Environment for Testing and Assessing Infrastructure Support of Connected Vehicle and Cooperative Highway Automation Applications

Draft Final Report

Florida Department of Transportation (FDOT) Project

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DISCLAIMER

METRIC CONVERSION CHART

Approximate Conversions to SI* Units					**Approximate Conversions from SI Units**				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH					**LENGTH**				
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
AREA					**AREA**				
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
VOLUME					**VOLUME**				
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
MASS					**MASS**				
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
TEMPERATURE (exact)					**TEMPERATURE (exact)**				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F
*SI is the symbol for the International System of Measurement									

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16. Abstract The consideration of cooperative driving automation (CDA) in the transportation system management and operations (TSM&O) processes has the potential for improving system performance in terms of safety, mobility, environmental impacts, and user satisfaction and acceptance. The goal of this project is to provide recommendations regarding the incorporation of CDA in TSM&O activities of the Florida Department of Transportation (FDOT). The project developed a concept of operation (ConOps) for this incorporation. The project also developed and demonstrated methods for testing and evaluating the infrastructure support of CDA. In addition, the project developed an action plan and a training plan to identify the action items required to establish and advance the practices needed for the infrastructure support of the CDA.

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EXECUTIVE SUMMARY

The consideration of cooperative driving automation (CDA) in the transportation system Management and operations (TSM&O) processes has the potential of providing additional benefits in improving system performance in terms of safety, mobility, environmental impacts, and user satisfaction and acceptance of the system and technology. The full benefits of the incorporation of CDA in TSM&O will not be realized for some time because the market penetration of CDA technology is not expected to be high in the near term. However, infrastructure owners and operators can prepare for the future by extending their CV hardware and software to accommodate CDA applications. This will allow the owners and operators to receive additional benefits in the near term even if the market penetrations of CDA are very low. Additional data collected from CDA vehicles, combined with those collected from connected non-automated vehicles, have the potential to enhance existing TSM&O strategies. In addition, the infrastructure information that will eventually be provided for CDA vehicles to support cooperative driving can be also useful for connected vehicles, even if these vehicles are not automated.

GOAL AND OBJECTIVES

The goal of this project is to provide recommendations regarding the incorporation of CDA in FDOT TSM&O activities based on the identification of the impacts of CDA on system performance to support achieving the FDOT TSM&O strategic plan goals, as well as to identify the actions and capabilities of the FDOT that are needed to enhance CDA impacts.

The specific objectives are:

- To develop a concept of operation (ConOps) for the incorporation of CDA features as part of the FDOT TSM&O processes, as well as for the support of the traffic management of CDA.
- To formulate methods for testing and evaluating the infrastructure support of CDA in simulation and controlled real-world test environments.
- To propose an action plan and a training plan to identify the action items required to establish and advance the practices needed for the infrastructure support of the CDA.

CONCEPT OF OPERATIONS

The vision for the ConOps of the incorporation of CDA in TSM&O is for the FDOT to start implementing infrastructure interfaces required for CDA by extending their current and planned traffic management strategies and CV infrastructure deployment applications to accommodate the CDA needs. With the limited market penetration of CDA vehicles in the traffic stream in the near future, the extension of the existing capabilities is recommended to be implemented in an evolutionary manner that will provide support to the existing applications and provide improvements to the system's performance as they are implemented. As the CDA vehicles begin to be incorporated in the transportation system, the already introduced enhancements to the system's operations can be used to support the CDA and make use of the CDA in improving TSM&O.

TEST PLAN

This study proposed a Test Plan for the infrastructure support of CDA in simulation and controlled real-world test environment. This plan can be used as a model in the development of future test and evaluation plans for applications that integrate TSM&O and CDA. The plan includes the referenced documents, test objectives and scope, items to be tested, features to be tested, test approaches, test environment setup, and test scenarios and procedures. It references, as a tool for testing, the Cooperative Automation Research for Mobility Applications (CARMA), which is an open-source cooperative driving automation platform developed by the Federal Highway Administration (FHWA). However, the plan is applicable and can be extended to other open-source and commercially available CDA systems.

DEMONSTRATION OF SIMULATION UTILIZATION IN TESTING AND EVALUATION

Although microscopic traffic simulation tools allow the coding of complex driving behaviors and control; their modeling of sensors, connectivity, and aspects of automation and cooperation is not detailed enough for testing the various software modules and hardware associated with CDA technology and their interactions with the surrounding environment. This study identified that the testing and evaluation of CDA and infrastructure support of CDA require two levels of modeling. The first level is the use of microscopic traffic simulation tools, extended with more realistic CDA representation, to quantify the traffic level impacts in terms of traffic efficiency, traffic safety and traffic stability. The second is the use of co-simulation environments, to assess vehicle level performance in the testing of CDA driving features, hardware and software, and associated maneuvers and interactions. The application used in this project as a case study to demonstrate the simulation utilization is the ramp metering in the presence of automated and cooperative merging.

ACTION PLAN, TRAINING PLAN, AND ALTERNATIVE ANALYSIS PLAN

This project also developed action plan, training plan, and alternative analysis plan. The action plan identifies the action items required to establish and advance the practices needed for the infrastructure support of the CDA in institutional and technical dimensions of maturity. The Training Plan proposes training modules for building the workforce required for the incorporation of CDA consideration in TSM&O based on the identified action plan. The Alternative Analysis Plan proposes methods to select and prioritize strategic and tactical actions to build the capabilities required for the TSM&O support of CDA.

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LIST OF ACRONYMS

AAM	Active Arterial Management
AASHTO	American Association of State Highway and Transportation Officials
ABS	Antilock Brake System
ACC	Adaptive Cruise Control
AD	Autonomous Driving
ADAS	Advanced Driver Assistance System
ADS	Automated Driving System
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
API	Application Program Interfaces
ASCT	Adaptive Signal Control Technologies
ATC	Advanced Traffic Controller
ATMA	Automated Truck-Mounted Attenuator
ATSPM	Automated Traffic Signal Performance Measures
AV	Autonomous Vehicles
AVI	Automatic Vehicle Identification
BCR	Benefit-Cost Ratio
BSM	Basic Safety Message
BWM	Best Worse Multicriteria Decision Making Method
C2C	Center to Center
CACC	Cooperative Adaptive Cruise Control
C-ADS	Cooperative Automated Driving System
CARLA	CAR Learning to Act
CARMA	Cooperative Automation Research for Mobility Applications
CAV	Connected and Automated Vehicles
CCTV	Closed-Circuit Television
CDA	Cooperative Driving Automation
CEI	Construction Engineering and Inspection
CI	Consistency Index
CITE	Consortium for Innovative Transportation Education
CMF	Capability Maturity Frameworks
CMM	Capability Maturity Model
ConOps	Concept of Operations
CPU	Central Processing Unit
CR	Consistency Ratio
CV	Connected Vehicles
DDT	Dynamic Driving Task
DIVAS	Data Integration and Video Aggregation System
DMS	Dynamic Message Signs
DPP	Data Privacy Plan
DSRC	Dedicated Short Range Communications
DSS	Decision Support System
EDAS	Evaluation Based on Distance from Average Solution
ESC	Electronic Speed Controller

ETSI	European Telecommunication Standards Institute
FDOT	Florida Department of Transportation
FHP	Florida Highway Patrol
FHWA	Federal Highway Administration
FSP	Freight Signal Priority
FSUTMS	Florida Standard Urban Transportation Model Structure
FTP	Florida Transportation Plan
GLOSA	Green Light Optimal Speed Advisory
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GUI	Graphic User Interface
HCM	Highway Capacity Manual
HEFT	Homestead Extension of Florida’s Turnpike
HIL	Hardware in the Loop
HOV	High Occupancy Vehicle
HSR	Hard Shoulder Running
HV	Human-Driven Vehicle
ICM	Integrated Corridor Management
IEEE	Institute of of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
ITS	Intelligent Transportation Systems
KPI	Key Performance Indicator
KSA	Knowledge, Skills and Abilities
lidar	Light Detection and Ranging
MAP	Map Data Messages
MCDA	Multicriteria Decision Analysis
MIL	Model Based Controller Design
MIO	Most Important Object
MOSAIC	Modular Selection And Identification for Control
MPC	Model Predictive Control
MPG	Miles per Gallon
MPO	Metropolitan Planning Organization
NCHRP	National Cooperative Highway Research Program
NHI	National Highway Institute
NMEA	National Marine Electronics Association
NTCIP	National Transportation Communications for Intelligent Transportation Systems Protocol
NPV	Net Present Value
OBU	Onboard Unit
ODD	Operational Design Domain
ODE	Operational Data Environment
OEDR	Object and Event Detection Response
OEM	Original Equipment Manufacturer
OS	Operating System
OV	Object Vehicle
PAPRIKA	Potentially All Pairwise Rankings of All Possible Alternatives
PCB	Professionally Capacity Building

PID	Proportional Integral Derivative
POP	Point of Presence
PP	Pure Pursuit
PTI	Planning Time Index
R-ICMS	Regional Integrated Corridor Management System
RI	Random Consistency Index
RISC	Rapid Incident Scene Clearance
RM	Ramp Metering
ROI	Return on Investment
ROP	Rules of Practice
ROS	Robot Operating System
RRSP	Road Ranger Service Patrols
RSE	Roadside Equipment
RSU	Roadside Unit
RSM	Road Safety Messages
RTMC	Regional Transportation Management Center
SAE	Society of Automotive Engineers
SCMS	Security Credential Management System
SD	Standard Deviation
SDSM	Sensor Data Sharing Message
SELS	Statewide Express Lane Software
SHRP2	Second Strategic Highway Research Program
SHSP	Strategic Highway Safety Plan
SI	International System of Units
SIL	Software in the Loop
SIRV	Severe Incident Response Vehicles
SIS	Strategic Intermodal System
SMAA	Stochastic Multicriteria Acceptability Analysis
SOG	Standard Operating Guidance
SPAT	Signal Phase and Timing Messages
SSM	Signal Status Messages
STAMP	Statewide Arterial Management Program
SUMO	Simulation of Urban Mobility
SV	Subject Vehicle
SWZ	Smart Work Zone
TCS	Traction Control System
TIM	Traffic Information Message
TMC	Traffic Management Center
TMS	Traffic Management System
TOPSIS	Technique for Order or Preference by Similarity to Ideal Solution
TOSCO	Traffic Optimization for Signalized Corridors
TraCI	Traffic Control Interface Library
TSM&O	Transportation System Management and Operations
TSP	Transit Signal Priority
TSS	Transportation Sensor Subsystem
TTC	Time to Collision

USB	Universal Serial Bus
USDOT	United States Department of Transportation
V2I	Vehicle-to-infrastructure
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VESC	Vedder Electronic Speed Controller
vphpl	Vehicle per Hour per Lane
VSL	Variable Speed Limit
WAVE	Wireless Access in Vehicular Environments
WWD	Wrong Way Driving/Driver
XIL	Everything in the Loop

1. INTRODUCTION

1.1 Background Statement

The Transportation System Management and Operations (TSM&O) Strategic Plan (FDOT, 2017) of the Florida Department of Transportation (FDOT) identified connected vehicles (CV) as one of the focus areas of the program. A major focus of the FDOT program has been on the vehicle-to-infrastructure (V2I) applications of connected vehicles (CV). However, there has been increasing interest in recent years in cooperative driving automation (CDA), considering its potential for additional transformative impacts on the transportation system.

An important component of vehicle connectivity and cooperative driving automation is the infrastructure support through V2I communications with roadside equipment (RSE) and/or with the cloud. There is a large number of CV mobility, safety, sustainability applications and several other cooperative automation applications that require support from the infrastructure. The various infrastructure elements, including the RSEs, controllers, and central software, will play a major role in ensuring the success of these applications.

The Federal Highway Administration (FHWA) has invested in Cooperative Automation Research for Mobility Applications (CARMA) as an open-source cooperative driving automation platform to encourage the development and testing of CDA technologies. This effort is providing a strong foundation for building CDA capabilities for both the vehicle side and the infrastructure side.

The consideration of CDA in the TSM&O processes has the potential to provide additional benefits in improving system performance in terms of safety, mobility, environmental impacts, and user satisfaction and acceptance. The full benefits of the incorporation of CDA in TSM&O will not be realized for some time because the market penetration of CDA technology is not expected to be high in the near term. However, infrastructure owners and operators can prepare for the future by extending their CV hardware and software to accommodate CDA applications. This will allow the owners and operators to receive additional benefits in the near term even if the market penetrations of CDA are very low. Additional data collected from CDA vehicles, combined with those collected from connected non-automated vehicles, have the potential to further enhance existing TSM&O strategies. The infrastructure information to be provided for CDA vehicles to support cooperative driving can also be useful for connected vehicles, even if these vehicles are not automated. An example is the ability to provide information ahead of incidents and work zones about the best lane to utilize, merging location, and operating speed. The above two enhancement management categories (data collection from vehicles and information provision) can provide significant benefits, even without the presence of or minor penetration of CDA. In addition to the above two categories of enhancement, a third enhancement management category requires the cooperation between the infrastructure and at least one CDA vehicle (e.g., emergency vehicle or a bus). The benefits of this category increase as the market penetration of CDA vehicles increases. Considering these benefits, an evolutionary approach for infrastructure support of CDA is recommended in this document.

The integration of CDA technologies into the TSM&O processes requires additional capabilities at traffic management centers and the roadside. Thus, there is a need to understand the impacts of these applications and the needed capabilities at the traffic management centers and the roadside, considering the anticipated increase in the market penetrations of these technologies. In addition, there is a need for the identification of testing and evaluation methods to support these capabilities.

1.2 Goal and Objectives

The goal of this project is to provide recommendations regarding the incorporation of CDA in FDOT TSM&O activities based on the identification of the impacts of CDA on system performance to support achieving the FDOT TSM&O strategic plan goals, as well as to identify the actions and capabilities of the FDOT that are needed to enhance CDA impacts.

The specific objectives are:

- The first objective is to develop a ConOps for the incorporation of CDA features as part of the FDOT TSM&O processes, as well as for the support of the traffic management centers and roadsides of CDA.

- The second objective is to develop methods for testing and evaluating the infrastructure support of CDA in simulation and controlled real-world test environments.

- The third objective is to propose an action and training plans to identify the action items required to establish and advance the practices needed for the infrastructure support of the CDA. The action plan is to be developed based on required actions to achieve different levels of capabilities in technical and institutional dimensions and subdimensions.

1.3 Vehicle Automation and Cooperation

The discussion in this document requires an understanding of the Society of Automotive Engineers' (SAE) definitions of CDA classes in the SAE J3216 standards issued in May 2020 (SAE International, 2021a) and the relationships between these classes and levels of automation previously defined in SAE J3016 (SAE International, 2021b). Before defining CDA classes, "No Cooperative Automation Vehicles" are defined as vehicles that do not interact with the surrounding vehicles or infrastructure. These vehicles can be manually driven or are autonomous vehicles. SAE J3216 classified the CDA into four classes according to the ability to state information (e.g., vehicle position, signal phasing and timing (SPaT)), sharing of intent (e.g., planned vehicle trajectory, changes to signal timing), and ability to seek agreement on a plan such as coordinated merge, lane change, or platooning. The following is a description of the classes of CDA according to SAE J3216 standards (SAE International, 2021a).

- No Cooperative Automation Vehicles are vehicles that do not interact with the surrounding vehicles or infrastructure. The vehicles can be manually driven or are autonomous vehicles.
- Class A: Status-sharing: vehicles have the capability to share and receive status information with surrounding vehicles and infrastructure but lack the ability to predict which vehicles in the vicinity can perform these actions.
- Class B: Intent-sharing: vehicles are capable of sharing information about their plans and can gather information on the intended actions of other vehicles, allowing for coordinated maneuvers.

- Class C: Agreement-Seeking: Class C involves vehicles and types of infrastructure that are able to interact collaboratively by negotiating together to execute cooperative tasks. This involves the exchange of a sequence of collaborative messages among specific CDA devices intended to influence the local planning of specific actions. Agreement-seeking cooperation includes an interactive exchange of messages that may include plans, and the acceptance or rejection of plans, or considerations for arriving at a consensus on a proposed plan. Depending on circumstances, CDA device agents may not follow a planned future action, and all entities must conduct competent operations regardless of others' actions.
- Class D: Prescriptive: In the Class D cooperation, prescriptive actions are directed to the vehicle for performance of dynamic driving task (DDT) or performance of a particular task by a road operator (e.g., changing traffic signal phase). The action is adhered to by a receiving CDA device agent(s) (e.g., "I will do as directed."). However, the participants have the full authority to accept the actions, except for very specific circumstances in which it is designed to accept and adhere to a prescriptive communication. Prescriptive cooperation does not require the willingness of the affected entities to cooperate. It relies on a pre-existing understanding between parties to adhere to commands, such as a specific aspect of task performance or under particular circumstances.

The levels of automation are defined according to SAE J3016 standards - Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles (SAE International, 2021b). Operating conditions, under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics. Clearly defining the design operating conditions for automated vehicles is crucial to ensuring the safety of the system. Hence, the Operational Design Domain (ODD) needs to be planned out carefully in advance.

This standard defines six levels of automation, as follows:

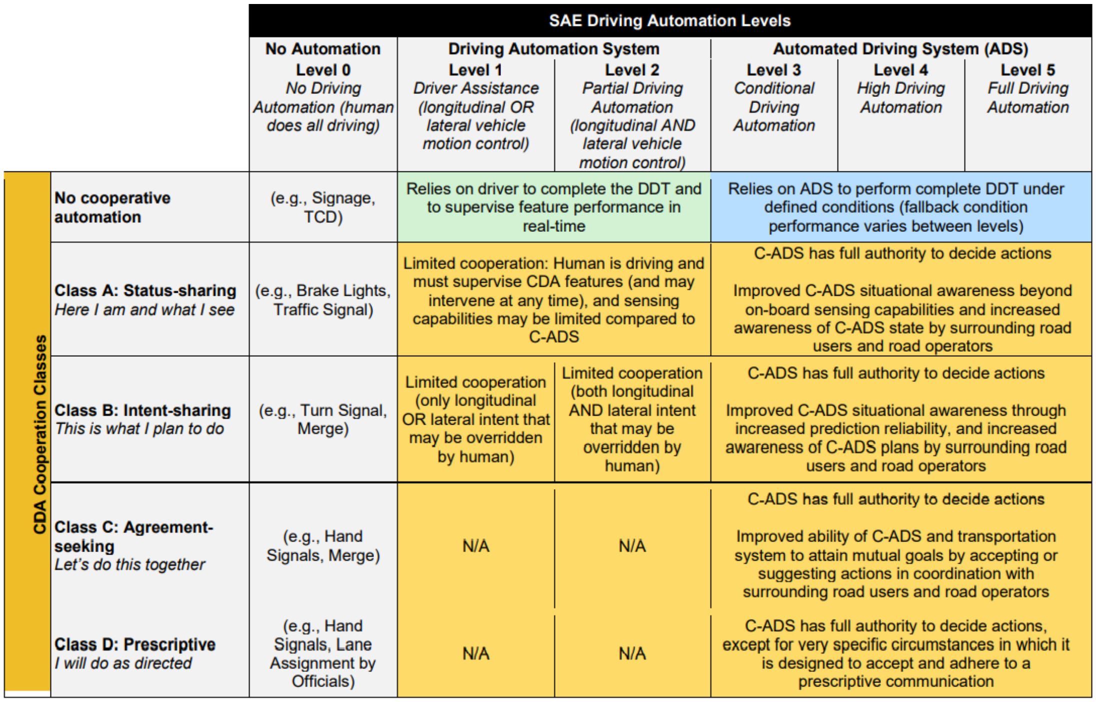
- No automation (Level 0): A driver manually executes all driving functions, such as braking, steering, car-following, etc.
- Driver Assistance - Function-specific Automation (Level 1): The ODD-specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask of the Dynamic Driving Tasks (DDT) (but not both simultaneously) with the expectation that the driver performs the remainder of the DDT.
- Partial Driving Automation (Level 2): The sustained and ODD-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control subtasks of the DDT with the expectation that the driver completes the Object and Event Detection and Response (OEDR) subtask and supervises the driving automation system. The driver must constantly monitor the roadway while driving and be ready to take over these controls in a short amount of time.
- Conditional Driving Automation (Level 3): The sustained and ODD-specific performance by an automated driving system (ADS) of the entire DDT with the expectation that the DDT fallback-ready user is receptive to intervening on ADS-issued requests and appropriately responding to DDT performance-relevant system failures.

- High Driving Automation (Level 4): The sustained and ODD-specific performance by an ADS of the entire DDT without any expectation that a user will respond to a request to intervene.
- Full Driving Automation (Level 5): The sustained and unconditional (i.e., not ODD-specific) performance by an ADS of the entire DDT without any expectation that a user will respond to a request to intervene.

The nature of vehicle cooperation differs based on the level of driving automation. Limited cooperation may be achieved for driving automation Levels 1 and 2 because this automation does not involve the complete detection and response of objects and events. More substantial cooperation can be achieved with automation Levels 3 through 5. Table 1 describes the relationship between cooperation and automation, as presented in SAE J3216 standards.

It should be mentioned that although the SAE standards refer to all six levels of automation as Driving Automation Systems, the Automated Driving System (ADS) in the standards reference Levels 3, 4, and 5. A Cooperative Automated Driving System (C-ADS)-Equipped Vehicle is defined in the SAE J3216 standards as a vehicle equipped with Levels 3, 4, or 5 driving automation and is capable of utilizing CDA.

Table 1. Relationship Between Classes of CDA Cooperation and Levels of Automation



		SAE Driving Automation Levels					
		No Automation	**Driving Automation System**		**Automated Driving System (ADS)**		
		Level 0 *No Driving Automation (human does all driving)*	**Level 1** *Driver Assistance (longitudinal OR lateral vehicle motion control)*	**Level 2** *Partial Driving Automation (longitudinal AND lateral vehicle motion control)*	**Level 3** *Conditional Driving Automation*	**Level 4** *High Driving Automation*	**Level 5** *Full Driving Automation*
CDA Cooperation Classes	**No cooperative automation**	(e.g., Signage, TCD)	Relies on driver to complete the DDT and to supervise feature performance in real-time		Relies on ADS to perform complete DDT under defined conditions (fallback condition performance varies between levels)		
	Class A: Status-sharing *Here I am and what I see*	(e.g., Brake Lights, Traffic Signal)	Limited cooperation: Human is driving and must supervise CDA features (and may intervene at any time), and sensing capabilities may be limited compared to C-ADS		C-ADS has full authority to decide actions Improved C-ADS situational awareness beyond on-board sensing capabilities and increased awareness of C-ADS state by surrounding road users and road operators		
	Class B: Intent-sharing *This is what I plan to do*	(e.g., Turn Signal, Merge)	Limited cooperation (only longitudinal OR lateral intent that may be overridden by human)	Limited cooperation (both longitudinal AND lateral intent that may be overridden by human)	C-ADS has full authority to decide actions Improved C-ADS situational awareness through increased prediction reliability, and increased awareness of C-ADS plans by surrounding road users and road operators		
	Class C: Agreement-seeking *Let's do this together*	(e.g., Hand Signals, Merge)	N/A	N/A	C-ADS has full authority to decide actions Improved ability of C-ADS and transportation system to attain mutual goals by accepting or suggesting actions in coordination with surrounding road users and road operators		
	Class D: Prescriptive *I will do as directed*	(e.g., Hand Signals, Lane Assignment by Officials)	N/A	N/A	C-ADS has full authority to decide actions, except for very specific circumstances in which it is designed to accept and adhere to a prescriptive communication		

1.4 Document Organization

This section describes the remaining contents of this document. Chapter 2 presents a proposed ConOps for the incorporation of CDA features as part of the FDOT TSM&O processes and for the support of the traffic management centers and roadsides of CDA. The vision for the incorporation of CDA in TSM&O, as presented in the ConOps, is for the FDOT to start implementing infrastructure interfaces required for CDA by extending their current and planned traffic management strategies and CV infrastructure deployment applications to accommodate the CDA needs in an evolutionary manner. The ConOps recommends three enhancement management categories that can be implemented in stages including: Data Support of Management, Information and Guidance Provision, and Fully Cooperative Operations and Management

Chapter 3 includes a test plan for the infrastructure support of CDA in simulation and controlled real-world test environment. This plan includes the referenced documents, test objectives and scope, items to be tested, features to be tested, test approaches, test environment setup, and test scenarios and procedures.

Chapter 4 provides demonstrations and recommendations regarding the use of traffic simulation and co-simulation in the testing and evaluation of CDA and infrastructure support. The chapter first presents a review of traffic simulation and co-simulation platforms for the testing and evaluation of automated and cooperative driving. The chapter also provides an overview of the use of traffic simulation and co-simulation in this study to model merge areas in the presence of automation and cooperation with and without ramp metering.

Chapter 5 includes a proposed action plan to identify the action items required to establish and advance the practices needed for the infrastructure support of the CDA. The proposed action plan is based on required actions to achieve different levels of capabilities in technical and institutional dimensions and subdimensions, identified based on a review of the capability maturity models and frameworks developed for TSM&O, connected automated vehicles (CAVs), and other active traffic management and transportation strategies and processes. In addition, the chapter includes a training plan that proposes training modules for the purpose of building the workforce required for the incorporation of CDA consideration in TSM&O based on the identified action plan. Finally, the chapter proposes methods to select and prioritize strategic and tactical actions to build the capabilities required for the TSM&O support of CDA.

2. CONCEPT OF OPERATIONS

Chapter 2 describes the remaining contents of this document. Chapter 2 presents a proposed ConOps for the incorporation of CDA features as part of the FDOT TSM&O processes and for the support of the traffic management centers and roadsides of CDA. The vision for the incorporation of CDA in TSM&O, as presented in the ConOps, is for the FDOT to start implementing infrastructure interfaces required for CDA by extending their current and planned traffic management strategies and CV infrastructure deployment applications to accommodate the CDA needs in an evolutionary manner. The ConOps recommends three enhancement management categories that can be implemented in stages including: Data Support of Management, Information and Guidance Provision, and Fully Cooperative Operations and Management.

2.1 Vision of the Incorporation of CDA in TSM&O

The vision of the concept presented in this document is based on the realization of the challenges for TSM&O as the transportation system enters a period in which there will be an increasing level of heterogeneity in the levels of connectivity, automation, and cooperation of the vehicles in the traffic stream. This challenge is even higher considering the dynamic changes in the market penetrations of these different types of vehicles in the traffic stream and the uncertainty associated with these dynamic changes.

The vision for the incorporation of CDA in TSM&O is for the FDOT to start implementing infrastructure interfaces required for CDA by extending their current and planned traffic management strategies and CV infrastructure deployment applications to accommodate the CDA needs in an evolutionary manner considering the abovementioned challenge. With the limited market penetration of CDA vehicles in the traffic stream in the near future, the extension of the existing capabilities should be implemented in an evolutionary manner that will provide support to the existing applications and provide improvements to the system performance as they are implement. As the CDA vehicles begin to be implemented, the already introduced enhancements to the system operations can be used to support the CDA and make use of the CDA in improving TSM&O. At this future stage, the additional extension of the capabilities will be implemented as needed.

Considering the above, the following enhancement management categories are recommended for this concept of operations for TSM&O.

- Enhancement Management Category 1 – Data Support of Management: This category of enhancements improves existing operational strategies by utilizing data from CV and vehicles equipped with CDA Class A and higher capabilities. This will involve using additional data collected from CV and CDA that can improve existing freeway, arterial, and integrated corridor management strategies such as ramp metering, signal control, incident and work zone management, and managed lanes. This includes CV data according to SAE J2735 and SAE J2945 standards. Additional vehicle-level measurements collected from connected automated vehicles and CDA can include more detailed statuses and situational data that are collected using various sensors and communication of vehicle intents and cooperation requests and acceptance, as described in SAE J3216 standards. The Information Systems section of this document presents information about the types of data that can be collected using connected vehicles, connected automated vehicles, and CDA.

- Enhancement Management Category 2 – Information and Guidance Provision: This category involves providing additional infrastructure information that can be used by CV and CDA. Current CV applications involve the provision of information according to SAE J2735 and various SAE J2945 standards, including SPaT, MAP (Geometry Message), traffic information messages (TIM), and Road Safety Messages (RSM). However, additional messages will need to be specified to support CDA such as the vehicle speed, gap setting, lane changing parameters, platooning parameters, and dynamic merge parameters. These messages, although required for CDA vehicles, can also be used by CV vehicles that are equipped with onboard units that are capable of receiving this information. CDA with Level 1 or Level 2 of automation and Class 1 and 2 of cooperation can receive broadcasted information and use them for longitudinal and lateral control but with no cooperation with the infrastructure. Higher levels of automation and classes of collaboration will allow us to also use this information in a similar manner but can also participate in Enhancement Management Category 3. The information from the infrastructure can improve CDA safety and mobility and expand the ODD by providing data that supplements the information gathered by vehicle sensors such as cameras, LIDAR, and radar. This level may include the provision of recommended strategic, tactical, and operational actions that can be used by both the connected vehicles and CDA vehicles. For example, the infrastructure can provide recommendations to alter driving behavior, such as increasing the car-following gaps on wet pavement, reducing speeds, or merging ahead of lane closures. This information could be provided to human-driven connected vehicles for use by the driver and to CDA-equipped vehicles to be used by the CDA.

- Enhancement Management Category 3 – Fully Cooperative Operations and Management: Enhancement Management Category 3 includes operational strategies that require the collaboration between the infrastructure and individual vehicles of automation level 3 and above and cooperation class 3 and 4. This involves the infrastructure providing vehicle specific guidance. In addition to status and intent sharing, as more CDA vehicles are introduced into the traffic stream, the FDOT can further enhance their operational strategies and implement new collaborative infrastructure strategies that require the collaboration between the infrastructure and the vehicles using CDA-specific communications. These enhancements will include the provision of prescriptive information and feedback from CDA vehicles to support Class C (agreement seeking) and Class D (prescriptive) of cooperative driving, according to the SAE J3216 Standards. The provided information will build on the information presented in Enhancement Management Category 2.

The enhancement categories in the above list will take advantage of the capabilities of connected and CDA vehicles to enhance TSM&O and accommodate the needs of CDA. The modified and new functions in the three categories will need to consider that various levels of vehicle automation according to SAE J3016 and the cooperation classes according to SAE J3216 will operate in the system simultaneously for a long time, with changing levels of market penetrations. The first two categories (Data Support of Management and Information Guidance and Provision) can provide benefits, even with no or limited CDA functions, but they are required to support the enhancements of the third category (Fully Cooperative Management and Operations). It is recommended that

FDOT will start implementing Category 1 enhancements and some of Category 2 enhancements, considering the limited availability of higher classes of the CDA in the early phases of the deployment. However, this implementation can be conducted in a manner that accommodates further enhancements to achieve the remaining Category 2 and Category 3 enhancements.

The enhancements listed above are recommended to be implemented in accordance with the goals, objectives, and priority focus areas of the FDOT TSM&O Strategic Plan (FDOT, 2017) and the FDOT Connected and Automated Vehicle (CAV) Business Plan (FDOT, 2019). A brief review of these plans is presented in the "Relationship to FDOT Plans" section of this chapter.

2.2 Stakeholders

The consideration and incorporation of CDA-based applications in the TSM&O requires coordination and collaboration between different stakeholders. These include:

- Infrastructure owners and operators, including the FDOT, MPOs/TPOs, and local agencies.
- FHWA CARMA Program
- Intelligent Transportation Systems (ITS) and connected vehicle technology manufacturer providers
- Automobile original equipment manufacturers (AOEMs)
- Third-party automated and cooperative driving automation hardware and software developers, manufacturers, and suppliers
- Fleet operators that have the potential to adopt CV and ADS technologies, including maintenance vehicles, commercial vehicles, transit vehicles, delivery vehicles, and transportation network companies (such as Uber and Lyft)
- Public safety agencies including law enforcement and emergency response agencies.
- Metropolitan planning organizations
- General public and users of the transportation system.

2.3 Relationship to FDOT Plans

The FDOT TSM&O Strategic Plan (FDOT, 2017) includes the vision, mission, goals, objectives, and priority focus areas of the TSM&O program. It also identifies action plans to be accomplished in three to five years. The mission is to "identify, prioritize, develop, implement, operate, maintain, and update TSM&O program strategies and measure their effectiveness for improved safety and mobility." The selected performance metrics include planning time index (PTI), throughput, delay reduction for all users, all lanes cleared times, crash rate, and crash severity. The Strategic Plan identifies six focus areas: TSM&O Mainstreaming, Arterial Management, Connected Vehicles, Express Lanes, Freeway Management, and Information Systems. This chapter identifies applications in the three categories of enhancements discussed above to consider and incorporate CDA in Arterial Management, Express Lanes, Freeway Management, and Information Systems focus areas of the Strategic Plan. The Connected Vehicles, specified as one of the focus areas of the FDOT TSM&O Strategic Plan, are considered to work in combination with CDA to support TSM&O.

The FDOT Statewide Arterial Management Program (STAMP) Action Plan (FDOT, 2018) identifies action items to advance the FDOT Statewide Arterial Management Program. The STAMP Plan identifies the following early initiatives related to the subject of this study:

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

These initiatives indicate a strong FDOT focus on using data from emerging technologies to estimate system performance, as well as on adaptive signal control in arterial management.

Considering the above focus, the FDOT developed *the 2019 Business Plan of the Connected and Automated Vehicles (CAV) Program* (FDOT, 2019). The Business Plan includes an institutionalized framework and timeframes to support statewide deployment. The plan identifies specific CAV action items. The ultimate objectives stated in the CAV Business Plan are to achieve Vision Zero, which envisions a fatality-free roadway network and a congestion-free transportation system in Florida using CAV technologies. The focus areas of the FDOT CAV Business plan to ensure effective CAV deployments are listed below.

- Policies and Governance
- Program Funding
- Education and Outreach
- Industry Outreach and Partnerships
- Technical Standards and Specifications Development
- CAV Implementation Readiness
- CAV Deployment and Implementation

The following sections of this chapter will discuss the concepts of the incorporation of the CDA in focus areas of the FDOT TSM&O Strategic Plan including information Systems, Freeway Management, Express Lanes, and Arterial Management.

2.4 Information Systems

Existing Condition: Information systems include the collecting, processing, archiving, and utilization of data and the provision of information to travelers. Although the applications are recognized as a separate focus area in the FDOT TSM&O Strategic Plan, it is also the basis for all of the incorporation of other focus area applications since all applications require data and information provision. The FDOT information systems, as listed in the FDOT TSM&O Strategic Plan, include the SunGuide® Software (http://www.sunguidesoftware.com/), FL511, Data Integration and Video Aggregation System (DIVAS), data archival systems, and performance assessment tools. These systems also include ATSPM tools, the FDOT Vehicle-to-Everything (V2X) Data Hub (currently under development), Statewide Express Lane Software (SELS), and the Central Florida Regional Integrated Corridor Management System (R-ICMS). The basic modules that support real-time traffic performance monitoring and estimation in the SunGuide®

software are the Traffic Detection (also known as the Transportation Sensor Subsystem (TSS)) module, the Travel Time module, and the data sharing with third-party vendor modules. The travel time is estimated based on point detectors, automatic vehicle re-identification (AVI) technologies (including electronic toll tag, license plate readers, and Bluetooth readers), and third-party vendor data (travel time and incident information). A "Connected Vehicle" module was introduced in SunGuide® that allows for the estimation of travel time based on connected vehicle data. The FDOT has initiated a project to develop the V2X Data Exchange Platform to collect and ingest all data generated from CAV projects, and TSM&O data from existing freeway management systems, arterial management systems, and commercial vehicle and freight management systems. The platform also includes application program interfaces (API) as needed, to ingest data from other systems into the V2X data exchange. This platform will provide the opportunity to collect and process data from multiple sources to support the TSM&O applications, as described in the remaining sections of this document. CDA can improve information system management by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: The FDOT can enhance and extending their V2X Data Hub, currently under development to allow it to capture cooperative vehicle data and automated vehicle data, in addition to the current plans of capturing, processing, and archiving connected vehicle data and data from other sources.

