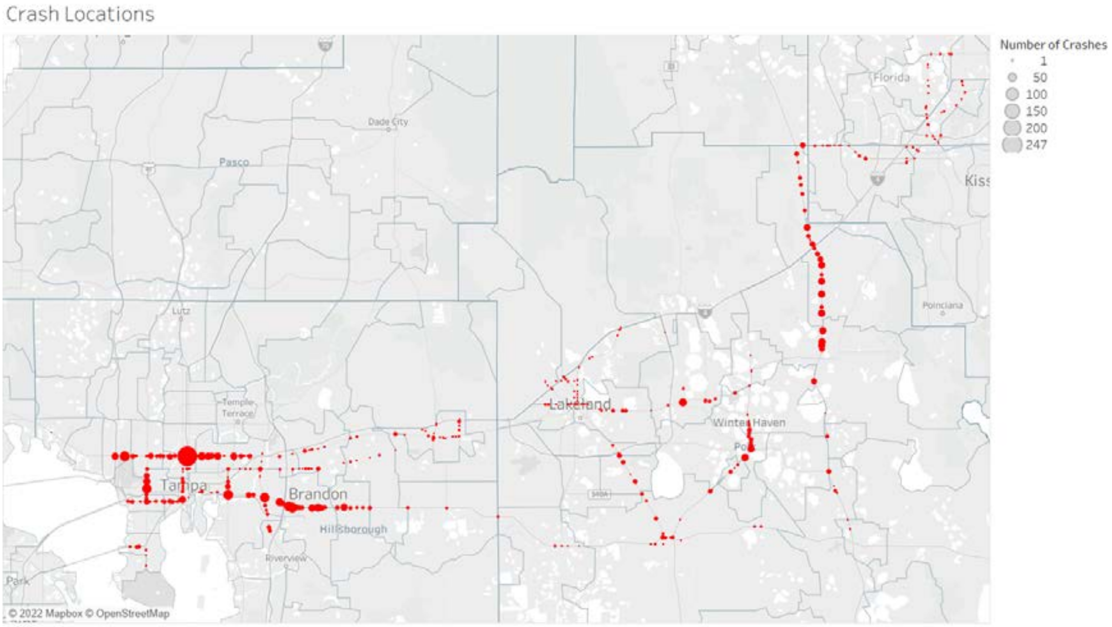
This system will use CV technology to dynamically change signal timing and improve percent arrival on green (POG), control delay, and improve safety and mobility at intersections. The objectives were to study the mobility and safety metrics at the deployment locations.

5.6.2 Deployment Locations and Datasets

The CV Traffic Signal System application will be deployed at numerous locations at intersections along I-4 diversion routes and major arterials in D1, D5, and D7. Crash data were gathered from Signal Four and the FDOT Open Data Hub from January 2017 to October 2021. Mobility data were collected primarily from the Signal Analytics Suite of RITIS and INRIX data for June 2022.

5.6.3 Safety Analysis

Crash locations are displayed in Figure 5-12. Most crashes occurred in D5 and D7. In D7, the crashes mainly occurred near Downtown Tampa and near Hillsborough Avenue. In 2017–2021, the greatest number of crashes at a particular location was 247.

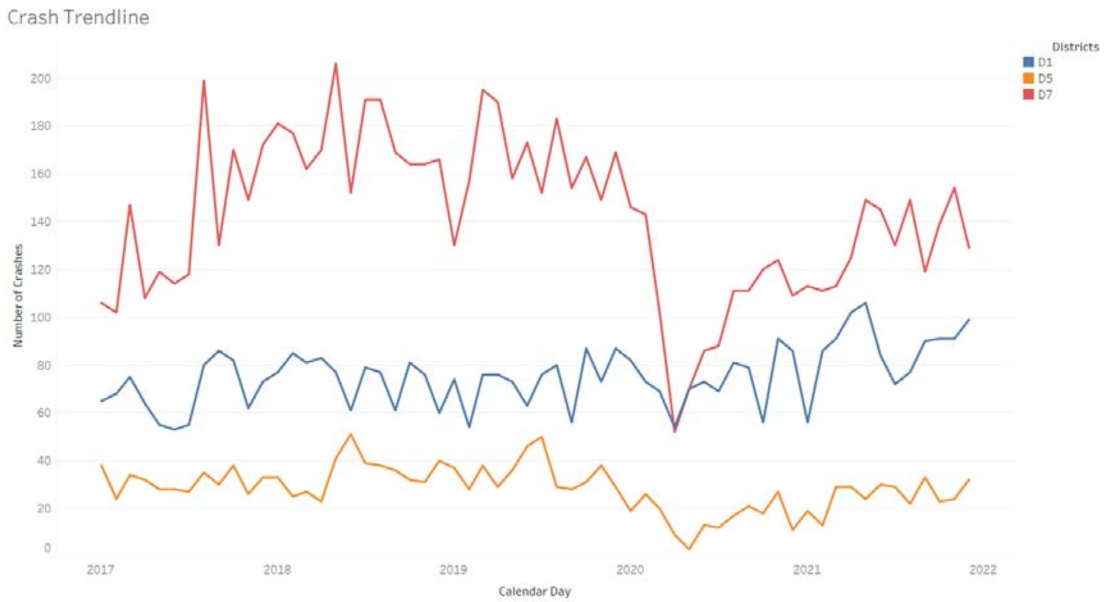


Map based on Longitude and Latitude. Size shows distinct count of Report Num. The data is filtered on S4 Crash 1, which keeps Angle, Rear End and Sideswipe.

Figure 5-12. Crash locations

Source: CUTR

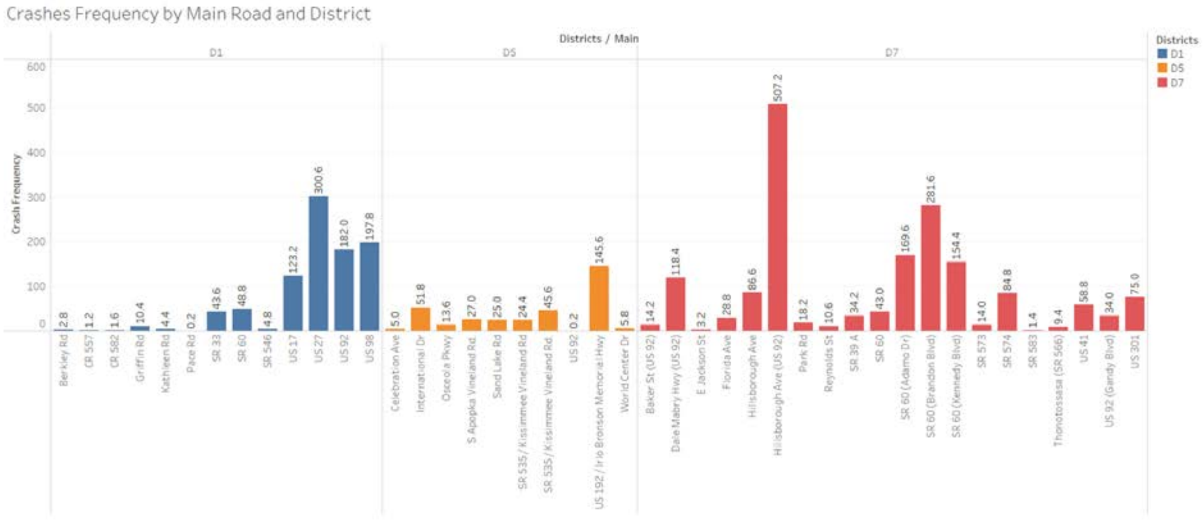
Crashes over the years are shown in Figure 5-13. Historically, D7 has had a greater number of crashes than D1 and D5. The crash trendline shows that the number of crashes decreased drastically for D7 in early 2020 due to the COVID-19 pandemic and reduction in the number of people traveling. In D1 and D5, crashes decreased but not as much as D7; they increased to near pre-pandemic levels in late 2020, after which an increasing trend can be seen.



The trend of distinct count of Report Num for Crash Date Month. Color shows details about Districts. The data is filtered on S4 Crash 1, which keeps Angle, Rear End and Sideswipe. The view is filtered on Districts, which has multiple members selected.

Figure 5-13. Crash trends by FDOT District, 2017–2022

Crash frequency normalizes crashes, as it averages them by number of years. Figure 5-14 shows that the highest crash frequency was in D7 and the lowest was in D5. Hillsborough Avenue (US-92) had the highest crash frequency in D7. These performance metrics will be compared in the "after" study.



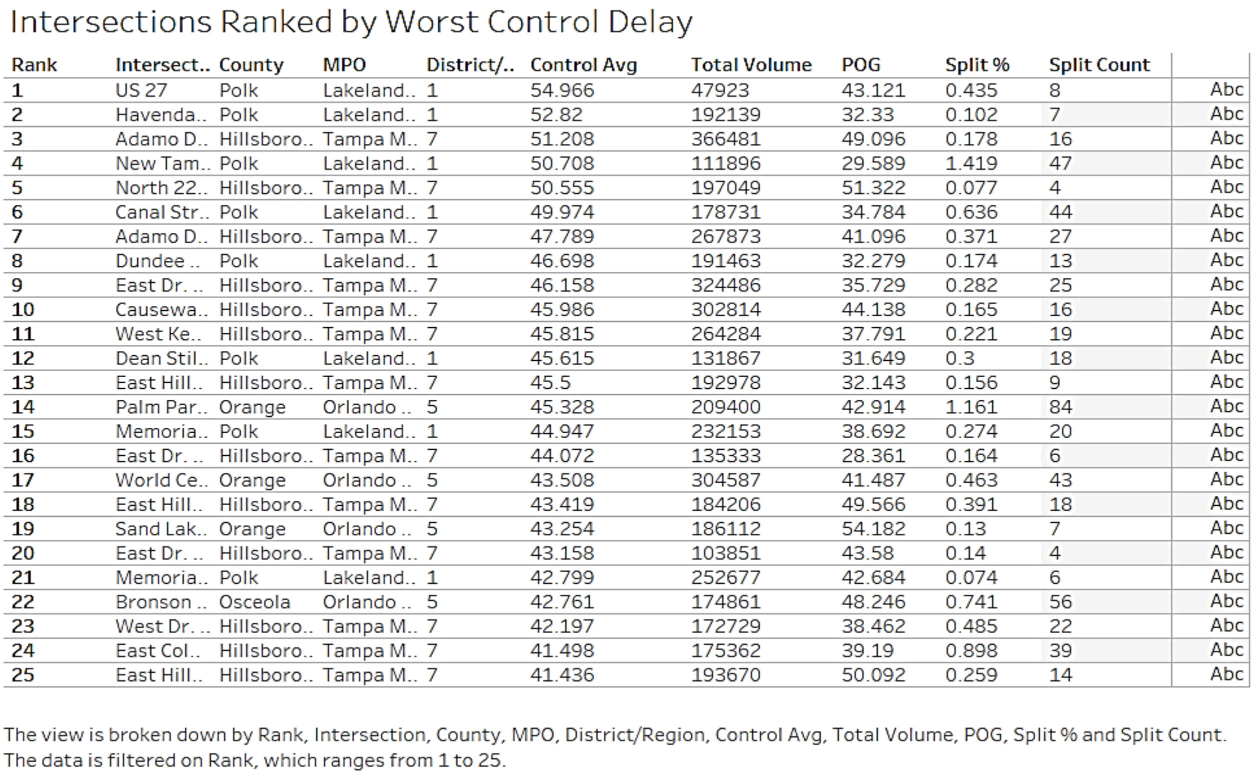
Crash Frequency for each Main broken down by Districts. Color shows details about Districts. The data is filtered on S4 Crash 1, which keeps Angle, Rear End and Sideswipe. The view is filtered on Districts, which has multiple members selected.

Figure 5-14. Crash frequency by main road and FDOT District, 2017–2022

5.6.4 Mobility Analysis

5.6.4.1 Ranked Intersection Locations

Figure 5-15 and Figure 5-16 show intersections ranked by control delay for the AM and PM peak hours of traffic for June 2022. As shown, the PM peak hours had higher control delays than the AM peak hours, indicating more traffic during that time period, which is reflected in total volume as well.

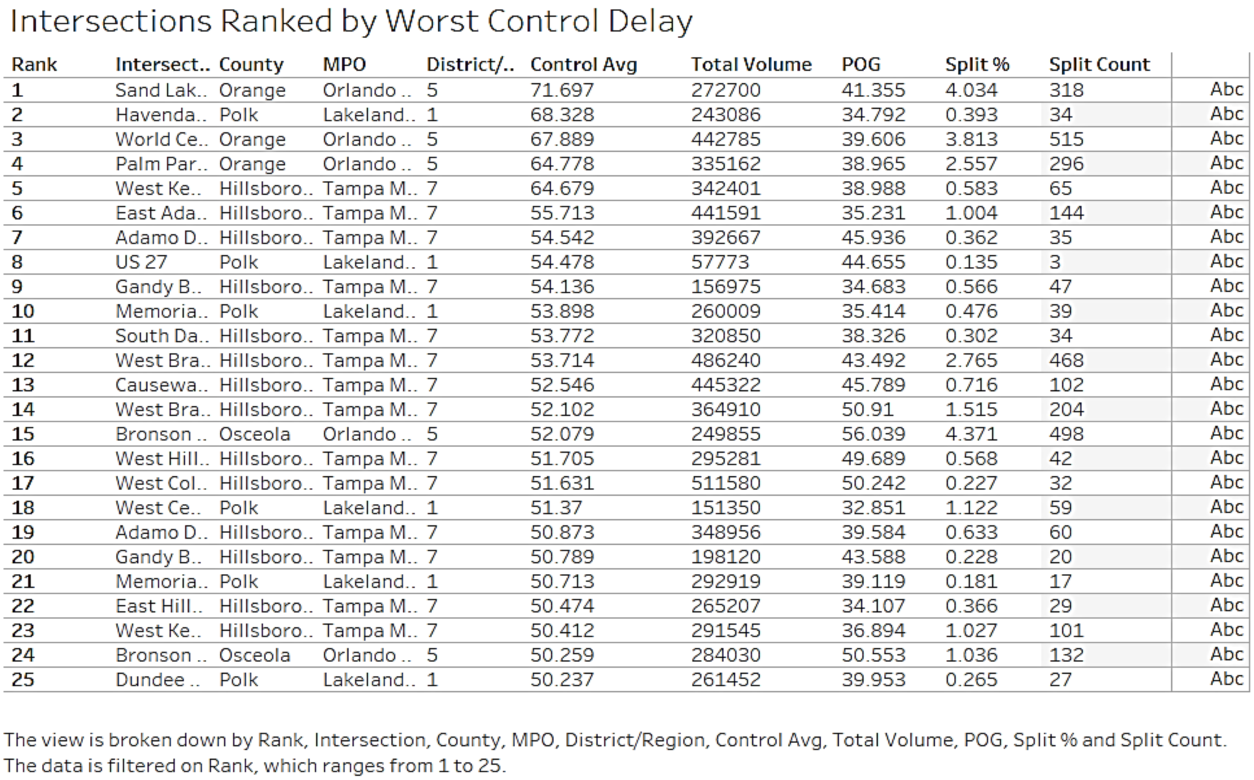


Intersections Ranked by Worst Control Delay

Rank	Intersect..	County	MPO	District/..	Control Avg	Total Volume	POG	Split %	Split Count	
1	US 27	Polk	Lakeland..	1	54.966	47923	43.121	0.435	8	Abc
2	Havenda..	Polk	Lakeland..	1	52.82	192139	32.33	0.102	7	Abc
3	Adamo D..	Hillsboro..	Tampa M..	7	51.208	366481	49.096	0.178	16	Abc
4	New Tam..	Polk	Lakeland..	1	50.708	111896	29.589	1.419	47	Abc
5	North 22..	Hillsboro..	Tampa M..	7	50.555	197049	51.322	0.077	4	Abc
6	Canal Str..	Polk	Lakeland..	1	49.974	178731	34.784	0.636	44	Abc
7	Adamo D..	Hillsboro..	Tampa M..	7	47.789	267873	41.096	0.371	27	Abc
8	Dundee ..	Polk	Lakeland..	1	46.698	191463	32.279	0.174	13	Abc
9	East Dr. ..	Hillsboro..	Tampa M..	7	46.158	324486	35.729	0.282	25	Abc
10	Causewa..	Hillsboro..	Tampa M..	7	45.986	302814	44.138	0.165	16	Abc
11	West Ke..	Hillsboro..	Tampa M..	7	45.815	264284	37.791	0.221	19	Abc
12	Dean Stil..	Polk	Lakeland..	1	45.615	131867	31.649	0.3	18	Abc
13	East Hill..	Hillsboro..	Tampa M..	7	45.5	192978	32.143	0.156	9	Abc
14	Palm Par..	Orange	Orlando ..	5	45.328	209400	42.914	1.161	84	Abc
15	Memoria..	Polk	Lakeland..	1	44.947	232153	38.692	0.274	20	Abc
16	East Dr. ..	Hillsboro..	Tampa M..	7	44.072	135333	28.361	0.164	6	Abc
17	World Ce..	Orange	Orlando ..	5	43.508	304587	41.487	0.463	43	Abc
18	East Hill..	Hillsboro..	Tampa M..	7	43.419	184206	49.566	0.391	18	Abc
19	Sand Lak..	Orange	Orlando ..	5	43.254	186112	54.182	0.13	7	Abc
20	East Dr. ..	Hillsboro..	Tampa M..	7	43.158	103851	43.58	0.14	4	Abc
21	Memoria..	Polk	Lakeland..	1	42.799	252677	42.684	0.074	6	Abc
22	Bronson ..	Osceola	Orlando ..	5	42.761	174861	48.246	0.741	56	Abc
23	West Dr. ..	Hillsboro..	Tampa M..	7	42.197	172729	38.462	0.485	22	Abc
24	East Col..	Hillsboro..	Tampa M..	7	41.498	175362	39.19	0.898	39	Abc
25	East Hill..	Hillsboro..	Tampa M..	7	41.436	193670	50.092	0.259	14	Abc

The view is broken down by Rank, Intersection, County, MPO, District/Region, Control Avg, Total Volume, POG, Split % and Split Count.
The data is filtered on Rank, which ranges from 1 to 25.

Figure 5-15. Top 25 intersections with worst control delay during AM peak hours



Intersections Ranked by Worst Control Delay

Rank	Intersect..	County	MPO	District/..	Control Avg	Total Volume	POG	Split %	Split Count	
1	Sand Lak..	Orange	Orlando ..	5	71.697	272700	41.355	4.034	318	Abc
2	Havenda..	Polk	Lakeland..	1	68.328	243086	34.792	0.393	34	Abc
3	World Ce..	Orange	Orlando ..	5	67.889	442785	39.606	3.813	515	Abc
4	Palm Par..	Orange	Orlando ..	5	64.778	335162	38.965	2.557	296	Abc
5	West Ke..	Hillsboro..	Tampa M..	7	64.679	342401	38.988	0.583	65	Abc
6	East Ada..	Hillsboro..	Tampa M..	7	55.713	441591	35.231	1.004	144	Abc
7	Adamo D..	Hillsboro..	Tampa M..	7	54.542	392667	45.936	0.362	35	Abc
8	US 27	Polk	Lakeland..	1	54.478	57773	44.655	0.135	3	Abc
9	Gandy B..	Hillsboro..	Tampa M..	7	54.136	156975	34.683	0.566	47	Abc
10	Memoria..	Polk	Lakeland..	1	53.898	260009	35.414	0.476	39	Abc
11	South Da..	Hillsboro..	Tampa M..	7	53.772	320850	38.326	0.302	34	Abc
12	West Bra..	Hillsboro..	Tampa M..	7	53.714	486240	43.492	2.765	468	Abc
13	Causewa..	Hillsboro..	Tampa M..	7	52.546	445322	45.789	0.716	102	Abc
14	West Bra..	Hillsboro..	Tampa M..	7	52.102	364910	50.91	1.515	204	Abc
15	Bronson ..	Osceola	Orlando ..	5	52.079	249855	56.039	4.371	498	Abc
16	West Hill..	Hillsboro..	Tampa M..	7	51.705	295281	49.689	0.568	42	Abc
17	West Col..	Hillsboro..	Tampa M..	7	51.631	511580	50.242	0.227	32	Abc
18	West Ce..	Polk	Lakeland..	1	51.37	151350	32.851	1.122	59	Abc
19	Adamo D..	Hillsboro..	Tampa M..	7	50.873	348956	39.584	0.633	60	Abc
20	Gandy B..	Hillsboro..	Tampa M..	7	50.789	198120	43.588	0.228	20	Abc
21	Memoria..	Polk	Lakeland..	1	50.713	292919	39.119	0.181	17	Abc
22	East Hill..	Hillsboro..	Tampa M..	7	50.474	265207	34.107	0.366	29	Abc
23	West Ke..	Hillsboro..	Tampa M..	7	50.412	291545	36.894	1.027	101	Abc
24	Bronson ..	Osceola	Orlando ..	5	50.259	284030	50.553	1.036	132	Abc
25	Dundee ..	Polk	Lakeland..	1	50.237	261452	39.953	0.265	27	Abc

The view is broken down by Rank, Intersection, County, MPO, District/Region, Control Avg, Total Volume, POG, Split % and Split Count.
The data is filtered on Rank, which ranges from 1 to 25.