This effort should also consider the additional data items that can be collected from CDA, as specified in upcoming SAE standards. Connected vehicle data can be captured by a roadside unit or can be sent to the cloud for processing and use. The CV message types and components are specified in the SAE J2735 standards (SAE International, 2022a) and various SAE J2945 standards (SAE International, 2017). The basic safety message (BSM), specified in J2735, contains valuable information that can be used in traffic management applications. Part 1 is sent in every BSM broadcasted 10 times per second and contains core data elements, including vehicle position, heading, speed, acceleration, steering wheel angle, and vehicle size. BSM Part 2 consists of a large set of optional elements that are not mandatory, and includes precipitation, air temperature, wiper status, light status, road coefficient of friction, Antilock Brake System (ABS) activation, Traction Control System (TCS) activation, and vehicle type. A large proportion of these parameters are currently unavailable from every vehicle. However, some of these parameters and additional status and intent information are expected with CDA.

This effort should consider the additional data items that can be collected from CDA and connected automated vehicles. The connected automated vehicles are expected to include broadcasted information by the vehicles derived based onboard sensor (e.g., Lidar, Radar, and Cameras) measurements such as the gaps to the preceding vehicles, difference in speed between vehicles on the same lane, and so on. The type of the information is specified in sensor data sharing message (SDSM) in an upcoming SAE standards (SAE International, 2022b). The shared sensor information in SDSM includes descriptions of the detected object characteristics using vehicle sensors such as size, location, motion state.

The additional data can also include specific information collected from CDA such as the time required for CDA to change lane after initiating the lane change maneuvers, the ability of the vehicle to achieve the speed change as commanded by the infrastructure, and so on. There is currently no ongoing effort to produce CDA message sets, but such effort is expected in the future.

In general, automated vehicles and CDA vehicles can provide additional information, such as event data, obstacles, back of queue, headway between vehicles, time for lane change, distance for lane change, willingness to cooperate, time-to-collision, headways, reaction time, and gap acceptance. The type of the obtained CDA information will be identified in a future task based on the examination of CARMA Analytics. The performance measures that can be estimated based on the newly collected data can be classified as follows:

- *Measures that are currently used for transportation system operations, management, and planning:* These measures include travel time, origin-destination, vehicle classification, queue length/back-of-queue, stops, ATSPM signalized intersection measures, event (incident, weather, and work zone) detection, and so on.
- *New measures for use in traffic management:* These include measures such as stops, accelerations and decelerations, standard deviations of speeds, intersection movement-level delays and queues, near-misses, emission, and route choice, gaps, number of oscillations, time-to-collision, latency in changing lanes, percentage following speed commands, and so on.

Hadi et al. (2019) assessed the quality of travel time estimates based on CV data on freeway and urban street segments and concluded that for a high demand freeway segment, a low market penetration (1%-2%) is generally sufficient to produce an error that is lower than 10%. For the urban street segments, however, this data quality cannot be achieved until the market penetration of CV exceeds 10%-15%. It should be noted that these results can be different for segments with different demands and configurations, particularly with regard to the congestion level and average spacing of intersections on the urban street segments. Hadi et al. (2021) examined the use of detailed metrics in combination with the commonly used macroscopic metrics for the estimation of traffic safety and mobility. The utilized disturbance metrics are the standard deviation of speed between vehicles, standard deviation of speed of individual vehicles, acceleration, jerk rate, number of oscillations, time exposed to time-to-collision, rear-end crash index, and a measure of disturbance durations. The authors used data clustering for better off-line categorization of the traffic conditions.

Enhancement Management Category 2 – Information and Guidance Provision: These enhancements will include the provision of situational awareness information and guidance to CV and CDA vehicles to influence the strategic (e.g., route and mode selection), tactical (e.g., lane selection and changing), and operational (e.g., car-following and gap acceptance) actions of drivers and automated vehicles with different levels of automation and cooperation. Additional information, such as signal phasing and timing, geographic maps, transit signal priority and emergency vehicle preemption status, and traveler information messages (TIM) will be provided to the vehicles, in addition to CDA-specific TIM messages. In addition, these enhancements will include the provision of information to support dynamic operation design domain (ODD) based on traffic and weather conditions. The ODD describes the conditions and circumstances under which the automated vehicles are designed to operate according to SAE J3016 standards. This includes environmental, geographical, and time-of-day restrictions, and required presence/absence of traffic and/or roadway characteristics. For example, vehicle automation can be restricted to access-controlled highways, low-speed traffic, fair weather conditions, geofenced areas for specific routes, and/or specific time of day (e.g., daylight operation only) (Animesh et al., 2019; Balse et al., 2019a).

Enhancement Management Category 3 – Fully Cooperative Operations and Management: This category of enhancement will build on the Category 1 and Category 2 enhancements of the Information System, described above, to collect data and provide information for use by a fully cooperative operations and management system.

2.5 Freeway Management

The FDOT TSM&O Strategic Plan indicates that the Freeway Management Program of the FDOT focuses on ramp metering (RM), Hard Shoulder Running (HSR), Integrated Corridor Management (ICM), FL511, regional transportation management center (RTMC) operations and traffic incident management and includes Severe Incident Response Vehicles (SIRV) and Road Ranger Service Patrols (RRSP). The freeway management operations are currently managed by the FDOT using the SunGuide® software.

This section presents freeway management concepts that can be categorized according to the three enhancement categories listed earlier for the incorporation of CDA in the freeway management applications. The addressed applications include On-Ramp Merge Support and Management, Incident Management, Work Zone Management, Speed Management, Lane and Shoulder Management, Car-following and Platooning Management, and Safety. Express Lane Management is discussed in a subsequent section since it is identified as a separate focus area in the TSM&O Strategic Plan.

2.5.1 On- Ramp Merge Support Management

Existing Condition: The FDOT manages on-ramp merge areas using adaptive ramp metering systems (referred to in Florida as ramp signaling). An example of an adaptive ramp metering module utilized in Florida is the Washington Department of Transportation's fuzzy logic algorithm. These systems utilize data collected by point detectors on the mainline and on-ramps as inputs. For example, the data inputs to the fuzzy logic algorithm include a) mainline occupancy upstream of the on-ramp; (b) mainline speed upstream of the on-ramp; (c) ramp queue occupancy; (d) advance queue detector occupancy; (e) high occupancy vehicle (HOV) bypass volume, if utilized; (f) downstream speed from one or more detector station(s); and (g) downstream occupancy from one or more detector station(s). The output from the fuzzy logic algorithm is a vehicle metering rate that is updated every 20 seconds. The decision to activate and deactivate the ramp metering is done through the use of a manually fixed schedule by an operator watching the CCTV camera streams at the traffic management center. Hadi et al. (2017) developed a method to activate ramp metering based on forecasting recurrent congestion, incidents, and bad weather conditions. Elefteriadou et al. (2011) considered the probability of traffic breakdown as part of the prediction of congestion for the purpose of setting the metering rate. Later, Hadi et al. (2015) modified the Fuzzy Logic algorithm to include the probability of traffic breakdown. CDA can improve on-ramp merge support and management by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: This enhancement uses the CDA and automated vehicles described earlier, in addition to BSM and CDA to calculate new measures to support ramp metering. The data can be used to determine geometry improvements, make decisions to activate metering, and update existing adaptive algorithms to select a metering rate. For example, the data can be used to identify the need for geometric improvements, such as increasing the acceleration distance and queuing storage, taking into account the truck requirements. In addition, the data can be used to support the decision to activate metering during the recurrent and non-recurrent conditions with the introduction of fine-grained measures by building on the methodology that uses detector data to reduce the probability of breakdown (Hadi, Xiao, et al., 2019). The data can also be used as additional inputs to ramp metering rate calculations in traffic adaptive ramp metering algorithms such as the Fuzzy Logic and Swarm algorithms, which can be enhanced to use this data for more effective proactive ramp metering. CV and CDA data will allow for better prediction of traffic breakdown and safety for use in metering decisions based on measures like the standard deviations of speed, accelerations/decelerations, time-to-collision, and number of oscillations, as opposed to prediction based on more macroscopic measures based on point detectors (see the discussion in the Information Systems section for more details). For example, the fuzzy logic algorithm implemented in Washington State and Miami, Florida can be enhanced by introducing new fuzzy rules that reflect the probabilities of breakdown, crashes, vehicle speeds, available gaps, accepted gaps, and ramp queues, all of which can be measured and/or estimated using CV and CDA data. New ramp metering algorithms can be written to take full advantage of high-resolution data from both vehicles and infrastructure.

Enhancement Management Category 2 – Information and Guidance Provision: This enhancement involves providing situation awareness and guidance to CV and CDA, such as recommending lane change to mainline traffic ahead of the merge area and speed for mainline and merging traffic by considering the geometry, weather conditions, and vehicle type. Scarinci et al. (2013) presented a ramp metering strategy that takes advantage of vehicles equipped with Cooperative Adaptive Cruise Control (CACC) technology, which recommends the cooperation of mainline vehicles for facilitating merging maneuvers of on-ramp vehicles released by ramp metering signals. The simulation analysis showed congestion reduction between 50 and 70 percent due to the cooperative system. Park & Smith (2012) evaluated a CV-enabled speed advisory, lane changing advisory, and gap selection advisory to enhance operations at the merge area. The results revealed that the proposed algorithm could help reduce the vehicle-hour travelled by about five percent and improve the average speed by up to nine percent, given that the compliance rate is high.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: These enhancements will involve infrastructure support of dynamic merge control initially coexisting with ramp metering. With this management, the speeds, gaps, and accepted gaps of the vehicles on the mainline and ramps can be controlled and guided by the infrastructure to improve performance, taking into account geometric and weather conditions. With the increase in the market penetration of CDA vehicles, the operations of the on-ramp merge and weave areas will improve significantly due to the dynamic merge conducted by Class C and Class D cooperative vehicles. Ramp merge control can operate a standalone application, or in combination with ramp metering to improve performance. Enhancement Category 3, including cooperative ramp metering and dynamic merge control, will have to consider the heterogeneous mixture of various levels of automation and cooperative driving. The dynamic merge is expected to utilize vehicle-to-vehicle (V2V) communications. However, the ramp metering realization of the cooperative nature of the vehicles may justify the provision of a priority non-controlled ramp lane or preemption of metering when a CDA vehicle sends its status and intent to the infrastructure. Enhancement Category 3 can also include the support of the dynamic merge control by providing a series of advisory messages to mainline vehicles approaching the merge point that prepare CDA vehicles for an upcoming merge and encourage or direct safe and consistent merging behavior. Pueboobpaphan et al. (2010) assessed an algorithm for automated on-ramp merging using simulation. The algorithm encourages smooth deceleration of the mainline vehicles upstream of the merging area to create gaps for the merging vehicles. The researchers found that the effectiveness of the merging assistant is more notable when the CACC penetration is 50 percent.

2.5.2 Incident Management

Existing Condition: Traffic incident management (TIM) is one of the most important functions of TSM&O. Incidents are detected based on data from multiple sources, including traffic detectors, external notifications, communications with the Florida Highway Patrol (FHP)/police, third-party vendor feeds, service patrol reporting, and/or video analytics. The operators enter additional information in the SunGuide® user interface, including verifying the location and severity of the incidents. The service patrol vehicles, referred to in Florida as the Road Rangers, communicate detailed information to the TMC that is critical for event management by using an application developed for this purpose. The FDOT traffic management centers, Road Ranger vehicles, and Rapid Incident Scene Clearance (*RISC)* provide critical capabilities in supporting incident verification, response, and clearance, and in incident site management. The SunGuide® system also provides the operator with the ability to associate alternate routes and events with the incident. CDA can improve work zone management by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: This category can use BSM and CDA data to allow for quicker detection, crash location identification, and potentially crash severity (based on level of damage) information from automated vehicles if such information is included in the upcoming SAE J3224 standards. Automated vehicle and CDA vehicle data can be also useful for determining the causes of incidents diagnosis in off-line analysis of incidents. The data can be used to improve onsite monitoring and site management practice. In addition, it will provide a better understanding of driver behavior in the vicinity ahead of incidents. The collected information can include adverse weather and pavement conditions, incident details, and the blockages of the lanes or shoulders. National Cooperative Highway Research Program (NCHRP)Research Report 904 (National Academies of Sciences, 2019) investigated the application of big data technologies to improve TIM, including improvement of scene management practice, resource utilization and management, safety, and enablement of predictive TIM, support for performance measurement and management, and support for TIM justification and funding. Enhancement Category 1 will introduce new types of performance metrics based on CV, CAV, and CDA that will allow for better prediction of incident occurrence and prediction of incident impacts on real-time operations for use in proactive incident management strategies. This can include near misses, time-to-collision, number of oscillations, speed differentials, headway distribution, and so on. The collected data can also help monitor driver lane-changing and car-following behaviors near the incidents, the factors impacting behavior and compliance, and the impacts of the behavior on traffic operations. The collected data can also be used to assist in TIM planning and justification of TIM program funding.

Enhancement Management Category 2 – Information and Guidance Provision: This category can also include the provision of guidance on route selection, lane selection, and speed ahead of the incident location. The information can also include providing approaching emergency vehicle information to the vehicles. This category will involve determining and disseminating the optimal routing, site location, and lighting status to emergency vehicles. It will also involve geofencing of an incident scene to reduce vehicle intrusion and provide alerts to responders about safety risks.
Enhancement Management Category 3 – Fully Cooperative Operations and Management: This category includes providing instruction of optimized lane utilizations, vehicle speeds, car-following gaps, and dynamic lane change and merge support ahead of the incidents. These enhancements provide optimal routings of emergency vehicles and instruct lane and route clearance to allow emergency vehicle passing. The CDA vehicles will negotiate with the infrastructure and confirm whether they will follow the prescribed actions. The above information can vary by vehicle attributes.

2.5.3 Work Zone Management

Existing Condition: FDOT is developing an action plan that will provide guidance for implementing Smart Work Zones (SWZs). The CAV Business Plan includes recommendations for near-term CAV pilot projects related to SWZs and autonomous truck-mounted attenuators. FDOT's Smart Work Zone Initiative will test and evaluate SWZ technologies using CAV and ITS applications (NOCoE, 2021). Later the FDOT, identified several emerging technologies for implementation that include but are not limited to queue detection and warning systems, speed monitoring and management systems, construction equipment alert system, travel time monitoring system, over-height vehicle warning systems, vehicle intrusion systems, and reduced speed alert systems. Recent FDOT District SWZ applications include queue warning, variable speed limit, smart arrow boards, and dynamic late/zipper merge. The FHWA developed the Work Zone Data Exchange specification to help make work zone data available for use to improve performance. CDA can improve work zone management by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support for Management: The enhancements in this category involve collecting CV and CDA data for detecting unplanned work, identifying work zone configuration, performance monitoring and prediction to support smart zone applications, providing a better understanding of driver behaviors ahead and in the vicinity of the work zone, and identifying the difficulties of automated vehicles in work zones. Location-specific data, the actions performed by vehicles as a result of their direct interactions, and the near misses can help in identifying the need for changes to work zone geometry and operations.

Enhancement Management Category 2 – Information and Guidance Provision: The provided information in these enhancements can include worker safety alerts, recommended routing and merge locations, and warning of any unexpected events, including intruding vehicles. The information will also support safe construction activities by providing parameters for staging work vehicles in a work zone. The information can be provided to workers using a mobile application.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: Fully cooperative operations and management provide approaching vehicles with optimized lane utilizations, dynamic speed harmonization that involves vehicle-specific (trajectory-based) speeds, car-following gap recommendations for CACC at and ahead of the work zone, and trajectory optimization. It will also include cooperative dynamic merge, cooperative construction vehicle access points, and cooperative truck-mounted attenuators, such as the automated truck-mounted attenuator (ATMA). If implemented, this enhancement can also support alternating one-way operations on a two-lane roadway.

2.5.4 Speed Management

Existing Condition: The SunGuide® System has a variable speed limit (VSL) module that allows operators to configure VSL messages and activation parameters. FDOT District 5 implemented a VSL system on I-4 in Orlando to reduce congestion and crashes during daily rush hours. The system analyzes sensor data and makes recommendations on adjusting speeds subject to an operator's confirmation. FDOT District 4 in Broward County implemented a VSL system to improve safety along a busy section of SR25/US27 (Okeechobee Road) near West Broward High School. This system includes CCTV cameras for the purpose of verifying proper VSL operation. CDA can improve speed management by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: These enhancements involve the use of information collected using CV and CDA vehicles to measure the location and attributes of the bottleneck, shockwaves, and queues. CDA will add additional data about the status and intent of the vehicles and the position of surrounding vehicles in relation to the CDA vehicles. These enhancements can also include predicting the probability of breakdown and changes to safety conditions that justify motorist alerts using machine learning and/or traffic flow theory.

Enhancement Management Category 2 – Information and Guidance Provision: The enhancements in this category involve providing guidance regarding back-of-queue and segment level speed harmonization, with consideration of traffic and environmental conditions.

Enhancement Management Category 3 - Fully Cooperative Operations and Management: These enhancements involve speed harmonization, which includes communicating vehicle-specific (trajectory-based) speed to CDA Levels 3 and 4 vehicles. The application can obtain feedback about the utilization of these speeds to achieve optimal operations at the freeway segment. Speed harmonization involves gradually lowering speeds upstream of a heavily congested area in order to reduce stop-and-go traffic. Simulation studies (Ghiasi et al., 2017; Learn et al., 2018; Talebpour et al., 2013; Yang & Rakha, 2017) found that speed harmonization can result in significant travel time reduction (e.g., a 10% reduction corridor-wide and a 35-percent reduction at localized bottleneck segments at CAV penetration rates of 10 percent or higher), and improvement in traffic smoothness and stability. Recent simulation studies (Ghiasi et al., 2017) and field experiments (J. Ma et al., 2021) prove the potential of a trajectory-based approach in enhancing traffic smoothness and therefore improving efficiency and safety.

2.5.5 Lane and Shoulder Management

Existing Condition: The FDOT TSM&O strategic plan specifies hard shoulder running as one of the freeway management strategy focus areas. In Miami, Florida, approximately nine miles of freeway at the SR 874 and SR 878 corridors were opening for the Bus On Shoulder (BOS) project in 2007. Buses were allowed to begin operating on the shoulders of these routes when the speed of general traffic fell below 25 miles per hour. Four years after their opening, a 50-percent reduction in the number of late buses running along the BOS corridor was found. Lane and shoulder control can be based on time-of-day or dynamic based on traffic conditions. An example is the application on a 6.5 miles section of I-66 between I-495 and US 50 in Fairfax County of Virginia. I-66 was originally time of day based (i.e., static part-time shoulder) and was opened first in 1992. The roadway section was converted to dynamic part-time shoulder use in 2015. In a FHWA project, Jenior et al. (2019) developed a control logic for dynamic part-time shoulder use that can be used to maximize the benefits of this application. CDA can improve lane and shoulder management by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: This category of enhancements uses CV and CDA data to support decisions to open and close the shoulder and lanes and to identify safety and mobility issues associated with lane and shoulder management. The collected data will also provide information about lane utilization and vehicle lane change behaviors.

Enhancement Management Category 2 – Information and Guidance Provision: These enhancements are modifications made to the FDOT central software and roadside infrastructure to allow the provision of information and guidance about the closure, opening, and restrictions (e.g., by vehicle type and occupancy) of shoulders and lanes. The enhancements can also include the provision of information to select the lanes that improve the performance of the system, discourage discretionary lane changes, and provide lane change advisory ahead of off-ramps or opened lanes or shoulders.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: These enhancements will include implementing a cooperative lane-balancing strategy to balance the traffic across lanes. They can also include cooperative dynamic lane changing with consideration of Cooperative Adaptive Cruise Control (CACC) and platooning. Optimizing the lane utilization could help to mitigate the congestion at freeway traffic bottlenecks.

2.5.6 Car Following and Platoon Management

Existing Condition: Currently, there is a limited management of car-following management by traffic management agencies, although queue warning may impact the car-following behaviors of drivers. CDA can improve car-following and platoon management by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management*:* These enhancements can include collecting information about the gaps left and platooning parameters under different traffic, geometry, and environmental conditions.

Enhancement Management Category 2 – Information and Guidance Provision*:* These enhancements can include disseminating warnings regarding the gaps left by vehicles under different traffic and environmental conditions.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: Fully Cooperative Operations and Management includes providing vehicle-specific gaps; specifying platoon size; and coordinating platoon formation, dissolution, and rear-join for vehicles external to the platoon. It can also set the intra-platoon and within platoon gaps and speeds. Simulation studies (Milanés & Shladover, 2014; Nowakowski et al., 2010; Shladover et al., 2012) showed that autonomous adaptive cruise control will have no effect or adverse effect on system performance. On the other hand, the existing studies showed that CACC can provide significant improvements in performance. This is because with autonomous adaptive cruise control (ACC) the equipped vehicle only reacts to changes in speed of the immediate leading vehicle and can result in instability in flow due to more than needed sensitivity and reaction time as is the case with human driven vehicles. The ability to get information about the movement of few leading vehicles will increase the stability. The drivers are also expected to have higher trust in CACC technology compared to autonomous ACC, which may make them set their system with more aggressive parameters. With the shorter following gaps enabled by CACC systems, lane capacity could increase from the typical 2,200 vehicles per hour to almost 4,000 vehicles per hour at 100 percent market penetration (Ghiasi et al., 2017). This improvement in performance is expected to be higher with the cooperation of an infrastructure that provides CACC and platooning parameters. The Highway Capacity Manual (TRB Forthcoming) will include information about the expected impacts of CACC on capacity for both freeways and arterial streets. An example of the provided information is shown in Table 2.

Table 2. The Impacts of CACC on the Maximum Service Volume (Capacity) of Basic Freeway Segments According to the HCM (TRB Forthcoming)

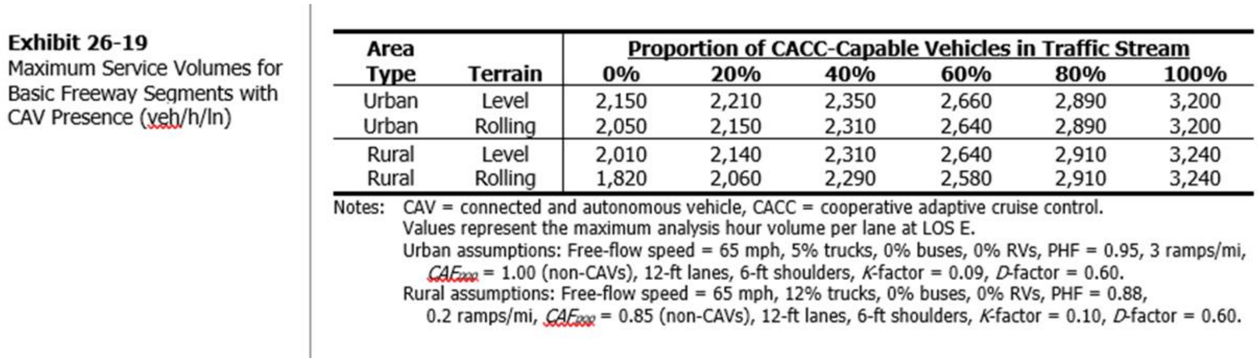


Exhibit 26-19
Maximum Service Volumes for Basic Freeway Segments with CAV Presence (veh/h/ln)

Area Type	Terrain	Proportion of CACC-Capable Vehicles in Traffic Stream 0%	20%	40%	60%	80%	100%
Urban	Level	2,150	2,210	2,350	2,660	2,890	3,200
Urban	Rolling	2,050	2,150	2,310	2,640	2,890	3,200
Rural	Level	2,010	2,140	2,310	2,640	2,910	3,240
Rural	Rolling	1,820	2,060	2,290	2,580	2,910	3,240

Notes: CAV = connected and autonomous vehicle, CACC = cooperative adaptive cruise control.
Values represent the maximum analysis hour volume per lane at LOS E.
Urban assumptions: Free-flow speed = 65 mph, 5% trucks, 0% buses, 0% RVs, PHF = 0.95, 3 ramps/mi, CAF_{2000} = 1.00 (non-CAVs), 12-ft lanes, 6-ft shoulders, *K*-factor = 0.09, *D*-factor = 0.60.
Rural assumptions: Free-flow speed = 65 mph, 12% trucks, 0% buses, 0% RVs, PHF = 0.88, 0.2 ramps/mi, CAF_{2000} = 0.85 (non-CAVs), 12-ft lanes, 6-ft shoulders, *K*-factor = 0.10, *D*-factor = 0.60.

2.5.7 Freeway Safety Applications

Existing Condition: The SunGuide® system has a Wrong Way Driving (WWD) system that receives detected WWD event data from field devices capable of detecting WWD. The WWD event in SunGuide® can also be created manually. When a WWD incident is detected, closed-circuit television (CCTV) and the associated presets can be automatically invoked. Specific DMS warnings and email and text recipients can be included in the response plans. SunGuide® also has a Safety Barrier module that provides the capability to receive barrier events when cars breach the roadside cable, resulting in a nearby strobe light being activated and crash location information transmitted to the traffic management center. Another freeway safety application is queue warning. CDA can improve freeway safety by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: These enhancements collect information about WWD and "near"-WWD. In addition, the enhancements collect information about the queues, crash occurrences, and near misses, and allow for the prediction of unsafe conditions and geometry in off-line and real-time operations.

Enhancement Management Category 2 – Information and Guidance Provision: These enhancements involve disseminating information to vehicles to improve safety, including back-of-queue information, rules of practice (conditions in which AV can operate), and segment level safe speed under different conditions.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: This category involves infrastructure-control of WWD vehicles, reactions to queues, and reaction to obstacles.

2.6 Express Lanes Management

Existing Condition: The goal of express lanes, according to the FDOT TSM&O Strategic Plan, is to reduce congestion, improve traffic performance, and give drivers travel options. Dynamic tolling is applied in Florida to maintain an acceptable level of performance on the express lane. FDOT has implemented or is implementing express lanes on I-95 in Miami-Dade County and Broward County; I-595 in Broward County; Palmetto Expressway in Miami-Dade County; I-75 in Broward County; I-295 in Duval County; I-4 in Orange County; Beachline Expressway in Orange County; Florida Turnpike in Orange County; Veteran's Expressway in Hillsborough County; and Homestead Extension of Florida's Turnpike (HEFT) in Miami-Dade County. Procedures for express lane planning, design, operations, and maintenance are being developed in an FDOT Express Lane Manual. The TSM&O functions associated with express lanes are to implement dynamic pricing and dynamic pricing in express lanes, monitor and enhance operations, ensure effective enforcement, and provide incident management. An example of the methods used for dynamic pricing is the application used by FDOT District 6, which is based on real-time detector measurements. This application set the toll rates based on the level of service defined based on density in accordance with the Highway Capacity Manual (HCM). The application calculates density as a function of the speed and volume measured by point detectors. The initial deployment of dynamic pricing utilized the average density for the entire I-95 Express facility as the decision variable. Later, an option was added to utilize the density based on the measurements of selected detectors (such as at bottlenecks) for the toll calculation. An Operator Interface is included to alert the operator of toll rate changes, allowing for modifications to these rates. CDA can improve express lanes management by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: The enhancements in this category collect and use CV and CDA data for better decisions regarding the pricing, access control, and eligibility of vehicles with different levels of automation, ridership, mode, and type. The collected data can also allow better access control by identifying the difficulty in weaving and merging/diverging maneuvers to/from the express lane. Depending on laws for resolving privacy issues, the collected data may allow for the detection of the number-of-occupants to support enforcement.

Enhancement Management Category 2 – Information and Guidance Provision: This includes disseminating information such as guidance for optimized express lane utilization under different traffic, incident, and weather conditions. The information can include segment level speed, reversible lane status, and lane change recommendations ahead of the express lane access point.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: This Category involves controlling the lane utilization, speed, lane changing, and car-following gaps, and platooning parameters in the express lane itself, upstream of the ingress to and downstream of the egress from the express lane, taking into account vehicles with different levels of automation and classes of cooperation. These strategies can potentially include dedicating a lane to ADS to optimize the operations. The operation of ADS in a separate managed lane will allow for higher probabilities of collaboration and traveling in platoons.

(Ma et al., 2019) defined the top-priority operational concept for CAV operation on managed lanes with the purpose of facilitating successful deployment of managed lane solutions. The high-priority applications involve platooning/CACC, cooperative merging, and speed harmonization (both segment-based traffic speed harmonization and trajectory-based) algorithms. The concept considers parameters that affect CAV operation, including design characteristics, physical characteristics, operational parameters, and technology requirements.

2.7 Arterial Management

According to the FDOT TSM&O Strategic Plan (2017), arterial management includes strategies such as regular retiming and coordination, adaptive signal control technologies (ASCT), integrated corridor management (ICM), active arterial management (AAM), utilizing CV in signal control, and Automated Traffic Signal Performance Measures (ATSPMs). These strategies can involve multimodal management that addresses general traffic, pedestrians/bicycle, transit, and freight in an integrated manner. Recent years have seen an increase in the development of ASCT and the adoption and use of ATSPM to improve system performance. ATSPM is addressed in the Information Systems section of this document. This section addresses the integration of CDA with the other strategies.

2.7.1 Signal Retiming and Coordination

Existing Conditions: Agencies have used signal timing optimization tools combined with the fine-tuning of signal timing based on limited data and field observations for the setting of signal timing plans. The utilized data is turning movement volume data collected for one day and approach volumes collected for two to seven days. Agencies normally fine-tune the signal timing after implementation to improve performance based on field observations. The agencies then update the signal timings either at predetermined intervals or when getting complaints from the public (Hadi et al., 2021). In recent years, agencies have started using high-resolution controller data and other data to estimate ATSPM (Day et al., 2015; Mackey, 2014; Sharma et al., 2007) for use to set and fine-tune signal timing parameters to improve progression and minimize delay. CDA can improve signal retiming and coordination by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: These enhancements use CV and CDA data to support signal retiming. Signal retiming will benefit from the additional and improved traffic data combined with the existing ATSPM. This should improve the signal timing process and potentially reduce the cost of the data collection. Initially, the data will be collected based on the BSM from connected vehicles that may not be automated to supplement sensor data, high resolution controller data, and conventional data collection. The connected vehicles will provide better estimates of the delays and queuing of individual movements on the same approach, arrival on green, red-light violations, acceleration/deceleration, and braking. As the market penetration of different levels of CDA increases, additional data will be collected, such as CACC and platooning utilization, headway settings, gap acceptance, platooning parameters, red light violation, and near misses. All these parameters can be used in better optimization of the signal timing. The data can also be used to monitor the movements of vehicles, bicycles, and pedestrians, allowing for better multimodal optimization of the signal plans. This category may also involve optimized timing considering CACC and ACC presence. With the introduction of automation, a better assessment is provided of the interactions and conflicts between these different types of users using messages based on CDA onboard sensors.

Enhancement Management Category 2 – Information and Guidance Provision: These types of enhancements are not applicable to signal retiming and coordination.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: These types of enhancements are not applicable to signal retiming and coordination.

2.7.2 Trajectory Management at Signalized Intersections

Existing Conditions: There are limited, existing methods that attempt to impact vehicle trajectory. Traditional methods that attempt to impact vehicle trajectories include the installation of advanced beacons to warn drivers of yellow and red signals at a downstream signal that has limited sight distance. Red-light violation cameras also attempt to influence driver behavior. In the past few years, private sector companies began providing information to motorists about downstream signal timing changes. These companies enter agreements with public agencies to obtain the signal timing in real-time operations and provide the information to subscribers to their services, usually in coordination with the original equipment manufacturers (OEMs). CDA can improve trajectory management at signalized intersections by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: This category involves collecting and processing trajectory information from CV with different levels of automation and cooperation to support ATSPM and traffic management.

Enhancement Management Category 2 – Information and Guidance Provision: This category provides SPaT and MAP information, intersection blocking warnings, red-light violation warnings, and pedestrian on crosswalk information to vehicles with the aim to impact vehicle trajectory to improve safety and mobility. The provision of Green Light Optimal Speed Advisory (GLOSA) is initially envisioned to be an onboard unit (OBU) application based on the SPaT and MAP messages provided by the infrastructure. The recommended speed allows the vehicle to pass through one traffic signal on green or to decelerate to a stop. However, there is an opportunity to improve performance by providing the recommended speed information to vehicles by the infrastructure to improve system performance. Such infrastructure-based applications can be used to ensure a platoon of vehicle progress through multiple signals. The infrastructure can use the data collected in the Category 1 enhancement, as well as data from other sources as inputs to the algorithm used to select the recommended speed. The application can account for traffic already waiting in a queue at the intersection in a speed setting.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: In these applications, the infrastructure provides detailed vehicle-specific speed and acceleration for vehicles to pass through multiple traffic signals, taking into account the CACC and platooning of vehicles. The activities of the Traffic Optimization for Signalized Corridors (TOSCO) project conducted by the Goudy et al. (2019) will provide an important basis for this effort. As determined in this project, TOSCO will optimize vehicle trajectories by implementing seven operating modes: Free-Flow, Coordinated Speed Control (optimized speed profile), Coordinated Stop, Creep, Coordinated Launch, and Optimized Follow (operates predominately as a member of a string under CACC speed and gap control). The provided parameters may be different for individual vehicles versus a string (platoon) of vehicles. The infrastructure facilitates this concept for all modes of operation (e.g., whether the signals are fixed-time or actuated; isolated or in coordination). This application can also include supporting the gap acceptance of the permissive left turns and right turns on red.

2.7.3 Adaptive Signal Control

Existing Condition*:* Adaptive Signal. Control Technologies (ASCT) have been proposed since the 1980s as an alternative to time-of-day operations to better accommodate varying traffic conditions. These systems utilize traffic sensors to provide inputs to the associated algorithms and have seen a considerable increase in their deployment in recent years. As stated earlier, ASCT deployment is an important focus area of the FDOT TSM&O Strategic Plan (FDOT, 2021) and STAMP Action Plan (FDOT 2018). Agencies from around the state have started implementing commercially available adaptive signal control from signal control system vendors. Evaluations of these systems show the effectiveness of these systems, particularly under traffic conditions with high variability and in systems that are not oversaturated due to the limitation of physical capacity. However, there are some limitations in existing ASCT. In addition to the need for sensors, these systems utilize aggregate traffic data from point detectors, such as volumes and occupancies. Existing adaptive systems and associated algorithms are still constrained by the low fidelity of data available from current point detection technologies, which reduces the performance of adaptive signal control. Overall, existing signal control systems have focused on general traffic, without consideration of various modes of transportation such as transit and pedestrians. CDA can improve adaptive signal control by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: Newly collected data will provide more detailed real-time traffic information to the infrastructure, including vehicle and other user trajectories. This data can be combined with sensor data for more effective adaptive control. These systems can be developed to accommodate under-saturation and over-saturation conditions, dilemma zone protection, multimodal consideration, and multi-objective optimization. (e.g., safety, mobility, and environmental impacts). An example of systems that have been proposed as a proof of concept of utilizing connected vehicle data in adaptive signal control is the Multimodal Intelligent Traffic *Signal* System (MMITSS) (Head et al., 2012). The MMITSS software was developed as part of the Cooperative Transportation System Pooled Fund Study for the use of CV data for signal control.

Enhancement Management Category 2 – Information and Guidance Provision*:* The provided information could include SPaT and MAP information to vehicles, pedestrians, and bicyclists, in conjunction with adaptive signal control. Due to the dynamic nature of adaptive signal control, the provision of such information can be challenging.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: The fully cooperative adaptive signal control will involve multi-objective optimization of the combination of signal control and vehicle trajectories with the consideration of CACC, CACC platooning, and the TOSCO effort. The system can be fully adaptive. It can also simply involve a platoon priority application that predicts whether an approaching platoon of vehicles will clear the intersection during the green phase to potentially extend the green or return early to the green within limits. Liu et al. (2018) investigated the effectiveness of an algorithm to assign the green time more efficiently to accommodate the platoons and found increases in vehicle speed and the average vehicle miles travelled per gallon fuel consumed (MPG) of about 10% when the CACC market penetration is 100%. In mixed traffic, the study found that the speed improvement exceeds 30% when the CACC market penetration is 40%.

2.7.4 Priority and Preemption

Existing Condition: Emergency vehicle preemption, transit signal priority (TSP), and freight signal priority (FSP) use technology to detect approaching high priority vehicles and alter signal timings to provide priority to transit vehicles. Emergency vehicle signal preemption results in an immediate provision of red for all directions. On the other hand, priority involves much less abrupt change to signal control to accommodate the approaching priority vehicles, such as a small extension of the existing green and termination of the red (early green). Priority and preemption can be implemented as a central control, in which the traffic management software makes the decision to change the signal status, or as a local control, in which the roadside infrastructure made these decisions. Typically, the same equipment is used in preemption and priority. The priority provisions can be implemented as conditional and unconditional. Conditional priority can be granted according to criteria, such as the number of passengers, route schedule adherence, truck and shipment attributes, or the time since the last priority was awarded. CDA can improve priority and preemption management by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: This category involves collecting additional data such as mobility and safety performance of priority vehicles and surrounding vehicles, near-side bus operations, and route-based performance. With the additional data, priority vehicles can be tracked at a relatively long distance upstream of the intersection(s), allowing for route-based priority, which may include multiple signals. An intersection controller can recognize the need to provide the priority earlier than what can currently be done with existing technology. This allows the controller to better prepare for the priority, such as serving the phases with non-priority calls to reduce the delays for the vehicles served by these faces. Another extension is dynamically modifying the signal timing for the clearance of long queues ahead of bus arrivals, or dissipating a long queue for the through movement that blocks the access of the left-turning bus to the left-turn pocket. The MMITS software (Head et al., 2012) mentioned earlier is capable of managing multiple priority requests that may be received from multiple vehicles, including emergency vehicles, transit vehicles, freight vehicles, bicyclists, and/or pedestrians. The system can implement different levels of preemption and priority for eligible vehicles of different modes or within the same mode.

Enhancement Management Category 2 – Information and Guidance Provision: With these enhancements, the roadside infrastructure will be enhanced to provide information to the onboard units can be used to inform priority vehicle’s drivers that their priority requests will be met using Signal Status Messages (SSM). This category can also include enhancing the central software and roadside equipment for the provision of routing information to emergency vehicles and express buses to avoid recurrent and non-recurrent congestion. This provision of routing information can be integrated with preemption and priority.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: This category includes cooperative clearance of lanes and routes ahead of emergency vehicles. This category also includes cooperative bus lanes, in which the vehicles are shifted out of the bus lane when a bus is approaching and use it otherwise.

2.7.5 Integrated Corridor Management

Existing Condition: There has been an increasing interest in deploying Integrated Corridor Management (ICM) strategies in Florida. Some regions have begun developing or have developed operational scenarios for ICM implementation involving multimodal and multi-facility operation and management strategies. FDOT District 5 is implementing a data-based and model-based decision support system (DSS), which is considered an important component of ICM. Other districts have implemented various ICM concepts. For example, FDOT District 4 and Broward Metropolitan Planning Organization (MPO) have developed a ConOps for an ICM for the I-95 corridor in Broward County. FDOT District 2 has implemented strategies for diverting traffic in case of incidents on I-95 to US-1 with RTMC operators monitoring congestion, post detour messages, and change signal timing to better control traffic flow on US-1. When an incident occurs on US-1, traffic can be diverted to I-95. Hadi, Xiao, et al. (2019) identified the ICM applications for implementation consideration in Florida. These applications include coordination of ramp metering and signal control, special signal plans during freeway and arterial incidents, alternative route and predicted travel time information provision to motorists, mode shift during severe highway or transit incidents, and restricting, rerouting, and delaying commercial traffic. CDA can improve integrated corridor management by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: This category includes the use of the additional data to obtain more detailed measures for better signal plan optimization and activation on alternative routes and incident events, as well as for integrating signal control with downstream ramp meters. For example, CV data can be used to identify the alternative routes, impacted turning movements along alternative routes, and the levels of impact (e.g., queue length, delay) for each movement under each incident scenario.

Enhancement Management Category 2 – Information and Guidance Provision: These enhancements include the provision of information regarding the performance on alternative routes and predicted travel time information provision, mode shift during severe highway or transit incidents, and restricting, rerouting, and delaying commercial vehicles.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: These enhancements include cooperative vehicle rerouting and cooperative restriction, rerouting, and delaying of commercial vehicles. The enhancements can include optimizing route guidance in combination with signal control optimization considering CACC and platooning and cooperative integration of signal control with ramp metering/cooperative dynamic merge.

2.7.6 Arterial Safety Applications

Existing Condition: Several ITS-based existing safety applications have been implemented, including red light violation cameras; signs with flashing lights warning of upcoming intersections, conflicts, and speed violations; dynamic location of police enforcement; speed violation cameras; oversized vehicle warning; and active railroad crossing warning. CDA can improve arterial safety by the enhancements listed in the following categories:

Enhancement Management Category 1 – Data Support of Management: This category involves collecting near-misses and crash occurrence information combined with other traffic flow parameters to predict crashes in off-line and real-time operations, and to potentially update the signal timing plans accordingly.

Enhancement Management Category 2 – Information and Guidance Provision: These enhancements involve warning drivers about red light violations, pedestrians on crosswalks, potential stop sign violation, unsafe speeds, railroad crossing, oversized vehicle restrictions, and bad weather and pavement conditions. This category also includes the provision of the rules of practice, which are the conditions in which the AV can operate.

Enhancement Management Category 3 – Fully Cooperative Operations and Management: These applications involve cooperative gap acceptance of permissive left-turn and right-turn on red, cooperative red light violation protection, cooperative gap acceptance at unsignalized intersection operation, cooperative pedestrian conflict resolution, cooperative railroad crossings, and cooperative oversized vehicle restriction.

2.8 Constraints and Challenges

The incorporation of CDA in TSM&O is associated with constraints and challenges that need to be addressed. It is expected that these issues will be addressed at the national and state levels as the CDA technology and applications mature and as their adoption increases. Additional answers will be provided as more experience and results are obtained in projects funded by FDOT, USDOT and other ongoing and upcoming efforts. The following is a summary of constraints and challenges associated with CDA incorporation in TSM&O.

Market Penetration: The increase in the market penetration of vehicle connectivity, automation, and cooperation is critical to achieving the benefits of the enhancements presented in this document. It is expected that the market penetration of connected vehicles will increase in the next few years, and the benefits of Category 1 and Category 2 enhancements can begin to be obtained. However, CDA is still in the research and development stages, and the benefits of Category 3 enhancements will not be realized until the adoption of CDA in the real world. The evolutionary approaches in this study should address this issue by realizing the benefits of the Category 1 and Category 2 enhancements before obtaining the benefits from the Category 3 enhancements. The evolutionary approach will also allow for the benefits to be received in a mixed environment of various levels of connectivity (connected/not connected), automation, and collaboration.

Required Technical Skills: The incorporation of CDA in TSM&O will require the building of additional staffing capabilities. Many of the required capabilities are also required for CV applications. However, additional training and workforce development will be needed to understand CDA and its incorporation in TSM&O. This can involve various business processes of TSM&O from planning to operations. Per the 2019 FDOT CAV Business Plan, FDOT will "*explore the need for developing the educational outreach program to inform transportation planners, managers, engineers, local agencies, and users (travelling public, motor carriers, other road users) about the CAV Program. Outreach will assist in providing a better understanding of how CAV infrastructure will be deployed and operated, while also addressing the infrastructure requirements, standards, implications, and challenges with CAV deployments.*" This educational outreach program will need to address CDA, as well as how FDOT is planning to incorporate CDA in TSM&O.

Data Management: The applications discussed in this report will generate a large amount of data that need to be processed, fused, used, and archived, in combination with data from other sources to estimate and predict system performance. There is a need to determine the data elements and metrics that need to be archived and the resolution of the archived information. The development of the FDOT V2X Data Hub mentioned earlier in this document will provide an opportunity to include CDA data and CDA-based measures in the system for FDOT off-line and online use.

Additional Infrastructure and Software Requirements: CDA incorporation in FDOT TSM&O will require the development and deployment of new TSM&O infrastructure support and software. This will add additional costs that need to be justified. The three categories of traffic management enhancement described in this document will allow getting benefits from the provision of the information needed for CDA to connected and non-automated vehicles and from collecting CV data in addition to CAV and CDA data prior to getting the full benefits from Enhancement

Management Category 3 (fully Cooperative Operations and Management). The development and deployment of additional infrastructure in support in stages according to the enhancement management categories will make it possible to justify the required investment from a benefit-cost point of view.

Evaluation and Testing Requirements: The developed applications will need to be evaluated and tested to ensure their effectiveness and that they operate as designed in a safe manner. The testing can be done in a simulation environment, hardware-in-the-loop simulation, test track, and real-world deployment. It is expected that initially the evaluation and testing will be done in a simulation environment and controlled test track environment such as that at the Florida Suntrax test track. The evaluation and testing of selected CDA TSM&O applications will be a focus of the future tasks of this project.

Liability: Liability can be an issue with several CDA applications to TSM&O. A large proportion of infrastructure-based connected vehicle applications involve sending infrastructure information such as SPaT and MAP messages but leave the guidance provision to commercially available applications that reside in the onboard units. As described earlier in this document, many of the proposed enhancements in Category 1 and Category 2 will require the guidance and control to be provided by the infrastructure, which can create liability concerns for the infrastructure owners and operators. It is recommended to develop requirements and associated testing to ensure a high level of accuracy and reliability of CDA applications to TSM&O. It is also important to follow the national efforts in addressing liability issues.

Standards Maturity: An important aspect of CDA application is the development and maturity of standards that are needed for CDA and infrastructure support of CDA. The USDOT has developed roadside unit (RSU) standards. In addition, the SAE developed connected vehicle messages, including J2735 and various J2945 standards. Additional SAE standards and updates to the existing standards are expected with the advancement of CDA support of the infrastructure.

Experience with CV-based Devices and Applications: There is limited experience with CDA and the incorporation of CDA in TSM&O. The FHWA CARMA project is building a strong foundation for this research. The developments and findings from this program and its partners and collaborators should be continuously reviewed and used for the developments and enhancements of CDA TSM&O applications.

Privacy: Privacy has been identified as an issue for CV deployments. This issue has been addressed based on findings from CV pilot projects and through the use of national and state standards and guidance. For example, the USDOT pilots have developed documents on the Data Privacy Plan (DPP), which provides guidance regarding the privacy of deployment participant data. The SAE message standards are also set to protect privacy. These standards, guidance, and findings will be applicable to CDA applications.

Security: The USDOT has partnered with the automotive industry and industry security experts to design and develop security systems and standards, referred to as the Security Credential Management System (SCMS). FDOT has implemented a security system in its CV deployment. The CDA TSM&O application is expected to be supported by such security systems. Further examination is expected at the national level and is expected to identify any additional security requirements for CDA TSM&O applications.

3. TESTING AND EVALUATION PLAN

This chapter presents a test and evaluation plan for selected CDA test cases and associated scenarios in simulation in a controlled testing environment at a test track such as the SunTrax test facility at 100 Transformation Way, Auburndale, FL 33823. This test plan identifies the referenced documents, test objectives and scope, items to be tested, CARMA architecture, features to be tested, test approaches, test environment setup, and test scenarios and procedures.

3.1 Referenced Documents

Below is a list of the documents that were used in the development of the requirement in this report:

1. IEEE Standard for Software and System Test Documentation, IEEE Computer Society Sponsored by the Software & Systems Engineering Standards Committee, July 2008 (Revision of IEEE Std 829-1998).
2. Vehicle-to-Infrastructure (V2I) Connected Vehicle Pilots Phase 2 Interoperability Test – Test Plan, https://rosap.ntl.bts.gov/view/dot/36715 Final Report – August 13, 2018, FHWA-JPO-18-691.
3. Infrastructure Connectivity Certification Test Procedures for Infrastructure-based CAV Components, Test Procedures, MAP – SAE J2735 Developed by Leidos, Inc. Date: December 23, 2019.
4. Infrastructure Connectivity Certification Test Procedures for Infrastructure-based CAV Components, Test Procedures, Signal Phase and Timing – NTCIP 1202v03 Developed by Leidos, Inc. Date: December 23, 2019.
5. Infrastructure Connectivity Certification Test Procedures for Infrastructure-based CAV Components, Signal Phase and Timing – SAE J2735 Developed by Leidos, Inc. Date: December 23, 2019.
6. Deliverables of the Connected Intersection project managed for the USDOT by the ITE.
7. ITS Standards for the Data Capture and Management Program – Test Plan for the SAE Submittal Developed by Consensus Systems Technologies Corporation (ConSysTec), FreeAhead Inc., and TransCore Inc Ltd March 9, 2017
8. CARMA Cloud Architecture. System Overview by USDOT and Leidos. https://usdot-carma.atlassian.net/wiki/spaces/CRMCLD/pages/2087583749/CARMA+Cloud+Architecture
9. CARMA Platform System Architecture. Deployment of Cooperative Automated Vehicle Capabilities: Integrated Prototype II. Architecture for CARMA System Version 4.0 – ROS2 By USDOT and Leidos. Retrieved from https://usdot-carma.atlassian.net/wiki/spaces/CRMPLT/pages/89587713/CARMA+Platform+System+Architecture
10. McConnell, M., Nallamothu, S., Bujanovic, P., and Stark, J. (2020). CARMA Platform Documentation. Development Resources. CARMA Platform Training Series: CARMA Platform V2X Architecture, CARMA Messenger, CARMA Cloud. Retrieved From https://usdot-

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11. CARMA Simulation Architecture. System Overview by USDOT and Leidos. https://usdot-carma.atlassian.net/wiki/spaces/CRMSIM/pages/2027225111/CARMA+Simulation+Architecture
12. FDOT Guidelines for University Publication and Presentation of Research. https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/docs/t2/university-guidelines-2020285147769.pdf?sfvrsn=edd6df4d_2
13. CARMA 1Tenth Github. https://github.com/usdot-fhwa-stol/carma-1-tenth
14. SunTrax Test Environments. https://www.suntraxfl.com/#explore
15. CARMA Simulation GitHub. https://github.com/usdot-fhwa-stol/carma-simulation

3.2 Test and Evaluation Objectives and Scope

The goal of this test plan is to provide a process for the testing and evaluation of the collaboration between the FDOT traffic management system (TMS) and cooperative automated driving systems, for selected use cases. The specific objectives of the testing are:

- Determine the impacts on traffic performance of collaborative activities between the FDOT infrastructure and the CDA vehicles operating using the CARMA platform under different traffic and environmental conditions.
- Determine the ability of the CDA vehicles to respond to and follow commands from the infrastructure under different traffic and environmental conditions.
- Determine the ability of CDA vehicles to detect and respond to vehicles, other objects, and events that may interfere with the maneuvers that are needed in response to the tactical maneuver commands from the infrastructure.
- Determine the ability of the CDA system to recover from an error in system components in a safe and acceptable manner.
- Determine the ability of the infrastructure to capture, process, and archive data from CDA vehicles.

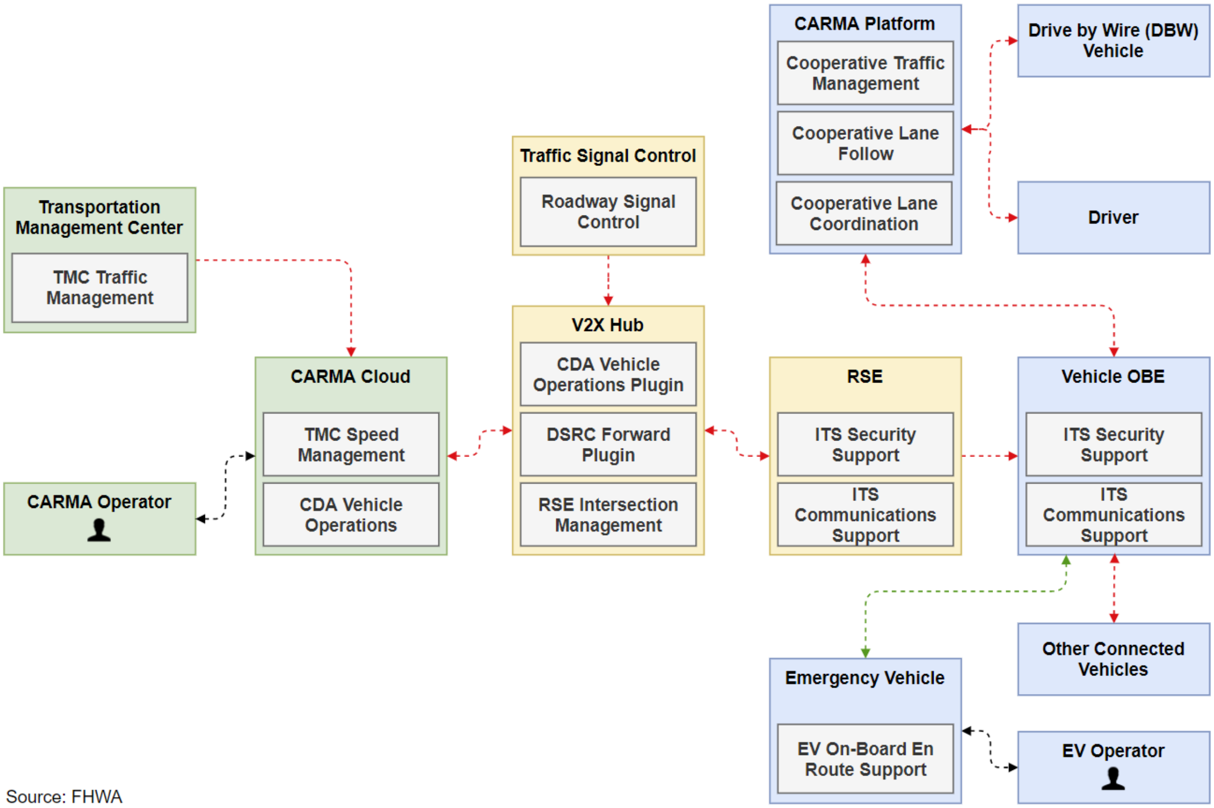
Two use cases detailed in this document, as examples, are related to traffic management in freeway merge areas as listed below.

- Infrastructure-Based Active Traffic Management Strategies for Merge Area in the Presence of CDA Vehicles
- Infrastructure-Based Support of Collaborative Merging Operations

Although this document addresses the above two use cases, many of the elements of the test plan are applicable to other cases of TSM&O support of cooperative driving automation including those specified in Sections 2.5, 2.6, and 2.7 of this document.

3.3 The CARMA Architecture

The CDA test plan can be conducted utilizing items from the CARMA ecosystem. To understand the testing approaches and procedures presented in this document, it is important to understand the architecture of CARMA. The CARMA architecture is shown in Figure 1. The CARMA Architecture is built upon main components that capture most of the interactions within the system. The first component is CARMA Cloud which provides traffic control and environment data to vehicles. CARMA Cloud collects data from multiple sources and transmits it to the AV. The second component is the V2X Hub, which serves as an intermediary communication platform and message format translator. The V2X Hub transmits messages to and from the cloud into communication devices including RSUs providing the appropriate message format and facilitates the routing task. The third component is the CARMA Platform that is installed on the CDA (CARMA) vehicles. CDA vehicles can be either a real vehicle, a scaled-down model (1Tenth), or a virtual vehicle in simulation. The CARMA platform consists of the control software that runs the vehicle and provides automation capabilities as well as vehicle communications that enables cooperative behavior. The fourth component is the CARMA messenger, which is a subcomponent of the CARMA Platform that is intended to be implemented on non-automated vehicles to provide communication capabilities to that vehicle so that it can interact with the other CDA vehicles on the road. Other components of CARMA Analytics and CARMA Co-Simulation. More details of the descriptions of the CARMA components mentioned above are presented in the subsections below except the CARMA Co-Simulation, which is described later in this document.



Source: FHWA

Figure 1. CARMA physical architecture

3.3.1 CARMA Cloud

The main function of CARMA Cloud is to provide a cloud-based management service and bi-directional communication with multiple automated vehicles simultaneously and provide information to support cooperative driving. CARMA Cloud will emulate a virtual traffic management center (TMC) in a cloud-based deployment, allowing the utilization of geofences and the implementation of Rules of Practice (ROP) by the owner and operator agencies. Such implementation can be done through the CARMA Cloud user interface (UI) directly and/or by integrating the CARMA Cloud with the TMC software (e.g., the SunGuide software at the FDOT transportation management centers). This allows the setting of the corresponding geofences or traffic rules by the TMC operator using the agency's traffic software interface. The input parameters can then be communicated to the cloud using a center-to-center (C2C) type of communication (Nallamothu, 2021).

In addition, CARMA Cloud will provide updates to tactical parameters for the freeway mainline CDA vehicles and CDA vehicles merging from the on-ramp such as the acceptable gaps and lane selection in the merge area. CARMA Cloud will also communicate CDA operation conditions to an actual or emulated traffic management center software that makes additional management decisions such as activating ramp metering and/or setting the ramp metering rates.

The transmission is done directly from CARMA Cloud to the vehicles or through the V2X Hub/CARMA Street that acts as the intermediate communication platform between the CARMA Cloud and the roadside units (RSUs). The system communicates the messages to the CARMA vehicle in the appropriate message format.

Examples of dynamic traffic control messages supported by CARMA Cloud include:

- Speed: This includes setting the speed limit or reduction in speed.
- Headway: This includes setting the time gaps for a single vehicle or platoon gap control in seconds.
- Platoon size: This is the setting used for the maximum platoon size in the number of vehicles in the platoon.
- Lane closure: This involves providing the locations of lane closures due to incidents or work zones.
- Lane restriction: This setting restricts access to specific lane(s) by vehicle class, occupancy, time of day, or other factors.

In this study, CARMA Cloud will be used to communicate the speed, headway, and lane selection in the merge area. Figure 2 summarizes the CARMA Cloud functionalities.

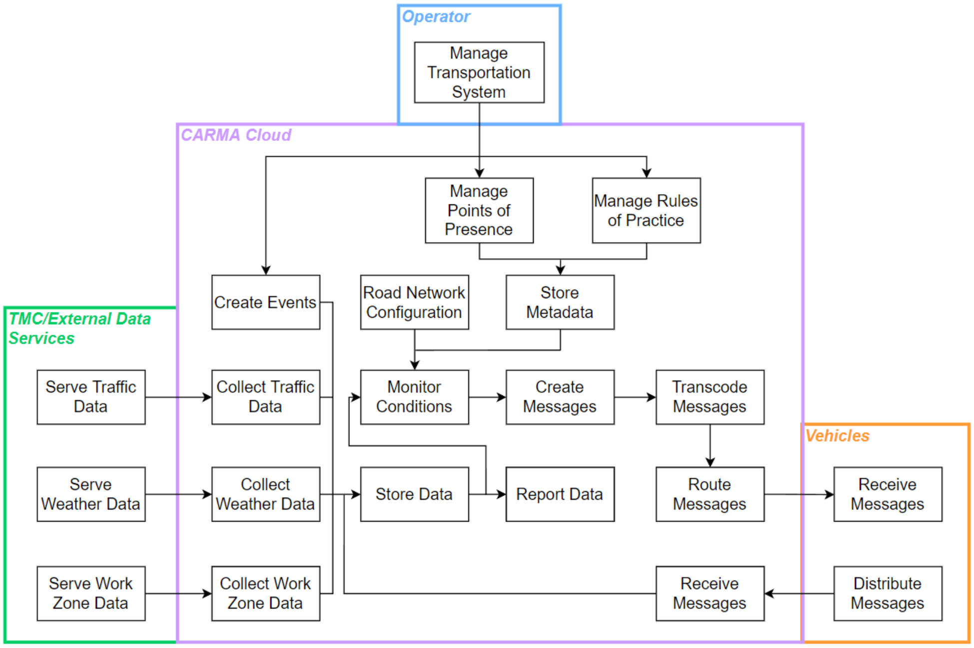


Figure 2. CARMA Cloud functions (Source: FHWA)

Figure 2 shows that the CARMA Cloud interacts with the traffic management center's (TMC's) software, operators, external data services, and the vehicles. CARMA Cloud collects traffic, weather, and work zone data from the TMC and/or other external data services, if applicable. This data can be stored under different file formats (e.g., .xlm, .csv, .bin) for aggregation and is used to support the management and operations. CARMA Cloud also has a user interface that allows the CARMA Operator to input parameters to set the ROP and Points of Presence (PoP) that CARMA will need to identify the RSUs associated with any implemented geofences (Nallamothu, 2021).

CARMA Cloud can create messages and distribute them to those vehicles on the road that need the information based on their current situation (e.g., weather, incident, platoon, gaps). These messages need to be translated and encoded before being transmitted depending on the channel and type of media used. For example, MAP messages for work zones will need to be transcoded in the SAE J2735 message format for broadcasting to the applicable RSUs. The transcoding function is available as part of the Operational Data Environment (ODE) of CARMA Cloud. Once the messages are transcoded, they need to be appropriately routed to the relevant POPs for broadcast and transmission to the affected vehicles. This is done based on the available metadata managed and configured by CARMA Cloud. The V2X Hub facilitates the routing task by receiving the information from the web services and then formatting and distributing the messages to the RSUs. Subsequently, the RSUs distribute the messages to the OBUs. Once the message is received by the equipped vehicle, the computer in that vehicle with the CARMA Platform will be able to read the message and follow the instructions, start the negotiation process, display useful information, and probably generate a feedback message. CARMA Cloud will collect the BSM messages and other information from these vehicles via the V2X Hub. The new observations will be stored together with data generated from the infrastructure, and this information is available for monitoring and the generation of new messages.

3.3.2 CARMA Analytics

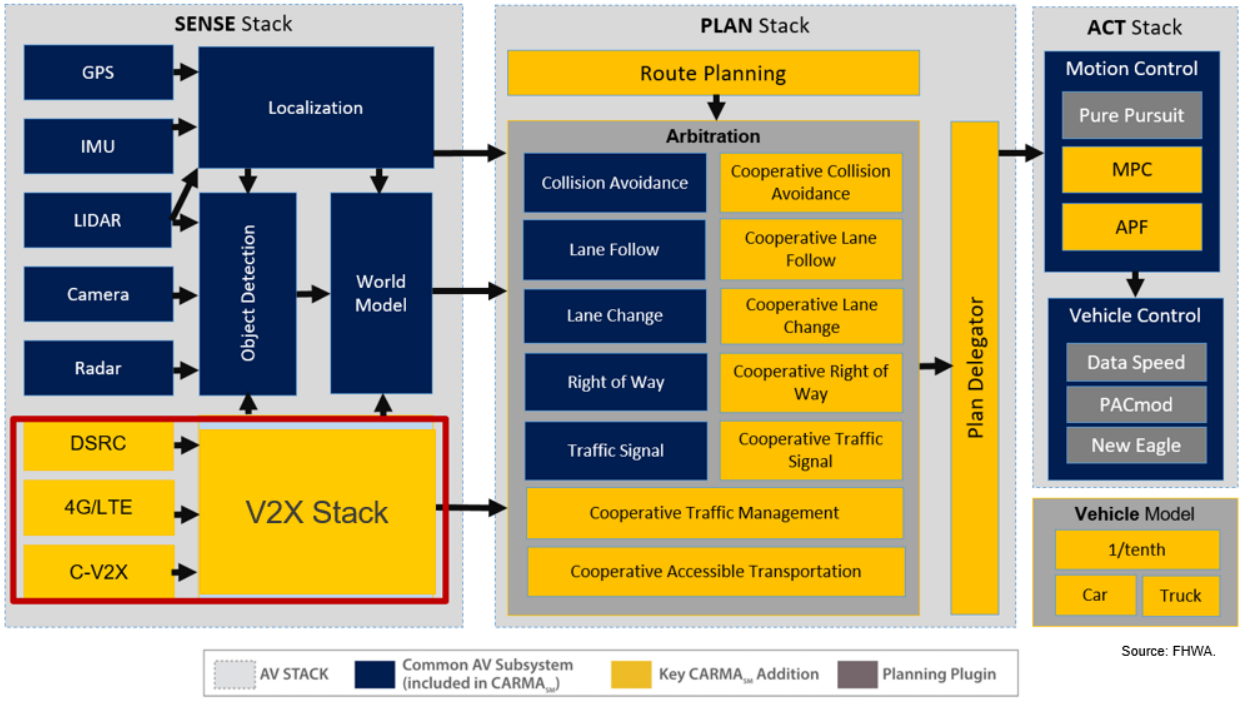
CARMA Analytics is a subcomponent of the CARMA Cloud that allows the collection, fusion, analysis, and management of transportation data, including CDA data. The CARMA Analytics architecture includes the following tasks:

- Data ingestion either from direct connection, data ingestion from a remote test environment, or data access from other sources in real-time
- Data storage and fusion
- Data transformation and processing to support research analysis
- Data transfer to research analysis environment

As described later in this test plan, one of the features to be tested and evaluated is Data Capturing and Archiving is to determine the ability of the system to capture and archive CDA and automated vehicle data to support TSM&O applications and processes. This includes testing the data captured and utilized in real-time operations as well as data archived for off-line utilization.

3.3.3 The CARMA Platform

The CARMA Platform is one of the central components in the CARMA Ecosystem. As stated earlier, the CARMA Platform is installed on the vehicles, and its main purpose is to enable communication and information sharing between vehicles and the vehicle and the infrastructure. Figure 3 presents a functional view of the CARMA Platform (McConnell & Romero, 2021; Vu, 2020). In the CDA testing and evaluation, the utilized CDA vehicles will have the CARMA Platform either physically installed on the onboard units, when real-world vehicles are used, or utilized as software-in-the-loop when co-simulation testing is used.



Source: FHWA.

AV - Automated Vehicle, **CARMA** - Cooperative Automation Research Mobility Applications, **GPS** - Global Positioning System,
IMU - Inertial Measurement Unit, **OBU** - On-Board Units, **V2X** - Vehicle-to-Everything, **LTE** – Long Term Evolution
* Supported by Autoware, **Supported vehicle controllers: Dataspeed, PACMOD, and New Eagle.
DSRC – Dedicated Short-Range Communication

Figure 3. CARMA Platform functions (McConnell & Romero, 2021)

3.3.3.1 The Sense Stack

The sense stack addresses how the vehicle perceives the environment around it by using all of the sensors in the vehicle by processing and interpreting the collected data into information that can be further used to support the vehicle movement planning process. The sense stack functions are displayed on the left-hand side of Figure 3. The red box shown within the sense stack represents the V2X component, which can operate through three communication protocols including DSRC, 4G/LTE, and C-V2X. The communication components of the CARMA Platform are comprised of two ROS nodes. These two nodes are the message nodes, that are in charge of receiving and decoding connected vehicle messages from the onboard units and the J2735 converter node, which is responsible for converting the SAE J2735 binary message units into base SI units.

3.3.3.2 The Plan Stack

The plan stack is shown in the middle of Figure 3. This stack is where the planning and decision-making processes take place to define the vehicle's behavior (maneuvers) and trajectory. The computation of the detailed trajectories is mostly delegated to the planning plugins as part of the guidance core system in the plan stack. During the decision process, the Arbitrator component is responsible for the decision-making, which aids in selecting the optimal maneuvers and trajectory. The overall arbitration process can be defined in the following steps:

- Once the user selects a route from the user interface, the Route Node publishes a route plan using high-definition map data in the context of automated driving.

- Then, the Arbitrator initializes the planning phase by providing a starting vehicle state.
- Next, it calls all the available strategic plugins to produce a new maneuver plan. Each plugin will have a particular purpose and specify a maneuver for a given set of circumstances.
- These plugins produce a sequence of maneuvers and send the sequence back to the Arbitrator.
- The Arbitrator dynamically designates the maneuvers sequence based on the established arbitration mechanism, and then it sends the selected sequential maneuvers list to the Plan Delegator, which now requests a detailed trajectory plan from the Strategic Plugins.
- Once the trajectory is defined, it is distributed to the trajectory validator and emergency handler.
- If a safety-critical issue is found, then the emergency handler will replace the necessary portion of the trajectory with a better alternative that will fix any safety issues. Otherwise, the safe trajectory is sent directly to the Trajectory Executor and Emergency Handler.

3.3.3.3 The Act Stack

When a trajectory is generated, it is distributed to the control plugins in the ACT Stack for execution. The control plugins generate the steering and speed commands needed to proceed with this trajectory and communicate these commands to the controller drivers for its execution. The controller drivers include the Pure Pursuit (PP) Wrapper and the Model Predictive Control (MPC) Follower Wrapper. The Trajectory Executor will continue running this process until either a new trajectory is published, or the last planned trajectory is exhausted.

3.3.3.4 Health Monitor

Another important component of the system is the Health Monitor. The Health Monitor is a ROS node in the CARMA Platform that manages the plugins drivers. The Health Monitor interacts with the hardware interface package which is a container for all the software drivers in the system. Given that each type of hardware device will require its own dedicated driver, each driver must comply with a standard interface that will allow the health monitor to detect and diagnose its performance. In this way, the health monitor keeps track of all the device drivers and planning plugins and reports the availability of these components back to the system using an alert channel specifically designated for that purpose. In the event of a device or plugin becoming inoperable, the system issues a warning. If the issued warning represents a critical failure, then the Health Monitor has the authority to shut down the system and return the control back to the human driver.

3.3.4 The CARMA V2X Hub

The V2X Hub is an open-source platform that facilitates data exchange between the roadside units that communicate with Connected and/or CDA vehicles and infrastructure elements such as traffic signal controllers and traffic management center management hardware and systems. The V2X Hub supports an integrated operation of multiple safety and mobility applications. As an interface system, the V2X Hub supports the collection, integration, and dissemination of data between infrastructure and vehicles (Anderson et al., 2018). The V2X Hub software was created to confirm with the applicable industry standards allowing a scalable and interoperable solution for the implementation of CAV deployments. V2X Hub is compliant with the following standards:

- IEEE 1609 – Family of Standards for Wireless Access in Vehicular Environments (WAVE). The WAVE standards define an architecture and standardized set of services and interfaces for V2V and V2I wireless communication (Wen & Weng, 2013).
- NEMA 0183 Standard. This interface standard defines electrical signal requirements and data transmission protocol for serial data bus (NMEA, 2018).
- NTCIP 1202 – Object Definitions for Actuated Traffic Signal Controller Units. This standard provides the information necessary for traffic management personnel to manage Actuated Traffic Signal Controller Units and contains object definitions to support transportation applications (Balse et al., 2019b).
- NTCIP 1203 – Object Definitions for DMS. Provides the vocabulary (commands, responses, and information) necessary for traffic management and operations personnel to advise and inform vehicle operators of current highway conditions using DMS (AASHTO et al., 2014).
- DSRC Roadside Unit Specifications v4.1. Sets the minimum requirements for DSRC roadside units (FHWA, 2016).
- RTCM 10402.3 – Recommended Standards for Differential GNSS (Global Navigation Satellite Systems) Service, Version 2.3. Standard used by differential satellite navigation systems (RTCM, 2001).
- SAE J2735 – Dedicated Short Range Communications Message Set Dictionary. The DSRC Message Set Dictionary supports interoperability among DSRC applications (SAE International, 2022a).
- SAE J2945/1 – Onboard Minimum Performance Requirements for V2V Safety Communications. This standard sets the minimum performance requirements for V2V safety system interoperability (SAE International, 2017).