Figure 5-16. Top 25 intersections with worst control delay during PM peak hours

5.7 Transit Signal Priority (PT09)

5.7.1 Application Description and Objectives

According to the Concept of Operations [78], TSP is a CV application that uses CV data to improve the operating performance of transit vehicles by reducing the time spent stopped at a red light. An RSU receives a request from transit vehicle OBU when the vehicle has a schedule deviation that needs to be corrected. The RSU validates the request and sends it to the controller, which then implements the TSP.

Specific objectives of the “before” phase of the project included:

- Selection of fixed-route bus corridors traversing the RSU-equipped intersections where the TSP application will be deployed (anticipated to be in FDOT D7)
- Collection of fixed-route transit data securely and efficiently from the General Transit Feed Specification (GTFS); emphasis is placed on achieving the desired data granularity to support future (after) analysis
- Performance of data structuring, sorting, and cleaning to establish required performance measures
- Analysis of corridor-level travel time and travel-time reliability along with bus arrival time deviations for the “before” TSP deployment phase

- Report findings and share data with evaluation team and USDOT

5.7.2 Deployment Locations and Datasets

Figure 5-17 shows the location of the planned RSU-equipped intersections that will deploy the TSP application. Four bus routes are deployed in this area that serve bi-directional trips—routes 55, with 99 bus stops and 13 RSUs to be deployed; 56, with 82 bus stops and 2 RSUs to be deployed; 304, with 125 bus stops and 4 RSUs to be deployed; and 350, with 33 bus stops and 1 RSU to be deployed. Based on RSU location, the TSP application will impact a total of 79 stops.

Data were obtained either through direct request to FDOT or from available online resources. Representatives of FDOT D5 provided Application Programming Interface (API) access to the historical GTFS-Real Time (GTFS-RT) feed within the Regional Integrated Corridor Management System (R-ICMS). Key performance measures derived from the raw GTFS data included travel time reliability/index, on-time performance, punctuality, and schedule deviations at the route and corridor levels (two or more successive stops).

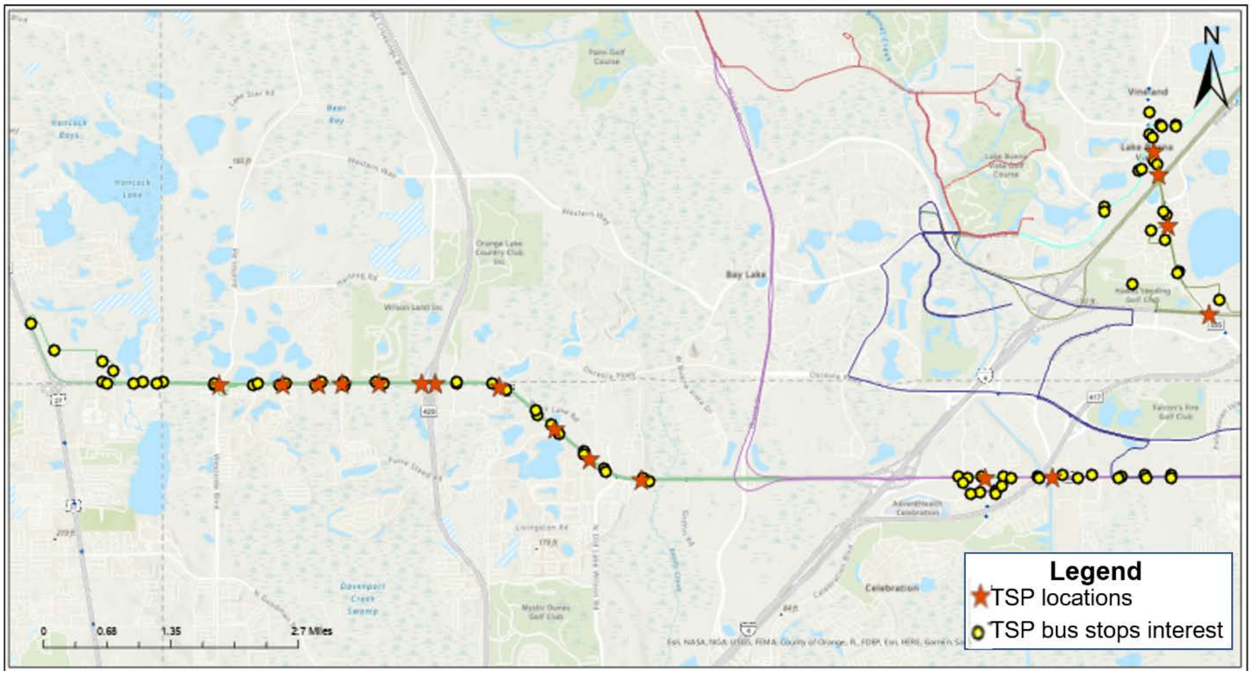


Figure 5-17. TSP deployment locations and nearest bus stops

Source: ConOps[78]

For more detailed information on TSP deployment locations, data collection, and analysis, see Task 2, Supplemental Report 1, Transit Signal Priority (PT09).

5.7.3 Analysis and Results

As part of the I-4-FRAME deployment, the TSP application is proposed to be implemented at 17 RSU-equipped intersections, all in FDOT District 5. Various continuous raw data elements that consist of trip-level and vehicle-level datasets were obtained via R-ICMS API to perform analyses. The analysis was conducted at the route and corridor levels to assess existing public transit performance within the study area. The route-level analysis, due to observed differences in intra-day traffic conditions, was divided into four or more periods to reflect conditions—early morning (5:00–8:00 AM), morning (8:00 AM–12:00 PM), noon (12:00–4:00 PM), afternoon (4:00–6:00 PM), and evening (6:00–11:00 PM).

Overall, the "before" analysis found that there are corridors that require optimization of on-time bus performance within the four routes. Results from the trip-level assessment showed that trips for routes 55 and 56 end earlier than their planned schedules. In general, across the four bus routes of interest, trips occurring during the morning and noon times were observed to be behind the fixed schedule, whereas trips occurring in the early morning, afternoon, and evening were ahead. The corridor-level analysis identified specific segments (i.e., corridors) and times within the fixed routes where the potential deployment of the TSP application might be more warranted and effective.

5.8 Intersection Safety Warning and Collision Avoidance (VS13)

The Intersection Warning and Collision Avoidance application will send Signal Phase and Timing (SPaT) data from the RSU regarding the signal timing and geometry of an intersection to a CV approaching an instrumented signalized intersection. The vehicle uses its speed and acceleration profile, along with the signal timing and geometry information, to determine if it appears likely that the vehicle will be able to pass safely through the intersection without violating the signal or colliding with other vehicles. If the vehicle determines that proceeding through the intersection is unsafe, a warning is provided to the driver and/or collision avoidance actions are taken, depending on the automation level of the vehicle. The RSU broadcasts a TIM to alert nearby motorists of the unsafe infringement on the intersection. Objectives of the task for this application were:

- Identification of locations where Intersection Warning and Collision Avoidance application will be deployed
- Collection of historical intersection crashes at these locations
- Calculation of performance measures for these locations and along the corridor

5.8.1 Deployment Locations

This Intersection Warning and Collision Avoidance application will be deployed at 402 signalized intersections on I-4 FRAME arterials, as shown in Figure 5-18.

Historical data were collected from Signal Four for a timeframe of five years (2017–2021). Data collection included the following steps: 1) create a buffer of 250-ft for each VS13 location, 2) spatially select Signal Four crashes that within VS13 buffers, and 3) filter crashes that satisfy the following criteria: a) do not occur in roadside parking lots, b) do not occur on over-head roads if near an interchange, and c) junction code in Signal Four data should be "Intersection" or "Intersection-related." In total, data for 23,742 crashes were collected for 402 VS13 locations.

The intersections at which VS13 applications will deploy overlap with TM04 applications (CV Traffic Signal system). Thus, the two applications share identical RSUs and the same mobility measures in the before-after study. Mobility data for VS13 and TM04 were retrieved from the INRIX Traffic Signal Analysis tool. Average delay, POG, and total volumes were collected at the VS13/TM04 intersections for AM peak (6:00–10:00 AM) and PM peak (3:00–7:00 PM).

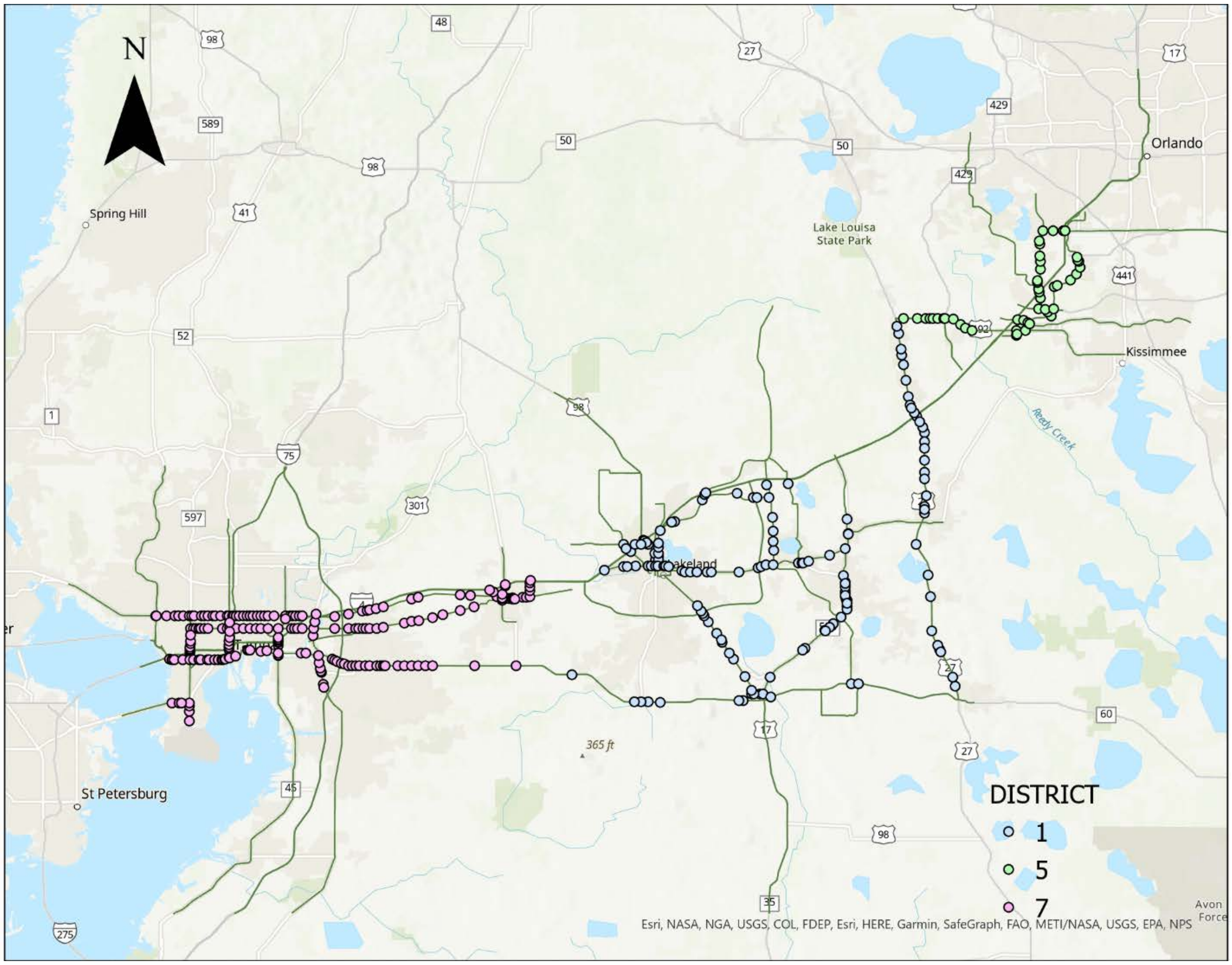


Figure 5-18. Deployment locations for Intersection Safety Warning and Collision Avoidance

Source: CUTR

5.8.2 Results

Table 5-8 presents the distributions of intersection crashes by year and severity for 2017–2021.

Table 5-8. Distribution of VS13 Crashes by Year and Severity

Year	Fatality	Injury	Serious Injury	PDO	Total
2017	6	1,255	88	3,418	4,767
2018	18	1,066	79	3,954	5,117
2019	10	1,093	50	4,105	5,258
2020	12	946	59	2,783	3,800
2021	22	1,097	55	3,626	4,800
Total	68	5,457	331	17,886	23,742

The mobility information for TM04 applications is the same as those for VS13; analysis results are shown in Figure 5-15 and Figure 5-16. For the AM and PM peak hours of traffic for June 2022, with intersections ranked by control delay.

The “before” crash and time reliability data represent the safety and mobility performance of intersections without the intersection warning and avoidance system, respectively. “Before” data will be compared to “after” data to examine the performance of the application.

5.9 Freight Signal Priority (CVO06)

5.9.1 Application Description and Objectives

According to the Concept of Operations, Freight Signal Priority (FSP) is a CV application intended to reduce stops and delays to increase travel time reliability for freight traffic, and for enhancing safety at intersections[78]. A commercial vehicle sends a request from the OBU to the RSU, and the RSU requests a priority call to the controller to grant right-of-way to the requesting vehicle. This application will be deployed along select corridors, mainly on SR-60.

A complete evaluation of the FSP application will adopt a before-after approach to assess the mobility changes observed from its deployment [75]. The main goal is to set up a baseline scenario leading to the evaluation of the FSP application. In this phase of the evaluation, focus was placed on defining the study area, data collection, analysis, and reporting on the baseline situation (“before” phase). Specific objectives of this assessment included:

- Development and execution of data collection plan along FSP deployment corridor
- Performance of data fusion, structuring, and cleaning to establish performance measures
- Assessment of route-level freight volumes, travel times, and travel-time reliability on weekdays and with respect to time of day
- Selection of a shorter corridor with higher freight data granularity and comparison with previously-determined generalized mobility performance measures
- Report on findings

5.9.2 Analysis and Results

The overall analysis performed used specific performance measures (TTI, PTI, BI, delay rate, POG, and control delay) to capture existing traffic trends during the “before” assessment of FSP deployment. The FSP application is proposed to be deployed at 64 RSU-equipped intersections. Route- and corridor-level breakdowns were adopted to assess the existing traffic conditions within the study area. A data fusion methodology was developed to append various data elements to a continuous dataset that consists of traffic and truck volumes, travel times and speeds, incidents, and geometric properties.

In general, the peak AM and PM travel periods were identified to occur between 6:00–10:00 AM and 3:00–7:00 PM. TTI distributions show varying traffic patterns by direction, corridor vs. route, and time of day. The PM peak period shows the worst average delay rate in both travel directions.

Aggregate intersection-specific measures were used to identify the top 10 intersections with low POG and high control delay. Intersections at Kennedy Boulevard, SR-39, Dale Mabry Highway, US-41, MacDill Avenue, and Lois Avenue show poor POG and control delay along the movements facilitating traffic flow through SR-60. Within the corridor, truck traffic was observed to be the highest in the EB direction. Initial results suggest that as the percentage of trucks in traffic increases, the delay rate increases. The goal was to model this relationship during the “after” assessment of the project to quantitatively define the impact of the FSP on freight travel reliability.

USDOT-recommended ranges were used for hourly travel time savings to calculate the total daily cost of travel time delays along the route. The bi-direction cost for truck operators alone was estimated to be about $100,870 per day. Overall, findings indicate the need for traffic and freight travel time improvements along SR-60, especially between 6:00 AM and 8:00 PM travel.

5.10 Advanced Railroad Grade Crossing (TM14)

The Advanced Railroad Grade Crossing application aims to leverage CV technologies to mitigate risks for motorists approaching an at-grade railroad crossing. Detection devices are used in conjunction with the RSUs in the communication process to generate TIM warnings of an approaching train. TIMs are broadcasted from the RSU to the OBU as a warning system to preclude entrance to an intersection when barriers are activated at the crossings and if a motorist is on a crash-imminent trajectory of an approaching train. Additionally, alerts via TIM warnings will be sent during to inform motorists of diversions or for extreme traffic conditions. Objectives of the task for this application were:

- Identification of locations where Advanced Railroad Grade Crossing application deploy
- Collection of historical vehicle-train crashes at identified crossings
- Calculation of performance measures for these locations and along corridor
- Report on findings

5.10.1 Deployment Locations and Datasets

The Advanced Railroad Grade Crossing application will be deployed at 26 signalized intersections near highway-rail at-grade crossings, as shown in Figure 5-19. The major roadway corridors with the application include SR-60, US-92, SR-574, US-41, SR-39A, and Park Road.

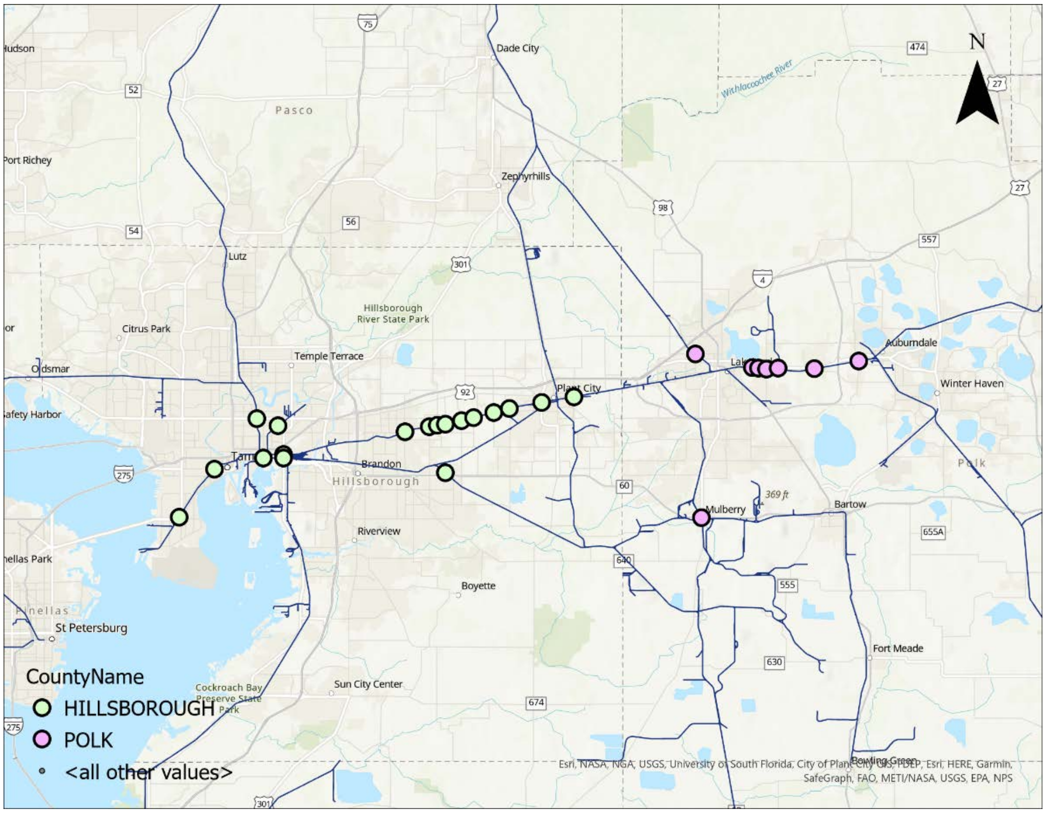


Figure 5-19. Deployment locations of Advanced Railroad Grade Crossing (TM14)

Source: CUTR

Data for vehicle-train crashes were collected from the Federal Railroad Administration (FRA) database [1]. As vehicle-train crashes at at-grade crossings are rare and random events, the timeframe of data collection was extended to 10 years (2012–2021). Data collection procedure was as follows: 1) match FRA crossing ID to TM14 application locations, and 2) retrieve vehicle-train crashes from the FRA database for each TM14 location by the matched FRA Crossing ID. Data for 18 vehicle-train crashes were collected for the 26 TM14 locations.

The TM14 application provides advance messages of extreme traffic conditions to drivers to encourage them to select alternative routes. This operation may reduce congestion and delay at signalized intersections near a rail crossing. To evaluate the impacts of TM14 applications on the mobility performance of rail crossings and adjacent intersections, mobility measures were collected from the INRIX system for the identified intersections with the applications.

INRIX mobility measures include travel time, speed, delay, and volume for each lane at an intersection. Data were collected at peak hours (morning peak—6:00–10:00 AM and afternoon peak—3:00–7:00 PM). The weighted average for the mobility measures at intersection levels were calculated using the following equation:

$$\mathbf{Weighted\ Average} = \frac{\sum(\mathbf{Measure_i} \times \mathbf{Volume_i})}{\sum \mathbf{Volume_I}} \qquad \textbf{(7)}$$

where, $\mathrm{Measure_i}$ is the mobility measure (travel time, speed, or delay) for the ith lane and $\mathrm{Volume_i}$ is the volume for the ith lane. The weight average represents the mobility performance of the whole intersection. (Note: INRIX data are unavailable for some locations.)

5.10.2 Analysis Results

Distribution of vehicle-train crashes at TM14 Locations are shown in Figure 5-20 and Figure 5-21.

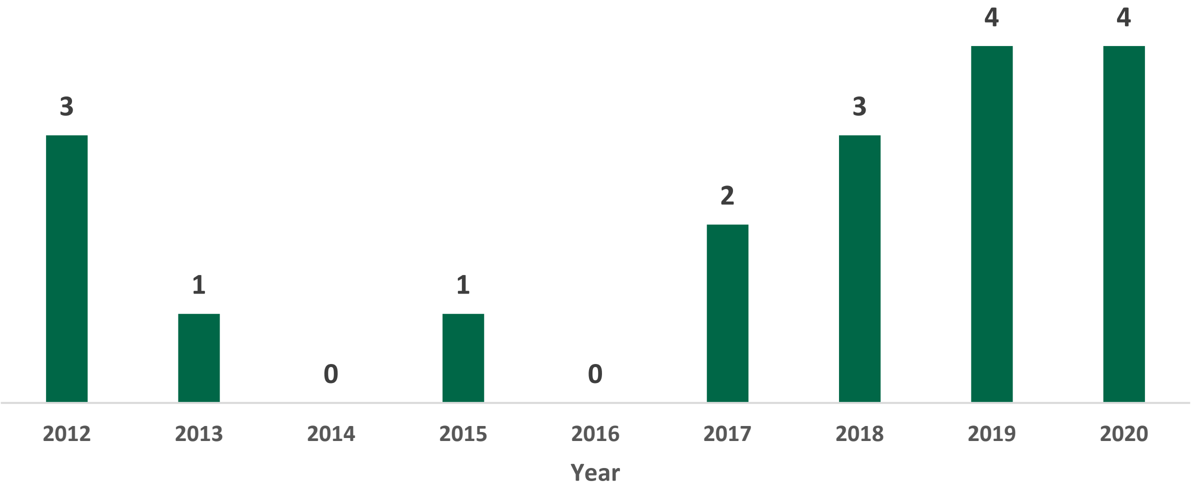


Figure 5-20. Distribution of vehicle-train crashes by year at TM14 locations

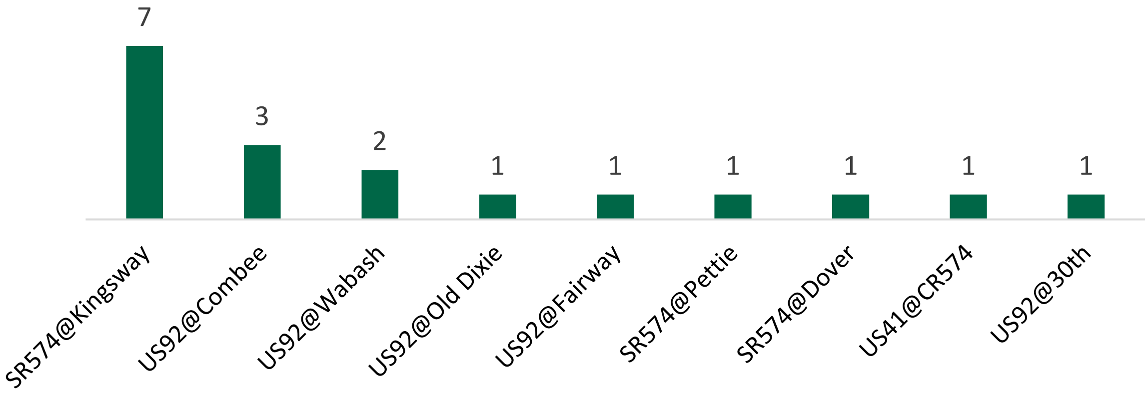


Figure 5-21. Distribution of vehicle-train crashes by site at TM14 locations, 2012–2021

The yearly average of vehicle-train crashes at TM14 locations was 18 crashes, 26 locations, and 10 years, equal to 0.069 vehicle-train crashes per location per year. The calculated mobility performance for May 2022 is shown in Table 5-9. The weight averages will be compared between "before" and "after" periods to address the impacts of TM14 applications on the mobility performance.

Table 5-9. Weighted Average Mobility Measures at TM14 Locations

Main Street	Cross Street	District	Total Volume	Weighted Average Speed (mph)	Weighted Average Control Delay (sec)	Weighted Travel Time (sec)
US 92	Fairway Ave	1	530051	47.437	5.501	14.9996
US 92	Combee Rd	1	730305	32.470	42.449	53.951
US 92	Fish Hatchery Rd	1	535780	42.177	11.949	21.389
US 92	Old Dixie Hwy	1	507252	38.378	23.059	32.721
US 92	Berkley Rd / Neptune Rd	1	808580	34.023	33.750	45.3758
SR 574	Valrico Rd	7	298346	34.769	15.491	28.312
SR 574	McIntosh Rd	7	288050	32.017	20.261	33.362
SR 574	Gallagher Rd	7	231988	35.937	15.016	26.029
SR 574	Moores Lake Rd/Dover Rd	7	254936	32.057	24.439	37.168
SR 574	Pettie Rd/Sydney Dover Rd	7	217827	20.184	14.200	26.245
SR 574	Forbes Rd	7	309481	31.938	22.394	35.270
SR 574	Turkey Creek Rd	7	289470	31.004	26.368	40.448
Park Rd	Baker St	7	698735	32.046	33.255	45.259
SR 60	St Cloud Ave	7	602057	40.650	20.285	30.045

The "before" crash and time reliability data represents the safety and mobility performance of railway crossings and connected corridors without the Advanced Railroad Grade Crossing system. The "before" data will be compared to the "after" data to examine the performance of the application.

5.11 OBU Penetration and Its Impact on Improving Safety and Mobility

5.11.1 Evaluation of OBU Penetration

The impact of OBU CV penetration rates has been evaluated by FL Polytechnic University for two applications: 1) Speed warning and enforcement (TM17) and Reduced Speed Zone Warning/Lane Closure (VS09). According to the report, the simulation results show that under heavy traffic conditions, the queue lengths build up relatively slow under VS09 compared to that observed without any implementation. Furthermore, the benefit obtained from only 20% market penetration level of OBUs is close to that observed under 100% level. On the other hand, the queue lengths under VS09 eventually catch up to those observed with no implementation. A 30% reduction in crashes was observed under VS09 and 26% under VS09 with 20% market penetration.

In addition, simulation results indicate that deployment of TM17 result in a 42% reduction in the number of crashes. Unlike the case of VS09, TM17 only provided 13%, a marginal reduction under 20% market penetration level. However, it was observed that even at 20% penetration, TM17 is successful in clearing the congestion more often than the case of no implementation

These findings suggest that there would be immediate benefit from the deployment for I-4 FRAME technologies. For further details refer to Report Deliverable 3 from FL Poly.

5.11.2 Impact of FCC Requirements and Changes for the C-V2X Band

C-V2X technology is at the vanguard of digital transformation, with the Federal Communications Commission (FCC) providing the operational spectrum, 5G Automotive Association (5GAA) members supplying the devices, and car OEMs and road operators planning commercial releases. C-V2X supports both direct (PC5/Sidelink) and mobile network-based (Uu) connections. Although cellular networks are not required to provide data transmission services in the direct mode of C-V2X, they can be used to complement end-to-end use cases [69]. Cellular network connectivity (Uu mode of C-V2X, also known as V2N) is used extensively in telematics services. Since 1996, when it initially appeared in automotive applications, its use has progressively increased across all vehicle brands and types. Over the previous three telematics design cycles, automakers have increased communication technology adoption and are rapidly reaching 100% attach rates [70]. Networked automobiles will provide features such as collision warnings, software updates, traffic and road condition updates [9]. The two modes of C-V2X function together seamlessly, as if they were on the same chipsets and platforms, which allows manufacturers to create new products with unified technology paths for improved performance and utility while also saving money [70].

In 1995, the National Transportation Safety Board (NTSB) proposed to the FCC [71] that CVs be given a dedicated spectrum, notably higher frequency bands, for transportation safety commutations. As a result, the FCC designated 75 MHz of the 5.9 GHz spectrum for intelligent transportation systems and CV technologies in 1999 [72]. In 2020, the FCC designated the upper 30 MHz of the 5.9 GHz ITS band for C-V2X technology in a Report and Order [73]. Therefore, the authorized spectrum for V2X was reduced from 75 to 30 MHz, leaving only two channels for V2X message distribution—10 MHz for DSRC and 20 MHz for C-V2x. Another factor to consider is the harmful interference of other competing technologies. Because of the new FCC spectrum limitations, the new U-NII-4 unlicensed band out-of-band emissions (OOBE) may cause interference with C-V2X transmission if they are too loud, especially from outside operations. This problem is compounded in busy city regions where Wi-Fi operations by vehicles, pedestrians, and other road users are expected.

The 5G Americas organization brings together top telecom service providers and manufacturers with the goal of promoting the advancement and full capabilities of LTE wireless technologies as well as their evolution to 5G. 5G Americas has requested 40 MHz of additional mid-band spectrum from the FCC to provide increased C-V2X capabilities and use cases. Meanwhile, the

C-V2X spectrum allocation of 30 MHz will assist transportation stakeholders significantly in terms of safety [74]. To ensure C-V2X performance in the permitted frequencies, 5G Americas has recommended that the FCC limit U-NII-4 OOBE from fixed outdoor network nodes to a maximum of -27dBM/MHz at the 5895 MHz edge [9]. 5G Americas recommends that client-to-client and mobile hotspot use of the U-NII-4 spectrum be forbidden due to a lack of isolation to safeguard C-V2X OBU receivers [74].

5.12 Security Credential Management System (SCMS) Impact Analysis

5.12.1 Introduction

CV technology has the potential to improve transportation systems regarding road capacity, congestion, energy, and safety by using DSRC, C-V2X, GPS, and other sensing technologies. This shared information can be used in several CV safety applications such as pedestrian alerts, vehicle collision warnings, and hazard warnings. However, it is critical for a CV system to have a trusted message sender and trustworthy messages. Concerns about cybersecurity and privacy grow as the topology of communication gets complex. In this regard, USDOT decided to implement a Security Credential Management System (SCMS) to effectively manage communication security for the CV deployments.

The SCMS is a proof-of-concept message security solution for V2V and V2I communication. It uses a Public Key Infrastructure (PKI)-based approach and certificate management algorithm to facilitate trusted communication. The PKI is a well-known encryption method that has been widely deployed in cybersecurity applications and basically impossible to decipher without accessing to the private key stored in the local devices. Authorized system participants use digital certificates issued by the SCMS to authenticate and validate the safety and mobility messages that form the foundation for connected vehicle technologies. To protect the privacy of vehicle owners, these certificates contain no personal or equipment-identifying information but serve as system credentials so that other users in the system can trust the source of each message. The SCMS also plays a key function in protecting the content of each message by identifying and removing misbehaving devices, while maintaining privacy.

5.12.2 Lessons Learned from Recent SCMS Operation with CV Pilots

According to [79], the CV Pilot programs were some of the first deployments to use devices fully connected to the SCMS. The goals of this effort were to demonstrate that the key concepts of the SCMS were feasible and that there were SCMS providers capable of meeting the certificate needs of deployed CV devices. Although successful, integration of CV Pilots devices with the SCMS has generated several lessons learned for deployment agencies, CV device vendors, and SCMS providers. The following are the most recent lessons learned from the CV Pilot deployments:

- **Issue 1: OBU Top-Off Failures** – OBUs are required to request updated certificates (periodically) while driving through a CV environment; an individual certificate is valid for only one week. An OBU may be capable of storing up to three years of certificates but depending on the deployment site may be able to obtain valid certificates only for shorter periods. Over time, the OBUs will eventually need to reach back to the SCMS to download additional certificates (this activity is known as certificate top-off). Some deployments limit the number of future weeks of certificates, necessitating more frequent top-off requests. A limited number of RSUs were provisioned within the environment to offer SCMS connection capable of supporting the top-off service. This led to situations in which many OBUs were trying to download top-off certificates from the same RSU at the same time, and some OBUs would not be able to download all of their top-off certs before exiting the RSU coverage area. The certificate download would then timeout before the OBU reached another RSU advertising an SCMS connection, creating a certificate download error and failure.

  - **Lesson Learned** – The deployer worked with the SCMS provider to troubleshoot these issues, which implemented a new auditing tool within the SCMS that logs all interactions between the device and the SCMS with error codes and timestamps. Deployment agencies should take advantage of this auditing tool to help them troubleshoot download requests if they are having these types of issues within their environment. Additionally, the IEEE 1609 Working Group is developing a more formal technical solution within IEEE 1609.13, Reliable Data Transport Mechanisms for Multiple Receivers. These issues were observed primarily in RSU-sourced download requests, and deployment agencies may want to consider other methods for downloading certificates if they are available.

- **Issue 2: Certificate Download Deactivation** – A network issue in one deployment site resulted in CV devices not connecting to the SCMS for a few weeks. The SCMS expected devices to connect and request certificates at least once within a two-week period. The failure to do so for this deployment triggered a deactivation feature within the SCMS; when those devices network connections were restored, the SCMS denied their requests for new certificates.

  - **Lesson Learned** – The SCMS provider updated the deactivation configuration to permit an OBU to remain dormant for a longer period. Where operationally possible, and where the security risk is low, it is better for devices to download more than a few weeks of certificates at a time.

- **Issue 3: RSU Application Certificate Top-off** – A likely network issue was causing RSUs to request new application certificates and the SCMS would then generate the new application certificates and post them for the RSU to download. The RSU would fail to receive the initial response from the SCMS and would then request a second set application certificates, which violated an internal SCMS policy that limits the number of certificates an RSU can request in a two-week period.

  - **Lesson Learned:** The SCMS provider updated its backend system and would respond with the initial set of application certificates generated if the RSU had not downloaded those certificates yet. This was likely a common real-world networking issue that this fix will hopefully resolve moving forward.

- **Issue 4: Enrollment Certificate Expiration** – A few vendors have requested enrollment certificates with only a 75-day validity period. The vendors will then ship devices, but they will not be installed and operated until the 75-day period has elapsed, which results in all future certificate requests being denied. This currently requires devices to start the enrollment process from the beginning, which can usually be accomplished only by the vendor.

  - **Lesson Learned:** A vendor provided an example script for creating enrollment requests, which used a 75-day validity period. It is likely vendors are copying this script without changing the validity period included in the example. Vendors should set their validity period to more operationally realistic periods (e.g., 3 years) or support a re-enrollment mechanism. All users should adopt, as a standard practice, reviewing all default settings and adjusting them to reflect their operational policies and expectations. At a higher level, when integrating collaboratively developed capabilities, default values should be left in place if their effect and purpose are not clearly understood.

- **Issue 5: Pseudonym Certificate Authority (PCA) Certificate Validity Issue** – Due to decisions made during the original CAMP-led SCMS activities, the PCA was designed with a shorter validity period to minimize security risks. The PCA is the certificate authority that generates all of the pseudonym certificates that the OBUs will use to sign their BSMs. The PCA will expire in roughly January 2023. Many OBUs request pseudonym certificates for three full years, causing an issue when requesting three years' worth of certificates after January 2020.

  - **Lesson Learned** – The SCMS vendor has developed a patch to be deployed by 2022. Currently, the SCMS has been updated to generate certificates only through January 2023. After the new PCA Certificate is in place and the patch is applied, devices will again be able to request three years of certificates. Moving forward the decision for how long the validity periods are for the different certificate authorities will reside with the SCMS Manager and will be subject to vote by the SCMS Manager voting members.

- **Issue 6: Local Certificate Chain File (LCCF) Implementation** – On August 5, 2020, an SCMS provider created a new Enrollment Certificate Authority (ECA) and PCA due to the situation described in Issue 5. When this was implemented operationally, a new LCCF was provided to all devices that connected to the SCMS that listed the new ECA and PCA as trusted certificate authorities. Most RSUs have two weeks of certificates; during the week of August 19, 2020, the RSUs started signing their messages with certificates from the new PCA. When this occurred, the OBUs were no longer able to use the RSU's advertised services because they no longer trusted the certificate authority that created the certificates. This was due to issues with the way the OBUs processed the new LCCF file.

- **Lesson Learned**: Device vendors and deployment agencies should ensure that the processing of the ancillary files associated with the SCMS, such as the LCCF, are tested fully. Vendors also should stay up to date on software updates for applications and libraries within their device. In some instances, these LCCF processing issues were already addressed in a previous software update that was not on applied to the effected OBUs.

The above issues were presented during the deployment of the three CV Pilots funded by USDOT. All issues were resolved, and measures were taken to inform future deployments as well as the SCMS authority for their resolutions.

5.12.3 FDOT SCMS Plan

FDOT is actively participating in the development of CAV technologies and the implementation of SCMS. In the implementation plan, the FDOT Central Office and FDOT Districts hold the distribution of SCMS certificates of CAVs. Other project stakeholders, including generic CAV stakeholders (CAV equipment providers) and travelers, will operate the SCMS devices with appropriate permission. Figure 5-22 shows the information flow between the stakeholders.

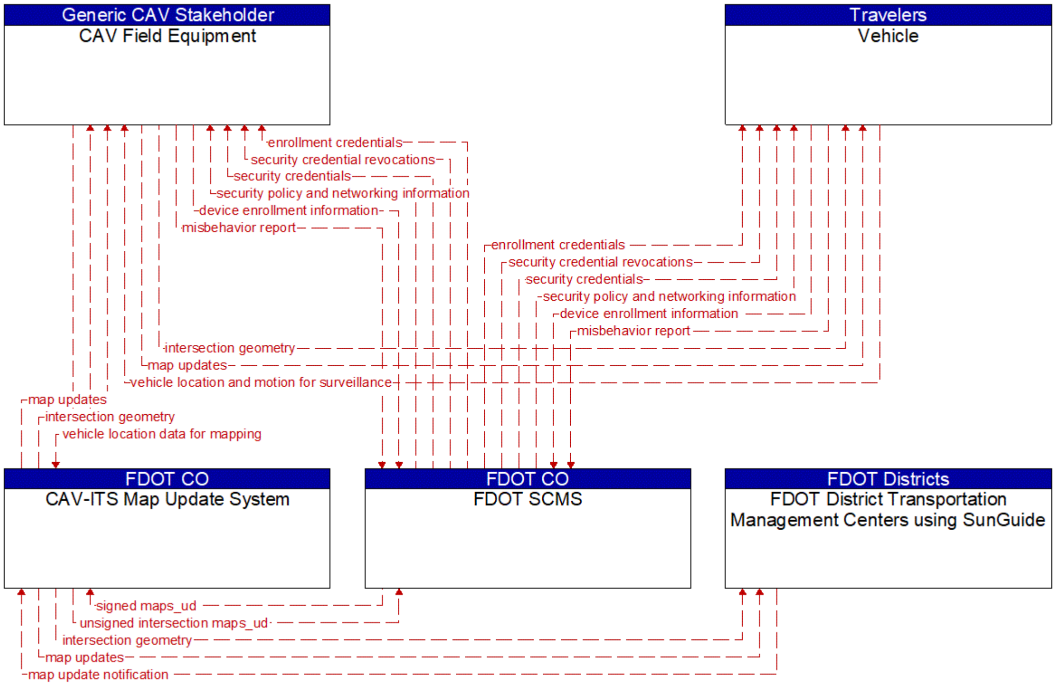


Figure 5-22. SCMS flow between stakeholders

5.12.4 Implementation

SCMS may be deployed in the I-4 FRAME as follows:

- Deploy SCMS at RSUs on I-4 to protect infrastructure information safety.
- Deploy SCMS at OBUs of fleet vehicles.

5.12.4.1 Benefits

The SCMS provides several benefits to different stakeholders, including:

- Integrity – messages are not modified between senders and receivers
- Authenticity – messages originate from a trustworthy and legitimate source
- Privacy – user privacy is well-protected
- Interoperability – different vehicle makes and models will be able to talk to each other and exchange trusted data without pre-existing agreements or altering vehicle designs

5.13 Implication of CARMA and Impact of Deployment in Project Corridor

5.13.1 Introduction

The Cooperative Automation Research for Mobility Applications (CARMA) is an initiative led by FHWA to enable collaboration for research and development of cooperative driving automation (CDA). The overarching purpose of CARMA is to transform transportation and improve efficiency and safety through automated vehicles working together and with roadway infrastructure.