In test scenarios of this evaluation plan, the V2X will be installed in a hardware unit to be used as a component of the RSE infrastructure to communicate with the RSU and CARMA Cloud, if the test is done using co-simulation, then the V2X will be used as a software-in-the-loop.

3.3.5 The CARMA Messenger

The CARMA Messenger is an onboard platform that is installed on connected non-automated vehicles to support the interaction between non-automated vehicles and CDA vehicles. This allows sharing information that is useful to perform cooperative tasks. The core components of CARMA messenger contain two ROS nodes, which are the message node and the J2735 converter node. The function of the message node is to take in ROS messages and convert them to binary blob and forward them to a wireless communication driver to allow the OBUs to broadcast the message directly. On the other hand, the J2735 converter node is responsible for converting the data in the messages from the SI units to the units specified in the J2735 standard specification. In test scenarios that involve communications between the CDA vehicles and connected non-automated vehicles, the CARMA messengers will be used as a component installed physically on the OBU, if the test is done using real-world vehicles or as a software-in-the-loop in the co-simulation.

3.4 Items to Be Tested

The tested items include the following:

- Virtual, miniature, or full-size CDA vehicles: The test vehicles can be virtual vehicles modeled in the utilized simulation environment. It can also be a CARMA 1Tenth (CARMA 1/10th), which is a scaled-down test vehicle used for the assessment of CDA applications and features and is equipped with different types of sensors, including LiDAR, cameras, radars, GPS, and communication devices. Once verified in the lab environment, the applications can be tested at the SunTrax test track using full-size CDA vehicles.
- A central software that has the capability to support CDA: This item will provide central support and management of the CDA. In early stages of the testing, the utilized software for this purpose can be the CARMA Cloud, which is an open-source software developed by the FHWA CARMA Program to provide cloud-based management of CDA in the transportation system and bidirectional communication, data exchange, and management of multiple remote vehicles simultaneously. It is anticipated that in real-world applications, a software like CARMA Cloud will be incorporated in or interfaced with traffic management software to exchange information and control parameters.
- Roadside equipment (RSE): This component provides the required communications between the CDA vehicles and the roadside infrastructure. If CARMA is used in the testing, the RSE includes CARMA Streets and a Vehicle-to-Everything (V2X) Hub connected to a commercially available RSU that communicates the information from the infrastructure to the onboard unit (OBU) of the CDA vehicles. CARMA Streets is an infrastructure-based application developed by the FHWA CARMA Program that provides edge computing to support CDA.
- Onboard CDA platform: This is a vehicle-based platform for automated vehicles to share information and intents, as well as to collaborate with other vehicles and infrastructure. The CARMA Platform is an example that includes plugins that support cruising (recognize and follow the speed limit and a cruising leading vehicle), yield (slow down or completely stop a vehicle to avoid a collision), lane change and merge (coordinate with vehicles in a lane to the left or right to make space to merge and change lanes safely), platooning (enable collaboration between vehicles to travel in platoons at a close range), and speed harmonization (follow dynamic speed commands).
- Co-simulation: This item is a co-simulation environment that integrates multiple simulations for the testing and evaluation of CDA. For example, the CARMA co-simulation includes:
    - CARLA, which is an open-source autonomous driving simulator.
    - SUMO, which is an open-source traffic simulation tool.
    - NS-3, which is an open-source software, network simulator for internet and communication systems.
    - MOSAIC, which is a multi-domain and multi-scale simulation framework for automated and connected mobility scenarios, a co-simulation manager and core runtime infrastructure.

- Onboard connected vehicle platform: This is a vehicle-based application for non-automated connected vehicles and CDA Class A and B vehicles, enabling communication with CDA Class C and D vehicles for transmitting alert messages and sharing data. CARMA Messenger provides this functionality.
- Data analytics platform: An example of a data analytics platform is CARMA Analytics, developed as a cloud-based architecture for researching the analysis of big CDA data sets. The architecture of CARMA Analytics addresses data ingestion and transfer, data storage and fusion, and the tools required for basic quality assurance and data analysis.

3.5 Features to Be Tested

This section identifies six dimensions of feature testing of the CDA infrastructure and vehicle collaboration for this test plan. Each CDA test scenario can be defined by the six dimensions of feature testing.

The following are the six dimensions of features to be tested.

- Collaborative Transportation Management: This testing involves testing the ability to implement enhanced collaborative transportation management strategies and the effectiveness and benefits of these implementations. As detailed in the ConOps in Chapter 2, the potential collaborative transportation management systems can be categorized as follows.
    - Enhancement Management Category 1 – Data Support of Management
    - Enhancement Management Category 2 – Information and Guidance Provision
    - Enhancement Management Category 3 – Fully Cooperative Operations and Management

- Data Capturing and Archiving: This testing determines whether the system is able to capture and archive CDA and automated vehicle data on a level of detail and quality that can be used to support TSM&O applications and processes.

- Tactical Maneuver Behaviors: This involves the testing of the tactical maneuver behaviors of CDA vehicles in response to infrastructure guidance information, such as lane following, lane changing, and speed setting. The tactical maneuver behaviors can be viewed as control-related tasks. The testing assesses the ability to send and deliver commands from the infrastructure to the CDA vehicles to impact the tactical maneuvers' behaviors. The plan also involves verifying the ability to accomplish the tactical maneuvers according to guidance, such as identifying the location, direction, speed, and angle of a lane change made in response to the infrastructure guidance.

- Operational Design Domain (ODD): The ODD features identify the operating environment during the test, such as the highway facility classification (e.g., urban freeway, urban arterial street, etc.), traffic conditions (different congestion levels with varying numbers of background traffic of non-automated vehicles), lane and shoulder blockages if any, pavement conditions, and environmental conditions. The environmental conditions can include specifying the lighting conditions, sun location, and rain/clear conditions for the test.

- Object and Event Detection and Response (OEDR): OEDR behaviors are related to the perception and decision-making related tasks of the CDA vehicles. This is related to the behaviors of the vehicles when they encounter other vehicles or objects in the same lane and adjacent lane(s) as they attempt to use the infrastructure guidance in car-following, lane changing, gap setting, and speed setting (e.g., detecting and responding to pedestrians).

- Failure Mode Behaviors: This testing involves the introduction of errors or faults that induce failures in the tested system, such as sensor and communication failures.

The following subsections provide an overview of the testing of the six dimensions of features according to this test plan. The details of the tests are provided later in this chapter.

3.5.1 Collaborative Transportation Management System

This dimension of feature testing involves testing the ability to implement enhancements that can be categorized in the three enhanced management categories as described above and to assess the benefits of these enhancements. Two collaborative transportation system management applications to support the traffic management of freeway on-ramp merge areas are listed below as examples. However, the testing can be applied to the other applications outlined in the ConOps, presented in Chapter 2.

3.5.1.1 Enhanced Active Traffic Management in the Presence of Collaborative Merging Operations

This tested application involves the use of connected, automated, and CDA vehicle data to determine the need to activate ramp metering and improve the ramp metering operations in terms of mobility and safety, with consideration of both human-driven and CDA vehicle operations. This can be classified as Enhancement Category Level 1 according to the categorization of the enhanced traffic management strategies, as presented above. In this application, the infrastructure will analyze the data collected from traffic sensors, connected vehicles, communicated automated vehicle sensors, and CDA vehicles, and will predict the probability of traffic breakdown at the merge area and conditions that will create congestion and difficulties in the merging operations of CDA vehicles. It will then activate an active traffic management strategy, such as ramp metering or speed harmonization that considers the measured traffic conditions. The system will utilize the CDA data of the type collected by CARMA Cloud, connected vehicle collected according to SAE J2735 standards, and automated vehicle data collected according to SAE J3224.

3.5.1.2 Infrastructure-Based Support of Collaborative Merging Operations

This enhancement can be classified as Enhancement Category 3 according to the categorization above and involves the infrastructure support of CDA vehicle merging operations. The system will evaluate the need for generating gaps in the right lane of the freeway mainline by providing instructions to the vehicles on this lane as they approach the merge area to generate gaps to facilitate the merging of the vehicles from the on-ramps, as well as to reduce potential conflicts.

The generation of gaps is accomplished by instructing these vehicles to slow down or change to the adjacent lane on the left. The infrastructure can also identify merging points and target gaps of specific sizes and positions and assign the vehicles to the target gaps. This can include the provision of the merge speed to minimize the operation and safety impacts of the merging traffic.

3.5.2 Data Capturing and Archiving

This test assesses whether the system is able to capture and archive CDA and automated vehicle data in a specific level of detail and quality that can be used to support various TSMO applications and processes. The test will document the type of data that can be captured by CARMA Cloud and archived and processed using CARMA Analytics, as well as any useful data that currently cannot be captured.

The test will compare the captured data with the data specified in various existing standards and standards that are being developed. Since some of these standards are still under development, it is not expected that the captured data by CARMA will meet these standards. Still, such a comparison is useful to determine the potential type of data that can be captured with the application of message standards. The message standards to compare to include:

- SAE J3224 - V2X Sensor-Sharing for Cooperative & Automated Driving
- ETSI TR 103 562 V2.1.1 (2019-12) Intelligent Transport Systems (ITS) Vehicular Communications; Basic Set of Applications; Analysis of the Collective Perception Service (CPS)
- SAE J2945/8 - Cooperative Perception System
- V2X Communications Message Set Dictionary J2735_202007

The SAE J3224 standards and ETSI TR 103 562 V2.1.1 (2019-12) standards are related to the communication of data collected using AV data sensors, including detecting nearby road users/objects such as foreign objects, vehicles, and pedestrians, and data on non-connected road users and safety-critical objects. SAE J2945/8 addresses the broadcasting of the perception information of other road users/objects nearby, both to understand cooperative perception sharing and improve the perception performance of other V2X-capable devices/systems.

CARMA Cloud collects additional data captured from CDA vehicles to determine whether the maneuver occurred as designed. This can include:

- The total duration of the negotiation process
- Frequency of negotiation success/failure (negative acknowledgments from neighboring vehicles)
- The number of attempts before a plan is accepted by all affected neighbors.
- Travel speed driven by each of the vehicles during the tests that can be used to create an accurate picture (playback) for evaluating driving within the vehicle's travel areas.
- Message latency indicating the time difference between Vehicle A sending the message and Vehicle B reading the message.

3.5.3 Tactical Maneuver Behaviors

The tactical maneuver behaviors in this plan refer to the control tasks of CDA vehicles that are impacted by the guidance commands from the infrastructure, such as commands for lane changing, speed following, and gap setting, as described below.

Lane Changing: This tested feature involves the CDA vehicles initiating the lane changing process in response to guidance by the system. The test will involve determining the ability of the CDA vehicle to accomplish the lane change, the point in time after receiving the guidance that the CDA vehicle initiates and completes the lane change, and the point and gap in which the vehicle is able to merge in relation to the guidance specification of these parameters. This test will be performed under different traffic conditions. The test will differentiate between obstructed lane change maneuvers such as at work zones and the end of an acceleration lane, in which the vehicles have to make a change at a point and unobstructed lane change such as mainline vehicles changing lanes from the right lane of the merge area of ramps to provide additional gaps for the merged traffic.

Speed Following: This test will determine if the CDA vehicles will drive according to the specified speeds received from the infrastructure, how long it will take the CDA vehicle to change its speed after the command is received (this can be defined by a time threshold to reach target command speed), and the acceleration and deceleration associated with the change in speed. The test will determine the actual speed vs. command speed once the target speed is reached, which can be defined in terms of an acceptable difference.

Gap Setting: This test will determine the ability of the CDA vehicle to maintain the gap for the leading vehicle as guided by the system in the managed zone, if such a command is provided, as well as how long it will take the CDA vehicle to achieve the gap separation after the command is received (this can be defined by a time threshold to reach a target gap), and the acceleration and deceleration associated with the change in the gap. The test will determine the actual gap vs. the command gap once the target gap is reached.

3.5.4 ODD Elements

The ODD elements will need to be specified for each test, including the roadway type, roadway surface, roadway edge and marking, roadway geometry, minimum speed and maximum speed, traffic congestion, weather conditions, pavement status (wet, dry), illumination, and participating vehicle connectivity. The base conditions for the test can be clear daylight conditions, with no impacts from the sun's location. However, the tests can be done under different environmental and lighting conditions according to the design and tested ODD elements.

3.5.5 Object and Event Detection and Response (OEDR) Capabilities

OEDR features that are related to the two use cases presented in Section 3.5.1 involve the CDA's ability to detect and respond to vehicles in its lane and adjacent lanes. Such a test will verify that the test CDA vehicle(s) will be able to detect other vehicles that it may have a conflict with on the same lane or adjacent lane(s). The test will also be able to detect the CDA responses to the detected vehicles, such as yielding to, changing speed, or adjusting the gaps in reacting to these vehicles, which can impact the response to the tactical maneuver command provided by the infrastructure. This verification will be done by monitoring the trajectories of the vehicles during the test. The CDA shall be able to keep the separation distances according to the specification of the CARMA system according to determined safe gaps. The test will determine the frequency of infringement on safe lateral and longitudinal gaps and the reasons for the infringement, the changes in speeds, and acceleration/deceleration of the CDA vehicles in excess of (or below) a specified threshold in response to interactions between the CDA vehicles and other vehicles. In test track and real-world testing, this category of testing can also include the frequency of disengagements by the drivers of Level 3 automated vehicles, which is the frequency of the events when drivers deactivate the automated vehicle feature and take manual control of the vehicles because of unsafe automated driving conditions.

The detection of objects and events may occur using the vehicle's perception sensors (LiDAR, cameras, radar, and/or ultrasonic sensors) or be based on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications that could supplement or augment the measurements by the perception sensors. Additional information may be obtained from onboard, three-dimensional digital maps that include information about static objects and infrastructure elements, such as the number of lanes, speed limits, and the presence of traffic control devices.

Examples of the CDA vehicle responses based on the collected information include:

- Vehicle following – maintain a safe following distance from the lead vehicle.
- Vehicle acceleration and deceleration – decrease and increase speed as appropriate at acceptable rates.
- Stopping – brake in a safe manner to a stop.
- Yield – yield the right-of-way to other road user(s).
- Changing lanes – implement the appropriate longitudinal and/or lateral control actions to shift into an adjacent lane.
- Aborting lane change – cancel the action to change lanes.
- Exiting the travel way – exits the travel way to a shoulder when warranted.

Some of the events that the automated vehicle will need to respond to can include the following actions.

- Lead vehicle decelerating (follow vehicle, decelerate, stop)
- Lead vehicle acceleration (accelerate, follow vehicle)
- Lead vehicle stopping (decelerate, stop)
- Lead vehicle turning (decelerate, stop)
- Vehicle changing lanes (yield, decelerate, follow vehicle)
- Vehicle cutting in (yield, decelerate, stop, follow vehicle)
- Vehicle entering roadway (follow vehicle, decelerate, stop)
- Opposing vehicle encroaching (decelerate, stop, shift within lane, shift outside of lane)
- Adjacent vehicle encroaching (yield, decelerate, stop)

- Lead vehicle cutting out (accelerate, decelerate, stop)
- Vehicles driving in the wrong way/direction (wrong-way driving)
- Pedestrian crossing road – inside the crosswalk (yield, decelerate, stop)
- Pedestrian crossing road – outside the crosswalk (yield, decelerate, stop)
- Pedal cyclist riding in lane (yield, follow)
- Pedal cyclist riding in dedicated lane (shift within lane)
- Pedal cyclist crossing road – inside the crosswalk (yield, decelerate, stop)
- Pedal cyclist crossing road – outside the crosswalk (yield, decelerate, stop)

3.5.6 Failure Mode Behavior Testing

This type of testing is performed to test the failure mode behavior utilizing the Health Monitor core functionality in CARMA. The objective is to examine if the CDA vehicles can handle failures or errors. The Health Monitor detects errors that cause the CDA vehicles to disengage and return to manual control.

3.6 Testing Approaches

This section provides an overview of three strategies that can potentially be used for the testing process. The three strategies are: testing using software-in-the-loop (SIL), testing using miniature vehicles (CARMA 1/10th) vehicles, and testing at test tracks.

3.6.1 Software-in-the-Loop

SIL allows testing of CDA in a virtual environment, which provides a safe and cost-effective approach before conducting the testing in a physical vehicle. The current development of CARMA involves the development of a co-simulation environment that integrates a CARLA simulator, SUMO simulator, and NS-3 communication network simulator using the MOSAIC framework (Vu, 2020).

Chapter 4 presents the details of this environment and other environments and tools that have the potential for use in testing and evaluating CDA and demonstrates the use of microscopic simulation and traffic simulation for this purpose.

3.6.2 Testing by Using CARMA 1/10th Vehicles

Some of the tests can be conducted using CARMA 1/10th vehicles, either by themselves or as part of the vehicle-in-the-Loop co-simulation. In the latter case, instead of modeling virtual CDA vehicles using the CARLA simulator, physical CDA vehicles are employed along with sensor devices and connected vehicle communications capability (Baird et al., 2020). The vehicles can be miniature vehicles, as is the case with the CARMA 1/10th or full-size vehicles . Figure 4 shows the CARMA 1Tenth physical vehicle.

Figure 4. One-tenth scaled-down physical vehicle (CARMA 1Tenth). Source: FHWA

Below is a list of the main components of CARMA 1/10th:

- Teleoperation feature, which gives humans or computers the ability to control (steer, accelerate, brake) a vehicle remotely. Teleoperation is used to control the throttle, brake, and steering angle of the CARMA 1Tenth vehicle, as well as to enable and disable autonomous driving.
- The mapping feature creates a 2D occupancy grid to help generate a map of the local environment. This requires driving the 1Tenth vehicle around a closed-loop area to generate the map and save it on the vehicle.
- Localization is used to localize the vehicle within the local environment.
- Pure-pursuit trajectory following, which is a path tracking algorithm that computes and provides the angular velocity that moves the vehicle from its current position to reach a look-ahead point in front of the vehicle.
- LIDAR and cameras
- Electronic Speed Controller (VESC), which is an open-source speed controller.

3.6.3 Test Track

Performing the test in a close-track environment allows the quantifying of the test cases' performances more realistically in a real-world environment. This test can be performed at the Florida SunTrax test tack. SunTrax is a large-scale test track with a cutting-edge facility developed by the Florida Department of Transportation and the Florida's Turnpike Enterprise for the research and development of emerging transportation technologies allowing testing in a safe and controlled environment (FDOT, 2023). One of the test facilities in SunTrax that is applicable to the testing of the merging area management test cases described earlier is the Loop Track, in which there are ramps merging into a multi-lane continuous loop track (see Figure 5). The testing using the test track can be done as a standalone or in combination with vehicle-in-the-loop simulation, as is the case with the CARMA 1/10th in-the-loop simulation, described earlier.

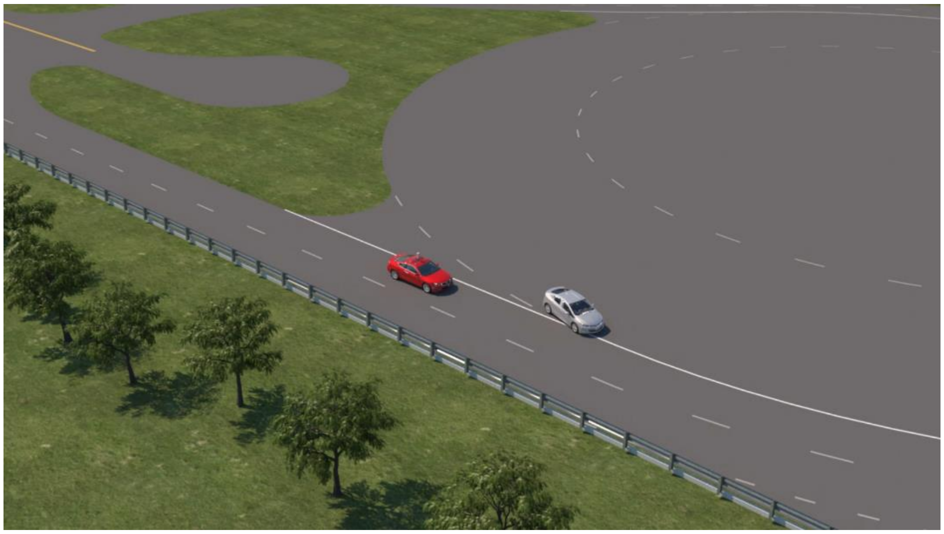


Figure 5. Loop track facility in the SunTrax test track.

3.7 Test Environment Setup

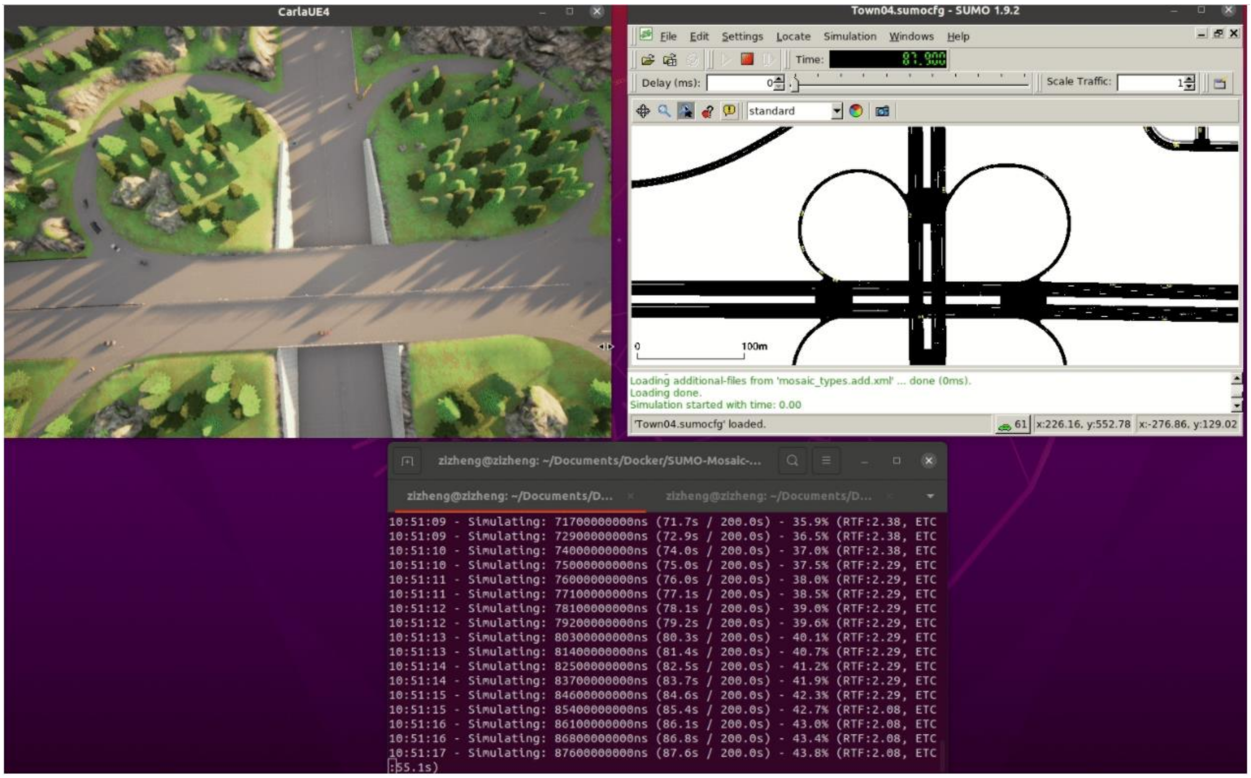
This section presents the requirements of computer and hardware devices that are needed for the tests and the procedure for the setup of the test environment of the CARMA simulation and the CARMA 1Tenth approaches.

3.7.1 CARMA Simulation

The main components that need to be set up in order to conduct the tests include the CARMA Platform running on an Ubuntu operating system and the co-simulation components. The co-simulation platform requires the following components:

- Ubuntu 16.04 (64-bit): The current CARMA Platform is running on the Ubuntu 16.04 open-source operating system on Linux.
- A high-performance computer with the recommended following specifications:
    - Intel i7 gen 9th - 11th / Intel i9 gen 9th - 11th / AMD Ryzen 7 / AMD Ryzen 9
    - A 4GB minimum graphics card will be needed to run a highly realistic environment for the CARLA simulator server. (NVIDIA RTX 2070 / NVIDIA RTX 2080 / NVIDIA RTX 3070, NVIDIA RTX 3080 recommended)
    - A 16 GB minimum RAM memory
- CARLA simulator
- SUMO microscopic traffic simulation model
- Network Simulator (NS-3) for V2X communication simulation

An example of the integration and synchronization of each component in the co-simulation developed by the CARMA research team is illustrated in Figure 6.



```
Loading additional-files from 'mosaic_types.add.xml' ... done (0ms).
Loading done.
Simulation started with time: 0.00
'Town04.sumocfg' loaded.
```

```
10:51:09 - Simulating: 71700000000ns (71.7s / 200.0s) - 35.9% (RTF:2.38, ETC
10:51:09 - Simulating: 72900000000ns (72.9s / 200.0s) - 36.5% (RTF:2.38, ETC
10:51:10 - Simulating: 74000000000ns (74.0s / 200.0s) - 37.0% (RTF:2.38, ETC
10:51:10 - Simulating: 75000000000ns (75.0s / 200.0s) - 37.5% (RTF:2.29, ETC
10:51:11 - Simulating: 76000000000ns (76.0s / 200.0s) - 38.0% (RTF:2.29, ETC
10:51:11 - Simulating: 77100000000ns (77.1s / 200.0s) - 38.5% (RTF:2.29, ETC
10:51:12 - Simulating: 78100000000ns (78.1s / 200.0s) - 39.0% (RTF:2.29, ETC
10:51:12 - Simulating: 79200000000ns (79.2s / 200.0s) - 39.6% (RTF:2.29, ETC
10:51:13 - Simulating: 80300000000ns (80.3s / 200.0s) - 40.1% (RTF:2.29, ETC
10:51:13 - Simulating: 81400000000ns (81.4s / 200.0s) - 40.7% (RTF:2.29, ETC
10:51:14 - Simulating: 82500000000ns (82.5s / 200.0s) - 41.2% (RTF:2.29, ETC
10:51:14 - Simulating: 83700000000ns (83.7s / 200.0s) - 41.9% (RTF:2.29, ETC
10:51:15 - Simulating: 84600000000ns (84.6s / 200.0s) - 42.3% (RTF:2.29, ETC
10:51:15 - Simulating: 85400000000ns (85.4s / 200.0s) - 42.7% (RTF:2.08, ETC
10:51:16 - Simulating: 86100000000ns (86.1s / 200.0s) - 43.0% (RTF:2.08, ETC
10:51:16 - Simulating: 86800000000ns (86.8s / 200.0s) - 43.4% (RTF:2.08, ETC
10:51:17 - Simulating: 87600000000ns (87.6s / 200.0s) - 43.8% (RTF:2.08, ETC
:55.1s)
```

Figure 6. The integration and synchronization of the co-simulation. (Source: FHWA)

3.7.2 CARMA 1Tenth Setup

To explain the CARMA 1Tenth setup process, the model can be broken down into subgroups of components, including:

- the structural components that consist of the chassis, platform decks, fasteners set, springs, and numbers.
- the sensors set, which includes the LiDAR, Camera, the Inertial Measurement Unit (IMU), and the VESC open-source speed controller that provides the possibility of adjusting multiple parameters; and
- the CPU unit that consists of the Nvidia TX2 module, together with a USB Hub with an integrated power adapter for connectivity, and other items such as a game controller, digital power wiring and plugs battery set, charger, and screws for sensor attachment.

The setup process starts with the preparation of the chassis. The recommended chassis is a 1/10 scale remote control car manufactured by Traxxas (model Slash 4x4). The preparation of the chassis consists of the removal of the receiver box and the stock Electronic Speed Controller (ESC), as well as the installation of the bumper and suspension system upgrade. Once the chassis is ready, the platform decks provided by RacecarJ can be attached to the chassis. This deck system consists of two levels of standoffs, where the lower level will hold the VESC, IMU, LiDAR, and

CPU, and the upper level will hold the power supply and the camera. The chassis on the other hand will serve to allocate the motor, servo controller, and the batteries (see Figure 7).

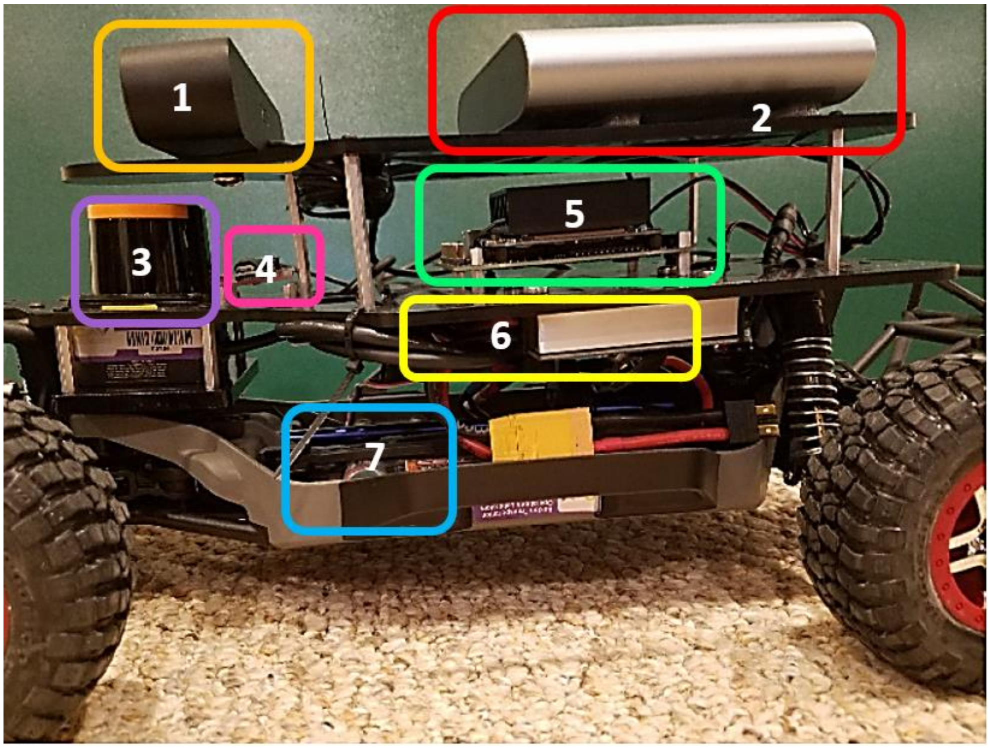


Figure 7. CARMA 1Tenth configuration. (Source: FHWA).

Notes: In the figure: 1: Camera; 2: Power Bank; 3: LiDAR; 4: IMU; 5: CPU; 6: VESC; 7: Motor

3.7.2.1 Electronic Speed Controller (ESC)

The Electronic Speed Controller (ESC) is an important component of the CARMA 1Tenth vehicles. It controls the torque in the electric motor and the speed of the vehicle. For the purposes of assembling the 1Tenth model, it is necessary to substitute the ESC that comes in the chassis provided by the manufacturer (Traxxas) for a more advanced version of the ESC known as the VESC. The VESC is an open-source speed controller that provides the possibility of adjusting multiple parameters, such as current and voltage filters, for the regulation of the speed, braking, and acceleration of the vehicle. Additionally, the VESC includes an integrated gyroscope, accelerometers, and magnetometers for 3D orientation, and computation of 3 axis acceleration values. For the setup, the VESC is controlled from the Jetson (CPU) through a USB cable. The battery is connected to the VESC through an XT-90 adapter, and the steering servo system is connected to the VESC using a three-pin JST-PH connector.

3.7.3 CARMA Platform Configuration

Configuration Management is an important aspect to consider when setting up the CARMA Platform. Configuration management defines what features or set of software are going to be used depending on the available hardware or physical system. A clear example is when two different vehicles may have different dimensions or different sensor set configurations (e.g., one LiDAR vs two LiDARs). Under this scenario, the main challenge is to find an appropriate way to manage such differences to ensure that the different models can run properly on the same featured set of software while trying to optimize the amount of scripts and avoid software duplication. To manage this scenario, CARMA implements a three-step configuration system, as shown in Table 3.

Table 3. CARMA 3-Step Configuration System

Step	Activity	Description
1	Software Configuration	• Consists of the feature set being used depending on the operational characteristics of the model. • Software Version
2	Vehicle Configuration	• Sensor Set Configuration • Vehicle network parameters (e.g., Internet Protocol) • Robot Operating System (ROS) configuration
3	Vehicle Calibration	• Physical properties associated with each individual vehicle • Sensor orientation and position • Physical properties of hardware components utilized in the model

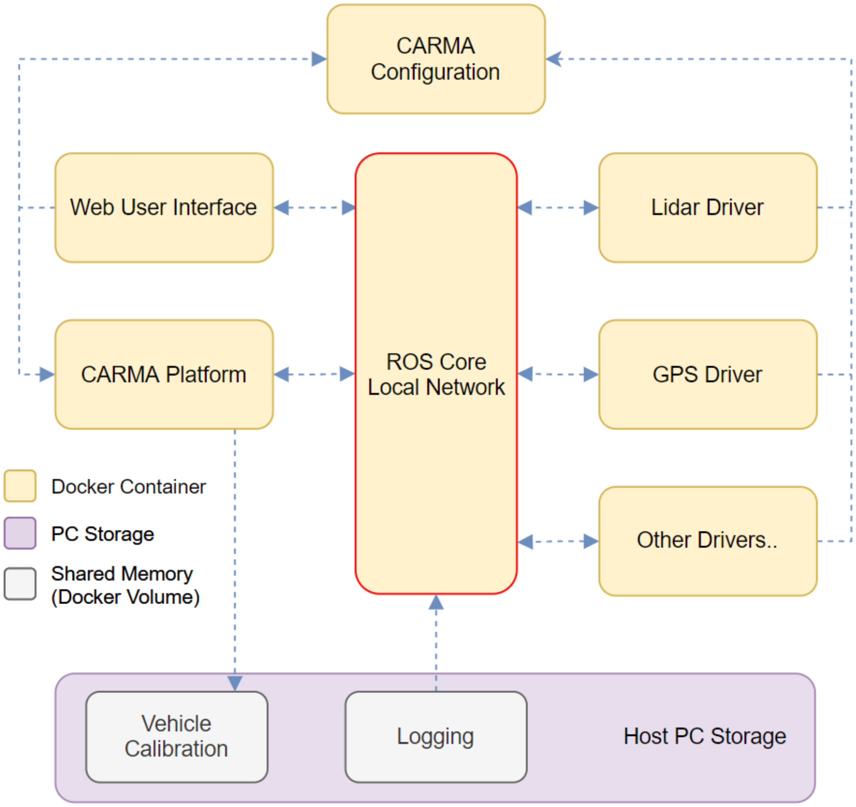
Source: FHWA

3.7.3.1 Configuration with Docker

To achieve the configuration management objectives, the CARMA configuration system implements configuration management with Docker. Docker is an open-source platform that helps developers simplify the building, deployment, and management of containerized applications. As a containerization platform, Docker allows developers to standardize executable objects by combining the application source code with the required dependencies and Operating System (OS) libraries necessary to run the code in any environment. The three main components of the containerization system include images, which are files containing the software installation; containers, which are the instances of the images that are currently running; and volumes, which are shared folders and files between the container and the host PC. Volumes are specifically important because of the concept of sharing in containerization. While having access to all of the required dependencies, the container also provides a specific configuration that implies that if the system is not able to see the external environment of the host computer, then in order to exchange information, a volume must be exposed to that container. Additionally, it is possible to have multiple containers running at the same time. This type of activity is managed by a system known as Docker compose, which is utilized by the CARMA Platform to manage multiple vehicle configurations.