CARMA is open-source software (OSS) that enables researchers and engineers to develop and test their CDA features. Figure 5-23 shows the CARMA eco-system product suite. The goal is to enable automated vehicles to interact with roadway infrastructure including but not limited to the vehicles, traffic signals, and people with mobile phones. These technologies will benefit the roadway system and potentially improve safety and mobility on the project corridor.

Figure 5-23. CARMA product suite

Source: FHWA

The CARMA eco-system has four components—CARMA Platform, CARMA Messenger, CARMA Streets, and CARMA Cloud. Collectively, CARMA enables cooperative driving automation at four different classes of cooperation specified in the Society of Automotive Engineers (SAE) 3216 standard as—status-sharing (Class A), intent-sharing (Class B), agreement-seeking (among CDA vehicles) (Class C), and prescriptive (Class D).

5.13.2 Deployment

This section explains various interfaces within CARMA and how they potentially could be deployed within the I-4 FRAME corridor.

5.13.2.1 CARMA Platform

CARMA Platform is a vehicle-based platform that enables cooperative automated driving research (C-ADS). It enables automated vehicles to interact with the roadway systems and elements through the CARMA product suite, including CARMA Cloud and real-time traffic data.

CARMA Platform can be leveraged to use algorithms developed in Autoware and facilitate research on cooperative behavior. It can be equipped on the fleet of FDOT vehicles, including service vehicle and transit buses. Mid-term deployment would involve FDOT partnering with external stakeholders and private fleet operators such as trucking companies, taxis, and shared mobility providers (e.g., Uber, Lyft) and deploying these technologies in their vehicles. The long-term deployment plan would be to collaborate with automobile manufacturers for this technology to be deployed in passenger vehicles. The I-4 FRAME project can be an excellent testbed for deploying CARMA Platform and testing the benefits in terms of mobility and safety. With vehicle cooperation, there will be fewer accidents, which will lead to improved travel time, reduced congestion, and other mobility benefits.

Figure 5-24 shows a CARMA Platform in a passenger vehicle, with the screens showing the surrounding view that the sensors are capturing through Autoware. Currently, CARMA Platform operates as an SAE C-ADS Level 3 Class A–D, as defined by the SAE J3216 Standard.

Figure 5-24. CARMA Platform-equipped vehicle

Source: FHWA

5.13.2.2 CARMA Messenger

CARMA Messenger is a vehicle-based application designed for non-automated or traditional vehicles to participate in cooperative driving. The transportation system in the foreseeable future will be heterogeneous traffic consisting of both human-driven and automated vehicles with different levels of automation. CARMA Messenger was developed for manual vehicles operating at SAE CDA Level 0-2 Class A–B. CARMA Messenger will enable these vehicles to communicate with other participants in the CARMA eco-system through a device such as an OBU or through cellular networks that will transmit safety or alert messages and share data with other vehicles to engage in CDA.

CARMA Messenger could use a deployment strategy similar to CARMA Platform, as both are downloadable vehicle-based applications. CARMA Messenger will benefit first responders and potentially improve TSP. This also will enable FDOT to achieve its safety and mobility goals.

5.13.2.3 CARMA Streets

CARMA Streets is an infrastructure-based downloadable application that works on the infrastructure side to support CDA by engaging with other products in the CARMA product suite through communication to improve mobility, safety, and transportation system management and operation.

CARMA Streets could be deployed at intersections with high control delay or poor POG identified in previously. CARMA Streets will enable improved signal control strategies and cooperative perceptions along interchanges. The I-4 FRAME project potentially could be beneficial to test “before” and “after” conditions.

5.13.2.4 CARMA Cloud

CARMA Cloud is an OSS service that is downloadable and cloud-based and enables communication and cooperation among different elements in the transportation system and cloud services. CARMA Cloud consists of two key components—CARMA Analytics and CARMA Command Center. CARMA Analytics facilitates data analysis and management of vehicle fleets and fusion and analysis of traditional transportation data such as speed, volume, travel time, etc. CARMA Command Center enables and supports Transportation System Management and Operations (TSMO) objectives and facilitates communication and data exchange. The Command Center module can also be used for managing multiple remote services simultaneously; for example, variable speed limits and headways could be implemented that could facilitate platooning of vehicles.

CARMA Cloud can be implemented at different TMCs across FDOT D1, D5, and D7. The advantages and use cases noted above can be implemented in each District TMC to effectively manage traffic conditions in the future.

5.13.3 Limitations

Although the CARMA product suite has many advantages, there are a few limitations:

- Cybersecurity – potentially a significant limitation; with everything connected and data being exchanged openly, cyberattacks are possible unless measures are taken to counter them.
- Cost – the initial cost of a CARMA setup could be high due to the need for additional infrastructure and components.
- Research – CARMA technology is still in the development phases, with ongoing research and evaluation in the nascent phases and demonstrations conducted recently.
- Public awareness and acceptance – the public will need to be educated about this new technology and made aware of the benefits and risks.

5.13.4 Conclusion

CARMA is a software that supports CDA, and the products work together in an eco-system that has the potential to improve safety and mobility when deployed in a corridor or city. CARMA enables communication among roadway elements, data exchange, and facilitation of TSMO. The products can be used to research the impact of cooperative driving automation across the transportation system. CARMA potentially can be implemented on the I-4 FRAME project through RSUs (e.g., for CARMA Streets), fleet vehicles (e.g., CARMA Platform, CARMA Messager), and associated TMCs. Comparing the proposed performance measures on safety, mobility, and energy after CARMA deployment with the benchmarks before deployment will yield quantitative information about the CARMA benefits.

6 Development of Predictive Analysis Methodologies

6.1 Introduction

Evaluation of the effectiveness of the I-4 FRAME technologies and applications is a critical step in the project. The before-after study, which will compare safety and mobility performance measures before (without I-4 applications) and after (with I-4 FRAME applications) implementation of I-4 FRAME applications, is an effective method for assessing the I-4 FRAME project. The principle of before-after studies is to compare the performance measures with and without the treatments (i.e., I-4 FRAME applications), keeping other factors consistent over the before-after stages.

This project developed prediction models for safety and mobility performance measures based on traffic and roadway data without I-4 FRAME applications. The predictive analytics covered the entire study area, including I-4, limited access routes, and arterial corridors. Completed tasks were as follows:

- Identification of data sources for data collection
- Collection of necessary data for model development
- Development of Safety Performance Functions (SPFs) for safety prediction
- Development of time reliability and delay cost projection models for mobility prediction

6.2 Development of Safety Performance Functions (SPFs)

6.2.1 Procedure for SPF Development

Crash frequency is a direct safety measure of roadway facilities and is widely used in transportation safety studies. The *Highway Safety Manual* (HSM) [80] defines SPFs to predict crash frequency based on given roadway characteristics (i.e., traffic characteristics, geometries, traffic controls). This study developed SPFs for I-4 FRAME corridors, including freeway segments and arterials, which will be used to estimate crash frequencies in the “after” period, without I-4 FRAME applications. Development of SPFs followed the procedure defined in the *FHWA Safety Performance Function Development Guide: Developing Jurisdiction-Specific SPFs* [81], as shown in Figure 6-1.

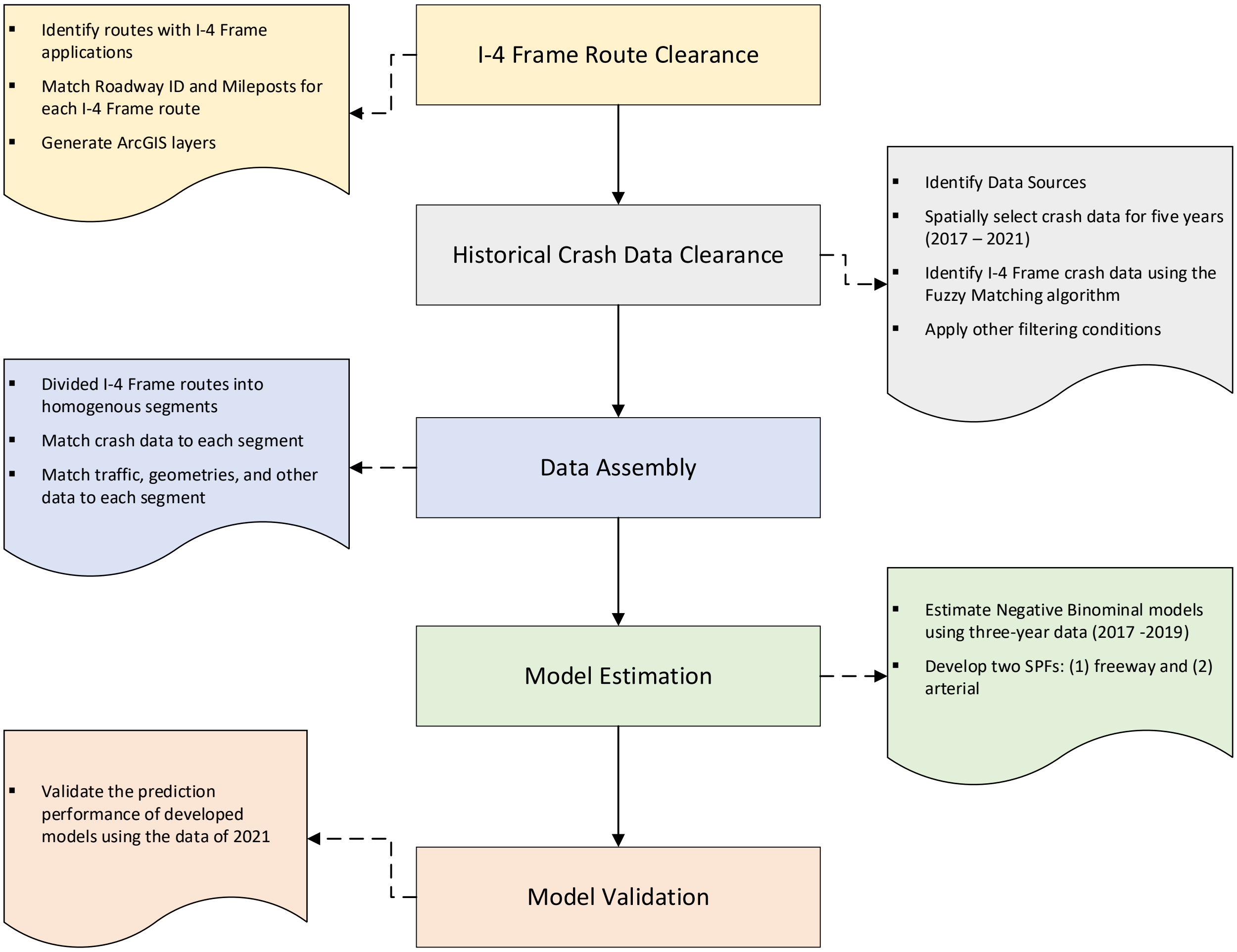


Figure 6-1. Procedure for developing I-4 FRAME safety performance functions

6.2.2 I-4 FRAME Routes Clearance

The first step in SPF development is to clear roadway routes with I-4 FRAME applications. The steps for route clearance include the following:

- **Identify I-4 FRAME routes.** The CUTR team obtained the Geographical Information Systems (GIS) layer of I-4 FRAME RSUs, which indicates the locations (coordinates) and associated I-4 FRAME applications. The CUTR team spatially joined the roadway segments (obtained from FDOT GIS layers) with the RSUs in ArcGIS. Any segments matched to one or more RSU(s) were identified as an I-4 FRAME route. Some coordinate errors in the original I-4 FRAME RSU layer were also corrected.
- **Match Roadway ID and mileposts.** For each identified I-4 route, the research team assigned the FDOT Roadway Characteristics Inventory (RCI) Roadway ID and beginning/ending mileposts to match crash and other data. Other information such as segment type (mainline or diversion route) and roadway functional classification (freeway or arterial) were also matched. Python codes were developed to conduct the

matching automatically, and the matched segments were reviewed to exclude any errors.

- **Generate GIS layer.** A GIS layer containing the identified I-4 FRAME routes with matched information was generated.

6.2.3 Historical Crash Data Clearance

6.2.3.1 Selection of Crash Data Sources

Two Florida crash databases were considered in this study—Signal Four Analytics and State Safety Office GIS (SSOGIS). Comparison of the two systems is shown in Table 6-1.

Table 6-1. Comparison of Crash Data Systems

	Signal Four Analytics	SSOGIS
Access	Permission needed	Public
Roadway types	All public roads	All public roads
Maintenance agency	University of Florida	FDOT Safety Office
Timeliness	Nightly update from FLHSMV	Fatal and serious injury crashes update weekly; other severity levels post-processed and available within 10 months
Location verification	No	Yes (verified by FDOT)
Roadway ID and milepost	No	Yes
RCI Information	No	Yes

The two crash databases were compared and showed that the crash information in SSOGIS from 2021 or later was incomplete. Thus, this study adopted Signal Four as the crash data source.

6.2.3.2 Signal Four Data Clearance

As Signal Four data do not have information on Roadway ID and milepost, the Signal Four data were cleaned by (1) spatial matching, (2) data filtering, and (3) matching Roadway ID and milepost by name.

- **Spatial matching** – A buffer of 250 ft was created for each I-4 FRAME route in ArcGIS. Signal Four crashes within the buffer were selected for further processing.
- **Data filtering** – Spatial matching may include crashes that occurred on non-road locations such as parking lots. As these crashes are not influenced by the I-4 FRAME applications, they were removed by a data field (ROAD_SYSTEM_IDENTIFIER = Parking Lots).
- **Fuzzy Matching for Roadway ID and Milepost** – The filtered crashes may contain crashes that occurred on side roads or over/under roads if near an interchange. The research team compared street names in crash data and I-4 FRAME routes to determine if the crashes occurred on I-4 FRAME routes. As street names in the Signal Four system were supplied by police officers, they were inconsistent over crashes and could be

identified as interstate, State Road, and County Road numbers or local names and their variants, so the information contains errors. It is not accurate to simply compare street names between Signal Four crashes and I-4 FRAME routes. As such, a Fuzzy matching algorithm was developed for matching, as described in Figure 6-2.

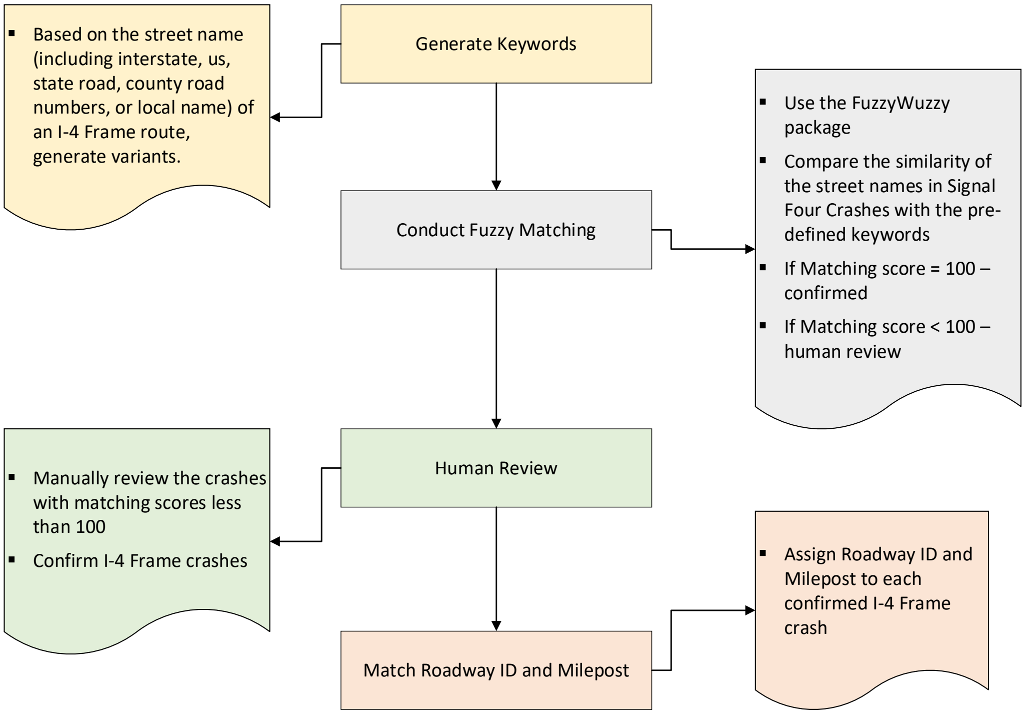


Figure 6-2. Fuzzy algorithm for street name matching

Signal Four crashes for five years (2017–2021) were identified, including 37,034 mainline crashes and 329,485 crashes on diverse routes. Figure 6-3 shows the distribution of identified crashes on I-4 FRAME routes over the five-year period.

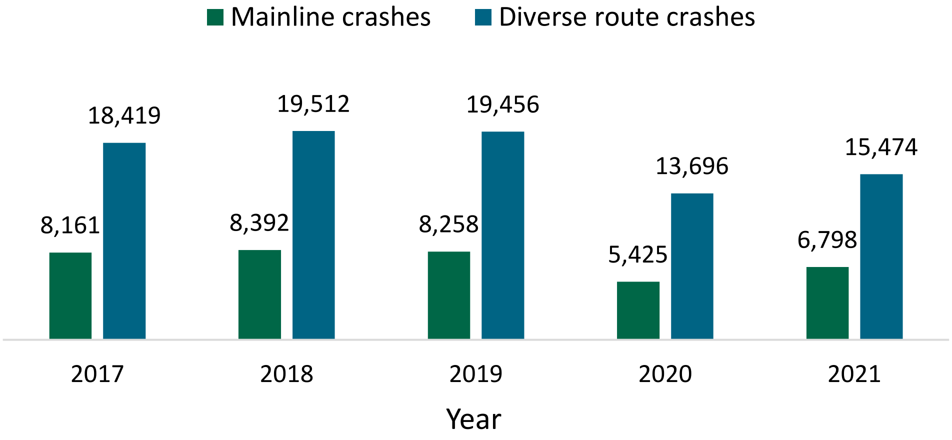
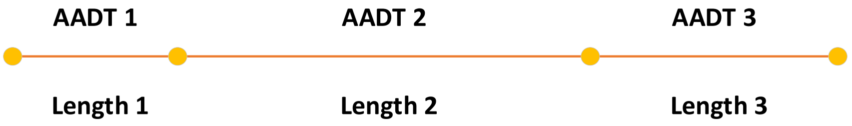


Figure 6-3. Identified I-4 FRAME crashes by year

6.2.4 Data Assembly

The I-4 FRAME routes were matched by crash data and RCI data (traffic and geometries) for modeling. As noted in the HSM, routes should be divided into homogenous sections with similar roadway characteristics within each section. However, homogenous segmentation could result in very short segments and lead to a zero-inflated issue [81]. To avoid this, the research team adopted aggregating roadway characteristics for a long segment. The weight average aggregation method is explained in Figure 6-4.



$$\text{Weighted Average AADT} = \frac{\sum(\text{AADT i } \times \text{Length i})}{\sum \text{Length i}}$$

Figure 6-4. Weighted average aggregation method

The procedure for data assembly was as follows:

- Step 1: Split I-4 FRAME routes by traffic signals (arterials) or interchanges (freeways); any splatted segments shorter than 0.1 miles were dropped.
- Step2: Calculate weighted averages of AADT, truck percentage, number of through lanes, median width, surface width, and shoulder width using the method defined in Figure 6-4.
- Step 3: Calculate the density of median openings (per mile) for arterials.
- Step 4: Identify horizontal curve presence and county.
- Step 5: Count crashes numbers for five years (2017–2021).

Datasets that contained crash and RCI data were created for modeling.

6.2.5 SPF Development

6.2.5.1 Methodology

The SPF is a Negative Binomial (NB) model that predicts expected crash frequency by given site characteristics. The equation for a SPF is as follows:

$$\boldsymbol{C = \exp\,(\beta_0 + \beta_1 LN(AADT) + \beta_2 LN(Length) + \beta X)} \qquad \textbf{(8)}$$

where C is the expected crash frequency (number of crashes per year); $LN(AADT)$ is the natural logarithm of AADT; $LN(Length)$ is the natural logarithm of length; X is the vector of other characteristics; and β_0, β_1, β_2, β are model coefficients.

The models developed in this study mainly included AADT and segment length as model inputs. Other characteristics also were considered because the overall before-after comparison will be conducted at a planning level and detailed geometric characteristics are unnecessary and the main change between the "before" and "after" stages is traffic conditions; other factors usually remain consistent.

Considering the different traffic characteristics between freeways and arterials, this study developed two models:

- SPF for freeway segments
- SPF for arterials

The STATA 17® package was used to estimate the models. The stepwise method was used to select independent variables from the collected traffic and geometric factors (i.e., AADT, truck percentage, median width, number of lanes, lane width, shoulder width, and density of median openings); only the significant variables at a 95% confidence level (p-value≤0.05) were retained in the models.

6.2.5.2 SPF for Freeway Segment

The fitted SPF for freeway segments is shown in Table 6-2.

Table 6-2. Fitted SPF for Freeway Segments

	Coefficient	**Standard Error**	***z-statistics***	***p*-value**	**[95% interval]**	
Logarithm of AADT	1.451	0.113	12.870	0.000	1.230	1.672
Logarithm of Length	0.651	0.097	6.700	0.000	0.460	0.841
Truck %	-0.082	0.021	-3.880	0.000	-0.123	-0.040
Weighted average shoulder width (ft)	-0.062	0.015	-4.050	0.000	-0.092	-0.032
Constant	-9.523	1.253	-7.600	0.000	-11.978	-7.068
Dispersion factor (alpha)	0.508	0.064			0.396	0.651
Number of observations = 120						
Log likelihood = -736.327						
LR test of alpha=0: chibar2(01) = 1.2e+04 Prob >= chibar2 = 0.000						

As the model was fitted using three-years of crash data (2017–2019), the following equation was used to implement the SPF for a given freeway segment:

$$\boldsymbol{C} = \exp\left(-\mathbf{0.082} \cdot \textbf{Truck\%} - \mathbf{0.062} \cdot \textbf{Shoulder width}\right) \cdot \boldsymbol{AADT}^{1.451} \cdot \textbf{Length}^{0.651} \cdot \boldsymbol{e}^{-9.523}/\mathbf{3} \qquad \textbf{(9)}$$

The SPF (Eq. 9) was applied on the I-4 FRAME freeway segments to predict crash frequencies for 2021. Comparison of predicted and observed crash frequencies for these segments is shown in Figure 6-5. The relative difference is 5.8%.

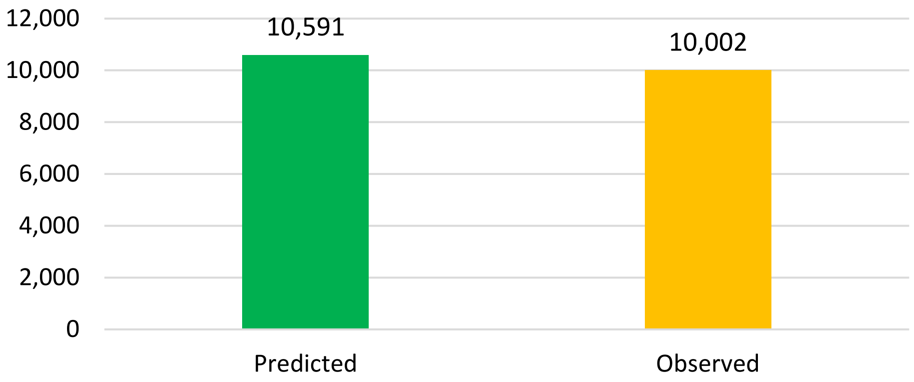


Figure 6-5. Comparison of 2021 predicted and observed crashes for I-4 FRAME freeway segments

6.2.5.3 SPF for Arterials

The fitted SPF for arterials is shown in Table 6-3.

Table 6-3. Fitted SPF for Arterials

	Coefficient	Standard Error	*z-statistics*	*p*-value	[95% interval]	
Logarithm of AADT	0.425	0.070	6.050	0.000	0.288	0.563
Logarithm of length	0.516	0.033	15.670	0.000	0.451	0.580
Density of median openings	0.033	0.005	6.540	0.000	0.023	0.042
Weighted average number of through lanes	0.064	0.034	1.880	0.060	-0.003	0.130
Hillsborough Co. (1-yes; 0-no)	0.296	0.070	4.240	0.000	0.159	0.433
Orange Co. (1-yes; 0-no)	0.737	0.128	5.740	0.000	0.485	0.989
Osceola Co. (1-yes;0-no)	0.713	0.134	5.310	0.000	0.450	0.976
Constant	-0.630	0.611	-1.030	0.302	-1.828	0.567
Dispersion factor(alpha)	0.469	0.030			0.414	0.531
Number of observations = 508						
Log likelihood = -2637.5611						
LR test of alpha=0: chibar2(01) = 1.6e+04 Prob >= chibar2 = 0.000						

As the model was fitted using three years of crash data (2017–2019), the following equation should be used to implement the SPF for a given freeway segment:

$$\boldsymbol{C} = \exp\left(\mathbf{0.033} \cdot \textbf{Density of median opennings} + \mathbf{0.064} \cdot \textbf{Weighted average number through lanes} + \mathbf{0.296} \cdot \textbf{Hillsborough} + \mathbf{0.737} \cdot \textbf{Orange} + \mathbf{0.713} \cdot \textbf{Osceola}\right) \cdot \boldsymbol{AADT}^{\mathbf{0.425}} \cdot \textbf{Length}^{\mathbf{0.516}} \cdot \boldsymbol{e}^{-\mathbf{0.630}}/\mathbf{3} \qquad \textbf{(10)}$$

The SPF (Eq. 10) was applied on the I-4 FRAME arterial segments to predict crash frequencies for 2021. Comparison of predicted and observed crash frequencies are shown in Figure 6-6. The relative difference is 0.76%.

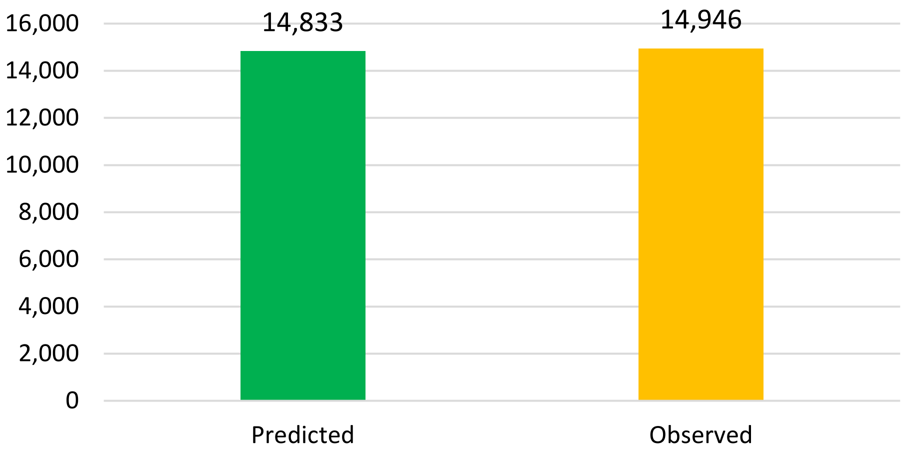


Figure 6-6. Comparison of 2021 predicted and observed crashes for I-4 FRAME arterial segments

6.3 Development of Mobility Comparison Methods

6.3.1 Performance Measures for Roadway Operations

Numerous performance measures can be used for analyzing roadway capacity and operational performance; travel time and volume data are generally required and used to compute these parameters. The following measures were used to characterize roadway mobility for the purpose of this study:

- **Buffer Index (BI)** – as described in Section 4.4.2
- **Planning Time Index (PTI)** – as described in Section 4.4.2
- **Travel Time Index (TTI)** – as described in Section 4.4.2
- **Vehicle Hours Traveled (VHT)** – defined as the time spent by vehicles on a roadway facility during the study period (i.e., one year); calculation of annual VHT is:

$$\textbf{Yearly } \boldsymbol{VHT} = \boldsymbol{AADT} \times \frac{\textbf{Hourly Average Travel Time (in minutes)}\times \mathbf{24}}{\mathbf{60}} \times \mathbf{365} \qquad \textbf{(11)}$$

- **Total Delay** – difference between free-flow travel time and observed travel time multiplied by AADT, adjusted by a day-of-the-week factor; it is the raw speed drop weighted by the VMT factor. Annual total delay is calculated by

$$\textbf{Total Yearly Delay} = \boldsymbol{VHT} - (\boldsymbol{AADT} \times \textbf{Hrly Ref Travel Time (min)} \times \mathbf{24} \times \frac{\mathbf{365}}{\mathbf{60}}) \qquad \textbf{(12)}$$

6.3.2 Estimation Methods for Total Delay

It is assumed that travel time along an I-4 FRAME route will be impacted by I-4 FRAME applications. Thus, time reliability measures (BI, PTI, TTI), as indicators of travel time quality, could be directly compared to capture the impacts of I-4 FRAME applications on travel time in a before-after study.

Total delay is a function of travel volume and travel time. Comparison of total delay in a "before" study needs to consider the influence of the variation of traffic volumes in the "after" years. The estimation of annual total delay in future years assuming without I-4 FRAME applications is:

$$\textbf{Future Total Delay without applications} = \left(\textbf{Future } \boldsymbol{AADT} \times \textbf{Hourly Travel Time in Base Years (in min)} \times 24 \times \frac{365}{60}\right) - \left(\textbf{Future } \boldsymbol{AADT} \times \textbf{Hourly Ref Travel Time in Base Years (in min)} \times 24 \times \frac{365}{60}\right) \quad \textbf{(13)}$$

Annual total delay in the after stage with I-4 FRAME applications can be calculated by:

$$\textbf{Future Total Delay with applications} = \left(\textbf{Future } \boldsymbol{AADT} \times \textbf{Future Hourly Travel Time (in min)} \times 24 \times \frac{365}{60}\right) - \left(\textbf{Future } \boldsymbol{AADT} \times \textbf{Future Hourly Ref Travel Time (in min)} \times 24 \times \frac{365}{60}\right) \quad \textbf{(14)}$$

Comparison of total delay can be the difference between future total delay without applications and future total delay with applications.

6.3.3 "Before" Mobility Data Preparation

The procedure for mobility data preparation is shown in Figure 6-7.

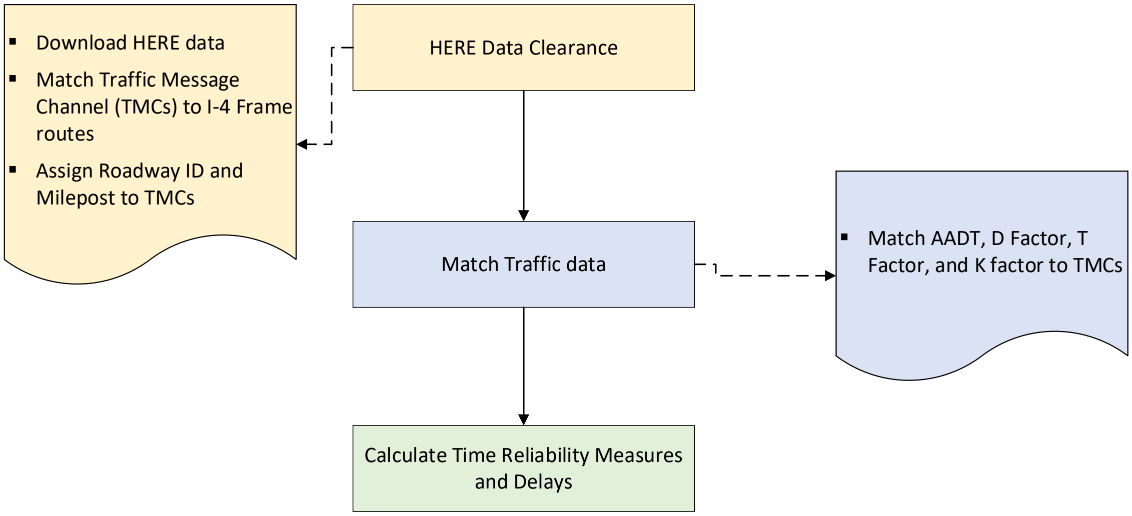


Figure 6-7. Procedure for "before" mobility data preparation

6.3.3.1 Perform HERE Data Clearance

HERE data provide operational data for both freeways and arterials and include:

- **Speed** – current estimated harmonic mean speed for the roadway segment in miles per hour
- **Reference Speed** – calculated "free flow" mean speed for a roadway segment in miles per hour; calculated based on the 85th-percentile point of the observed speeds on that segment for all time periods, which establishes a reliable proxy for the speed of traffic at free-flow for that segment

- **Travel Time** – time it will take to drive along a roadway segment (distance traveled / speed)

HERE data were used to calculate time reliability measures and total delays in the "before" study. Raw HERE data were downloaded from RITIS, which uses a Traffic Message Channel (TMC[1]) to indicate a roadway segment (by direction).

Data fields in the raw HERE data include the following:

- **data source** – data set of record; included only in Massive Data Downloader exports when choosing to merge data sets into a single CSV file
- **tmc** – unique 9-digit value identifying TMC[1] segment
- **road** – route number or common name of roadway
- **direction** – overall direction of roadway
- **intersection** – cross street and/or interchange associated with TMC[1] segment
- **state** – postal abbreviation of state to which TMC[1] segment is assigned
- **miles** – length of TMC[1] segment
- **road order** – numerical value indicating in what order the TMC[1] segment would be encountered when traveling downstream relative to other TMC[1] segments on same road
- **start latitude** – latitude of beginning of TMC[1] segment
- **start longitude** – longitude of beginning of TMC[1] segment
- **end latitude** – latitude of end of TMC[1] segment
- **end longitude** – longitude of end of TMC[1] segment
- **tmclinear** – reference to Linear TMC[1] that includes TMC[1] segment; Typically, several TMC[1] segments are part of a Linear TMC[1], which usually represents a road corridor through a single county; the purpose of this column is to provide assistance for filtering and locating TMC[1] segments and simplifying the process of linking consecutive TMC[1] segments
- **type** – type of TMC[1] code—P1 is typical TMC[1] code; P3 indicates national, state, and county boundaries, rest areas, toll plazas, major bridges, etc.; P4 is for ramps.
- **county** – county in which TMC[1] segment located

HERE data were organized by channel, which indicates a unique road segment by direction. As HERE data do not include FDOT RCI Roadway ID and mileposts, each TMC was matched to I-4 FRAME routes. The matching steps are as follows:

- **Step 1 – Generate TMC starting and ending layers**: HERE data provide the coordinates for the starting and ending of each TMC. The research team imported TMC beginnings and endings into ArcGIS as point feature layers.
- **Step 2 – Linear reference**: The research team used the Linear Reference function in ArcGIS to locate TMC beginnings and endings along the nearest I-4 FRAME route. The Roadway ID and milepost were also produced for each TMC beginnings and endings.
- **Step 3 – Review**: The matched TMCs and I-4 FRAME routes were verified by reviewing road names included in TMCs, and beginnings and endings of the verified TMCs were merged. The final list of TMCs includes TMC information (TMC code, direction, roadway ID, beginning milepost, ending milepost) and I-4 FRAME information (associated applications).

6.3.3.2 Match Traffic Data

Directional AADT information was collected from the Florida Traffic Information database for four years (2018–2021) and matched to each verified TMC[1]. As a unique number indicates a traffic sensor (site), the matching assigned the closest traffic sensor to a TMC[1] if located on the same segment. A directional AADT—ASCAADT, milepost ascending direction (EB, NB), DSCAADT – milepost descending direction (WB, SB)—from the matched traffic sensor was given to the TMC[1] based on roadside information in the TMC[1] dataset. Other traffic information, such as D factor, T factor, and K factor, were retrieved from the FDOT RCI database and matched to TMC[1]s based on Roadway ID and milepost.

6.3.3.3 Calculate Performance Measures

With the verified TMC[1]s, the research team calculated the time reliability measures (BI, PTI, TTI) and annual total delay for I-4 FRAME routes (either freeway or arterial) by four years (2018–2021) using Eqs. 1–3 and 11–12. The reference travel time (free-flow speed travel time) was calculated based on the 85th-percentile point of the observed speeds on that segment for all time periods. Usually, the midnight period (0:00–4:00 AM) with very little traffic was used to calculate the free flow speed travel time.

Mobility performance measures for I-4 FRAME routes (freeways and arterials) were reported in the Task 1 report. This report provides two examples for performance calculations—I-4 mainline freeway segments (Figure 6-8 to Figure 6-11) and SR-60 segments in Hillsborough County (Figure 6-12 to Figure 6-15).