3.7.4 *CARMA Deployment*

Figure 8 shows a graphical representation of the CARMA Deployment concept indicating the interactions and information flows between its multiple objects. At the top of the figure, we have the CARMA configuration, which is a Docker image that stores the specific configuration of the vehicles that are being used. This is storing the Docker proposed file that indicates the version of the software being run, the specific hardware drivers, and the IP address and port numbers associated with those drivers so that they can properly connect with the physical hardware. The CARMA script is utilized to execute the necessary commands for the system to start and read the configuration, including the rest of the containers that are also matched to the same configuration. On the right-hand side of Figure 12, there are multiple docker containers that are associated with the existing number of drivers, depending on the hardware that is being used. The container in the middle of the figure represents the Robot Operating System (ROS) Core, that together with the CARMA Platform container on the left, provides all the primary business logic for the system. The vehicle calibration parameters are located on the bottom left side of the figure. As previously mentioned, this node is used to account for the specific properties of the vehicles that are being utilized and not just for the sensor set configuration. A volume called "vehicle calibration" is exposed on the host PC. This volume is read by the CARMA Platform to encode the corresponding physical properties of the vehicle. Additionally, all these containers have access to a logging volume that allows them to write their logs in real time directly to the host vehicle.



Source: FHWA

Figure 8. CARMA deployment concept

3.8 Test Cases, Scenarios, and Procedures

This section includes the test scenarios and associated testing procedures of enhanced merge area management in the presence of CDA vehicles. As stated earlier, the two applications used as example test cases are:

- Infrastructure-based Support of Collaborative Merging Operations: This project addresses two types of test cases associated with this application. These test cases include:
    - Mainline gap creation to facilitate merging test cases.
    - Dynamic merge with merge parameter setting by the infrastructure test cases.

- Enhanced Active Traffic Management in the Presence of Collaborative Merging Operations: This test plan addresses one type of the test case associated with this application, as an example. The test case is:
    - Ramp Metering Parameter Setting with CDA Consideration

Test scenarios and procedures are presented for each test case. A test scenario can be defined by the six dimensions of testing features described earlier. The six dimensions are the Traffic Management Support, Data Capturing and Archiving, Tactical Maneuver Behaviors, ODD Elements, OEDR Capabilities, and Failure Mode Behaviors. The specification for each of the features in each dimension can be viewed as a core component of the test scenario, although some dimensions may not be applicable to some test cases and associated scenarios. The framework described in this document is flexible enough to support the definition of the test scenarios that can be applied to simulation, closed test-track, and open-road testing.

3.8.1 Set of Rules of Practice (ROP)

As previously stated, CARMA Cloud emulates a virtual TMC in a cloud-based deployment, allowing the implementation of Rules of Practice (ROP) by the agencies for the implementation of TSMO strategies and AV applications. For example, the TMC can set and manage rules for variable speed limits or speed harmonization in response to congestion, adverse weather conditions, or incidents and communicate the corresponding settings to the appropriate vehicles through the RSUs within the geofence's operating domain. The user can set the corresponding parameters via the CARMA Cloud user interface or using the agency's software interface.

3.8.2 Infrastructure-Based Support of Collaborative Merging Operations

This enhancement involves the traffic management system that evaluates the need for generating gaps in the freeway mainline traffic by giving instructions to the vehicles on the mainline approaching the merge area to generate gaps to facilitate the merging of the vehicles from the on-ramps and to reduce potential conflicts. The infrastructure will also identify the merging points and target gaps of specific sizes and positions and assign the vehicles to target gaps based on estimates of the trajectories. This can include the provision of the speed of merge to minimize the operation and safety impacts of the merging traffic.

3.8.3 Mainline Gap Creation Test Cases

These test cases are related to creating gaps in mainline traffic to facilitate on-ramp metering. As described earlier, these test cases are related to applications, in which the traffic management system provides a command to mainline CDA vehicles to change lanes or change speed ahead of a merge to provide a gap in traffic for vehicles to merge from the ramp. This involves two test cases:

- Test Case Mainline Gap Creation by Lane Change: CARMA Cloud provides a command to mainline CDA vehicles to change lanes ahead of a merge to provide gaps in traffic for vehicles to merge from the ramp.
- Test Case Mainline Gap Creation by Speed Change: CARMA Cloud provides a command to mainline CDA vehicles to change speed ahead of a merge to provide gaps in traffic for vehicles to merge from the ramp.

The testing and evaluation effort will assess the performance of the system with the use of the two applications under different conditions based on the reported evaluation criteria listed later in this section. The test scenarios and procedures presented in this section are applicable to both use cases.

3.8.4 Units Tested

The units tested include CDA vehicles and non-CDA vehicles, as well as central and roadside TMS components. Depending on the test, the vehicles can be virtual in the utilized co-simulation modeling platform, CARMA 1/10th, or CARMA full-size vehicles. The following is a list of the units tested.

- The subject vehicle (SV) is a CDA vehicle (CARMA vehicle) on the freeway mainline with automation level 3 or higher according to SAE J3016 standards and cooperative driving class C or higher according to SAE J3216 standards.

- The object vehicles (OVs) are non-CDA vehicles (conventional) traveling on the same lane of the SV. The OVs also include non-CDA vehicles (conventional) on the adjacent lanes in the Mainline Gap Creation by Lane Change test case.

    - A variation of the test cases is to have the OVs as connected vehicles to test the utilization of basic safety messages (BSM), according to SAE J2735 in supporting OEDR capabilities.
    - A second variation of the test cases is to have the OVs as CDA vehicles to test the cooperation between vehicles in car-following and lane changing.
    - A third variation of the test cases is to have the OVs as automated but not connected vehicles (autonomous vehicles) with different levels of automation according to the Society of Automotive Engineers (SAE) J3016 standards, as described above.
    - A fourth variation of the test cases is to have the OVs as vehicles with Level 1 and Level 2 automation.
- The on-ramp merging vehicles can be non-connected human driven, connected human-driven, autonomous non-connected vehicles, and/or CDA vehicles. In the tests of this

project, the vehicles will be assumed to be human-driven non-connected vehicles.

- The CARMA Cloud will act as a central system and communicate with CARMA messengers onboard the CDA vehicles either directly or through the V2X Hub/CARMA Street connected to an RSU.

3.8.4.1 Test Objectives and Metrics

The objectives of the test and the evaluation metrics associated with each objective are listed below.

- Determine the mobility and safety benefits of the provision of lane change command to provide gaps for merging.
    - Reduction in mainline travel time in seconds per vehicle.
    - Reduction in ramp travel time in seconds per vehicle.
    - Increase in freeway throughput in vehicles per hour.
    - Reduction in abrupt speed changes due to the interactions between the mainline and on-ramp vehicles at the influence merge area.
    - Reduction in the number of traffic conflicts, especially the rear-end conflicts and side-swipes conflicts.

- Determine the ability of the CDA vehicles to change lanes and change speed to provide gaps for merging.
    - Successful lane change of SV when receiving a lane change command and merges between two OVs on the adjacent lane with a minimum separation distance with each OV that will be specified as a function of the OV speed.
    - Successful speed change of SV receiving a speed change command.
    - SV vehicle completing speed change or lane change before reaching the merge area.
    - Limiting the acceleration/deceleration and yaw rate to the limits expected from "regular human driving".
    - Changing lanes or speed of SV with a trajectory that emulates as much as possible "regular human driving".
    - Activating and deactivating the turn signal of the SV to support the lane change.

- Determine the ability of CDA vehicles to detect and respond to vehicles in the SV lane and adjacent lane (using sensors in case of non-connected OVs, and both sensors and BSM messages in case of connected OVs).
    - SV reducing its speed to maintain a safe, speed-dependent following distance behind the leading OV.
    - SV not changing lane if that generates conflicts with OVs on the adjacent lane.
    - SV reacting in a safe manner to the lead vehicle decelerating.
    - SV reacting in a safe manner to the lead vehicle stopping.
    - SV reacting to a cutting vehicle from the adjacent lane.

- Determine the ability of the CDA to recover from an error. Error handling is developed under CARMA Health Monitor core functionalities. If an error occurs, it is detected by the Health Monitor, and the vehicle disengages and returns to manual control. This measure is not applicable to the testing using co-simulation or the testing using CARMA 1/10th vehicles. The measure is only applicable to closed-track testing or open-road testing.

  - The ability of the system to disengage, resulting in the SV driver taking manual control of the vehicle, in case of sensor and GPS failures.
  - Number of disengagements per test run

3.8.4.2 Test Scenarios

The test will be conducted with different levels of congestion, ranging from free-flow to stop-and-go operations (Level of Service F), as follows:

- Test Case Mainline Gap Creation by Lane Change – 1 Free Flow
- Test Case Mainline Gap Creation by Lane Change - 2 LOS B
- Test Case Mainline Gap Creation by Lane Change – 3 LOS E
- Test Case Mainline Gap Creation by Lane Change - 4 LOS F
- Test Case Mainline Gap Creation by Speed Change – 1 Free Flow
- Test Case Mainline Gap Creation by Speed Change - 2 LOS B
- Test Case Mainline Gap Creation by Speed Change – 3 LOS E
- Test Case Mainline Gap Creation by Speed Change - 4 LOS F

All scenarios will involve a mainline vehicle (SV) equipped with CDA features, which will be driven on the right lane of a freeway with two lanes. As it approaches an on-ramp merge area, it receives a command from the central system. The purpose of the provided command is to reduce speed or move from the right lane to provide gaps for the merging vehicles from the on-ramp.

3.8.4.3 ODD Characteristics

The test will be conducted for a two-lane freeway on-ramp merge segment that is straight and flat, with clear lane markers and dry pavement. The base test will be conducted in daylight with a clear sky, dry conditions, and no impacts from the sun. The test will be conducted under different mainline and ramp volumes and different acceleration lanes configurations. Variations of the test case include adverse weather conditions such as moderate rain and heavy rain, fog, and wet pavement, nightlight with and without adverse weather conditions, and other conditions.

3.8.4.4 Test Procedure Description

The test will involve an SV on the center of the right-most lane, one OV vehicle ahead of the SV vehicle on the same lane, and two OVs on the center of the adjacent left lane. All vehicles will initially be static ahead of an emulated merge area at a location that allows them to accelerate to their steady-state speed in advance of the merge area. The SV is positioned adjacent to the following OV vehicle (OV_2) in the adjacent lane. Then, the vehicles will start moving to reach steady-state speeds, time headways, and distance headways that are specified for each test scenario. The vehicles will maintain the approximate longitudinal and lateral separation distances at all times. Before starting the test, the test team must ensure that sensor failure detection should result in stable operation or handle errors gracefully. Each individual test will end once the SV successful changes lane from the rightmost lane ahead of the merge area, and stops at the predefined final destination, fail to change lane ahead of the merge area, or the automated features are disengaged due to failures. Once the test is finished, the ADS features are disengaged automatically, if they are not already disengaged.

In the case of the co-simulation testing, additional non-CDA and/or CDA simulated vehicles will be modeled in the traffic model (e.g., SUMO or Vissim), such that the impact on the traffic stream performance can be assessed.

3.8.5 Mainline Vehicle Lane Change Scenarios

In the scenarios of the Test Case Mainline Gap Creation by the Lane Change test case, the CARMA platform on the SV is activated and the SV is given a target point and a gap to change to the left lane through CARMA Cloud commands that are communicated to the vehicle. The test team must be sure that all systems have been initialized and are operable, and the plugins must be active in the default mode. The plugins that participate in the test case should be selected through the user interface. The guidance system must be operable and able to receive geofence messages from CARMA Cloud via the User Interface. The test team must ensure that the World CARMA system is engaged and the POP, weather zone events, geofences, and ROP have been set appropriately.

Each trial ends when the SV successfully changes lanes to merge between two OVs, the SV fails to merge before the merging segment, or the SV driver must intervene because of a failure. After the end of the trial, the driver disengages the CDA feature, if it is not already disengaged.

Examples of the criteria to indicate that a trial passes the test are listed below.

- The tested system improves mobility and safety by reducing mainline travel time, on-ramp travel time, freeway throughput, traffic conflicts, and abrupt speed changes.
- The CARMA vehicles are able to safely change lanes to provide gaps for merging.
- Successful lane change of SV when receiving a lane change command and merges between two OVs on the adjacent lane with a separation distance that does not exceed ±X ft from the specified separation distance that will be specified as a function of the OV speed.
- The number of vehicles (SVs) that were not able to complete lane change before reaching the merge area is less than X%.
- Average and distribution of the time required to merge.
- Average and distribution of the merging distance from the on-ramp merge area
- Mainline vehicles acceleration is less than X ft/s2.
- Mainline vehicles deceleration is less than X ft/s2.
- On-ramp vehicles acceleration is less than X ft/s2
- On-ramp vehicles deceleration is less than X ft/s2
- SV vehicle performing lane changing yaw rate is less than X degrees.
- The SV can activate and deactivate the turn signal of the SV to support the lane change.

3.8.6 Mainline Vehicle Speed Change Scenarios

In the scenarios of the Gap Creation by Lane Change test case, the CARMA platform on the SV is activated, and the SV is given a target speed through CARMA Cloud commands that are communicated to the vehicle. Before starting the test, the test team must ensure that sensor failure detection should result in stable operation or handle errors gracefully, that all systems have been initialized and are operable, and the plugins must be active in the default mode, as described for the Mainline Vehicle Lane Change Scenarios.

Each trial ends when the SV successfully changes lanes to merge between two OVs, the SV fails to merge before the merge segment, or the SV driver must intervene because of a failure. After the end of the trial, the driver disengages the CDA feature.

Each trial ends when the SV successfully changes speed and maintains the separation distance and headway to the leading vehicle, allowing more gaps for on-ramp vehicles to merge and the SV stops at the target destination, the CDA vehicle fails to achieve the gap before the merge segment, or the SV driver must intervene. After the end of the trial, the SV driver disengages the CDA feature, if it is not already disengaged.

Examples of the criteria to indicate that a trial passes the test are listed below.

- The tested system improves the mobility and safety by reducing mainline travel time, on-ramp travel time, freeway throughput, traffic conflicts, and abrupt speed changes.

- The CARMA vehicles are able to safely reduce speed to provide gaps for merging.

- Successful speed change of SV when receiving a speed change command.
- The speed of the vehicles does not exceed ±1.5 mph compared to the rules of practice specified by CARMA Cloud through the User Interface
- Number of vehicles (SVs) that were not able to complete speed change before reaching the merge area less than X%
- Mainline vehicles acceleration is less than X ft/s2
- Mainline vehicles deceleration is less than X ft/s2
- On-ramp vehicles acceleration is less than X ft/s2
- On-ramp vehicles deceleration is less than X ft/s2

3.8.6.1 Dynamic Merge with Merge Parameter Setting by the Infrastructure

This section describes a test case that is related to the infrastructure-based support of the dynamic merge infrastructure support with merge parameter setting by the infrastructure. As described earlier, the test case is related to identifying merging points and target gaps of specific sizes and positions and assigning the vehicles to the target gaps. This test case in this project is referred to as:

- Test Case Dynamic Merge Infrastructure Support

3.8.6.2 Units Tested

The units tested include CDA vehicles and non-CDA vehicles, as well as central and roadside components. Depending on the test, the vehicles can be virtual in the utilized co-simulation modeling platform, CARMA 1/10th, or CARMA full-size vehicles. The following is a list of the units tested.

- The SV is a vehicle with automation level 3 or higher, according to SAE J3016 standards, and cooperative driving class C or higher according to SAE J3216 standards driving on an on-ramp and ready to merge into the freeway mainline.

- The Object Vehicles (OVs) are vehicles approaching the merging area on the right lane of the highway in the merge area. The OVs are non-CDA vehicles; rather, they are connected vehicles traveling on the right lane in the merge area.
    - A variation of this test case is to have the vehicles approach the merging area as CDA vehicles to test the cooperation between vehicles in dynamic merge control operations.

- The CARMA Cloud acts as a central system and communicates with CARMA messengers onboard the CDA vehicles either directly or through the roadside infrastructure about the specific gaps to be used by the vehicles in the merging process.

3.8.6.3 Test Scenarios

The test scenarios involve testing under different congestion levels. Variations of the test can include testing under different weather conditions, lighting conditions, pavement conditions, and different levels of connectivity, automation, and cooperation capabilities for the object vehicles.

The test scenarios under different levels of congestion include:

- Dynamic Merge Infrastructure Support - 1 Free Flow
- Dynamic Merge Infrastructure Support - 2 LOS B
- Dynamic Merge Infrastructure Support - 3 LOS E

- Dynamic Merge Infrastructure Support - 4 LOS F

In all scenarios, the SV merges from the on-ramp to the highway with the OVs driving on the mainline approaching the merging area. In the base scenarios, the OVs are connected but not automated or cooperated, but this can vary as additional scenarios are considered in the test. The SV will receive information from the infrastructure (CARMA Cloud) regarding recommended parameters for merging. The SV equipped with CDA capabilities will use this information in their merging operations. If the OVs are also CDA vehicles of cooperation Class C or higher, the SV will negotiate with other CDA vehicles during the merging operations to facilitate the merging.

The central system collects data to support the determination of the acceptable gaps, including vehicle trajectory data and weather data. The trajectory data will be collected using CV, automated vehicle sensor data, cooperative vehicle negotiation data, and an infrastructure sensor. The infrastructure will distribute the messages to the OBUs of the CDA vehicles. Once the messages are received by the vehicle, the onboard CARMA Platform enabled computer will be able to read and interpret the messages, including the parameters and the rules of practice set by CARMA Cloud, and will consider these parameters for the arbitrated planning and negotiation with other vehicles.

3.8.6.4 Test Objectives and Metrics

The metrics related to the test objectives are described as follows:

- Determine the mobility and safety benefits of the provided merging parameters.
    - Reduction in mainline travel time in seconds per vehicle
    - Reduction in ramp travel time in seconds per vehicle
    - Increase in freeway throughput in vehicles per hour
    - Reduction in abrupt speed changes due to the interactions between mainline and on-ramp vehicles at the influence merge area
    - Reduction in the number of traffic conflicts, especially rear-end type of conflicts that potentially occur due to a hard brake and side-swipe conflicts.
- Assess the ability of the central system to provide and maintain situational awareness during the merging operations.
    - Data quality in terms of the ability to collect, aggregate, and disseminate data to support the setting of the merging parameters by the infrastructure.
    - Latency of information delivery between the central system and the CDA vehicles.
- Determine the ability of the CARMA vehicle to perform merging under different scenarios according to the Rules of Practice (ROP) set by the CARMA Cloud.
    - The SV successfully changes lanes and merges between two OVs on the adjacent lane according to the provided information, with a minimum separation distance of equal or more than xx ft with each OV and according to the provided rules.
    - The SV does not accelerate/decelerate by more than xx mph of the speed limit with an acceleration/deceleration that does not exceed what is expected by human drivers.
    - Successful merging of the SV receiving the merging command on the on-ramp and

    merges between two OVs on the adjacent lane with a minimum separation distance with each OV that will be specified as a function of the OV speed.
  - Completing the SV lane change before reaching the end of the acceleration lane area.
  - The percentage of accepted gaps made according to received rules.
  - Limiting the acceleration/deceleration and yaw rate to the limits expected from "regular human driving."
  - Merging of the SV with a trajectory that emulates as much as possible "regular human driving."
  - Activating and deactivating the turn signal of the SV to support the merging.
- Determine the ability of CDA vehicles to detect and respond to vehicles in the SV lane adjacent lane.
  - Ability of the system Trajectory Validator/Emergency Handler module to identify and rectify a portion of the trajectory.
  - Number of events or trajectory portions that were modified.
  - Number of modified trajectories that were successfully executed by the trajectory executor.
  - SV reducing its speed to maintain a safe, speed-dependent following distance behind the OV.
  - SV not changing lanes if that generates conflicts with OVs on the adjacent lane.
  - SV reacting in a safe manner to the lead vehicle decelerating.
  - SV reacting to a cutting vehicle from the adjacent lane.
  - SV reducing its speed to maintain a safe following distance behind the OV.

- Determine the ability of the CDA to recover from errors. Error handling is developed under CARMA Core functionalities (Health Monitor). If an error occurs, it is detected by the Health Monitor and the vehicle disengages and returns to manual control. This measure is only applicable to closed-track testing and highway testing.
  - Ability of the system to disengage, resulting in the SV driver taking manual control of the vehicle, in case of sensor and GPS failures. The location and manner of the disengagement will be recorded in the experimenter's notes.
  - Number of disengagements per test run.

3.8.6.5 ODD Characteristics

The test will be conducted for a two-lane freeway merge segment from a one-lane on-ramp that is straight and flat, with clear lane markers and dry pavement for daylight conditions with a clear sky, no rain, no impacts from the sun. Variations of the test case include adverse weather conditions, such as moderate rain, heavy rain, fog, and wet pavement. Other variations include performing the test under night conditions with and without adverse weather conditions. Freeways with different number of freeway mainline lanes and on-ramp lanes can be used in other variations of the test.

3.8.6.6 Test Procedure Description

Initially, the SV is driving on the on-ramp toward the highway. The SV requires a lane change to be accomplished before the end of the acceleration lane to merge into the freeway mainline right lane. The right lane has OVs with different congestion levels, from LOS A to LOS F, depending on the scenario. These OVs can be connected vehicles, CDA vehicles, or a mixture of the two depending on the scenario. The goal is to accomplish the lane change in a smooth and safe manner before the end of the acceleration lane.

Before starting the test, the test team must ensure that sensor failure detection should result in stable operation or handle errors gracefully, that all systems have been initialized and are operable, and the plugins must be active in the default mode, as described for the Mainline Vehicle Lane Change Scenarios.

Each test ends when the SV is successful in safely merging into the highway and stops at the predefined final destination, fails to merge, or the SV driver must intervene because of a failure. After the end of the trial, the driver disengages the CDA feature if it is not already disengaged.

Examples of the criteria to indicate that a trial passes the test are listed below.

- The tested system improves the mobility and safety by reducing mainline travel time, on-ramp travel time, freeway throughput, traffic conflicts, and abrupt speed changes.
- The CARMA vehicles are able to safely merge in freeway mainline traffic.
- Successful merging of SV when receiving a lane change command and merges between two OVs on the adjacent lane with a separation distance that does not exceed ±X ft from the specified separation distance that will be specified as a function of the OV speed.
- The number of vehicles (SVs) that were not able to complete lane change before reaching the end of the acceleration lane is less than X%.
- Mainline vehicles acceleration is less than X ft/s2
- Mainline vehicles deceleration is less than X ft/s2
- On-ramp vehicles acceleration is less than X ft/s2
- On-ramp vehicles deceleration is less than X ft/s2
- SV vehicle performing lane changing yaw rate is less than X degrees
- Speed of the vehicles does not exceed ±1.5 mph compared to the rules of practice specified by CARMA Cloud through the User Interface
- Vehicles do not deviate from the specified lane
- The SV can activate and deactivate the turn signal of the SV to support the lane change

3.8.7 Enhanced Active Traffic Management in the Presence of Collaborative Merging Operations

The test case in this section involves the use of connected, automated, and CDA vehicle data to determine the need to activate ramp metering to improve the ramp metering operations and safety, considering both human-driven and CDA vehicle operations. It will also test the development and use of new adaptive ramp metering algorithms that consider human-driven vehicles and CDA vehicles. This can be classified as Enhancement Category Level 1 according to the categorization presented above. The following test case is discussed in this document.

- Ramp Metering Parameter Setting with CDA Consideration

Other test cases of enhanced management could be included, such as speed harmonization to support the merging operation.

3.9 Ramp Metering Parameter Setting with CDA Consideration

In this test case, the infrastructure will analyze the data collected from traffic sensors, connected vehicles, and CDA vehicles, and will predict the probability of traffic breakdown and safety issues at the merge area and the difficulties of the merging operations of CDA vehicles. It will then activate ramp metering and/or dynamic speed strategies. The activated ramp metering strategies consider the traffic conditions, as well as the trajectories of the CDA and human-driven merging vehicles and their ability to merge in traffic. In addition to considering the CDA trajectories, this strategy will potentially consider the trajectories of connected human-driven vehicles and traffic information collected using infrastructure sensors. The system will utilize CDA data of the type collected by CARMA and/or according to SAE J2945/8 standards, connected vehicle collected according to SAE J2735 standards, and automated vehicle data collected according to SAE J3224. The CDA data will help determine the ability of the CDA vehicles to merge with mainline traffic.

3.9.1.1 Units Tested

The unit tested will be an emulated traffic management central and roadside infrastructure that will collect data from multiple simulated sources and activate ramp metering based on the collected data. The simulated traffic management system will interface with CARMA Analytics, CARMA Cloud, CARMA Street, and V2X Hub to collect additional data for use in setting the ramp metering parameters. The test will include a mixture of simulated CDA vehicles and human-driven vehicles with different levels of connectivity on the freeway mainline and on-ramps.

3.9.2 Test Scenarios

The test is conducted under different congestion levels and different market penetrations of connectivity and cooperation. The test scenarios will involve simulating a freeway segment with a bottleneck location at a merge area. The following scenarios will be tested:

- Ramp Metering Parameter Setting with CDA Consideration - Activation Support
- Ramp Metering Parameter Setting with CDA Consideration - Rate Setting Support

The “Ramp Metering Parameter Setting with CDA Consideration - Activation Support” scenario is for under congestion levels that are close to the capacity of the segment prior to traffic breakdown. At this stage, the ramp metering has not been activated. The central system will determine the probability of traffic breakdown, probability of near misses, and inability of the CDA and possibly other vehicles to merge effectively due to the limited number of appropriate gaps in traffic. The central system will provide a recommendation to activate ramp metering based on these determinations. The utilized data in this scenario will include those from traffic sensors, SAE J3275 standards, SAE J3224 standards, SAE J2945/8 standards, and CARMA Analytics.

The “Ramp Metering Parameter Setting with CDA Consideration - Rate Setting Support” scenario will use the data from the multiple sources identified above for the selection of adaptive ramp metering parameters. The performance of the adaptive signal control in supporting the merging of CDA vehicles and improving traffic operations and safety in the merge area is compared with the existing adaptive signal control systems, such as the fuzzy logic algorithm-based ramp metering implemented in Miami, Florida.

3.9.2.1 Test Objectives and Metrics

The objectives of the test and the evaluation metrics associated with each objective are listed below:

- Evaluate the data quality collected by the CARMA Analytics in terms of:
    - Total number and percentage of missing records
    - Total number and percentage of erroneous records
    - Total downtime, which is defined as the total period of time when the data is incomplete or erroneous due to factors such as communication failures or sensor failures.
- Determine the ability of the CARMA Analytics to analyze the captured data exchanges between the CDA vehicles and between CDA vehicles and human-driven connected vehicles during the negotiations for maneuvers execution.
    - Determining the duration of the negotiation process
    - Determining the total number of successes/failures in negotiations
    - Determining the total number of negotiation attempts before the proposed plan is accepted by all involved vehicles.
- Assess the responsiveness of the developed ramp metering system.
    - Degree of the responsiveness of the metering rates to real-time changes in performance metrics
    - Latency of the responsiveness of the metering rates to real-time changes in performance metrics
- Determine the mobility and safety benefits of the developed ramp metering compared to the conditions with no ramp metering.
    - Improving the merging operations of CDA operations in terms of the duration of the merging process, the total number of success/failures in attempting the merging, and the percentage of successes of the total merging attempts
    - Reduction in mainline travel time in seconds per vehicle
    - Reduction in ramp travel time in seconds per vehicle
    - Increase in freeway throughput in vehicles per hour .
    - Reduction in abrupt speed changes due to the interactions between mainline and on-ramp vehicles at the influence merge area
    - Reduction in the number of traffic conflicts, especially rear-end type of conflicts that potentially occur due to a hard brake and side-swipe conflicts.
- Determine the mobility and safety benefits of the developed ramp metering compared to the conditions with the existing fuzzy logic algorithm ramp metering.

- Improving the merging operations of CDA operations in terms of the duration of the merging process, the total number of success/failures in attempting the merging, and the percentage of successes of the total merging attempts
- Reduction in mainline travel time in seconds per vehicle
- Reduction in ramp travel time in seconds per vehicle
- Increase in freeway throughput in vehicles per hour.
- Reduction in abrupt speed changes due to the interactions between mainline and on-ramp vehicles at the influence merge area
- Reduction in the number of traffic conflicts, especially rear-end type of conflicts that potentially occur due to a hard brake and side-swipe conflicts

3.9.2.2 ODD Characteristics

The test will be done for a two-lane freeway merge segment for one lane on-ramp that is straight and flat, with clear lane markers and dry pavement. The test will be done during daylight with a clear sky, dry conditions, and no impacts from the sun. Variations of the test case include adverse weather conditions, such as moderate rain and heavy rain, fog, and wet pavement. Other variations include performing the test under nightlight with and without adverse weather conditions. Freeways with different number of freeway mainline lanes and on-ramp lanes can be used in other variations of the test.

3.9.2.3 Test Procedure Description

The tests associated with the enhanced active traffic management in the presence of collaborative merging operations will utilize simulation analysis in obtaining the necessary information for the test. The simulation results will be used for the verification of the data quality collected by the CARMA Analytics and to determine the ability of the CARMA Analytics to analyze the captured data exchanges between the CDA enabled vehicles during the negotiations for maneuvers execution. The test will also use simulation analysis to assess the improvements in traffic operations and safety and CDA merging operations compared to conditions with no ramp metering and conditions with existing ramp metering algorithms. The test will use the performance metrics listed in the Test Objectives and Metrics section.

The test will involve a freeway mainline segment with an off-ramp and an on-ramp, with different proportions of connected and CDA vehicles and different total demand levels. The connected vehicles in the simulation will be set to broadcast BSM according to the SAE J2735 standards, including speed, acceleration, geographic latitude and longitude, elevation, yaw rotation rate, and so on. The infrastructure is assumed to capture the BSM data and is broadcasted by the vehicles' OBUs and transmitted to the roadside units or to the central system. In addition, the system will be set to capture the CDA vehicle data, including data exchanges occurring during the negotiation process that takes place between CDA vehicles with cooperation class C and higher, as collected by CARMA. The infrastructure will also capture messages broadcasted according to the newly developed SAE J2945/8 and SAE J3224 standards. The SAE J2945/8 standards provide the guidelines for V2X enabled entities in broadcasting information regarding their perception of nearby objects to achieve cooperative operations and improve the performance of other V2X enabled systems. The SAE J3224 presents the definitions for sensor data sharing messages (SDSM). The SDSM will include automated vehicle sensor data, such as relevant descriptions of detected objects or other vehicles and their characteristics, such as the objects' location, size, and motion state.

The data from the above sources will be reduced and fused with data from traffic sensors in the simulation model, which is assumed to be installed in the vicinity of the merge area. A new algorithm will be developed and tested in simulation to recommend the activation of a ramp metering algorithm, based on the measured information. The algorithm will be tested in the simulation to determine its effectiveness and impacts as assessed using the various measures identified earlier.

The collected data will assist in the derivation of new measures for use in traffic management, including:

- The collection of BSM from connected vehicle data will assist in the derivation of new measures of the operation of freeway segments that are not currently being used. This can include the standard deviation of speeds for individual vehicles, the standard deviation of speeds between vehicles, the standard deviation of speeds between data points for a predetermined time interval, acceleration/deceleration, and the jerk which can also be defined as the second derivative of velocity.

- Given the current low market penetration levels for both CV and CDA enabled vehicles, it is believed that the utilization of SDSM will provide additional information to support the calculation of the measures, which can be calculated using CV BSM data, as shown in the above-bulleted list. Additional measures, such as the distributions of time headways and distance headways, can be obtained based on the SDSM.

- CDA data will assist in the derivation of new metrics related to the success and latency of the merging process of the CDA.

The data collected above can be used as inputs to the ramp metering activation and ramp metering parameter setting algorithms. In addition, it will be used in the testing to evaluate the impact of the developed algorithms on the performance, as assessed by the test case performance measures described earlier. This can include the evaluation of the efficiency of the CDA merging operations with and without ramp metering, and in terms of the rate of success/failures of the negotiations that take place during the merging, as well as the average duration of the negotiation process that takes place between CDA equipped vehicles and the overall number of negotiation attempts before the negotiation between SV and OV comes to an end (once the proposed plan is accepted). The evaluation of the measures will also serve as important insight for the need to modify the rules of practice using the CARMA User Interface.

Examples of the criteria to indicate that a trial passes the test are listed below.

- Data quality collected by the CARMA Analytics in terms of:
    - Total number of null records do not exceed X%

  - Total number of records with erroneous data do not exceed X%
  - Total downtime does not exceed X% from the total time in the analyzed period
- CARMA Analytics ability to analyze the captured data exchanges between the CDA enabled vehicles during the negotiations for maneuvers execution.
  - Total duration of the negotiation process for the merging maneuver does not exceed X seconds.
  - Proportion of negotiation failures during the analyzed period does not exceed X%
  - Average number of negotiations attempts before a proposed plan is accepted by all the involved vehicles is not more than X negotiation attempts
- Responsiveness of the developed ramp metering system
  - Accuracy of the prediction of the traffic state utilized as input for the ramp metering system (fuzzy logic) is at least x%
- Mobility and safety benefits of the developed ramp metering compared to the conditions with no ramp metering and conditions with an existing ramp metering algorithm (the fuzzy logic algorithm) by increasing freeway throughput and reducing mainline travel time, on-ramp travel time, traffic conflicts, and abrupt speed changes.
- Improved merging operations of CDA vehicles in terms of the duration of the merging process, the total number of success/failures in attempting the merging, and the percentage of successes of the total merging attempts.
  - The total duration of the merging process does not exceed X seconds
  - The proportion of failed merging attempts is less than X% of the total merging events during the analyzed period.

4. DEMONSTRATION OF SIMULATION UTILIZATION IN TESTING AND EVALUATION

This chapter provides recommendations regarding the use of traffic simulation and co-simulation in the testing and evaluation of CDA and infrastructure support. The chapter presents a review of traffic simulation and co-simulation platforms for the testing and evaluation of automated and cooperative driving. The chapter also provides and overview of the use of traffic simulation and co-simulation in this study to model merge areas in the presence of automation and cooperation with and without ramp metering.

As stated in the previous chapters, the performance of CDA has been assessed using simulation environment and closed test tracks technology for different test cases and under different scenarios. Most CDA research utilizes traffic simulation because traffic simulation has the flexibility and capability in setting up different use cases and scenarios, and requires less cost, time, and resources compared to real-world testing. Microscopic traffic simulation models have been used to simulate CDA vehicle, taking advantages of their ability to simulate each vehicle movement at small time steps (e.g., every 1/10th of a second) and that these models can be extended to include new car following and lane changing behaviors and control algorithms such as those associated with automated vehicles and CDA.

In recent years, researchers and evaluators have developed and utilized co-simulation environments for CDA testing. These co-simulation environments typically include a microscopic traffic simulation combined with other simulation tools and automation and cooperation platforms. These co-simulation environments include autonomous driving simulation tools such as CAR Learning to Act (CARLA) that simulate vehicle dynamics and the performance of onboard sensor devices used for object and event detections. These sensors can be modeled and configured in the simulation to reflect their functionalities and performance. The user can change, for example, the number and positions of the cameras, the field of vision, and their detection range. It is important to include traffic simulation models as part of this co-simulation to provide traffic performance measurements because while the vehicle dynamics simulators such as CARLA can provide realistic vehicle dynamics control and sensor simulation, they cannot provide traffic performance measures such as delay, travel time, density, and queue length. Moreover, microscopic models used in traffic simulations such as car following, lane changing, and gap acceptance have long been developed, investigated, and updated; so, they are much more mature in simulating real-world driving behaviors compared to what can be simulated in vehicle dynamic simulators. The CARMA co-simulation environment is also being integrated with a communication simulation tool (NS-3) to emulate the delay and loss in sending and receiving messages and data exchange. In addition, the co-simulation environments have been integrated with CDA software-in-the-loop and/or hardware-in-the-loop platforms such as those of the OpenCDA and CARMA, discussed later in this chapter. The following subsections present more discussion of the use of traffic simulation and co-simulation platforms in testing and evaluating CDA.

4.1 Microscopic Traffic Simulation

In microscopic traffic simulations, new algorithms can be written to model CDA through the use of the Application Programming Interface (API) of the utilized traffic simulation tools such as

Simulation of Urban Mobility (SUMO), Vissim, Aimsun, and TransModeler. These tools have built-in algorithms that are supposed to reflect the impact of automation and cooperation but in much less realistic way than what could be achieved with the introduction of more detailed algorithms coded using the API facilities of these tools. The four microscopic simulation tools mentioned above are the most widely used worldwide. SUMO is an open-source tool, while the other three tools are commercial tools. SUMO is used in this project, as it is the tool utilized in co-simulation tools like the CARMA and OpenCDA co-simulation tools. If an evaluation and testing project uses a combination of a co-simulation tool environment (that includes a microscopic traffic simulation as part of the environment) and separately a microscopic traffic simulation as a standalone model, as is done in this study and explained later in this document, then it is recommended to use the same microscopic traffic simulation tool used in the co-simulation as a standalone tool in the evaluation and testing. This allows better identification of the relationship between the measures obtained from the two types of simulation and fine-tuning of the modeling parameters based on examining the performance and results of the two types of simulation.

In SUMO, the API facility is referred to as Traffic Control Interface (TraCI) library, which is a module that allows the user to access, retrieve, and change the parameters of vehicles and other objects in the simulation. Although TraCI allows the coding of complex driving behavior and control; their modeling of sensors, connectivity, and aspects of automation and cooperation is not detailed enough for testing the various software modules and hardware associated with CDA technology and their interactions with the surrounding environment. For example, although some parameters of the onboard sensors such as detection ranges can be approximated in simulation; the actual performance of the sensors that is impacted by sensor types and positions, occlusions, geometry, lighting, and weather conditions, and so on are best modeled using co-simulation. However, traffic simulation has a major advantage over existing co-simulation environments (co-simulation includes traffic simulation as part of the environments) in that the computational requirements of co-simulation only allow the modeling of short periods of time for short roadway segments and for only few CDA vehicles. Thus, the assessment of system level impacts of CDA on traffic measures for periods of time such as 15 minutes, 60 minutes, or longer periods of time cannot be achieved using co-simulation. An extended traffic simulation model rather than co-simulation should be used for traffic performance assessment, as detailed later in this document.
This study has identified that the testing and evaluation of CDA and infrastructure support of CDA require 1) the use of microscopic traffic simulation tools such as SUMO, Vissim, Aimsun, and TransModeler, possibly extended with more realistic CDA modeling, to quantify the traffic level impacts in terms of traffic efficiency, traffic safety and traffic stability, and 2) the use of co-simulation tools, such as those reviewed in this study to assess vehicle level performance in the testing of CDA driving features, hardware and software, and associated maneuvers and interactions.

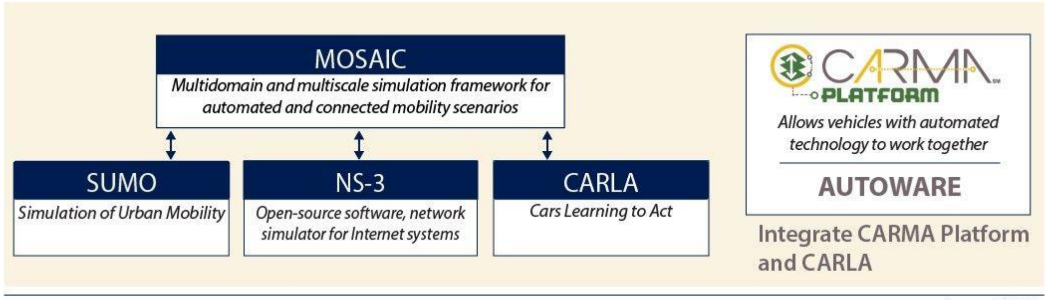
4.2 Co-Simulation Platforms

As stated earlier, co-simulation integrates traffic simulation with high-fidelity vehicle dynamic and sensor simulator, a CDA software-in-the-loop or hardware-in-the-loop platforms, and in some cases communication simulation to achieve the required high level of details for testing CDA driving and control features. The co-simulation can be used to test CDA driving, and control features such tactical maneuver behaviors, performance under operational design domain (ODD) elements, object and event detection and response (OEDR) capabilities, and failure mode behavior testing. For automated and CDA vehicle testing, the ODD elements that the vehicles are expected to be operate under will need to be specified. The ODD elements include attributes such as the roadway type, roadway surface, roadway edge and marking, roadway geometry, minimum speed and maximum speed, traffic congestion, weather conditions, pavement status (wet, dry), illumination, and participating vehicle connectivity. OEDR is an automated vehicle feature that is used to detect and respond to vehicles within its detection range. Testing the OEDR capabilities is to verify that the CDA vehicle(s) will be able to detect other vehicles that may have a conflict with on the same lane or adjacent lane(s). The test will also be able to detect the CDA responses to the detected vehicles, such as yielding to, changing speed, or adjusting the gaps in reacting to these vehicles, which can impact the response to the tactical maneuver command provided by the infrastructure. The Failure Mode Behaviors involves the introduction of errors or faults that induce failures in the tested system, such as sensor and communication failures and the examination of how the automated system responses to the failures. The following subsections present descriptions of existing co-simulation platforms.

4.2.1 CARMA Everything-in-the-Loop (XIL) Co-Simulation

The CARMA Program was developed by the FHWA to encourage cooperative research on CDA (USDOT, 2022a). As part of this effort, the CARMA research team has developed the CARMA everything-in-the-loop (XIL) simulation, as a co-simulation environment to support the evaluation of CDA applications (USDOT, 2022b). It should be noted that at the current phase of the development, this project has mainly focused on integrating a CARMA software-in-the-loop environment with a vehicle dynamic and sensor simulation (CARLA), a microscopic traffic simulation (SUMO), and a communication simulation (NS-3). Future developments may allow using CARMA hardware-in-the-loop instead or in addition to software-in-the-loop. CARMA XIL simulation utilizes MOSAIC (Eclipse Foundation, 2023b), which is a multi-domain and multi-scale simulation framework that works as a co-simulation manager and a core runtime infrastructure.

The CARMA environment includes four components to support cooperative driving automation research and development: CARMA Cloud, CARMA Platform, CARMA Messenger, and CARMA Streets, as described above (USDOT, 2022b). These components will need to be modeled in simulation and thus integrated either as software-in-the-loop or hardware-in-the-loop for full evaluation of the environment. The first component to be integrated with the co-simulation is the CARMA Platform, which is a vehicle-based platform for automated cooperative vehicles to share information and intents, as well as to collaborate with other vehicles and infrastructure in the simulation environment. The CARMA team is working on integrating other CARMA components in the co-simulation. Figure 9 shows the framework of CARMA XIL Co-Simulation. The functional architecture of the CARMA co-simulation is depicted in Figure 10. As shown in this figure, information regarding the vehicle state, surrounding roadway features, as well as messages from other vehicles and the infrastructure, are passed from the simulation to the CARMA Platform. The Plan Stack in the CARMA Platform uses this information to determine a trajectory plan for both the longitudinal and lateral maneuvers of the CDA vehicles. Then, the Act Stack will compute the detailed maneuver for the low-level control commands, including throttle, brake, and steering control needed to proceed with this trajectory.



Source: FHWA

Figure 9. CARMA XIL co-simulation framework (Source: FHWA, 2021).

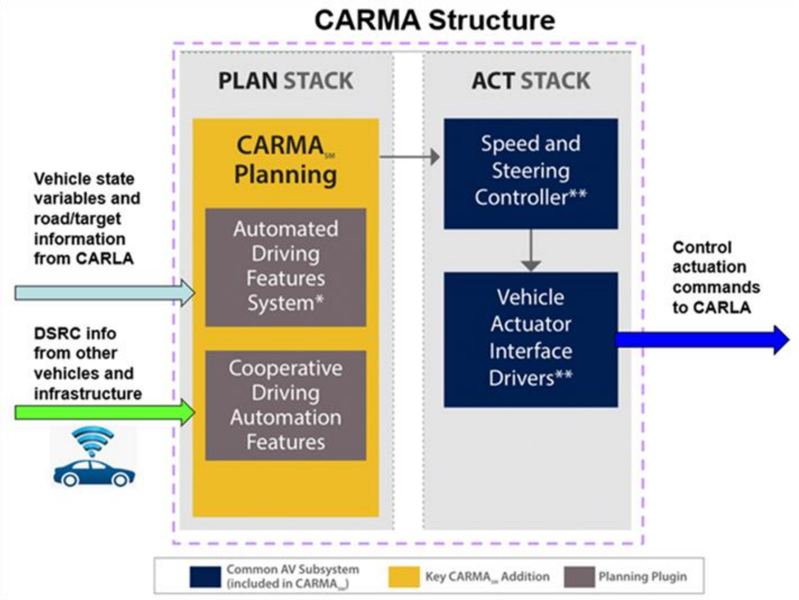


Figure 10. High-level functional architecture of the CARMA Platform and simulation integration (Source: Vu, 2020).

Figure 11 shows examples of the displays of the CARLA simulation environment. The integration of CARLA in the CARMA XIL simulation requires a feedback loop between the components of the environment. CARLA simulates virtual vehicles, sensors, roadway geometry, and other objects, whereas each CARMA instance generates a control command for the subject vehicle. Note that each vehicle simulated in CARLA is also modeled in the SUMO traffic simulator. The connection between the individual simulators (i.e., CARLA, SUMO, and NS-3) is established with the help of the MOSAIC framework.

Figure 11. Screenshot from the CARLA simulation environment (Source: Nallamothu & Rush, 2023).

A data store is shared between the components of the CARMA co-simulation, as shown in Figure 12. The vehicle motion is determined based on the control commands from CARMA and is reflected in the CARLA and SUMO environments with respect to the road and the world coordinate system. The motion and status of the vehicle is sent back to CARMA. Once the CARMA platform receives this information, it will generate new guidance decisions based on this new information, and the feedback control commands will be applied by the subject vehicle in CARLA and SUMO.

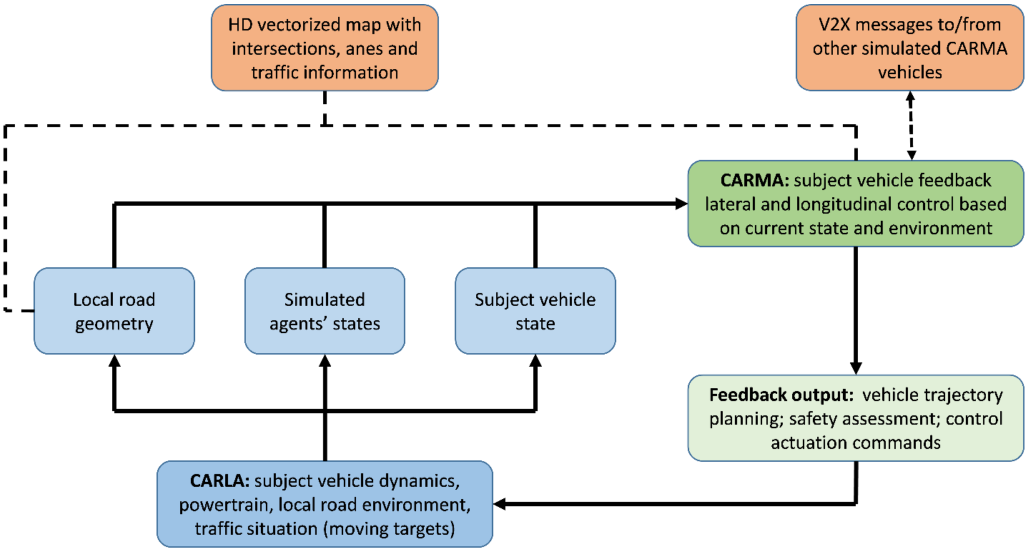


Figure 12. Subsystem's functionality of CARLA and CARMA integration (Source: Vu, 2020).

At the beginning of this project, the research team intended to use the CARMA co-simulation to demonstrate the evaluation of the infrastructure support of CDA. However, it soon became apparent that this environment was still under development and testing and thus was not ready for this project in time. This issue has been discussed with the FDOT project management team. In this discussion, there was an agreement to use a different co-simulation tool that is mature enough to use for testing, considering the project schedule. Thus, other co-simulation options were explored, as discussed below.

4.2.2 OpenCDA

OpenCDA is an open-source co-simulation, developed by the Mobility Lab at University of California in Los Angeles. It can be used to model CDA, although its CDA driving and control platform is not as detailed as that of the CARMA XIL simulation, because the latter potentially integrates all the components developed as part of the CARMA program. However, OpenCDA provides a simple automated driving and cooperative driving platform that can be used in CDA testing, including perception, localization, planning, control, and vehicle-to-everything (V2X) communication modules.

The framework of OpenCDA consists of cooperative driving system, traffic simulation (SUMO), vehicle dynamic and sensor simulation (CARLA), data manager and repository, and scenario manager, as depicted in Figure 13. The cooperative driving system contains a layer that emulates the generation, processing. and utilization received from onboard sensors such as the lidar and camera devices. This layer is called the sense and perception layer and involves the object detection, localization, and prediction tasks of driving automation. A second layer called the plan layer is responsible for generating plans for the vehicles to follow and vehicle trajectories based on predetermined origin and destination locations. A third layer, the application layer, includes cooperative driving modules that allow driving tasks such as cooperative merging and platooning based on cooperative perception and localization. The fourth layer, the actuation layer, is where low-level vehicle dynamic controls take place. These controls comprise throttle, brake, and steering, which are outputs from the underlying vehicle controller. In the co-simulation, CARLA simulates these controls using the Proportional Integral Derivative (PID) controller as a default to control the vehicle dynamics. However, the users can replace PID with other vehicle controllers such as Model Predictive Controller (MPC) in the simulation using the CARLA Python-based API.

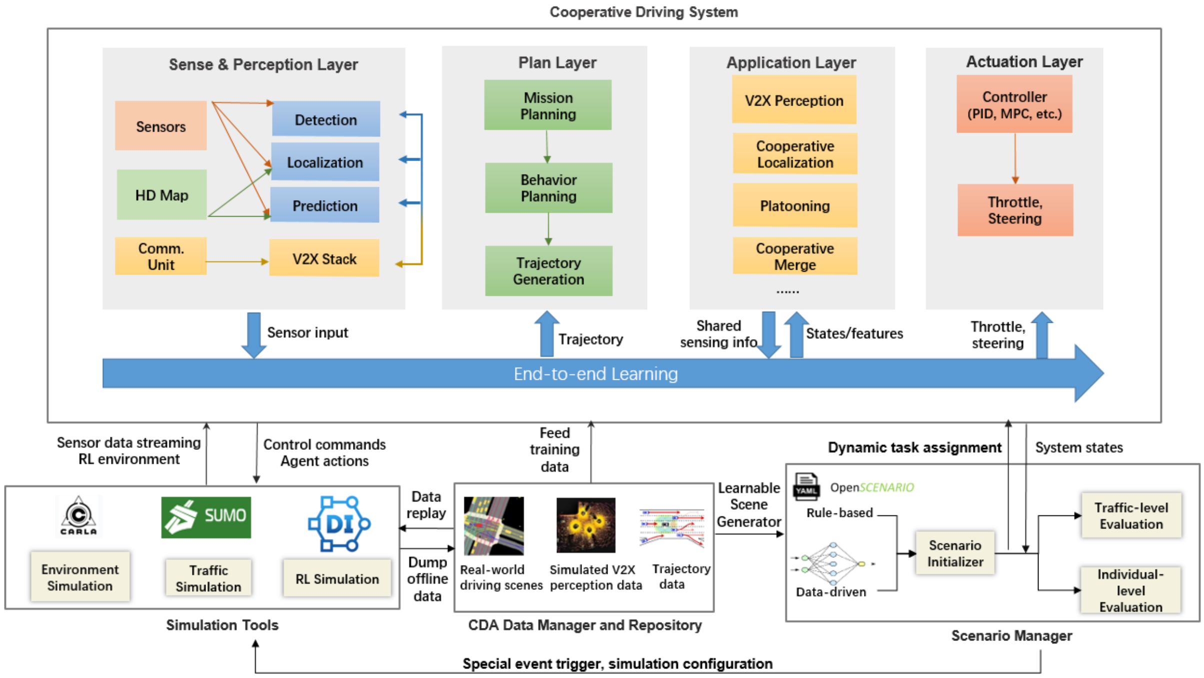


Figure 13. OpenCDA framework

The OpenCDA co-simulation platform integrates CARLA with SUMO simulation. CARLA simulation was developed to support the testing of autonomous driving system. It has the flexibility in configuring sensor devices and providing a realistic environment for simulating the interaction of automated vehicles with static objects such as buildings and dynamic objects such as vehicles and pedestrians. In addition, CARLA allows configuring different weather conditions (sun, rain, and fog) and lighting conditions in the model. The parameters and performance of the onboard sensor devices such as cameras and lidars can also be configured. The virtual sensor devices of the vehicle in CARLA allows the vehicle to detect the surrounding objects and measure the distance from itself to these objects, as well as to collect data about the vehicles an the surrounding. SUMO is a microscopic traffic simulation software, and it is responsible for generating background traffic of human-driven vehicles in the co-simulation environment.

As stated earlier, Figure 13 shows the components of OpenCDA. More details about these components will be discussed later in this report. The Cooperative Driving System in Figure 13 contains the Sense and Perception Layer which is a layer that emulates sensor information from sensors including lidar, camera, Inertial Measurement Unit (IMU), and Global Navigation Satellite System (GNSS), devices simulated in CARLA. Figure 14 shows the camera views of a CDA vehicle in CARLA as part of the OpenCDA co-simulation platform. The number of cameras, position, field of vision, and other camera specifications can be adjusted by the user. The range of the lidar sensor can be also configured, and by default it is set to 165 feet (50 meters). Figure 15 shows the output view from the lidar sensor on the CDA vehicle.

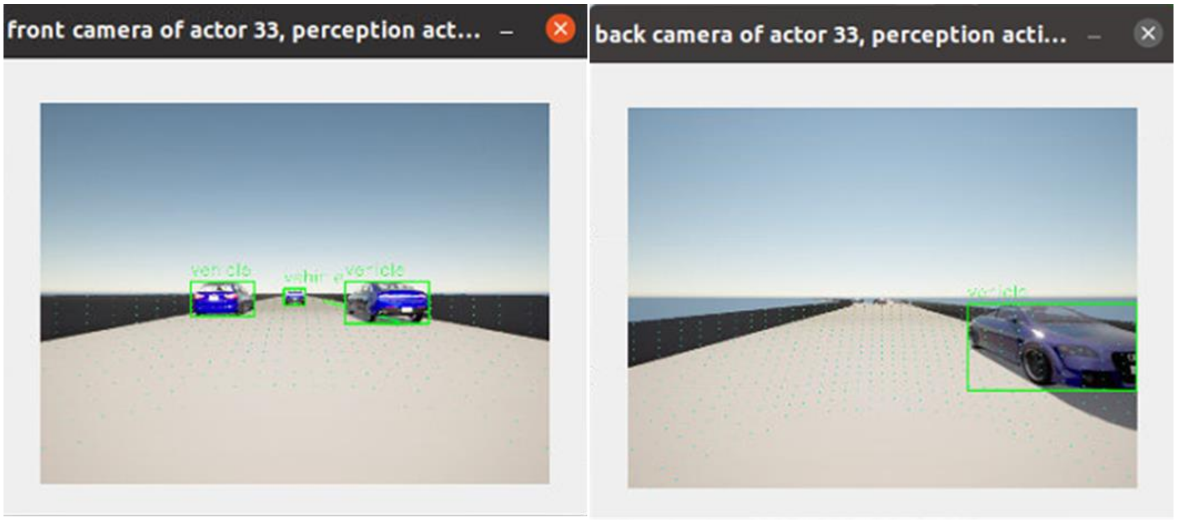


Figure 14. Camera views from a CDA vehicle in the OpenCDA co-simulation

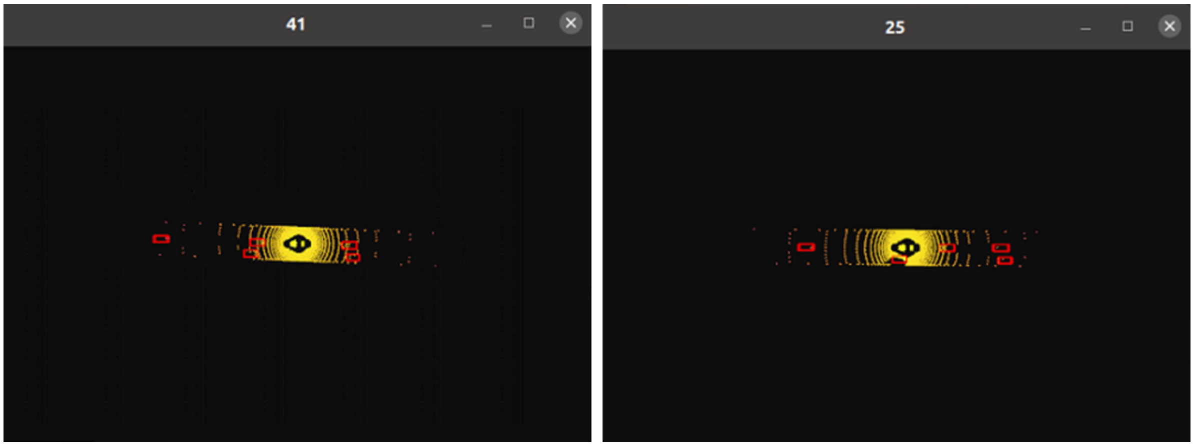


Figure 15. Lidar output retrieved from CDA vehicles.

The sensing data from sensor devices are then passed to the Detection, Localization, and Prediction tasks of the Sense and Perception Layer, as depicted in Figure 13. The data from different sensor sources can be integrated to enhance the performance of cooperative driving systems. The Detection module in Figure 13 is responsible for detecting surrounding objects including vehicles and the infrastructure. The object detection algorithm applied in the Detection module, called You Only Look Once (YOLO), was developed, trained, and tested with a large dataset and is commonly used in both research and industry efforts in various applications. Figure 16 shows an example of an object detection task using the YOLO algorithm. The detected vehicles and infrastructure objects are labeled with a predicted vehicle class (e.g., vehicle and truck) and a confidence level in the prediction. The Localization component in Figure 13 deals with the position retrieval of the vehicles based on the GNSS sensor. The GNSS sensor reports the current position (Latitude, Longitude and Altitude) based on GNSS, which is calculated by adding the position metric to an initial ego reference location defined in a MAP. Another important simulated sensor device is the IMU that provides measures such as those related to the accelerometer, gyroscope, and compass. This allows the co-simulation to retrieve information such as acceleration, orientation, angular velocity, and cardinal direction. The Plan Layer in Figure 13 is responsible for generating vehicle trajectories based on predetermined origin and destination locations.

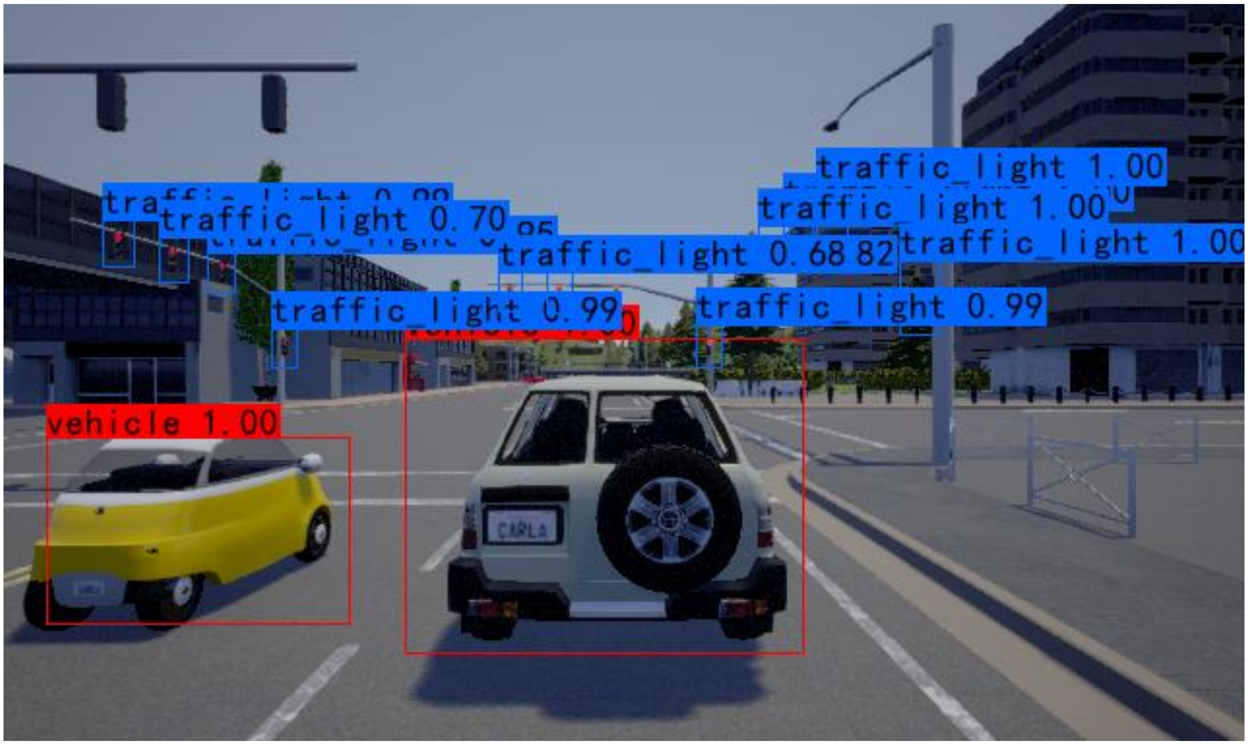


Figure 16. Object detection using YOLO algorithm. (Source: Xiao, 2020).

The Application Layer currently has two CDA applications: platooning and cooperative merge. The two applications work together or separately. For example, the mainline CDA vehicles can be in platoons or not platoons with cooperative merging from an on-ramp. Lastly, the Actuation layer is where low-level vehicle dynamic controls are made including the control of the throttle, brake, and steering. OpenCDA uses the PID controller as a default controller for the Actuation layer since CARLA uses the PID controller as the default controller. Generally, the PID Controller is the most common controller that has been used in the industry in many disciplines and applications. In autonomous driving applications, the PID controller has been implemented to control self-driving vehicles to follow a selected trajectory. In CARLA, the PID controller regulates vehicle dynamic controls (throttle, brake, and steering) by using proportional, integral, and derivative components to compute the output (the control action). Figure 17 shows the generalized structure of a PID Controller. In this study, the Set-Point is the target speed and location of the subject vehicle. The Error Value is calculated from the difference between the Set-Point and the measured value and is passed to the Proportional, Integral, and Derivative components, which allow these components to make the required calculations to determine the Control Signal, is provided as feedback to the Set-Point until the error value is minimized.

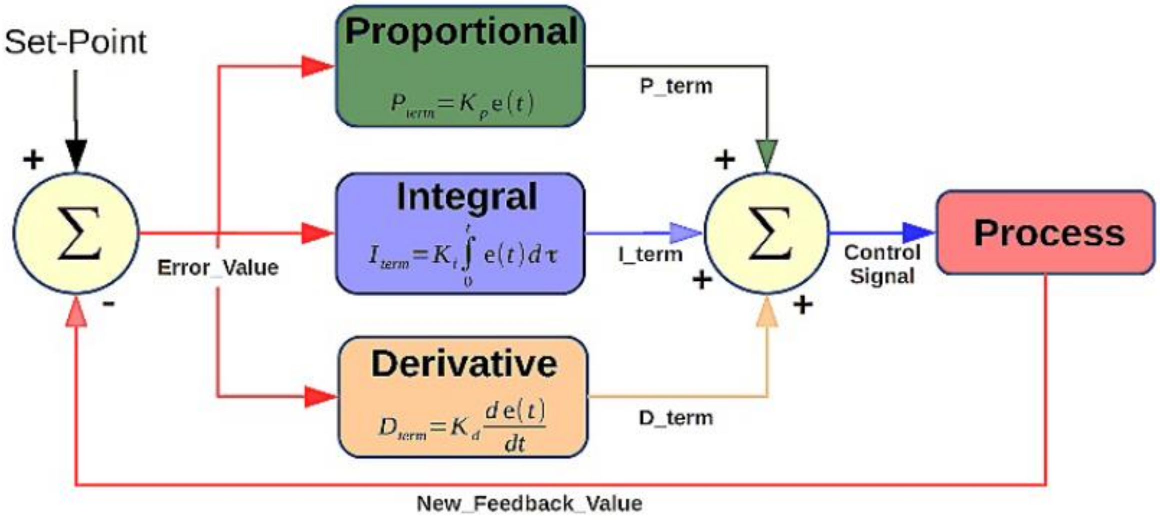


Figure 17. Generalized structure of PID controller.

4.2.3 CoEXist Co-Simulation Tool

CoEXist is the name of a European project initiated with the aim of increasing the capability of agencies, researchers, and other stakeholders to understand and become ready for the eventual transition to a road network that is shared by both conventional human driven vehicles and AVs. One of the main objectives of the project is to provide automation-ready transportation modeling tools capable of simulating several types of scenarios and AV driving logic (Rahal, Pechberti, Sukennik, et al., 2017).

The CoEXist project developed a co-simulation modeling environment using existing software including PreScan autonomous driving simulator and the microscopic simulation tool Vissim. The co-simulation incorporates AV control logic developed by the partners from the Institut du Véhicle décarboné et communicant et de sa mobilité (VEDECOM) and Renault (Rahal, Pechberti, Heijke, et al., 2017). The default values of the parameters used in these tools were validated using data collected from a real-world AVs implementation (Rahal, Pechberti, Sukennik, et al., 2017). The following text and subsections describe the components of the CoEXist co-simulation tool.

PreScan is a simulation software for the development, testing and validation of advanced driver assistance systems (ADAS) and autonomous driving (AD) technologies. The software provides a graphical user interface (GUI) that allows the users to create and modify vehicles and model their sensors, set up driving scenarios, and run the simulation (MathWorks, 2023d). Figure 18 provides a depiction of the modeling steps involved in the PreScan simulation process.

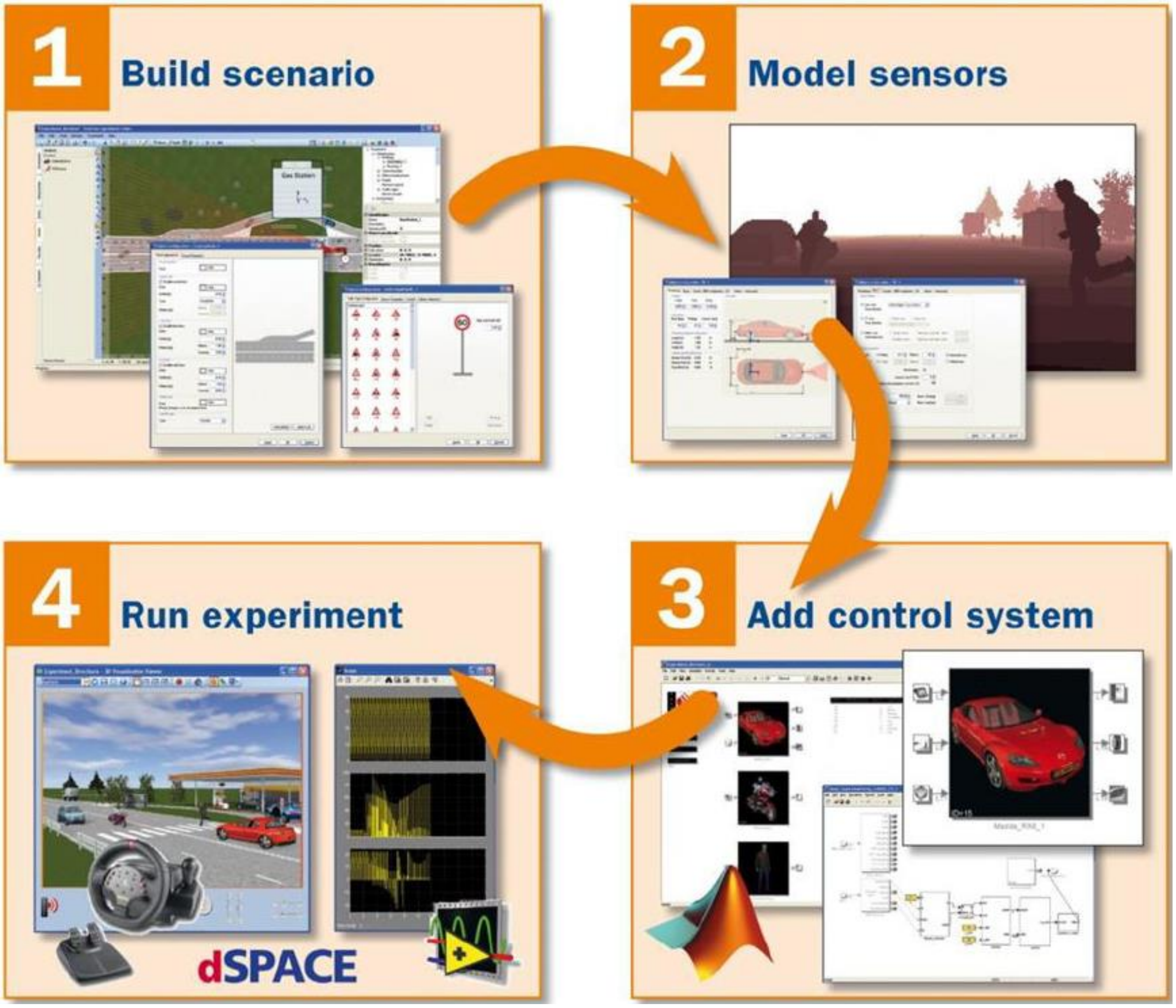


Figure 18. PreScan modeling and simulation process (Source: Rahal, Pechberti, Heijke, et al., 2017).

The modeling steps presented in Figure 18 include:

1. Building scenario: Through its GUI, PreScan allows the users to build and edit traffic scenarios including different types of road sections, infrastructure components, and different lighting and weather conditions.
2. Sensor modeling: PreScan models a wide range of sensors used in Advanced Driver Assistance Systems (ADAS) and AV technologies, including radar, lidar, camera, ultrasound, GPS and antennas for V2X communications. The GUI allows the user to set different combinations of the types of these sensors and adjust the settings related to each sensor.
3. Control System: PreScan provides an interface with MATLAB and Simulink to design and test algorithms for data processing, sensor fusion, decision making, and control. This interface also allows the users to import existing MATLAB and

Simulink Models such as the Vehicle Dynamics Blockset, which is described in the following subsections.

4. Run Simulation: The simulation in PreScan provides a 3D visualization of output as well as the possibility to generate graphics for analytics and performance evaluation (Rahal, Pechberti, Heijke, et al., 2017)

PreScan can be implemented using model-based controller design (MIL) as well as real-time tests with software-in-the-loop (SIL) or even hardware-in-the-loop (HIL) systems.