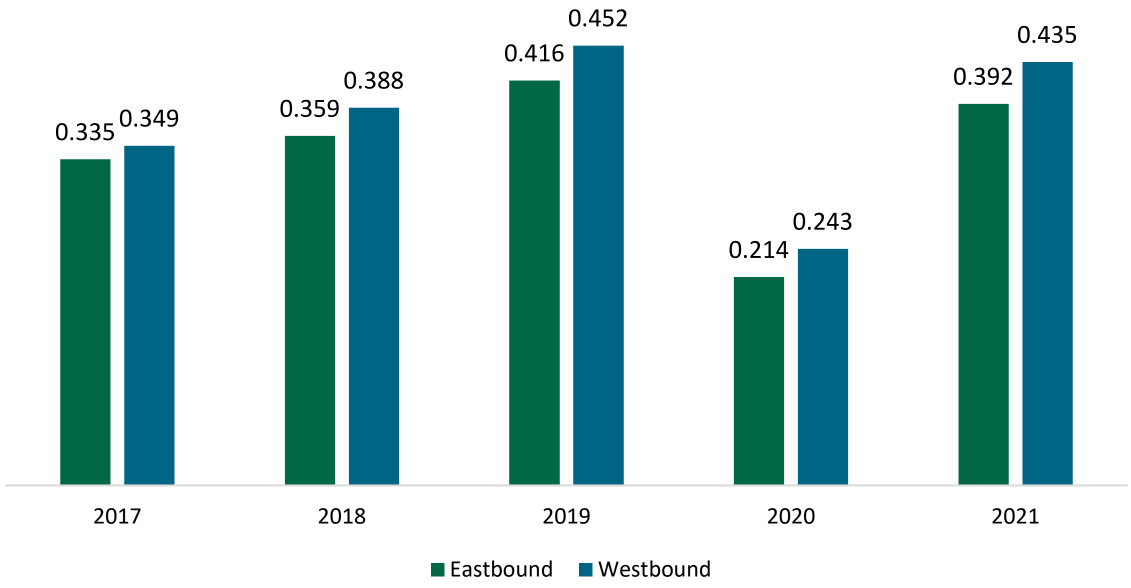


Figure 6-8. I-4 Mainline average BI, 2017–2021

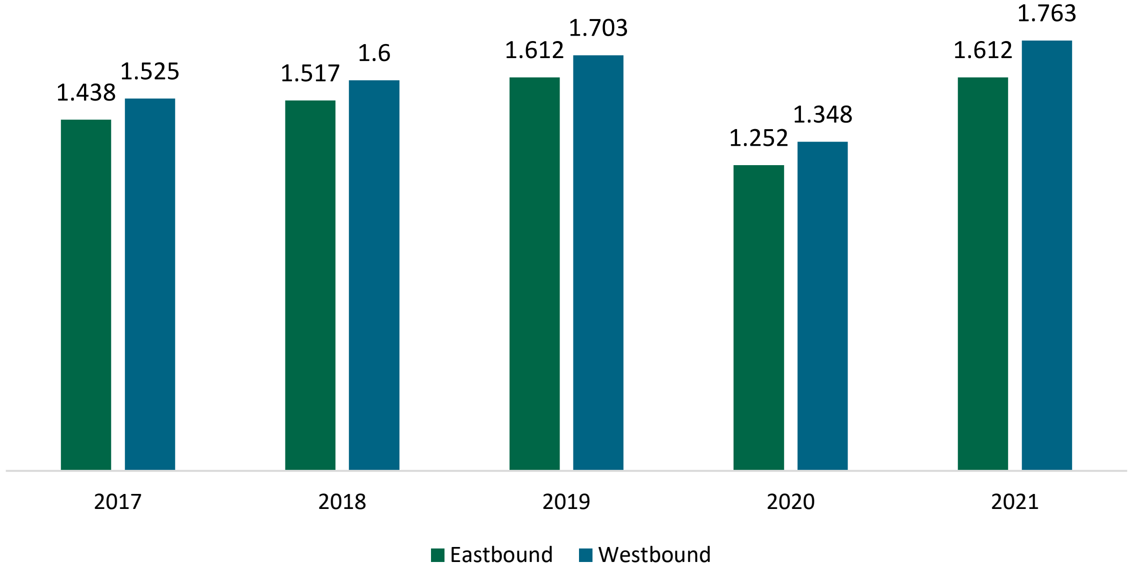


Figure 6-9. I-4 Mainline PTI, 2017–2021

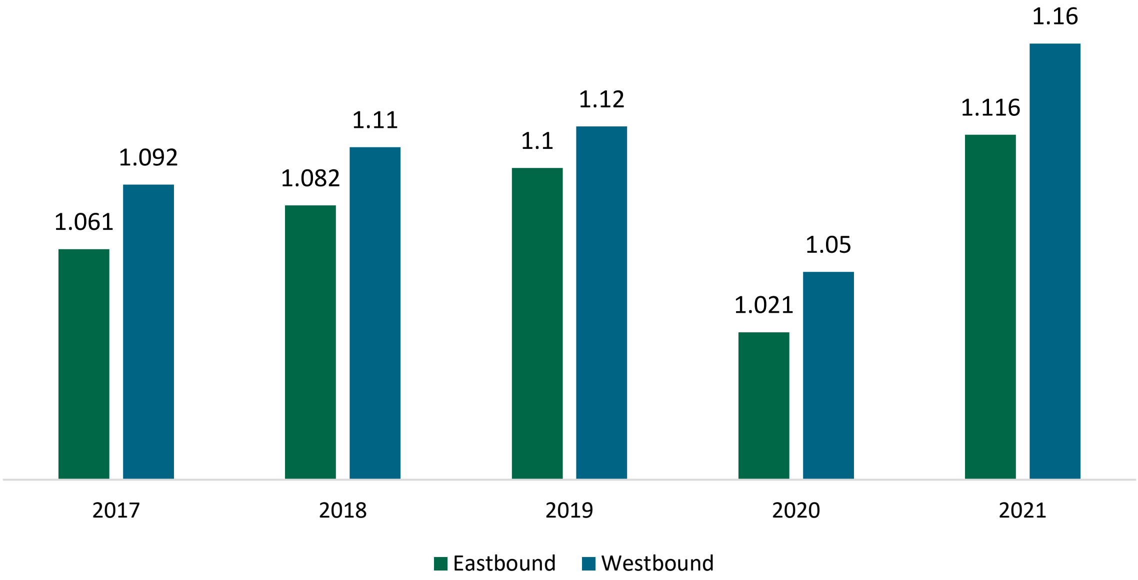


Figure 6-10. I-4 Mainline TTI, 2017–2021

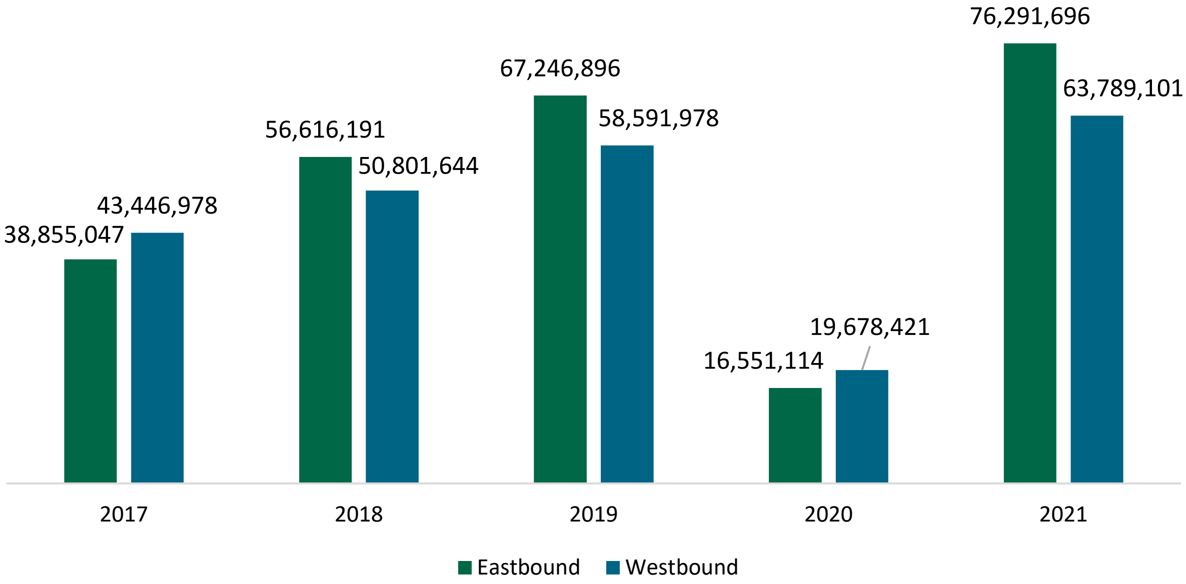


Figure 6-11. I-4 Mainline Total Delay (veh-hours), 2017–2021

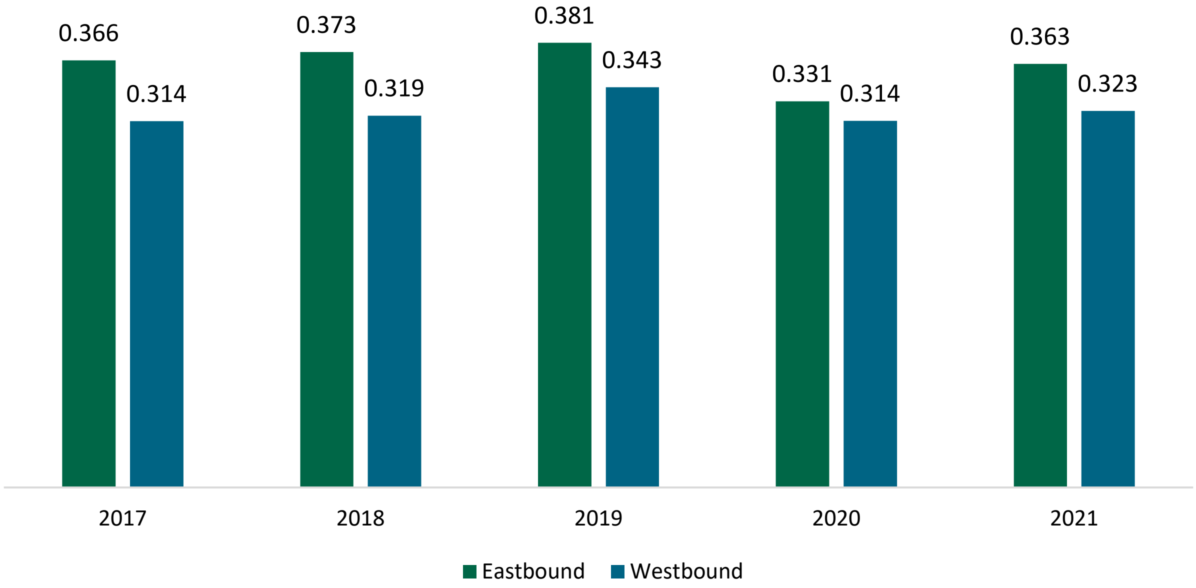


Figure 6-12. SR-60 (Hillsborough County) average BI, 2017–2021

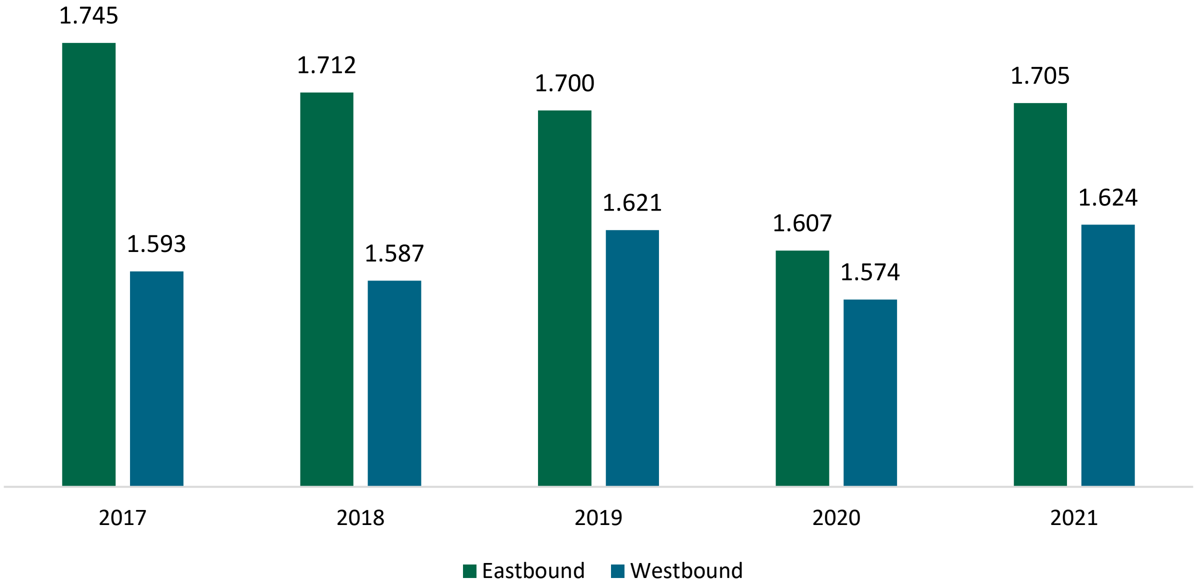


Figure 6-13. SR-60 (Hillsborough County) PTI, 2017–2021

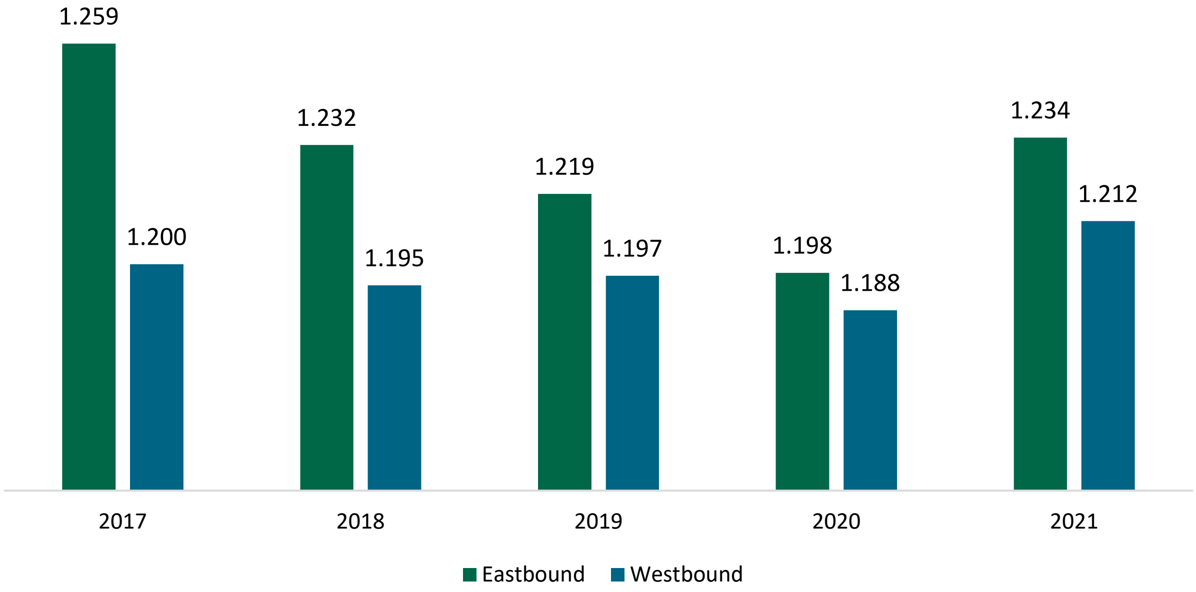


Figure 6-14. SR-60 (Hillsborough County) TTI, 2017–2021

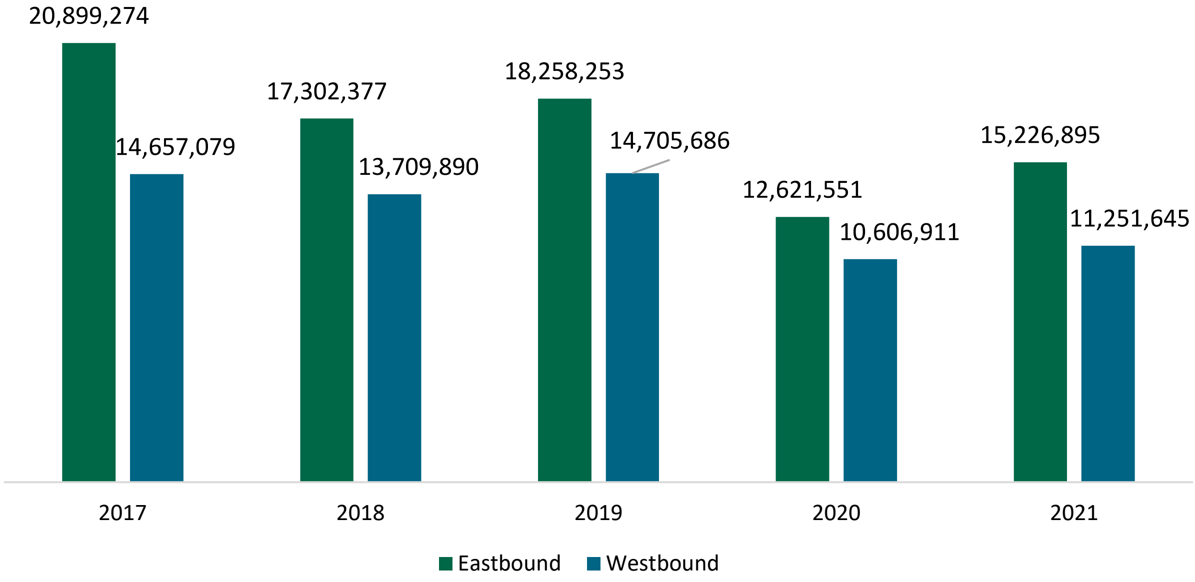


Figure 6-15. SR-60 (Hillsborough County) Total Delay (veh-hours), 2017–2021

6.4 Summary

Prediction models were developed to estimate safety and mobility performance on I-4 FRAME routes for future years, assuming without I-4 FRAME applications. The prediction models include:

- SPF for freeway segments
- SPF for arterials
- Total delay for with and without I-4 FRAME applications

The SPFs were used to estimate the crash frequencies in the “after” stage, assuming without the applications, with changed traffic volumes. For the before-after stage, an Empirical Bayesian before-after study [80, 82] will use the developed SPFs to address the overall safety effects of I-4 FRAME applications for all segments, considering the influence from the variation of traffic volumes in the “before” and “after” stages.

The total delay models assume that the implementation of I-4 FRAME applications will significantly influence average travel time and its variants (speed, delay, etc.). Total delay difference is calculated by the difference of average travel time in the before-after stages. These models will be continuously updated in the “after” study based on the latest data to improve their accuracy.

7 Future of CAV Deployments—Transitioning to C-V2X

The FCC mandated transition of ITS services from DSRC to C-V2X technology [73] according to a timeline [83], which may pose challenges for the V2X industry. First, C-V2X technology is not as mature as DSRC technology, which has been through several generations and variations of sensor technology, and costs associated with DSRC technology are significantly lower than those associated with the C-V2X technology [1]. Nonetheless, the transition from DSRC to C-V2X technology gives the C-V2X industry permission to deploy C-V2X RSUs and OBUs. This should ensure that C-V2X is widely adopted by automakers and suppliers, limiting further fragmentation and allowing the industry to benefit from economies of scale. THEA in Tampa is an example of an ongoing CV Pilot program in the U.S. dealing with this transition. In this program, spectrum interference is being tested after the switch from DSRC to C-V2X technology [84]. The THEA research team faces a hurdle in maintaining activities because DSRC was not authorized to broadcast beyond July 2022. As a result, the DSRC-to-C-V2X transition has three options—transitioning DSRC communication to the highest authorized channels, halting DSRC activities, or obtaining a waiver from the FCC to continue the operation are the first three steps.

Although transitioning to C-V2X might be challenging for the automotive industry and agencies, this new technology provides many opportunities for CAV deployment programs. C-V2X will send messages more reliably than DSRC when the distance increases [14, 15], even with restricted lines of sight and a smaller range at intersections [85]. Highway deployments, which typically benefit from improved range, will also benefit from higher dependability with C-V2X [85]. Moreover, the longstanding issue that OEMs are unlikely to implement two V2X radios is addressed by the upcoming deployment of C-V2X [85]. Two radios would have been required for DSRC multi-channel functioning with a control channel, one for channel 172 and V2V and the other for V2I safety communications. With C-V2X, this is not the case, as radio resources inside a single device using a single broad channel can be prioritized for certain messages.

The automobile industry has demonstrated a significant interest in using C-V2X technology. Given regulatory clarity, Ford has indicated its intention to equip some of its vehicles with C-V2X by 2022 [86], and other manufacturers are anticipated to follow suit. In other areas worldwide, especially in China, several automobile businesses are deploying C-V2X [87]. Building on the CAT Coalition’s work to establish documented best practices for adopting C-V2X technology, USDOT and ITE have begun producing and publishing recommendations for Connected Intersections in preparation for the arrival of V2X production cars on U.S. roadways [85].

8 Comparative Assessment of DSRC and C-V2X OBUs

8.1 Comparative Study on Various Use Cases of FL511 Application and Deployed OBUs

The I-4 FRAME project plans to use the FDOT customer-centric Florida 511 (FL511) website and smartphone application for providing real-time information to travelers on I-4 and associated arterials as a supplement to the RSUs for providing information to motorists. This section provides an overview of the FL511 framework and a brief comparative assessment on various use cases within the I-4 FRAME study area.

FL511 is a state-wide real-time Advance Traveler Information System (ATIS) that provides traffic and travel information such as congestion, crashes, construction, maintenance, and travel times via website and mobile application to travelers. With ATIS, FDOT's FL511 monitors all interstates, toll facilities, and several major Florida routes to provide alternative travel plans for drivers. The ultimate goal of the FL511 is to create a safe and efficient traffic environment by tracking current traffic conditions as an integral part of Florida's TSM&O program. FL511 provides up-to-date information and data by using sensors and cameras, mainly from FDOT, installed along Florida's roadways and sharing this information throughout Florida to accomplish its goal. The data are obtained by Florida's Advanced Transportation Management System (ATMS) software, known as SunGuide, and sent to FL511 for use on the website and smartphone. FL511 offers information to the users bilingually in English and Spanish [88].

FL511 consists of multiple interconnected elements and collects vehicle, traffic, incident, maintenance, construction, work zone, and weather information from these elements and provides it to the public. Figure 8-1 shows the FL511's interconnected diagram and existing/planned elements within the framework.

Specifically, FL511 communicates with ITS-equipped vehicles with OBU to provide convenient, safe, and efficient travel by using OBU's vehicle-based sensory, processing, storage, and communications functions. The capabilities of OBU can be applied to passenger cars, trucks, and motorcycles, as well as commercial vehicles, emergency vehicles, transit vehicles, and maintenance vehicles. The main component of an OBU is its communication function, which allows V2V and V2I information transfer. Moreover, route guidance capabilities allow for the creation of an optimal route and informing drivers along the travel route by using advance sensors and enhanced driver interfaces so that the driver travels along the selected routes in a safe, efficient, and consistent manner [89]. It is also worth mentioning that physical objects such as sensors, processors, driver interfaces, and actuators support all six levels of driving automation as described in SAE J3016 [90].

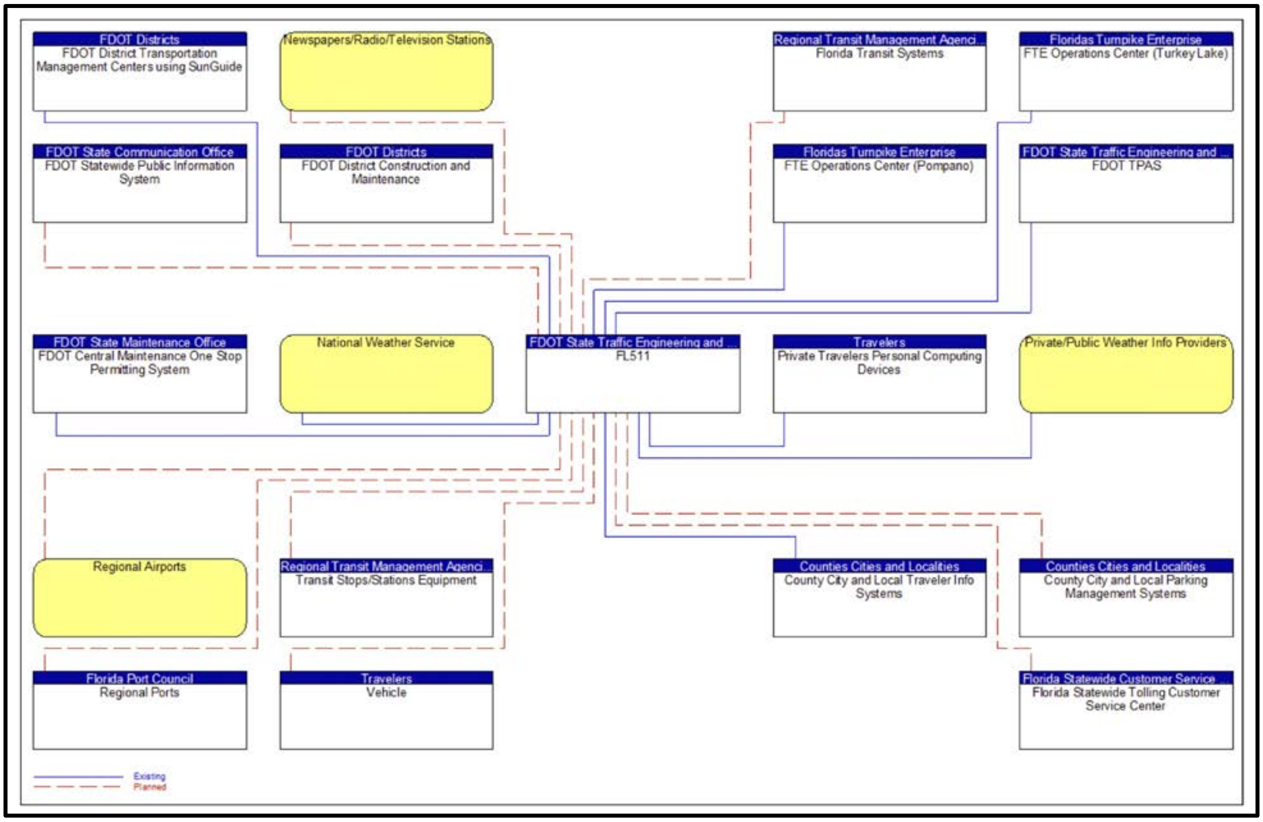


Figure 8-1. FL511 interconnected diagram

(Source: https://teo.fdot.gov/architecture/architectures/statewide/html/elements/gel99.html)

FL511 supports one-way and two-way communication options that include different information services, from basic broadcast to advanced personalized information. Figure 8-2 illustrates the existing and planned interconnected information flow between a vehicle and different sources. For example, a vehicle can transfer its location and motion for surveillance and get information such as intersection geometry and parking facility from the CAV field equipment. In particular, FL511 and ITS-equipped vehicles transfer information either as a source or destination source, as shown in Table 8-1. Although information such as traffic conditions, road conditions, advisories, and payment information flow from FL511 to the vehicle, requests such as toll and parking information flow from the vehicle to FL511. Table 8-1 also shows the potential CV applications of the I-4 FRAME which can be used to transfer information between the FL511 and vehicle.