As stated earlier, the PreScan development utilizes Simulink and MATLAB. Simulink is a widely known general purpose platform for developing and simulating dynamic systems. Simulink provides a graphical user interface that allows users to build dynamic systems in a workflow environment, managing blocks that represent mathematical functions, physical components, and logical operators, and can be configured to perform specific tasks such as designing controllers and analyzing system performance (MathWorks, 2023e). MATLAB, on the other hand, is a high-level programming language and numerical computing environment that provides a wide range of tools for data analysis, visualization, and algorithm development. MATLAB is used in conjunction with Simulink to develop complex algorithms and perform post-processing analysis of simulation results (MathWorks, 2023c). The following provides a more detailed description of the PreScan components.

4.2.3.1 *Vehicle Dynamics Blockset*

The "Vehicle Dynamics Blockset" in Simulink is a co-simulation tool that allows for the integration of different simulation models and environments for AV simulation. The Vehicle Dynamics Blockset is a collection of blocks that can be used to model vehicle dynamics, powertrain, and control sensor systems in Simulink. It includes pre-built models of vehicle dynamics and powertrain systems that can be customized for different vehicle types (MathWorks, 2023f). The tool includes a range of detailed mechanical models for different vehicle components, such as the suspension, tires, steering, and brakes. The tool also includes blocks for modeling sensors and actuators commonly used in vehicle control systems, such as accelerometers, gyroscopes, and electronic throttle controls.

4.2.3.2 *Automated Driving Toolbox*

The Automated Driving Toolbox developed in MATLAB/Simulink provides tools and algorithms for designing, simulating, and testing ADAS and autonomous driving systems. The toolbox provides a set of customizable components and examples that can be used to develop algorithms for perception, sensor fusion, path planning, and control (MathWorks, 2023a). The Automated Driving Toolbox includes features such as:

- Sensor modeling: The tool provides accurate modeling of sensors such as cameras, lidar, radar, and ultrasonic sensors, which can be used for perception and sensor fusion.
- Perception algorithms: The tool provides algorithms for detecting and tracking objects, including pedestrians, vehicles, and traffic signs, using data from sensors.
- Sensor fusion: The tool provides tools for combining data from multiple sensors to create a more accurate and complete understanding of the environment.

- Trajectory planning: The tool provides tools for generating safe and efficient trajectories for the vehicle, considering factors such as road boundaries, other vehicles, and traffic rules.
- Control algorithms: The tool provides algorithms for controlling the vehicle's speed, steering, and braking, based on the planned trajectory and the vehicle's current state and sensor inputs.

Figure 19 provides an example of the interface for automated vehicle sensor modeling and the associated default parameters (MathWorks, 2023a).

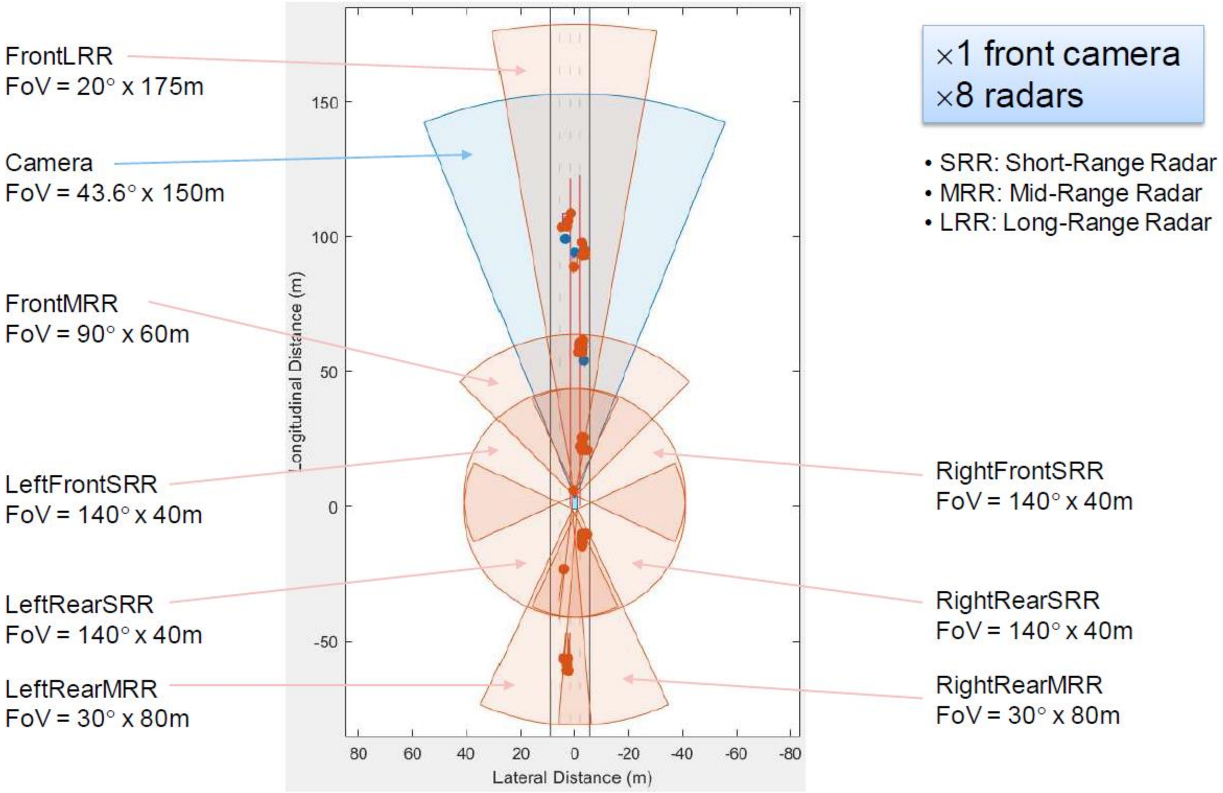


Figure 19. Sensor configuration for CAV modeling in the Simulink Automate Driving Toolbox (Source: MathWorks, 2023a).

4.2.4 Car Following in Simulation Models

The car following tasks of automated vehicles are accomplished through adaptive cruise control (ACC) with autonomous vehicles and cooperative adaptive cruise control (CACC) with connected automated vehicles that cooperate with each other. ACC utilizes information about the distance and speed of the leading vehicle measured by the onboard sensors to automatically adjust the vehicle's speed, while maintaining a safe distance to the preceding vehicle by controlling the throttle or brake (L. Xiao & Gao, 2010). If the vehicle in front slows down, the ACC system will slow down the vehicle to maintain a safe following distance. Conversely, if the vehicle in front speeds up or changes lanes, the ACC system will increase the speed of the vehicle to match the new traffic conditions (National Safety Council, 2023). The CACC is an extension of the ACC that allows using information from vehicles in front of the subject vehicle through vehicle-to-vehicle communications in car following decisions. Through field testing and simulation, the CACC has been proven to improve the capacity of the highway and stability of traffic flow compared to those with ACC driving and human driving. The following section describes ACC and CACC modeling in traffic simulation and co-simulation platforms.

4.2.5 ACC and CACC Modeling in SUMO

Modules have been incorporated in traffic simulation models such as SUMO, Vissim, and TransModeler to model ACC and CACC driving in the traffic stream. For example, in SUMO, which is the traffic simulation tool used in this study, the incorporated ACC and CACC models are based on the research work performed by Milanes et al. (2014) and L. Xiao et al., (2017). The ACC and CACC control in the utilized algorithm are subdivided into three modes as follows:

- Speed control mode: The function of this mode is to maintain the user pre-defined desired speed. This mode is activated when there are no vehicles within the sensing range or when there are no vehicles ahead of the ego vehicle within 393.6 feet (120 meter). Ego vehicle, as used in this document, is a connected, automated, and/or cooperative vehicle, the behavior of which is of primary interest in evaluation, testing, trialing, and/or operational scenarios.
- Gap control mode: The objective of this control mode is to maintain a constant time gap between the ego vehicle and its predecessor.
- Gap-closing control mode: The objective of this mode is to produce a smooth transition from speed control mode to gap control mode. The gap-closing control mode is activated when the distance between the ego and the preceding vehicle is less than 328 ft (100 m).

An additional control mode, referred to as the collision avoidance control mode, was later introduced in the utilized algorithm. The collision avoidance mode prevents the occurrence of rear-end collisions under safety compromised conditions. This mode is activated when the distance between the ego and the preceding vehicle is less than 328 ft (100 m), and the gap deviation turns negative (Lücken. Leonhard et al., 2019).

The experiments carried out by Milanés & Shladover (2014) and (Gunter et al., 2021) demonstrated that longitudinal control systems such as the ACC and CACC can produce significant impacts on the traffic flow. The results of the study also show that strings of consecutive ACC vehicles are more likely to produce instability by amplifying the speed variations from preceding vehicles, whereas the CACC equipped vehicles were able to produce much more stable following responses. According to Milanés & Shladover (2014) currently deployed ACC systems as provided by vehicle manufacturers are string instable, which affects the mobility and reliability of traffic. Other research works confirms that most commercial vehicles manufacturers deploy string instable ACC controllers because they chose to favor comfort over functionality (Gunter et al., 2021). The ACC system implemented in SUMO is an improved ACC model (a stable model), but in their documentation SUMO provides the gain control parameters for string instable model that better replicate the industry controllers to allow investigating the effects of string instability (Eclipse Foundation, 2023a). In our research, we used these gain control parameters that replicate the industry controllers.

4.2.6 ACC Implementation in Automated Vehicle Controllers

ACC and CACC have been implemented in automated vehicle controllers like the PID and MPC. For example, the algorithm implemented in the MPC takes into consideration factors such as the vehicle dynamics, desired speed, and the speed of nearby vehicles to compute an optimal speed that achieves the desired performance objectives while satisfying the kinetic feasibility and safety constraints. The MPC-based ACC systems have the advantage of having the possibility to be multi-objective and therefore able to handle complex control objectives such as maintaining a safe following distance, reducing fuel consumption, and minimizing jerk or discomfort for passengers.

Recent studies have implemented and tested MPC-based ACC systems and claim to have achieved a better performance than traditional ACC systems by utilizing a multi-objective optimization function that is able to generate satisfactory acceleration and deceleration commands in maintaining the required inter-vehicle distance, keeping the relative speed close to zero; while utilizing constraints on the acceleration, deceleration, and speed parameters (Kural & Güvenç, 2010). Other studies have incorporated safety and fuel economy objectives in the MPC algorithm formulation by providing constraint parameters that limit the jerk caused by the variation in acceleration (Luo et al., 2010; Naus et al., 2010). Some other studies have proposed the implementation of ACC systems based on MPC that integrates a PID controller with the objective of reducing oscillations in order to increase safety (Toroman & Vojić, 2021). (Lu & Shladover (2018) tested a system that utilizes MPC based variable speed limit (VSL) in combination with CACC on vehicles equipped with V2I communications. In this implementation The VSL system can directly communicate the speed limit parameter to the equipped vehicles. The results demonstrated that significant improvements could be achieved in terms of travel time and delay reduction as well as average speed and volume even at market penetrations as low as 10%. The term market penetration in this document refers to the proportion of equipped (connected, automated, and/or cooperated vehicles) in the traffic stream.

4.2.7 CACC Implementation in OpenCDA

The OpenCDA co-simulation includes a platooning application for the testing of the effectiveness of CACC. The platooning application allows CDA vehicles to cooperatively form into a platoon. In this application, there are two driving modes, which are the Leader Drive mode and the Platoon Maintaining mode. In a platoon of CDA vehicles, a platoon leader keeps listening to platoon joining requests from CDA vehicles. If no request has been received, the platoon leader will be in a Leader Driver mode, in which the leader uses the car following behaviors of CDA vehicles outside the platoon. At the same time, the remaining platoon members keep moving forward steadily while assuring that the minimum inter-vehicular gap time is met according to the Platoon Maintaining mode. With this Platoon Maintaining mode, each vehicle in the platoon must receive the trajectory data of the vehicle immediately in front of it, In the case that the Platoon Leader receives a platoon joining request, the Platoon Leader will share information regarding the routes, destination, and current position with the requesting CDA vehicle. The negotiation between the platoon leader and the joining CDA vehicle will take place in order to determine the feasibility of joining the platoon. If the request is rejected, then the joining CDA will keep searching for another platoon to join.

In OpenCDA, the car-following behavior according to the CACC algorithm is primarily based on a gap regulation, in which the time gap between the platoon members is maintained at a predetermined time gap. If a CACC-enabled vehicle is not in a platoon, it will continue driving with the default car-following algorithm within CARLA, which is a simplified ACC-based car following model   The pseudocode of the car-following behavior in the CACC algorithm is shown below.

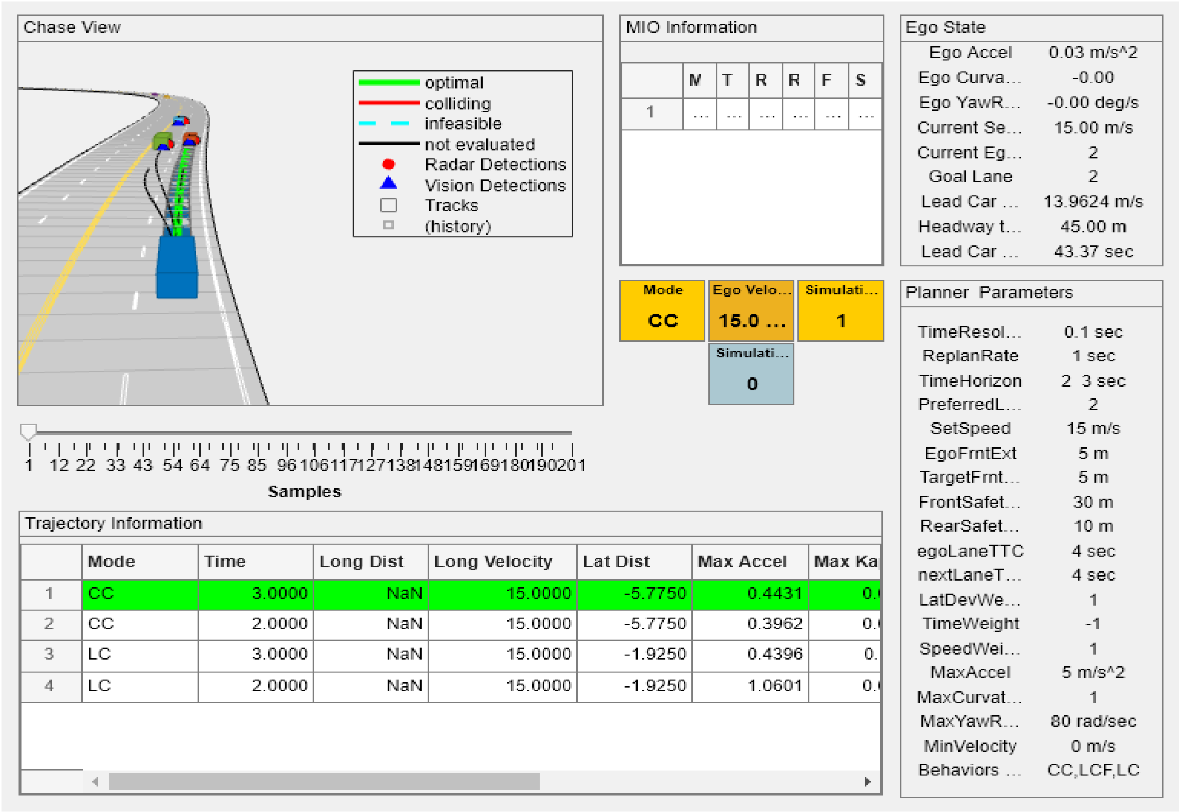
```
Initialize platoon information list
For Every platoon member: Do
    If the member is a platoon leader then
        Speed maintaining mode with vehicles outside the platoon
    Else
        Retrieve the speed of the vehicle in front
        Retrieve the speed of the ego vehicle itself
        Compute the speed difference
        Predict the front vehicle’s position in the next time step
        Calculate the current distance between the front and ego vehicles
        Calculate the speed for the next time step
    End if
End for
```

4.2.8 Automated Lane Changing and Merging in Simulation

The research team has not identified an automated lane changing and merging algorithm implementation in SUMO. Thus, the team borrowed the lane changing model implemented in the MPC controller of the CoEXist tool for autonomous merging and the lane changing model of the OpenCDA for cooperative merging and implemented these models in SUMO. These models described in the following subsections and their implementations allow the use of SUMO as a standalone tool to simulate the impacts of vehicle automation and cooperation on traffic flow.

4.2.9 Automated Lane Changing and Merging in the MPC Controller

The lane change system in the MPC controller senses the environment by searching for the most important objects (MIOs) surrounding the ego vehicle utilizing the onboard sensors. Then, the lane change planner in the MPC samples the terminal states for different possible vehicle behaviors and motion prediction of neighboring vehicles and generates candidate trajectories. Once the candidate trajectories are generated, the model evaluates the cost associated with each trajectory and checks the kinematic feasibility of the proposed trajectory as well as the possibility of collision. Finally, the lane change planner chooses the best trajectory and starts negotiating the lane change that is ultimately executed by the lane change controller. The cost function in MPC quantifies the performance of the system over time by computing the sum of weighted penalties on various measures. The algorithm then performs optimization based on evaluating the future states of the system, with the goal of finding the control sequence that minimizes the cost function subject to the system dynamics and constraints. Figure 20 below shows an example of the interface of the Lane Change Test Bench application in the tool used in the CoEXist project (MathWorks, 2023b).



Mode: CC
Ego Velo…: 15.0 …
Simulati…: 1
Simulati…: 0

Ego State

Ego Accel	0.03 m/s^2
Ego Curva…	-0.00
Ego YawR…	-0.00 deg/s
Current Se…	15.00 m/s
Current Eg…	2
Goal Lane	2
Lead Car …	13.9624 m/s
Headway t…	45.00 m
Lead Car …	43.37 sec

Planner Parameters

TimeResol…	0.1 sec
ReplanRate	1 sec
TimeHorizon	2 3 sec
PreferredL…	2
SetSpeed	15 m/s
EgoFrntExt	5 m
TargetFrnt…	5 m
FrontSafet…	30 m
RearSafet…	10 m
egoLaneTTC	4 sec
nextLaneT…	4 sec
LatDevWe…	1
TimeWeight	-1
SpeedWei…	1
MaxAccel	5 m/s^2
MaxCurvat…	1
MaxYawR…	80 rad/sec
MinVelocity	0 m/s
Behaviors …	CC,LCF,LC

Trajectory Information

	Mode	Time	Long Dist	Long Velocity	Lat Dist	Max Accel	Max Ka
1	CC	3.0000	NaN	15.0000	-5.7750	0.4431	0.
2	CC	2.0000	NaN	15.0000	-5.7750	0.3962	0.
3	LC	3.0000	NaN	15.0000	-1.9250	0.4396	0.
4	LC	2.0000	NaN	15.0000	-1.9250	1.0601	0.

Figure 20. Graphic user interface for the Lane Change Test Bench Model in Matlab/Simulink. (Source: MathWorks, 2023b).

The MPC controller adjusts both the steering angle and longitudinal acceleration of the ego vehicle to make sure that the ego vehicle follows the chosen trajectory. The optimal actions computed by the controller satisfy constraint parameters related to speed, acceleration, and steering angle of the vehicle (see Figure 21). The MPC algorithm takes into consideration several factors such as the vehicle's position, velocity, and acceleration, as well as the road conditions and other surrounding vehicles, to generate a set of optimal control inputs. These control inputs are then used to control the vehicle's steering, braking, and acceleration in real-time, with the goal of achieving safe and efficient operation. MPC in autonomous driving can be used for a variety of tasks, such as trajectory planning, speed control, and obstacle avoidance.

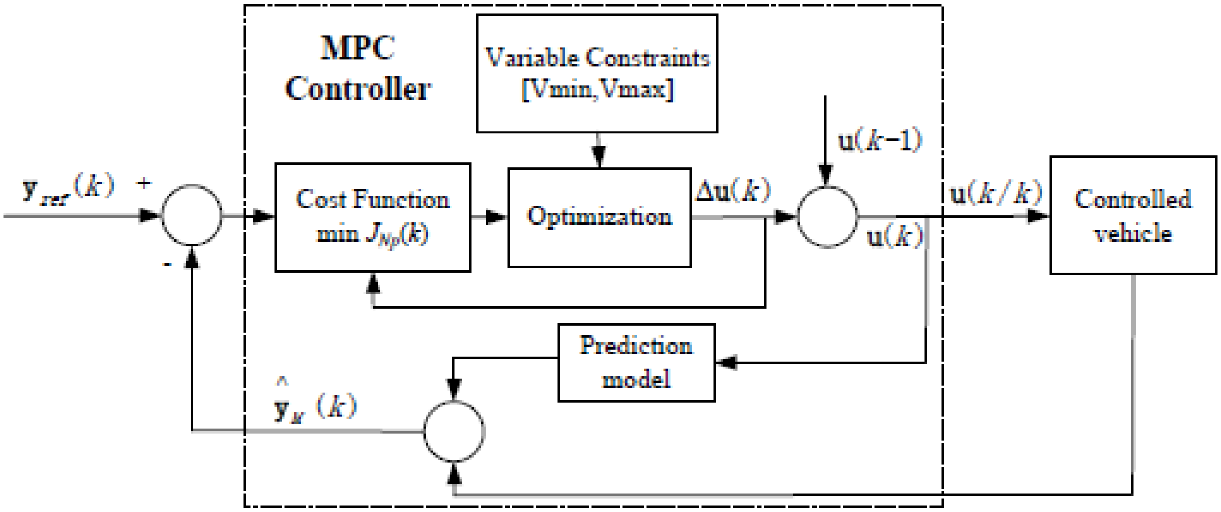


Figure 21. Structure of the Model Predictive Control (MPC) Algorithm. (Source: Zheng et al., 2013).

As stated earlier, the researchers of this study implemented the lane changing algorithm used as part of the CoEXist project tool in SUMO. This application utilizes an MPC controller to automate the lane change task. To implement the model in SUMO, this study performed a translation of the driving logic defined by the algorithm to implement it in Python using the TraCI facility of SUMO. However, it has been generally realized, by multiple researchers and analysts, that the implementation of this algorithm in SUMO has its limitations due to limits on the capabilities of traffic simulation software like SUMO such as the lack of available methods in TraCI to access the vehicle lateral control parameters (lateral acceleration, yaw rate, and steering wheel angle). Thus, it was not possible to transfer the complete MPC model from the Simulink software in the CoEXist tool to SUMO, but a simplified version of the algorithm was implemented where the algorithm takes care only of the longitudinal control, and once an available gap is selected and it is safe to change lane, the algorithm gives the command to change lane to the ego vehicle. However, the algorithm does not control the lane change maneuver for every time step until the ego vehicle reaches the center of the target lane. The following paragraphs provide more details on the elements of the model that was used to implement the model in SUMO.

Perception - Sensor Set Configuration: For the sensor set configuration, the automated lane changing implemented in SUMO, as implemented in this research uses the default sensor configuration and its parameters from the Simulink Automated Driving Toolbox of the tool used in the CoEXist project. The ego vehicle perception is coded in SUMO utilizing the “object context subscription” method available in TraCI, which allows obtaining specific values from the MIOs surrounding the ego object for every simulation time step (Eclipse Foundation, 2023c). While implementing this method, it was necessary to apply additional context subscription filters. The implementation also involves specifying the detection radius reflecting the upstream and downstream detection distances to match the sensor set parameters described in the Automated Driving Toolbox in Simulink. The output of the subscription method allowed retrieving the vehicle type, lane ID, position, and speed of the ego vehicle as well as for each vehicle or MIO detected within the detection radius of the ego vehicle (Eclipse Foundation, 2023c, 2023d). Once the subscription results are retrieved, the time to collision (TTC) and the gap deviation (the difference between the measured gap and the desired gap) between the ego vehicle and the leading vehicle in the target lane are computed.

Ego Vehicle Status and Lane Change Mode: Three main statuses are defined for the ego vehicles including the lead car following status (LFS), lane change status (LCS), and collision avoidance status (CAS). The LFS is active when the ego vehicle is on the acceleration lane and tries to get to the desired position to proceed to change lane. The LCS is activated once the ego vehicle reaches the desired position (i.e., a position in which the ego vehicle meets the gap on the target lane and the minimum gap, minimum time headway, and relative speed parameters are met). When the LCS is activated the ego vehicle proceeds to change lane. The CAS is a built-in feature in SUMO related to the lane changing mode parameter. The lane change model in SUMO discriminates between four reasons to change lane including:

- Strategic: the vehicle must change lane to be able to continue its route.
- Cooperative: the vehicle change lane to create a gap and allows other vehicles to change lane.
- Speed gain: When a vehicle changes lane to be able to drive at a faster speed.
- Obligation to drive on the rightmost lane.

While running a simulation, SUMO computes an internal request at each time step to either stay on the current lane or change lane. When there is an external lane change request command from TraCI, and the external request conflicts with the internal request resolution from SUMO, the dispute is resolved according to the current settings of the external lane change request.

Decision Making: The speeds, position and gap deviation obtained from the perception algorithm are fed into the controller to provide the optimal acceleration for the ego vehicle to get to the desired position and speed efficiently and safely to be able to change lane. A cost function is implemented to provide a measure of the performance of the MPC controller in meeting the desired objectives of the application. The cost function defines a trade-off between achieving the desired position and speed of the ego vehicle by trying to minimize the gap deviation, while limiting the maximum acceleration or deceleration to ensure passenger comfort. The weights assigned to the gap and acceleration costs reflect the importance of each component in achieving the desired objectives. The cost function is used by the MPC algorithm to generate optimal acceleration/deceleration commands for the ego vehicle over a defined time horizon. The optimization process seeks to minimize the cost function subject to constraints on the state and control inputs, such as the physical limitations of the vehicle and the traffic conditions.

4.2.10 Automated Lane Changing and Merging in OpenCDA

OpenCDA developed a cooperative merging algorithm to help simulate the cooperative merging operations of on-ramp AVs in mainline platoons. The algorithm has three merging types: front merge, back merge, and middle merge. The merging type is determined based on the current vehicle information available to the freeway mainline vehicles and on-ramp vehicles.

As an on-ramp CDA vehicle approaches the freeway merge, the vehicle keeps searching for CDA vehicles on the mainline to cooperate with. If there is only one mainline CDA vehicle is present and no platooning of vehicles are found, the merging type will be determined by simply measuring the angle between the merging vehicle and the subject mainline vehicle. If the angle is less than 90 degrees, then a back merge will be executed. Otherwise, the merge will be determined as a front merge. When a platoon of vehicles is found on the mainline, the system will choose the middle merge for the merging vehicle. Once a middle merge is determined, the following mainline vehicle will be instructed to generate a gap to facilitate the on-ramp vehicle merging. Meanwhile, the on-ramp vehicle could also adjust its speed so that the merging maneuver is smooth and safe. However, it might be the case that an on-ramp CDA vehicle cannot find any mainline vehicles within their communication range. Then, the on-ramp vehicle will continue to merge without cooperation. In this case, the merging decision is solely based on the information collected by the sensor devices. A pseudocode of the merging algorithm is shown below.

```
Initialize Mainline and on-ramp vehicle information list
For Every mainline vehicle found within the communication range: do
    Define vehicle platooning status (Lead, Follow, or not in a platoon)
    Store Vehicle ID, Vehicle Type, Lane ID, Position, and Speed in the list
End for
For Every on-ramp vehicle found within the communication range: do
    Find Vehicle ID, Vehicle Type, Lane ID, Position, and Speed
    Find Mainline vehicles information (those within the communication range)
    For every vehicle ID:
        Compute Potential arrival time to merging point of mainline vehicles and the ego vehicle
        Do select the mainline vehicle(s) to cooperate with based on the potential arrival time
        Compute Vehicle orientation relative to the mainline vehicle
        Find Merging type based on the orientation and position
        If Merging type is Front Merge or Back Merge then
            adjust the speed according to the current position
        End if
        If Merging type is Middle Merge then
            adjust the speed according to the current position
            If time gap between leading and following vehicles < min gap then
                Following vehicle decelerates to open the  gap for merging
            End if
            If time gap between leading and following vehicles > min gap then
                Check potential collision on the target lane
                The ego vehicle merges onto the target lane
            End if
        End if
    End for
```

4.2.11 Simulation Tools Utilization in this Study

This study utilized simulation tools for testing and evaluating advanced automated merging support and ramp metering in the presence of automated and cooperative vehicles. The testing and evaluation of these strategies were based on both vehicle-level measures assessed using a co-simulation platform (the OpenCDA platform) and traffic-level measures assessed using microscopic traffic simulation (SUMO), as shown in Figure 22. When using SUMO by itself to assess the traffic measures, this research utilized the built-in car following behaviors of human driven, ACC, and CACC vehicles in SUMO. For lane changing, this study also used the built-in lane changing algorithm for human driving in SUMO. However, the utilized lane changing algorithms for autonomous vehicles and cooperative vehicles were based on those used in the MPC controller and OpenCDA because these maneuvers cannot be adequately modeled using the built-in algorithms in SUMO. This extension of SUMO to include the lane changing algorithms for autonomous vehicles and cooperative vehicles was accomplished by writing Python code utilizing the TraCI facility of SUMO. The vehicle-level measures assessed using OpenCDA includes the time required to complete merge, average speed of the merging vehicle, and the standard deviation of acceleration and speed during the merging process, as shown in Figure 22. Figure 22 also shows that the traffic level measures assessed using the SUMO traffic simulation include the average delay time and vehicle throughput of the merge area.

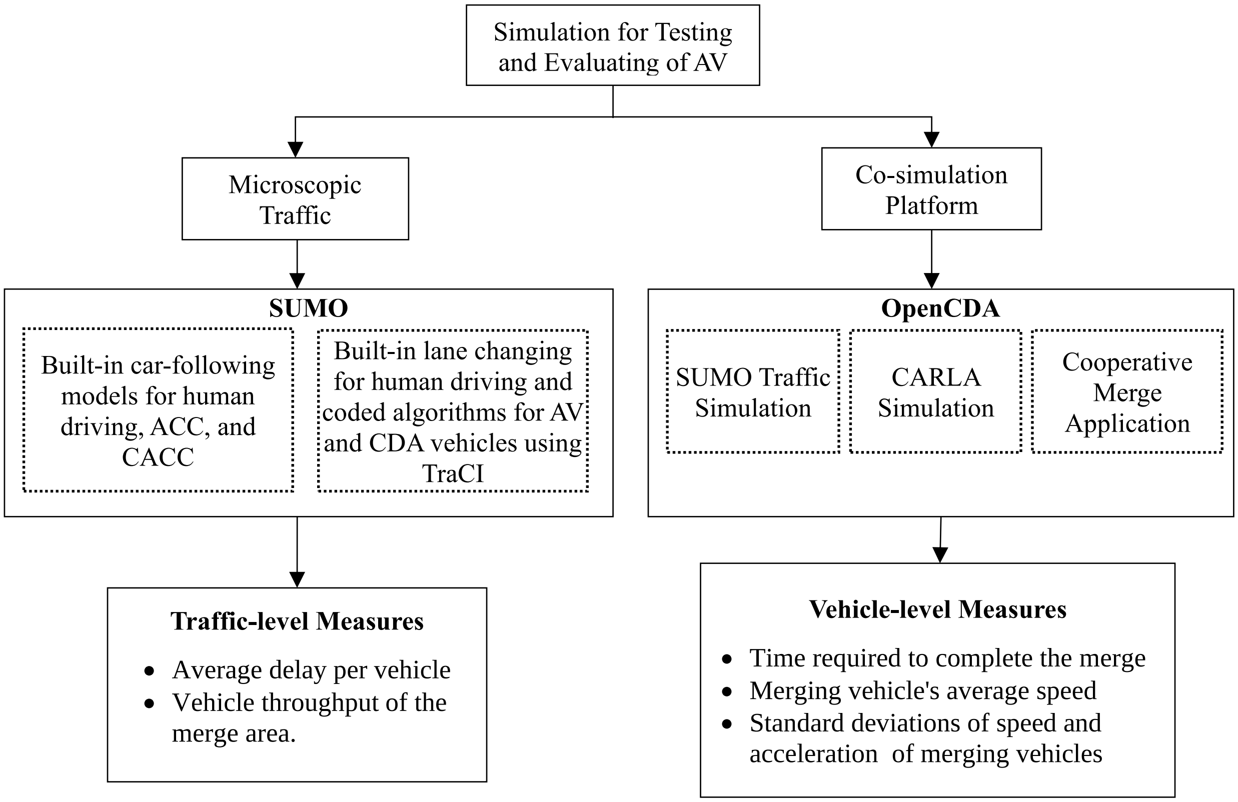


Figure 22. Flowchart of simulation modeling utilization in this study.

4.3 Ramp Metering in the Presence of Automated and Cooperative Merging

Beginning of this project provides a comprehensive list of enhanced cooperative transportation management applications in different categories that can be implemented when considering the interaction between CDA and traffic system management and operations (TSM&O). This section reports on the results from using traffic simulation and co-simulation for assessing ramp metering in the presence of automated and cooperative merging. This tested application involves the use of CDA vehicle data in setting the ramp metering rates. This can be classified as Enhancement Category 1 according to the categorization of the enhanced traffic management strategies, as presented above. In this application, the infrastructure can analyze the data collected from traffic sensors, connected vehicles, and potentially communicated automated vehicle sensors and CDA vehicles and will use this information to set the ramp metering using an enhanced algorithm that extends the existing fuzzy logic algorithm based on traffic sensor data that is used in the I-95 ramp metering implementation in Miami, FL (Bogenberger & Keller, 2001). The simulation is used to assess the performance of the enhanced ramp metering and the impacts of autonomous driving and CDA driving in the presence of ramp metering compared to the performance with no ramp metering. The purpose is to determine the interaction between ramp metering and various levels of automation and cooperation of the mainline and merging on-ramp vehicles. Such determination will indicate how data from emerging vehicle technologies can be useful in improving traffic management and if ramp metering will still be useful with the presence of automation and collaboration. This section first describes the enhanced ramp metering algorithm derived in this study using data collected from connected and CDA vehicles. This is followed by a detailed description of the simulation scenarios and associated simulation procedures to assess the performance of the new algorithm and the performance of ramp metering in the presence of cooperative merging operations. It then presents the results of the analysis.

4.3.1 Modeling Ramp Metering in Simulation

This study simulated different types of ramp metering control in SUMO including no control, fixed control, the fuzzy logic adaptive ramp metering control of the type implemented in Washington State and Miami, FL, and an improved version of the fuzzy logic algorithm that utilizes a combination of data obtained from loop detectors and microscopic data provided by connected and automated vehicles. For the fixed control scenario, the ramp metering control was coded in the SUMO Net file as a junction placed on the on ramp with a fixed rate of 15 vehicle per minute, which is the maximum rate usually used for metering single lane on-ramps. For the no control scenario, the implemented logic activates a command from TraCI to “switch off” the traffic signal, so that the vehicles could pass freely from the on-ramp to the mainline regardless of the traffic conditions.

A logic was developed in the TraCI interface for SUMO using Python to implement the adaptive fuzzy logic ramp metering algorithm. Two scripts were created in Python. The main script serves to run the simulation and manages the interaction with SUMO by retrieving data and setting the metering rate. A second script was created as a helper code to define the logic of the fuzzy logic algorithm. The pseudocode for the implementation of the helper script is shown below.

```
Define fuzzy variables:
    Initialize Antecedents
    Initialize Consequents
Populate fuzzy variables
    Define custom membership functions
    Define rules
Implement Model:
Define RM control
Define control function (fuzzy controller)
    Compute Output()
    Return Output
```

The logic accomplishes the data retrieval function of the main script by managing a subscription to the simulated point traffic detectors at different locations including upstream of the merging area, downstream of the merging area, at the stop-bar of the on on-ramp, and the advance queue detector on the on-ramp. The subscription to these detectors allowed to retrieve speed and occupancy for each time step at the upstream and downstream locations as well as occupancy for the on-ramp locations, which are needed for the fuzzy logic algorithm. The pseudocode of the main script that is used for running the simulation and determining the metering rate using the fuzzy logic algorithm is presented below.

```
TraCI start simulation
Initialize lists for detectors' data
    Subscribe to detectors
    Simulation step()
        Get subscription results
        Compute timestep average speed at each location
        Compute timestep average occupancy at each location
        If steps % 60 seconds == 0:
            Compute 1 min average speed at each location
            Compute 1 min average occupancy at each location
            Call control function
            Return output
            Compute new metering rate
            Set new phases
        End if
```

As indicated by the above pseudocode, data is retrieved from the detectors for every time step for use in computing the metering rate. The data retrieved from each lane is averaged every second at each location. Then, the speeds and occupancies are averaged every 60 seconds and these averaged values are used as inputs to the fuzzy logic algorithm, which updates the metering rate every minute.