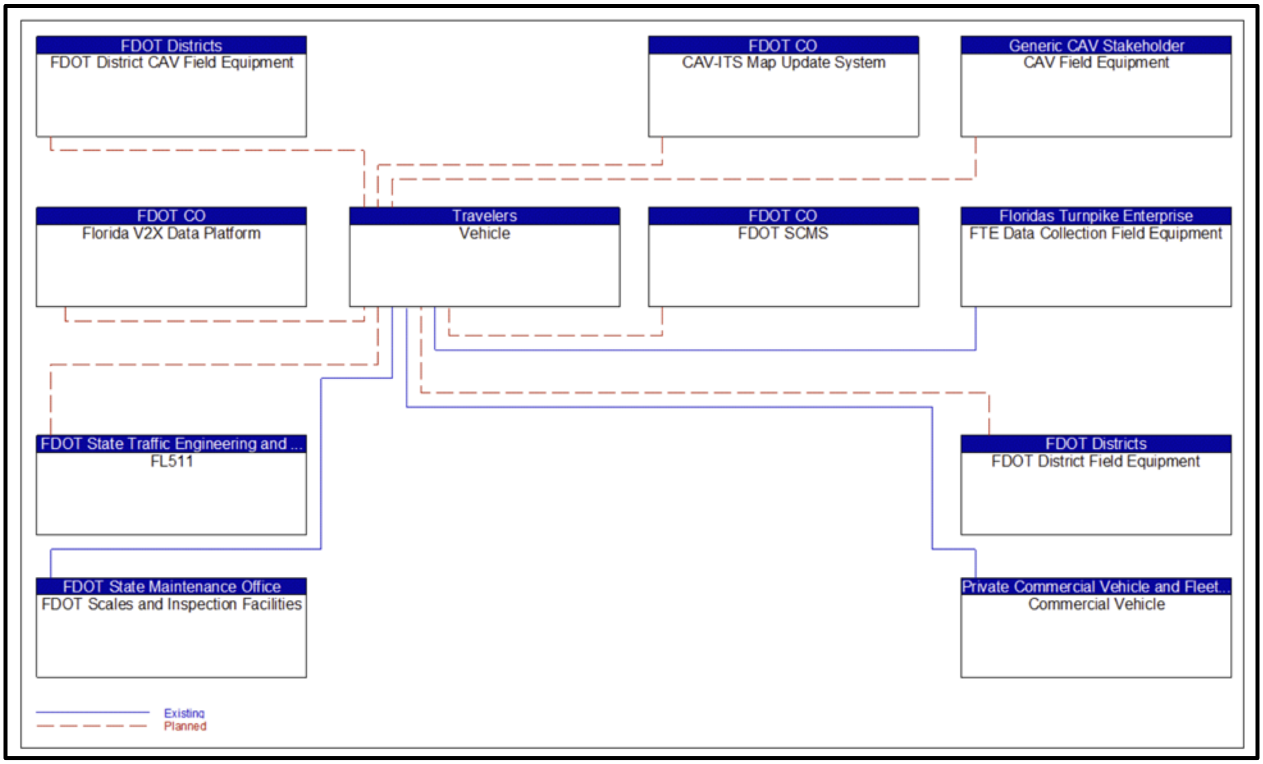


Figure 8-2. Vehicle interconnected diagram

Source: *https://teo.fdot.gov/architecture/architectures/statewide/html/elements/gel196.html*

Table 8-1. Information Flow Between FL511 and Vehicle

Information Flow	Source Element	Destination Element	Explanation	Status	Planned I-4 FRAME Use Cases
Interactive Traveler Information	FL511	Vehicle	Traveler information provided in response to a traveler request. The provided information includes traffic and road conditions, advisories, incidents, restrictions, payment information, transit services, parking information, weather information, and other travel-related data updates and confirmations.	Ongoing	VS09, VS08, VS07, PS07, MC06
Traveler Alerts	FL511	Vehicle	Traveler information alerts reporting congestion, incidents, adverse road or weather conditions, parking availability, transit service delays or interruptions, and other information that may impact the traveler. Relevant alerts are provided based on traveler-supplied profile information including trip characteristics and preferences.	Ongoing	TM25, TM17, TM12, TM08
Traveler Request	Vehicle	FL511	A request for traveler information including traffic, transit, toll, parking, road weather conditions, event, and passenger rail information. The request identifies the type of information, the area of interest, parameters that are used to prioritize or filter the returned information, and sorting preferences.	Ongoing	NA
User Profile	Vehicle	FL511	Information provided to register for a travel service and create a user account. The provided information includes personal identification, traveler preferences (e.g., maximum transfer wait time, maximum walking distance, mode preferences, special needs), device information, a user ID and password, and information to support payment transactions, if applicable.	Ongoing	NA

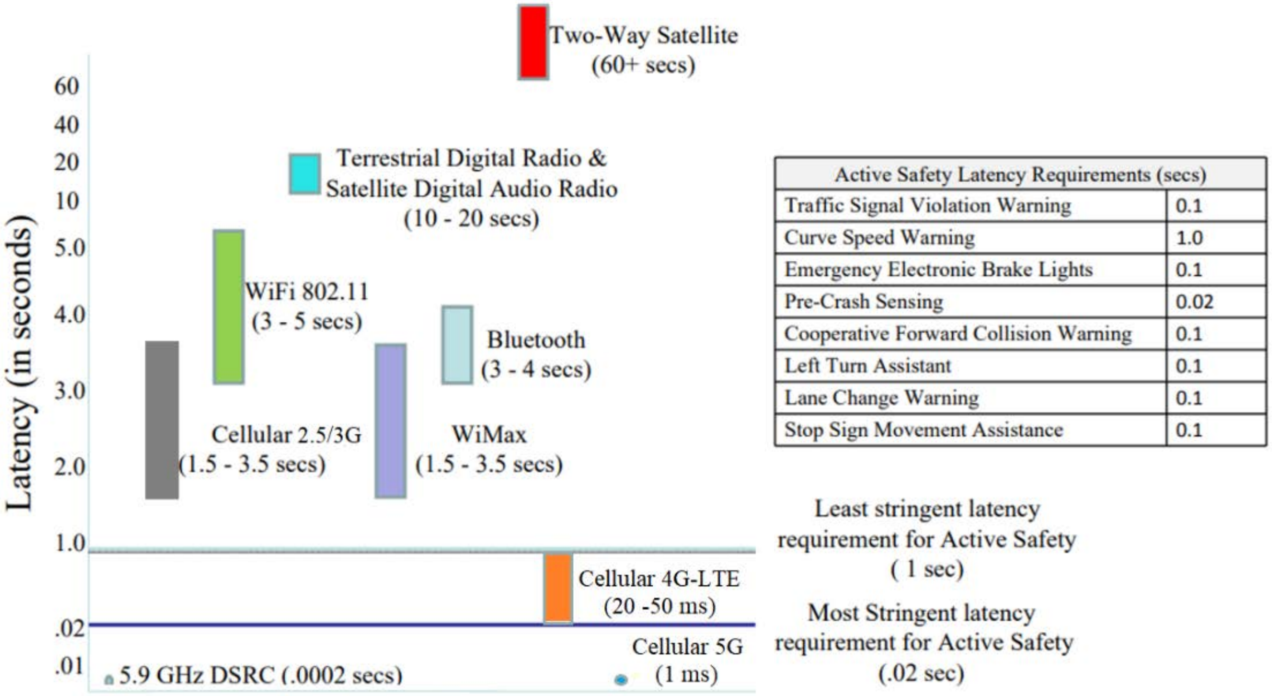
Source: *https://teo.fdot.gov/architecture/architectures/statewide/html/projects/projarch11.html*

8.2 Smartphone Application vs. OBU Application Performance

As the market penetration of vehicles with either DSRC or C-V2X OBU is not expected to reach levels of 10–20% in time to achieve the full potential benefits of the I-4 FRAME CV technologies, mobile-based applications potentially could be used as proxies to OBUs in the delivery of advisories other than crash-avoidance warnings.

Researchers have used mobile applications to broadcast information from RSUs to the user. This evaluation focused on the OBU emulator developed by UCF and its potential use cases in the I-4 FRAME project [91]. The emulator uses sensors within smartphones—gyroscope, GPS, accelerometer, barometer, and magnetometer—to estimate driving parameters such as longitudinal control, position, mode, and trajectory [91]. The OBU emulator was mainly designed for V2I and V2PP2V applications within the Android and iPhone (iOS) operating systems via wireless communication (i.e., between end users, device/application, and cloud computing) of locally collected data.

To investigate the deployment of applications within the emulator environment, latency (communication delay within data transmission) and granularity (frequency of data generation/sampling) requirements must be met. Figure 8-3 shows the varying latencies by the type of communication technology used together with latency requirements for active safety applications.



Active Safety Latency Requirements (secs)	
Traffic Signal Violation Warning	0.1
Curve Speed Warning	1.0
Emergency Electronic Brake Lights	0.1
Pre-Crash Sensing	0.02
Cooperative Forward Collision Warning	0.1
Left Turn Assistant	0.1
Lane Change Warning	0.1
Stop Sign Movement Assistance	0.1

Figure 8-3. Latency comparison between communication technologies

Source: [92, 93]

As the emulator uses cellular technologies to broadcast warnings, low latency is key. With the advancements in cellular technologies, latencies have improved substantially, from up to 3.5 seconds (2.5/3G) to as low as 1ms (5G), allowing for the broadcasting of warnings. However, other factors such as granularity, positioning accuracy, and communication range also play crucial roles in successful communication exchange. Table 8-2 shows a summary of guidelines for connected vehicle applications. In general, for most V2V and V2I applications, a maximum latency of 100ms and a granularity of 10Hz is required. Further, safety applications also require a high positional accuracy of 1.5m.

Table 8-2. Summary of Communication Guidelines for Select CV Applications

Category	Application	Type	Frequency (Hz)	Max Latency (ms)	Positioning Accuracy (m)	Communication Range (m)
Low Latency, High Granularity	Forward Collision Warning	V2V	10	100	1.5	300
	Blind Spot Warning	V2V	10	100	1.5	150
	Lane Change Warning	V2V	10	100	1.5	150
	Emergency Brake Warning	V2V	10	100	1.5	150
	Do Not Pass Warning	V2V	10	100	1.5	300
	Red Light Violation Warning	V2I	10	100	1.5	150
	Intersection Collision Warning	V2V/V2I	10	100	5	150
	Left Turn Assist	V2V/V2I	10	100	5	150
	Emergency Vehicle Warning	V2V/V2I	10	100	5	300
	Vulnerable Road User Collision Warning	V2P/V2I	10	100	5	150
	Control Loss Warning	V2V	10	100	5	300
	Abnormal Vehicle Warning	V2V	10	100	5	150
	Hazardous Location Warning	V2I	10	100	5	300
High Latency, Low Granularity	Green Light Optimal Speed Advisory	V2I	2	200	1.5	150
	Speed Limit Warning	V2I	1	500	5	300
	In-Vehicle Signage	V2I	1	500	5	150
	Traffic Jam Warning	V2I	1	500	5	150

Source: [94, 95]

Based on the initial OBU emulator latency experimental results, round-trip latency varied between 85ms and 150ms [91]. It should be noted that these tests were carried out using 4G-LTE, and further latency reductions are expected with the deployment of 5G technologies. However, as of 2020, use of 5G networks across the U.S. was estimated at 3% and 4G at 91% [96]. This is expected to change by 2025, with 5G market penetration predicted to increase to 68% [96]. In the current state, only advisories and high latency applications can be readily deployed using the OBU emulator.

Table 8-3 shows the potential use cases in which the OBU emulator could be sufficiently deployed after further refinements to the application. The current state of the application and latency should allow for the timely reception of informational advisories (i.e., no immediate threat or preventive action required by the user), especially in areas with sufficient GPS coverage.

Although Table 8-3 shows the potential feasibility of the OBU emulator within the apps planned for deployment along the I-4 FRAME, it is still unclear whether the system will perform adequately and as intended in all traffic, climate, and environmental conditions with the simultaneous deployment of several applications due to the limited system testing and relatively small sample size.

In addition, although smartphones are relatively common, the OBU emulator was tested in relatively high-end devices (Samsung Note 9 and iPhone XS with unit costs greater than $550 [97]) with better internal specifications (requiring the presence of advanced sensors such as gyroscope, GPS, accelerometer, barometer, and magnetometer, along with 4G/5G cellular capabilities), further impacting shelf readiness, latency compliance, estimated user penetration, and equity in terms of usability/access to all functionality within the emulator application.

Table 8-3. Potential V2I and V2P Use Cases Within Proposed I-4 FRAME Applications

ID	Application	Type and Description	OBU Emulator Feasible
VS13	Intersection Safety Warning and Collision Avoidance [Arterial only]	A connected vehicle approaching an instrumented signalized intersection will receive Signal Phase and Timing (SPaT) data from the RSU regarding the signal timing and the geometry of the intersection. The vehicle uses its speed and acceleration profile, along with the signal timing and geometry information to determine if it appears likely that the vehicle will be able to pass safely through the intersection without violating the signal or colliding with other vehicles. If the vehicle determines that proceeding through the intersection is unsafe, a warning is provided to the driver and/or collision avoidance actions are taken, depending on the automation level of the vehicle. The RSU would broadcast Traveler Information Message (TIM) message	Partial (advisory broadcast only)

ID	Application	Type and Description	OBU Emulator Feasible
		to alert nearby motorists of the unsafe infringement on the intersection.	
VS12	Pedestrian and Cyclist Safety [Arterial only]	Integrates traffic, pedestrian, and cyclist information from roadside or intersection detectors and new forms of data from wirelessly connected, nonmotorized traveler-carried mobile devices to request right-of-way or to inform non-motorized travelers when to cross and how to remain aligned with the crosswalk or pathway based on real-time Signal Phase and Timing (SPaT) and MAP information. It also provides warnings to approaching vehicles that a nonmotorized user is crossing or in the pathway.	Partial (advisory broadcast only)
VS09	Reduced Speed Zone Warning/Lane-Closure [Freeway only]	Broadcasts information on reduced speed zones that include (but are not be limited to) construction/work zones, school zones, and pedestrian crossing areas. TIM will be created and transmitted from the respective Regional Traffic Management Center (RTMC) via SunGuide©.	Yes
VS08	Queue Warning [Freeway only]	Broadcasts information to warn motorists of back-of-queue in order to minimize or prevent rear-end or other secondary collisions. RTMC would receive data from detectors integrated into SunGuide© and/or from vehicle OBUs that automatically broadcast their queued status information (e.g., rapid deceleration, disabled status, lane location). TIM warning motorists of congestion ahead will be created and transmitted from the respective RTMC via SunGuide©.	Partial (advisory broadcast only)
VS07	Road Weather Motorist Alert and Warning [Freeway only]	The RTMC will receive data generated by the traffic detectors, CCTV cameras, road weather information systems (RWIS), and other weather dissemination sources. The RTMC would evaluate the weather condition and TIM will be created and transmitted from the respective RTMC via SunGuide©.	Yes
TM25	Wrong Way Vehicle Detection and Warning [Freeway only]	Broadcasts TIM to oncoming drivers of a wrong way driver. The proximity of the TIM alerts will be determined utilizing Wrong Way Driving DMS messaging criteria. The RTMC would obtain data from RSUs and supplementary systems that detected a wrong way vehicle on the main roadway or exit ramps. TIM will be created and transmitted from the respective RTMC via SunGuide©.	Partial (advisory broadcast only)
TM17	Speed Warning and Enforcement [Freeway only]	Broadcasts information to warn drivers of reduced speed recommendations based on the roadway conditions ahead. The RTMC will receive data generated by the traffic detectors, CCTV cameras, video image	Yes

ID	Application	Type and Description	OBU Emulator Feasible
		processing system, and other legacy ITS equipment. TIM will be created and transmitted from the respective RTMC via SunGuide©.	
TM14	Advanced Railroad Grade Crossing [Arterial only]	Detection devices are used in conjunction with RSUs in the communication process to generate TIMs that warn of an approaching train. TIMs are broadcasted from the RSU to the OBU to preclude entrance to an intersection when barriers are activated at the crossings and if motorist is on a crash-imminent trajectory of an approaching train. Additionally, alerts via TIMs will be sent to inform motorists of diversions or for extreme traffic conditions.	Partial (advisory broadcast only)
TM12	Dynamic Roadway Warning [Freeway only]	Broadcasts information on back-of-queues, roadway hazards, road weather conditions, road surface conditions, and obstacles or animals on the road. TIM will be created and transmitted from the respective RTMC via SunGuide©.	Partial (advisory broadcast only)
TM08	Traffic Incident Management System [Freeway only]	Broadcasts traffic incident management information from incident detection, maintenance and construction management, and emergency management centers via the RSUs. TIM will be created and transmitted from the respective RTMC via SunGuide©	Yes
TM04	Connected Vehicle Traffic Signal System [Arterial only]	Use CV data to determine whether signal timings for an intersection or group of intersections should be adjusted to improve traffic flow, including allowing platoon flow through the intersection.	No
TI07	In-Vehicle Signage [Freeway and Arterial]	Broadcasts regulatory, warning, and informational signs and signals directly to drivers through in-vehicle devices. The information provided could include static (e.g., upcoming or current signs) or dynamic information (e.g., current signal states and local conditions warnings) [98].	Yes
TI03	Dynamic Route Guidance [Freeway only]	Combines multi-disciplinary processes to detect, respond to and inform motorists with the goal of broadcasting information on advanced route planning and guidance that is responsive to current traffic conditions. With connected and automated systems in place, a TIM message will provide route messages to motorists regarding any major incidents along their route.	Partial (advisory broadcast only)
PT09	Transit Signal Priority [Arterial only]	Use CV data to improve the operating performance of the transit vehicles by reducing the time spent stopped at a red light. The RSU would receive request from transit vehicle OBU when the vehicle has a schedule deviation that needs to be corrected. The RSU would	No

ID	Application	Type and Description	OBU Emulator Feasible
		validate the request and then send request to the controller. The controller would implement the transit signal priority.	
PS07	Incident Scene Safety Monitoring [Freeway only]	Broadcasts information to alert drivers of incident zone operations. The RTMC will obtain data from emergency vehicles and generate and transmit TIM from the respective RTMC via SunGuide©.	Partial (advisory broadcast only)
PS03	Emergency Vehicle Preemption [Arterial only]	Use CV data to improve the operating performance of the emergency vehicles by facilitating the movement of public safety vehicles through the intersection by clearing queues and holding conflicting phases. The RSU would receive a request from the emergency responder vehicle OBU. The RSU would validate the request and sent to the controller to implement the emergency preemption.	No
MC06	Work Zone Management [Freeway only]	Broadcasts information to motorists in areas where maintenance, construction, and utility work are ongoing. TIM will be created and transmitted from the respective RTMC via SunGuide©.	Yes
CVO06	Freight Signal Priority [Arterial only]	Use CV data to reduce stops and delays for increased travel time reliability for freight traffic, and for enhancing safety at intersections. The commercial vehicle sends a request from the OBU to the RSU. The RSU requests priority call to the controller to grant right-of-way to the requesting vehicle.	No

9 Conclusions and Lessons Learned

9.1 Conclusions from the USF-CUTR I-4 FRAME Project "Before" Study

In this USF-CUTR I-4 FRAME project "before" study, the research team successfully completed project tasks and achieved the project objectives. The CUTR team (1) identified mobility challenges on the project corridor and document how the I-4 FRAME project is addressing the goals set out by FDOT, (2) conducted "before" data collection and data analysis on 15 selected transportation systems and services, (3) developed methodologies for evaluating the safety and mobility performance and benefits of the I-4 FRAME project, (4) studied OBU technology and compare various aspects of both DSRC and C-V2X OBUs, (5) performed a comparative study on various use cases of FL511 application and deployed OBUs, and (6) assisted FDOT in developing a DMP and a PEP for the I-4 FRAME project to submit to FHWA. The data analysis results and research findings from all project tasks performed for Phase 1 have established solid baseline data and a framework for future "after" data collection and a before-after study to evaluate the effectiveness and assess the benefits of the I-4 FRAME project deployment.

9.2 General Lessons Learned during the "Before" Study

The I-4 FRAME project deployment is estimated to take place between 2022 and 2025, with the first portion of RSU deployments in FDOT D7 completed in late 2024. During this period of "before" deployment, the FCC provided a deadline of July 5, 2022, to transition out of the lower portion of the bandwidth and cease any existing operations and use of those channels [99]. The I-4 FRAME project deployment has, from the beginning of the RSU system acquisition, worked to acquire and deploy the newer generation of communication systems, including the C-V2X communications and not the older DSRC, which is now about to become obsolete. The I-4 FRAME project has not been greatly affected by this change, except for some delays in procuring an RSU vendor and units due to the change. The remainder of the deployment should occur in a timely fashion, not affecting the project timeline severely. Based on lessons learned, this impact could be minimized by following these steps:

- Monitoring closely developments of the technology and FCC licensing and mandates
- Preparing for any technology changes by providing manufacturers and vendors with exact timelines on deployment
- Ensuring the project timeline matches industry outcomes on technological changes
- Engaging team members that participate in other deployments to ensure that lessons learned are transferred and follow recommendations from those projects

In addition, the FDOT deployment team can draw from several resources available after deployment of the three CV Pilots in the U.S. The USDOT Intelligent Transportation Systems Joint Program Office (ITS JPO) maintains a website with documentation for all phases of the Pilots, news, reports, and other relevant resources. All Pilots have released lessons learned documents that are available for future deployers [100] as well as specific resources for future deployment teams [101].

The I-4 FRAME project deployment is currently underway. After completion of the “after” data collection, before-after study, and overall evaluation, an overall set of lessons can be developed to inform future deployments within FDOT or in the U.S.

9.3 Lessons Learned from THEA CV Pilot Phase 4 Interoperability Tests

During Phase 4 of the THEA CV Pilot, USDOT used the site to conduct extensive OBU interoperability and interference tests to compare and assess DSRC and C-V2X. THEA CV Pilot deployers provided support by gathering, processing, and routing data to USDOT for internal analysis. At the time of this writing, the USDOT is in the process of finalizing the analysis and producing a final report. As such, the findings are not made public yet.

10 References

1. Harding, J., et al., *Vehicle-to-vehicle communications: readiness of V2V technology for application*. 2014, United States. National Highway Traffic Safety Administration.
2. RGBSI. *7 Types of Vehicle Connectivity*. 2022; Available from: https://blog.rgbsi.com/7-types-of-vehicle-connectivity.
3. Zhou, H., et al., *Evolutionary V2X technologies toward the Internet of vehicles: Challenges and opportunities.* Proceedings of the IEEE, 2020. **108**(2): p. 308-323.
4. MacHardy, Z., et al., *V2X access technologies: Regulation, research, and remaining challenges.* IEEE Communications Surveys & Tutorials, 2018. **20**(3): p. 1858-1877.
5. IEEE, *IEEE Standard for Information Technology—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments*. 2010: IEEE Piscataway, NJ, USA.
6. Kiela, K., et al., *Review of V2X–IoT standards and frameworks for ITS applications.* Applied Sciences, 2020. **10**(12): p. 4314.
7. Srichalee, T. and S. Poochaya. *5GNR: The Suitable Communication Technology for V2X in Thailand Vehicular Environment*. in *2021 9th International Electrical Engineering Congress (iEECON)*. 2021. IEEE.
8. Kenney, J.B., *Dedicated short-range communications (DSRC) standards in the United States.* Proceedings of the IEEE, 2011. **99**(7): p. 1162-1182.
9. 5G American, *Vehicular Connectivity: C-V2X & 5G*. 2021, 5G American.
10. Ma, X., X. Chen, and H.H. Refai, *Performance and reliability of DSRC vehicular safety communication: a formal analysis.* Journal on Wireless Communications Networking, 2009. **2009**: p. 1-13.
11. Cisco, V., *Cisco visual networking index: Forecast and trends, 2017–2022. White paper.* 2018. **1**(1).
12. CNET. *5G could make self-driving cars smarter and commutes safer*. 2019; Available from: https://www.cnet.com/tech/mobile/5g-could-make-self-driving-cars-smarter-commutes-safer/.
13. Autocrypt. *DSRC vs. C-V2X: A Detailed Comparison of the 2 Types of V2X Technologies*. 2021; Available from: https://autocrypt.io/dsrc-vs-c-v2x-a-detailed-comparison-of-the-2-types-of-v2x-technologies/#:~:text=Then%2C%20what%20are%20some%20of,faster%20speeds%20and%20higher%20reliability.
14. Bazzi, A., et al., *On the performance of IEEE 802.11 p and LTE-V2V for the cooperative awareness of connected vehicles.* IEEE Transactions on Vehicular Technology, 2017. **66**(11): p. 10419-10432.
15. Weber, R., J. Misener, and V. Park. *C-v2x-a communication technology for cooperative, connected and automated mobility*. in *Mobile Communication-Technologies and Applications; 24. ITG-Symposium*. 2019. VDE.
16. California Connected Vehicle Testbed. 2017; Available from: https://caconnectedvehicletestbed.org/index.

17. MCDOT. *CONNECTED VEHICLES PROGRAM*. 2007; Available from: https://www.maricopa.gov/640/Connected-Vehicles-Program.
18. NOCoE, *SPaT Challenge Overview.* 2016.
19. DelDOT. *Integrated Transportation Management Program*. 2022; Available from: https://deldot.gov/Programs/itms/index.shtml?dc=projects.
20. FHWA, *U.S. Department of Transportation Awards $2.5 Million Grant to Georgia for Connected Vehicle Technology.* 2019.
21. Department of Trnasportation. *A Signal Phase and Timing (SPaT) system for connected vehicle applications in Georgia was estimated to cost $6.64 million (2019-2020).* 2020; Available from: https://www.itskrs.its.dot.gov/its/benecost.nsf/ID/087bb15032f3188d85258519006723dd.
22. HIDOT, *Connected Vehicle Sensors Installed in East Hawaii.* 2020.
23. Li, H., et al., *Connected Vehicle Corridor Deployment and Performance Measures for Assessment.* 2019.
24. MnDOT. *MNDOT Connected Corridor Project*. 2020; Available from: https://www.dot.state.mn.us/its/projects/2016-2020/connectedcorridors/onepager.pdf.
25. FDOT. *Gainesville SPaT Trapezium*. 2019; Available from: https://www.fdot.gov/traffic/teo-divisions.shtm/cav-ml-stamp/cv/maplocations/gains-trapezium.shtm.
26. FDOT. *Osceola County Connected Vehicle Signals*. 2022; Available from: https://www.fdot.gov/traffic/teo-divisions.shtm/cav-ml-stamp/cv/maplocations/osceolal.shtm.
27. FDOT. *US 90 Signal Phase and Timing Tallahassee*. 2022; Available from: https://www.fdot.gov/traffic/teo-divisions.shtm/cav-ml-stamp/cv/maplocations/us90-spat.shtm.
28. Barbaresso, J., et al., *USDOT's Intelligent Transportation Systems (ITS) ITS strategic plan, 2015-2019*. 2014, United States. Department of Transportation.
29. Gay, K. and V. Kniss, *Safety pilot model deployment: lessons learned and recommendations for future connected vehicle activities*. 2015, United States. Department of Transportation.
30. NYC Connected Vehicle Project. 2022; Available from: https://cvp.nyc/.
31. Wyoming DOT Connected Vehicle Pilot, 2022.
32. THEA Connected Vehicle Pilot. 2022; Available from: https://theacvpilot.com/.
33. Viray, R., et al., *Virginia connected vehicle test bed system performance (V2I system performance).* 2016.
34. c-its.kr. *Cooperative-Intelligent Transport Systems (C-ITS) pilot*. 2022; Available from: http://www.c-its.kr/english/getMain.do.
35. International, I. *Tri-nation cooperation on C-ITS Corridor*. 2016; Available from: https://www.itsinternational.com/its7/feature/tri-nation-cooperation-c-its-corridor.
36. Benjamin, S., S. Young, and M. Sarvi, *AIMES White Paper: edge computing for CAVs and VRU protection*. 2019, Australian Integrated Multimodal EcoSystem.
37. DIGNNET-PS, *Urban test field for automated and connected driving in Berlin*. 2019.

38. Turley, A. *Smart Mobility Tests Drive Singapore Closer to Smart City of the Future*. 2016; Available from: https://www.nxp.com/company/blog/smart-mobility-tests-drive-singapore-closer-to-smart-city-of-the-future:BL-SMART-MOBILITY-TESTS-DRIVE.
39. Colorado Department of Transportation. *CDOT and Panasonic Take First Steps to Turn I-70 into Connected Roadway*. 2018; Available from: https://www.codot.gov/news/2018/july/cdot-and-panasonic-take-first-steps-to-turn-i-70-into-connected-roadway.
40. Harry, R. *Las Vegas to pilot C-V2X communications with Commsignia and Qualcomm*. 2019; Available from: https://www.traffictechnologytoday.com/news/connected-vehicles-infrastructure/las-vegas-to-pilot-c-v2x-communications-with-commsignia-and-qualcomm.html.
41. CAMP LLC, *C-V2X Performance Assessment Project*. 2019.
42. Freeman, M. *Pilot project to test connected car technology on San Diego roadways San Diego roadways*. 2020; Available from: https://www.sandiegouniontribune.com/business/story/2020-07-22/new-pilot-project-to-test-connected-car-technology-on-san-diego-roadways.
43. Lynch, J. *$9.95M for “smart intersections” across Ann Arbor*. 2021; Available from: https://news.engin.umich.edu/2021/01/9-95m-for-smart-intersections-across-ann-arbor/.
44. Center for Connected and Automated Transportation. *Improving the Efficiency of Trucks via CV2X Connectivity on Highways*. 2020; Available from: https://ccat.umtri.umich.edu/research/u-m/improving-the-efficiency-of-trucks-via-cv2x-connectivity-on-highways/.
45. Stevens, T. *Ford's cars will start talking to each other in 2022*. 2019; Available from: https://www.cnet.com/roadshow/news/ces-2019-ford-c-v2x/.
46. Dahncke, M. *Audi collaborates to deploy C-V2X communication technology on Virginia roadways*. 2019; Available from: https://media.audiusa.com/en-us/releases/437#:~:text=The%20Virginia%20C%2DV2X%20deployment,number%20of%20road%20hazards%20and.
47. Dahncke, M. *Blue Bird, Fulton Co. Schools join Audi, Applied Information on connected vehicle deployment to boost school bus and school zone safety*. 2021; Available from: https://media.audiusa.com/en-us/releases/465.
48. Access Wire. *China Deployed the World First ''Three Layers'' Interoperability V2X Application Demonstration*. 2018; Available from: https://www.accesswire.com/529257/China-Deployed-the-World-First-Three-Layers-Interoperability-V2X-Application-Demonstration.
49. IOT-automotive. *Ford Tests C-V2x Technology for The First Time on Public Roads in China, Vehicles “Speak” to the World Around Them*. 2018; Available from: https://iot-automotive.news/ford-accelerates-connectivity-strategy-in-china-targets-production-of-first-c-v2x-equipped-vehicle-in-2021/.
50. Automotive Industry Portal. *Development Strategy for China’s Smart Car Innovation*. 2020; Available from: https://www.marklines.com/en/report/rep2012_202004.

51. International, I. *Zhejiang to launch C-V2X and 5G-enabled vehicles in China*. 2019; Available from: https://www.itsinternational.com/its7/news/zhejiang-launch-c-v2x-and-5g-enabled-vehicles-china.
52. Xiang, D., *Update on C-V2x Deployment in China*. 2019.
53. Misener, J. *China paves way to enhanced safety with C-V2X*. 2021; Available from: https://www.itsinternational.com/its5/its7/feature/china-paves-way-enhanced-safety-c-v2x.
54. Qualcomm Technologies Inc. *ConVeX Consortium Hosts Europe's First Live C-V2X Direct Communication Interoperability Demonstration Between Motorcycles, Vehicles, and Infrastructure*. 2018; Available from: https://www.qualcomm.com/news/releases/2018/07/04/convex-consortium-hosts-europes-first-live-c-v2x-direct-communication.
55. Transport for West Midlands, *Connected & Autonomous Vehicles are the future –the West Midlands is leading the way*. 2018.
56. Le Strade dell'Informazione. *Smart Road: Anas porta l'Italia verso la mobilità del futuro*. 2021; Available from: https://www.lestradedellinformazione.it/rubriche/le-strade-della-mobilita/smart-road-anas-porta-litalia-verso-la-mobilita-del-futuro.
57. Project, C. *Connected Corridor for Driving Automation*. 2022; Available from: https://concordaproject.eu/.
58. 5G-CARMEN. *5G for Connected and Automated Road Mobility in the European Union*. 2022; Available from: https://5gcarmen.eu/.
59. 5gcroco. *Fifth Generation Cross-Border Control*. 2022; Available from: https://5gcroco.eu/.
60. 5G-MOBIX. *5G-MOBIX in a nutshell*. 2022; Available from: https://www.5g-mobix.com/about.
61. 5g-routes. *5th Generation connected and automated mobility cross-border EU trials*. 2022; Available from: https://www.5g-routes.eu/.
62. Qualcomm Technologies Inc., *C-V2X Trial in Japan.* 2018.
63. Marklines. *Mobility for Commercial Vehicles: Field testing of truck platooning on public roads*. 2019; Available from: https://www.marklines.com/en/report_all/rep1909_201908.
64. International, I. *NTU and M1 to develop Singapore 5G C-V2X testbed*. 2019; Available from: https://www.itsinternational.com/its7/news/ntu-and-m1-develop-singapore-5g-c-v2x-testbed.
65. Frost, A. *Successful 5G C-V2X communication between AVs demo in Korea*. 2019; Available from: https://www.traffictechnologytoday.com/news/autonomous-vehicles/successful-5g-c-v2x-communication-between-avs-demo-in-korea.html.
66. International, I. *Qualcomm partner with LG Electronics on connected car solutions, South Korea*. 2017; Available from: https://www.itsinternational.com/its5/news/qualcomm-partner-lg-electronics-connected-car-solutions-south-korea.
67. ASTRI. *ASTRI launches one of the world's largest C-V2X public road tests*. 2021; Available from: https://www.astri.org/news-detail/astri-launches-one-of-the-worlds-largest-c-v2x-public-road-tests-promoting-smart-mobility-to-improve-the-citys-mobility-competence-while-enhancing-road-safety-and-

efficiency/#:~:text=(30%20March%202021)%20The%20Hong,as%20well%20as%20the%20network.

68. Eriksson, H. *Australian-first connected vehicle trial set to make roads safer*. 2018; Available from: https://exchange.telstra.com.au/australian-first-lexus-connected-vehicle-trial-set-to-make-roads-safer/.

69. Miao, L., J.J. Virtusio, and K.-L.J.S. Hua, *Pc5-based cellular-v2x evolution and deployment.* 2021. **21**(3): p. 843.

70. Ellis, J. *C-V2X global market momentum continues to accelerate*. 2021; Available from: https://www.qualcomm.com/news/onq/2021/01/27/c-v2x-global-market-momentum-continues-accelerate.

71. National Transportation Safety Board, *Safety Recommendation*. 1995: Washington, D. C.

72. Federal Communications Commission, *FACT SHEET: Modernizing the 5.9 GHz Band*, F.C. Commission, Editor. 1999: Washington, D.C.

73. Federal Communications Commission, *First Report and Order, Further Notice of Proposed Rulemaking, and Order of Proposed Modification*. 2020: Washington, D.C.

74. 5G Americas, *Comments on C-V2X in the 5.9 GHz Band*. 2021.

75. Concas, S. and S. Ranka, *Interstate-4 (I-4) Florida's Regional Advanced Mobility Elements (FRAME) Project Evaluation Plan*. 2021, Florida Department of Transportation.

76. Geoplan Center of University of Florida, *Signal 4 Analytics*. 2022.

77. CATT-Lab, *Regional Integrated Transportation Information System (RITIS): Event Query Tool*. 2022, University of Maryland

78. FDOT-TSM&O, *Concept of Operations (ConOps) for I-4 Florida's Regional Advanced Mobility Elements (FRAME) Project*. 2021.

79. Intelligent Transportation Systems Joint Porgram Office. *Lessons Learned From Recent Secure Credential Management Systems (SCMS) Operation with the CV Pilots*. 2022 [cited 2022; Available from: https://www.its.dot.gov/pilots/cvp_scms.htm.

80. American Association of State Highway and Transportation Officials, *Highway Safety Manual*. 2010, AASHTO: Washington DC.

81. Srinivasan, R. and K.M. Bauer, *Safety Performance Function Development Guide: Developing Jurisdiction-Specific SPFs.* 2013.

82. Gross, F., B.N. Persaud, and C. Lyon, *A Guide to Developing Quality Crash Modification Factors.* 2010.

83. Federal Communications Commission. *FCC Public Notice*. 2022; Available from: https://docs.fcc.gov/public/attachments/DA-22-612A1.pdf.

84. Concas, S., et al., *Connected Vehicle Pilot Deployment Program Performance Measurement and Evaluation–Tampa (THEA) CV Pilot Phase 3 Evaluation Report*. 2021, United States. Department of Transportation. Intelligent Transportation ….

85. Qualcomm. *Transitioning to C-V2X – what you need to know*. 2021; Available from: https://www.qualcomm.com/news/onq/2021/06/transitioning-c-v2x-what-you-need-know.

86. Musulin, K. *Ford to deploy C-V2X tech in all new vehicles in 2022*. 2019; Available from: https://www.smartcitiesdive.com/news/ford-cv2x-tech-new-vehicles-2022/545412/.

87. Business.News. *The Chinese market is expected to lead the development of V2X*. 2021.

88. Florida-511. *ABOUT FL511*. 2022 [cited 2022 20 Aug]; Available from: https://fl511.com/about.
89. FDOT. *Florida Statewide and Regional ITS Architectures*. 2022 [cited 2022 20 Aug]; Available from: https://teo.fdot.gov/architecture/architectures/statewide/html/entities/vobe.html.
90. SAE-J3016, *J3016_202104: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. 2021, SAE International.
91. Abdel-Aty, M.A., et al., *Using Smartphone as On-board unit (OBU) Emulator Implementation Study.* 2020.
92. Emilio, M. *Wireless/RF Technology for the Next Telecom Evolution*. 2019 [cited 2022 15 Aug]; Available from: https://www.eetimes.eu/wireless-rf-technology-for-the-next-telecom-evolution/.
93. CAMP, *Vehicle Safety Communications Project Task 3 Final Report: Identify Intelligent Vehicle Safety Applications Enabled by DSRC.* 2005.
94. ALLION-Labs. *C-V2X Scenario Simulations and Validation*. 2022 [cited 2022 15 Aug]; Available from: https://www.allion.com/automotive/cv2x-validation/.
95. SAE-J2945/1, *J2945/1: On-Board System Requirements for V2V Safety Communications*. 2020, SAE International.
96. GSMA, *The Mobile Economy North America 2021*. 2021, GSMA Association.
97. Cordella, M., et al., *Durability of smartphones: A technical analysis of reliability and repairability aspects.* Journal of Cleaner Production, 2021. **286**: p. 125388.
98. ARC-IT *TI07: In-Vehicle Signage*. 2022.
99. Federal Communications Commision, *Public Notice DA 22-612*. 2022.
100. Intelligent Transportation Systems Joint Program Office. *CV Pilot Deployment Program-Success Stories and Lessons Learned*. 2022 [cited 2022; Available from: https://www.its.dot.gov/pilots/success.htm.
101. Intelligent Transportation Systems Joint Porgram Office. *ITS Professional Capacity Building Program: Connected Vehicle Deployer Resources*. 2022 [cited 2022; Available from: https://www.pcb.its.dot.gov/CV_deployer_resources.aspx.