This study enhanced the fuzzy logic algorithm for ramp metering control by incorporating data from connected and automated vehicles in the fuzzy logic control algorithm. The hypothesis is that the enhanced algorithm can better account for traffic system performance compared to existing adaptive ramp metering control systems that rely solely on data from loop detectors. By incorporating high-resolution data from connected vehicles, the enhanced algorithm is expected to act quickly and more accurately in adjusting the metering rates in response to detected changes in traffic conditions. Another advantage of such enhanced algorithms is that they could account for the driving behavior and associated performance of different types of vehicles with different levels of automation and collaboration.

In this context, the goal was to create new fuzzy variables and membership functions defined based on the data available from connected and automated vehicles based on simulation data. To achieve this, the object context subscription method was utilized in SUMO to retrieve information from the connected and automated vehicles in the simulation at each time step in a resolution of 1/10th of a second. Once the data was retrieved, the simulation data was analyzed to identify key variables that could influence the ramp metering control, such as speed, volume, density, occupancy, space gap, and time gap distributions. Figure 23 shows the speed distributions sampled over periods of 15 minutes during a one hour of simulation. Figure 24 shows a similar analysis for the time gap distributions. Figures 23 and 24 shows significant differences in the distributions of data points collected from the equipped vehicles and grouped every 15 minutes. This variability confirms the potential of using equipped vehicle data in quantifying changes in traffic patterns and thus in ramp metering control.

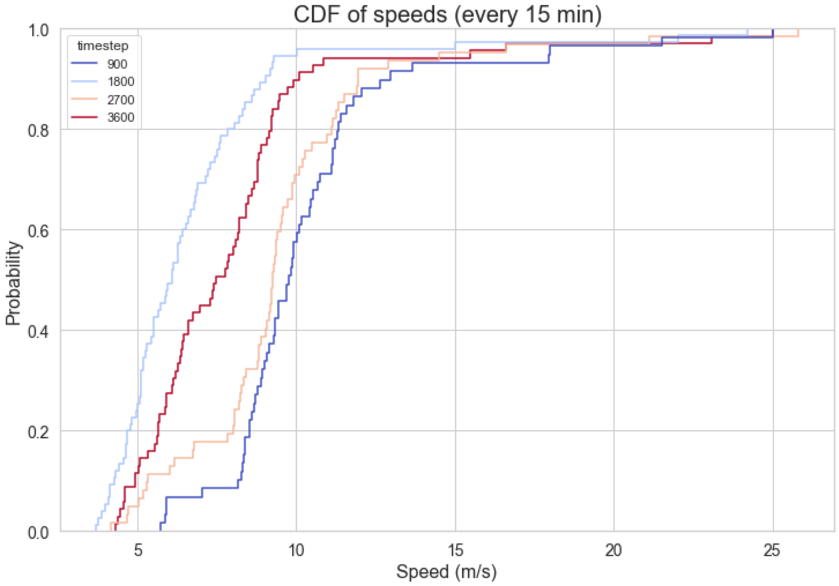


Figure 23. Distribution of speeds obtained based on equipped vehicle data at estimated at 15-minute intervals.

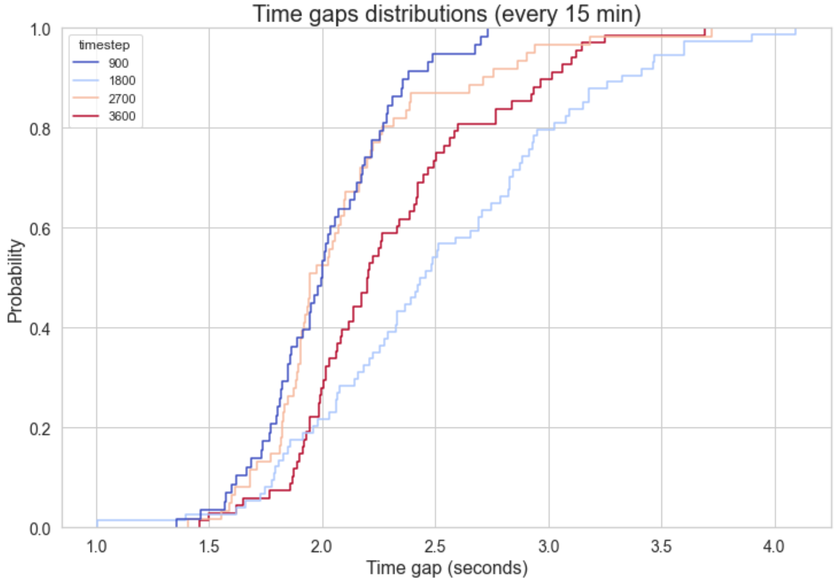


Figure 24. Distribution of time gaps on the rightmost lane on the mainline at the merge area obtained based on equipped vehicle data at estimated at 15-minute intervals.

It was decided to explore the use of speed and time gap measures estimated based on the data collected by the sensors of the equipped vehicles in traffic control. Clustering analysis was performed to identify data points with similar performance for use in setting the fuzzy logic sets. The produced clusters allowed identifying different traffic states that can be used to inform traffic control. Figure 24 shows an example of the output of the clustering analysis. Figure 24 reveals that the clustering algorithm was able to identify different patterns of traffic flow in terms of speed and time gap. In this example, the purple dots (Cluster 3) represent the free flow state characterized by speeds within the range of 25 m/s to 35 m/s and time gaps greater than 6 seconds. The blue dots (Cluster 1) represent the state in uncongested conditions characterized with high speeds similar to Cluster 3, but with significantly lower time gaps within the range of 2 seconds to 4 seconds. The red dots (Cluster 0) represent the transition cluster, where the speed is lower, and the time gap is less than 2.2 seconds. Finally, Cluster 2 (green dots) represents the congested cluster where the speeds are below 20 m/s and the time gaps are below 1.8 seconds.

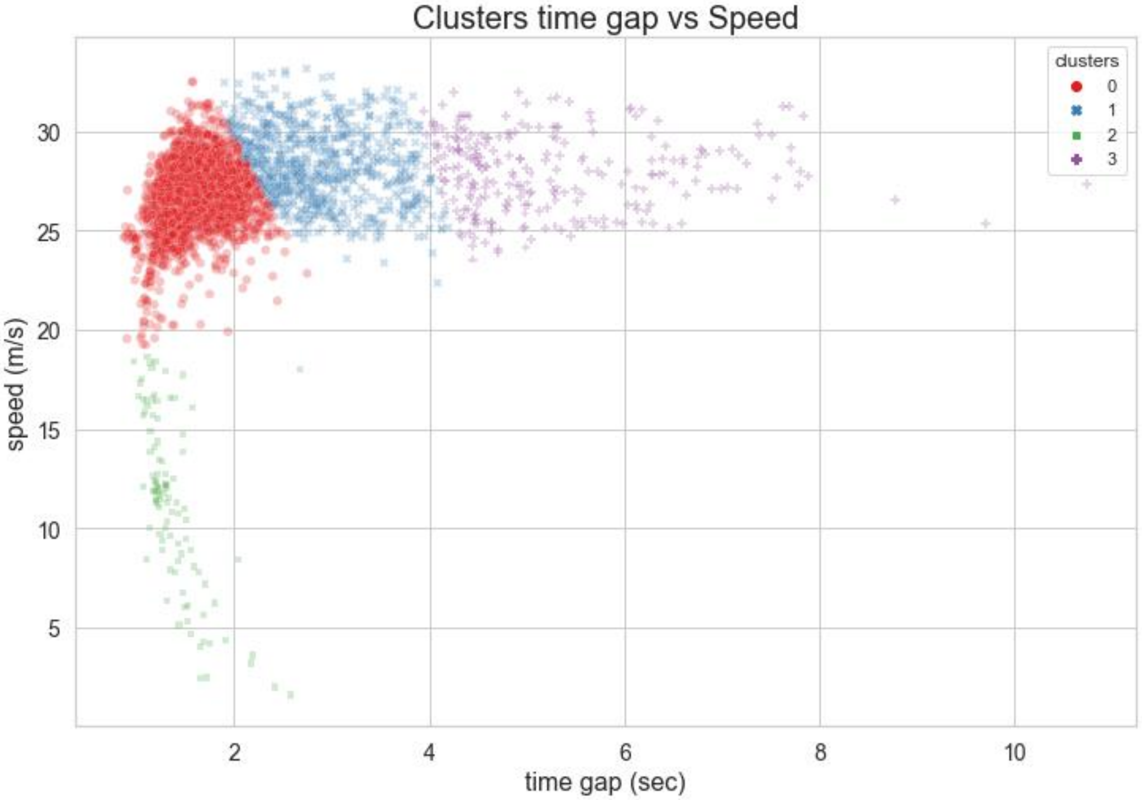


Figure 25. Example of the clustering analysis output based on time gap and speed relationship.

The identification of the traffic states, as described above, allows the definition of the new variables in the fuzzy logic and their membership functions in the fuzzy system by using a triangular membership function where the peak of the triangle represents the cluster centroid and the width is given by the boundaries of the cluster for each variable (e.g., speed range, and time-gap range). Once the new membership functions were defined and coded in Python, the enhanced algorithm was developed using two scripts similar to the traditional fuzzy logic algorithm. The "helper" script was used to define the logic of the algorithm, and it follows a similar structure as the pseudocode presented earlier. For the execution of the algorithm, a main script was developed with the pseudocode presented below for determining the metering rate using the enhanced fuzzy logic algorithm.

```
TraCI start simulation
Initialize lists for detectors' data
Initialize lists for AVs' data
    Subscribe to detectors
    Subscribe to AVs
    Simulation step()
        Get subscription results
        Compute timestep average speed at each location
        Compute timestep average occupancy at each location
        If AV is in simulation = True:
            Get Subscription Results
        End if

        If  steps % 10 seconds == 0:
            Compute 5 seconds average speed
            Compute 5 seconds average time-gap
            Compute 5 seconds average space-gap
            Call control function
            Return output
            Compute new metering rate
            Set new phases

            Elif steps % 60 seconds == 0:
            Compute 1 min average speed at each location
            Compute 1 min average occupancy at each location
            Call control function
            Return output
            Compute new metering rate
            Set new phases
        End if
```

In the pseudocode presented above, at every time step, the algorithm searches for CAVs on the mainline upstream of and at the merging area. Then, the averages for time gap, speed and gap distance are computed every 10 seconds. Based on the computation of these values, the algorithm is able to update the metering rate as necessary.

4.3.2 Traffic Simulation Scenarios

As stated earlier, this study utilizes SUMO traffic simulation extended in this study to assess the impacts of different ramp metering strategies in the presence of AVs and CDA vehicles. Considering the lack of automated and cooperative merge consideration in SUMO, the research team extended the tool to model the autonomous merging based on that of the MPC automated driving controller used in the co-simulation environment used in the CoEXist project, as discussed in Section 2. The research team also extended the SUMO model by incorporating the cooperative merging models borrowed from the OpenCDA, as also discussed in Section 2. The ACC and CACC used in the car following driving task in the SUMO simulation in this study were those already available in SUMO based on the algorithms of Milanés & Shladover (2014), as described earlier. The simulated merge area was calibrated to produce the capacity estimated using the highway capacity manual procedure (HCM) for different combinations of mainline and on-ramp volumes. The analysis period for the simulation run was set to one hour for each run with a 15-minutes warm up period. Each scenario was run 10 times using different seed numbers and the output of the simulation runs were averaged to produce the metrics used for the evaluation. The metrics include average delay per vehicle, average travel time, average speed, and average volume. The simulation is done under two traffic flow levels as follows.

- Traffic flow level 1: This level involves 1,900 vphpl on the mainline and 650 vphpl on the on-ramp. This scenario presents conditions that are approaching capacity.
- Traffic flow level 2: This level involves 2,100 vphpl on the main lanes and 750 vphpl on the on-ramp. This scenario presents conditions that slightly exceed capacity.

The simulation is used to assess the following merging operation scenarios with and without ramp metering.

- Human driven vehicles
- Autonomous merge of AV with human driving on the mainline (assuming on-ramp autonomous vehicles with Level 1 automation in merging and no cooperation)
- Autonomous merge of AV with ACC driving on the mainline (assuming mainline and on-ramp autonomous vehicles with Level 1 automation and no cooperation)
- Autonomous merge of AV with CACC driving on the mainline (assuming on-ramp autonomous merge with Level 1 automation, cooperative car following on the mainline, and no cooperation in merging)
- Cooperative merge of AV and CACC driving on the mainline (assuming on-ramp cooperative merge with Level 1 automation and cooperative car following on the mainline)

For each of the above scenarios, four different ramp metering control alternatives were tested as follows:

- No ramp metering.
- Fixed ramp metering
- Adaptive ramp metering using the fuzzy logic algorithm.
- Adaptive ramp metering using the enhanced fuzzy logic algorithm.

The following subsections present further details on the simulation of vehicles with different types of connectivity, automation, and cooperation.

4.3.3 Human Driven Vehicles

The impacts of different settings of ramp metering are first assessed when all vehicles in the traffic stream on the mainline and on-ramp are human driven vehicles. This is the base scenario used as a reference for comparison purposes. The metrics produced by running the traffic simulation (SUMO) of these base scenarios are compared with the results obtained when introducing vehicles with different levels of automation and cooperation under different ramp metering settings.

4.3.3.1 Autonomous Merge of AV with Human Driving on the Mainline

This scenario involves AVs that are autonomously merging from the on-ramp to the freeway mainline without connectivity and collaboration. In this scenario, the autonomous merge is accomplished assuming that the vehicles on the mainline are driven by humans. The merging process in the simulation utilizes the algorithm borrowed from the MPC controller and coded in SUMO by this project team.

In this scenario, the AVs use their onboard sensors to detect the position and speed of the vehicles on the mainline, when they are within the detection range of the onboard sensors. The AV retrieves information from its sensors at every time step of the simulation (1/10th of a second) and identifies the potential gaps that are available to merge once it reaches the acceleration lane. Once a gap is identified, the merging AV evaluates if the gap satisfies the minimum acceptable gap criterion. When a gap is selected for merging, the AV will adjust its speed and proceed to merge when it is safe to do so. This scenario is replicated under different AV market penetrations on the on-ramps including: 25%, 50%, 75%, and 100%.

4.3.3.2 Autonomous Merge of AV with ACC-Equipped Vehicles on the Mainline

This scenario involves AVs that are autonomously merging from the on-ramp to the mainline without connectivity and collaboration, as is the case with the scenario presented in the previous section. However, in this scenario, AV vehicles are assumed to operate on the mainline with level 1 automation as they accomplish the car following driving task using ACC. The merge is based on the algorithm borrowed from that implemented in the MPC controller and coded in SUMO. The utilized ACC algorithm is the one developed by Milanés & Shladover (2014), which has been already incorporated in SUMO. The results from using two sets of parameters of the ACC algorithm are compared in this study: those that produce unstable traffic flow, expected to be implemented by the industry, and those that produce stable traffic flow that were developed by researchers (see the earlier discussion on the subject).

This scenario is replicated under different market penetrations of on-ramp AVs and mainline ACC-equipped vehicles including: 25%, 50%, 75%, and 100%. The market penetrations for the merging AVs from the on-ramp and the mainline ACC vehicles are assumed to be the same.

4.3.3.3 Autonomous Merge of AV with CACC Driving on the Mainline

This scenario involves AVs that are autonomously merging from the on-ramp to the mainline without connectivity and collaboration, as is the case with the scenario presented in the previous section. However, in this scenario, the AV vehicles on the mainline are assumed to be cooperatively driven utilizing CACC to accomplish the car following task. The merge is based on the algorithm borrowed from that implemented in the MPC controller and coded in SUMO. The utilized CACC algorithm is the one developed by Milanes and Shladover (2014), which has been already incorporated in SUMO.

This scenario is replicated under different market penetrations of AV and ACC equipped vehicles including: 25%, 50%, 75%, and 100%. The market penetrations for the merging AVs from the on-ramp and the mainline CACC vehicles are assumed to be the same.

4.3.3.4 Cooperative Merge of AV with CACC Driving on the Mainline

This scenario involves CDA vehicles that are cooperatively merging from the on-ramp to the mainlines with connectivity and collaboration. The merging process in the simulation utilizes the algorithm borrowed from the OpenCDA and coded in SUMO in this study. The AV vehicles on the mainline are assumed to be cooperatively driven utilizing CACC. The utilized CACC algorithm is the one developed by Milanes and Shladover (2014), which has been already incorporated in SUMO.

This scenario is replicated under different CAV and CACC equipped vehicles market penetrations including: 25%, 50%, 75%, and 100%. The market penetrations for the merging AVs from the on-ramp and the mainline ACC vehicles are assumed to be the same.

4.3.4 Traffic-Level Assessment Results

As reported in the previous section, this study simulated multiple scenarios involving different traffic levels, ramp metering control types, and market penetrations of automation and cooperation on the mainline and on-ramp. The study assessed the resulting system performance in terms of average delay per vehicle and average throughput.
Table 4 and Table 5 compare the average delay in seconds per vehicle under different scenarios. Table 4 shows the delays for a combination of freeway and on-ramp traffic flow that results in traffic demands approaching but not exceeding the segment capacity. Table 5 shows the delays when the demand exceeds the capacity and flow exceeds the segment capacity. As expected, the delays in Table 5 are significantly higher than the delays in Table 4. Figures 25 to 28 show some of the results in Table 5 to allow better visualization and comparison of the results for different scenarios. Only the results from Table 5 (not Table 4) are visualized since they allow clearer comparison of the different scenarios.

The results in Tables 4 and 5 and Figures 25 and 26 indicate that autonomous merge with human driving on the mainline or ACC driving using the stable ACC algorithm reduces the delay with and without ramp metering. However, the scenario under which the driving on the mainline uses the unstable ACC algorithm increases delay compared to human driven driving. Autonomous merge with CACC (AV+CACC) and autonomous merge with stable ACC (AV+ACC) produced comparable results. However, the cooperative merge with CACC driving on the freeway (CDA+CACC) results in the highest reductions in delay, significantly lower than the delays of other scenarios indicating the effectiveness of cooperative merge in reducing the delay.

Table 4. Average Delay by Market Penetration and Control Type with Demand Approaching Capacity (Mainline Flow=1,900 vphpl; Ramp Flow=650 vphpl).

Market Penetration	Scenario	Average Delay (sec/veh)			
		No Control	Fixed Rate	Fuzzy	Enhanced Fuzzy
0%	HV + HV	23.45	22.75	19.97	17.56
25%	AV + HV	16.88	16.28	16.25	15.28
	AV + ACC (unstable)	27.71	26.89	23.60	20.76
	AV + ACC (stable)	16.38	16.17	15.89	13.18
	AV + CACC	17.28	17.06	16.76	13.91
	CDA + CACC	10.34	10.01	9.80	9.44
50%	AV + HV	15.99	15.24	15.02	14.92
	AV + ACC (unstable)	26.40	25.62	22.48	19.78
	AV + ACC (stable)	14.16	13.58	13.54	12.59
	AV + CACC	14.35	13.75	13.72	12.75
	CDA + CACC	9.03	8.72	8.14	8.02
75%	AV + HV	15.39	14.91	14.75	14.61
	AV + ACC (unstable)	24.91	24.17	21.81	18.66
	AV + ACC (stable)	11.98	11.86	11.54	11.16
	AV + CACC	12.22	12.09	11.65	11.38
	CDA + CACC	7.08	6.83	6.49	6.17
100%	AV + HV	14.62	14.51	14.07	13.72
	AV + ACC (unstable)	23.82	23.12	21.55	18.05
	AV + ACC (stable)	11.88	11.63	10.89	10.75
	AV + CACC	11.92	11.89	11.35	11.12
	CDA + CACC	6.62	6.08	5.29	5.05

HV = Human Driven vehicles; AV = Automated Vehicles; ACC = Adaptive Cruise Control; CACC = Cooperative Adaptive Cruise Control; CDA = Cooperative Driving Automation.

Table 5. Average Delay by Market Penetration and Control Type with Demand Slightly Exceeding Capacity (Mainline Flow = 2,100 vphpl; Ramp Flow = 750 vphpl).

Market Penetration	Scenario	Average Delay (sec/veh)			
		No Control	Fixed Rate	Fuzzy	Enhanced Fuzzy
0%	HV + HV	108.54	98.77	76.83	68.28
25%	AV + HV	77.21	73.14	66.02	62.14
	AV + ACC (unstable)	88.40	85.61	82.77	78.64
	AV + ACC (stable)	66.44	64.70	58.41	54.97
	AV + CACC	53.31	51.14	50.48	49.53
	CDA + CACC	16.51	15.92	15.88	14.23
50%	AV + HV	67.17	65.13	59.81	54.82
	AV + ACC (unstable)	85.65	82.99	81.91	80.37
	AV + ACC (stable)	45.45	42.50	37.38	33.96
	AV + CACC	48.76	45.80	40.03	36.44
	CDA + CACC	10.05	9.77	9.16	8.58
75%	AV + HV	41.36	40.85	39.63	38.41
	AV + ACC (unstable)	79.85	77.37	76.36	74.93
	AV + ACC (stable)	34.33	33.04	29.06	26.40
	AV + CACC	36.72	34.49	30.15	27.45
	CDA + CACC	8.49	8.20	7.81	7.42
100%	AV + HV	37.89	35.89	32.40	29.50
	AV + ACC (unstable)	66.71	64.63	63.79	62.59
	AV + ACC (stable)	29.52	27.60	24.28	22.06
	AV + CACC	30.68	28.82	25.19	22.93
	CDA + CACC	6.87	6.44	6.23	6.19

HV = Human Driven vehicles; AV = Automated Vehicles; ACC = Adaptive Cruise Control; CACC = Cooperative Adaptive Cruise Control; CDA = Cooperative Driving Automation.

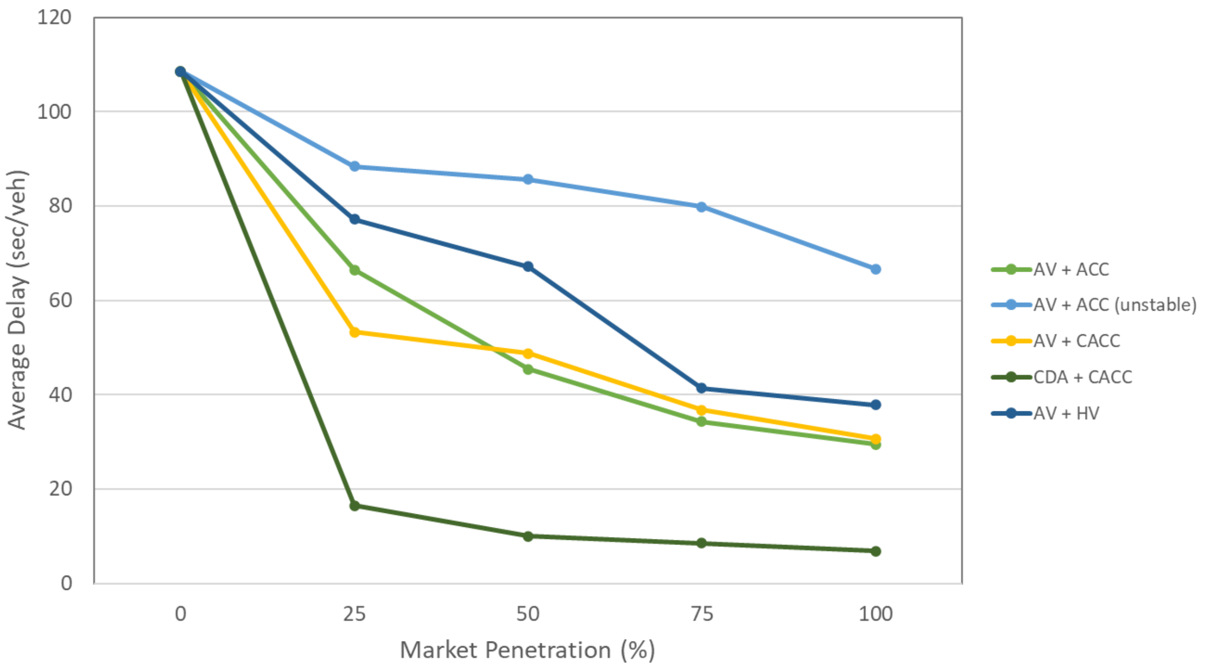


Figure 26. Average delay with no ramp metering with different market penetrations of automation and cooperation. (Mainline Flow=2,100 vphpl; Ramp Flow=750 vphpl).

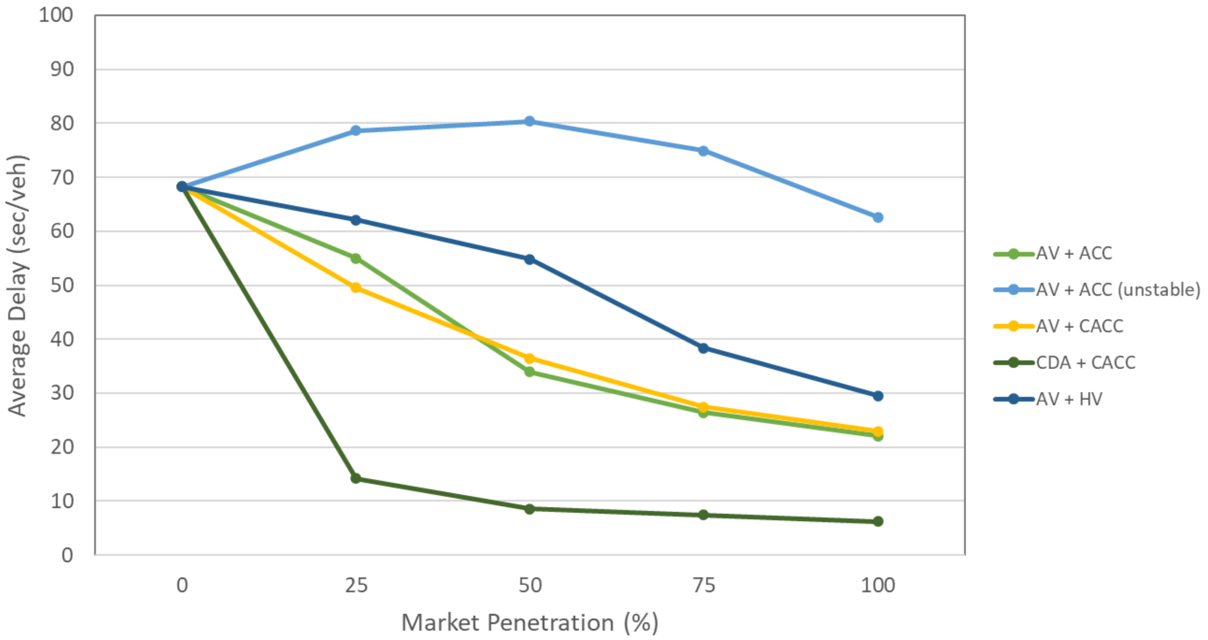


Figure 27. Average delay with enhanced fuzzy ramp metering with different market penetrations of automation and cooperation. (Mainline Flow=2,100 vphpl; Ramp Flow=750 vphpl).

Tables 4 and 5 and Figure 28 and Figure 29 indicate that ramp metering, particularly the adaptive metering resulted in a decrease in delay, particularly with the higher demands. The enhanced fuzzy logic algorithm ramp metering produced the best results followed by the fuzzy logic algorithm, followed by fixed ramp metering. With the demand close to capacity, Table 1 shows that the enhanced fuzzy logic-based metering produced about 25% reduction in delay compared to no metering (17.56 sec/veh. vs. 23.45 sec/veh) with human driven vehicles. The fixed metering produced a 4% reduction in delay compared to no metering (22.75 sec/veh. vs. 23.45 sec/veh). The base fuzzy logic metering resulted in about 15% reduction in delay (19.97 sec/veh. vs. 23.45 sec/veh).

With the higher demand and human driven vehicles (0% market penetration of automation and cooperation), Table 5 and Figures 27 and 28 show that the enhanced fuzzy logic-based metering produced about 37% reduction in delay compared to no metering (68.88 sec/veh. vs. 108.54 sec/veh). The fixed metering produced a 9% reduction in delay compared to no metering (98.77 sec/veh. vs. 108.54 sec/veh). The base fuzzy logic metering resulted in about 29% reduction in delay (76.83 sec/veh. vs. 108.54 sec/veh). However, Table 4 and Table 5 and Figure 27 and 28 indicate that the impact of ramp metering decreases with the increase in the market penetration of cooperative driving automation due to the increase in the capacity of the merge area with the increase in the market penetration.

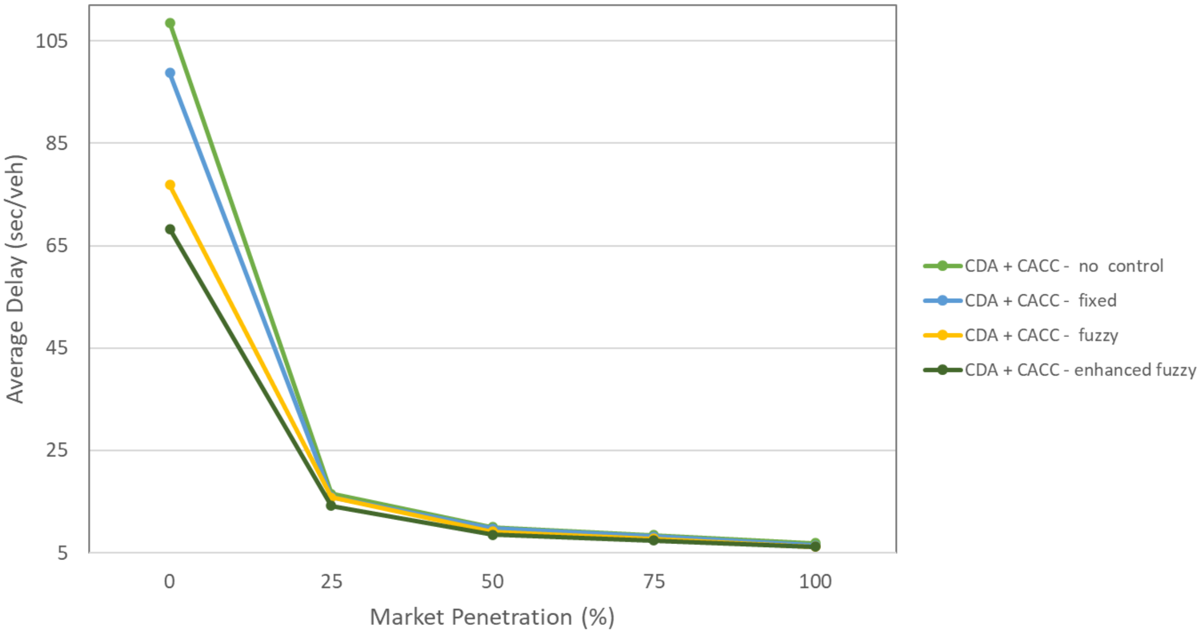


Figure 28. Average delay by metering control type and market penetration for the CDA+CACC scenario. (Mainline Flow=2,100 vphpl; Ramp Flow=750 vphpl).

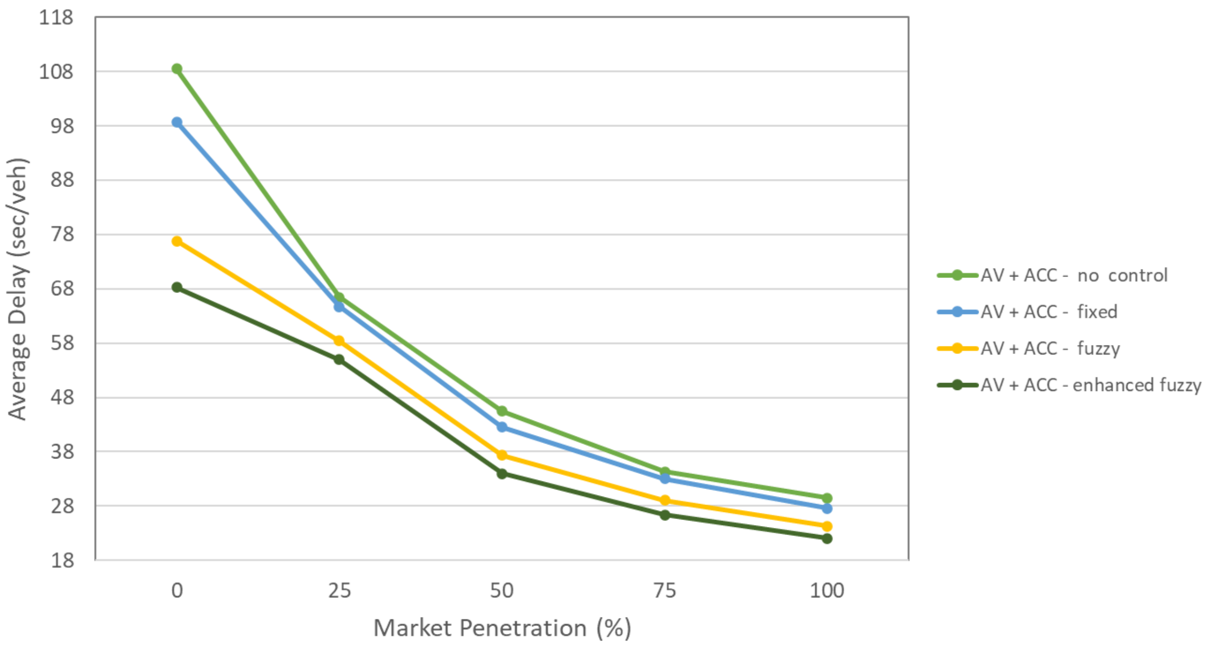


Figure 29. Average delay by metering control type and market penetration for the AV+ACC scenario. (Mainline Flow=2,100 vphpl; Ramp Flow=750 vphpl).

Tables 6 and 7 present the throughput results for the two traffic levels. As expected, Table 6 shows that the throughput does not change at the lower volume level with ramp metering and/or the introduction of automation and cooperation, which approach but does not exceed capacity. When demand is lower than capacity, the throughput is equal to the demand. However, the results in Table 7 indicate that ramp metering and automation and cooperation technologies can increase the capacity of the traffic network. However, the results in Table 7 are not sufficient to estimate the capacities of all scenarios and additional analysis was needed, as described next.

Table 6. Average Volume by Market Penetration and Control Type (Mainline Flow=1,900 vphpl; Ramp Flow=650 vphpl).

Market Penetration	Scenario	Average Throughput (veh/hr)			
		No Control	Fixed Rate	Fuzzy	Enhanced Fuzzy
0%	HV + HV	2197	2200	2204	2207
25%	AV + HV	2201	2203	2207	2209
	AV + ACC (unstable)	2184	2187	2189	2191
	AV + ACC (stable)	2198	2202	2209	2213
	AV + CACC	2208	2211	2212	2215
	CDA + CACC	2219	2221	2224	2228
50%	AV + HV	2204	2207	2209	2212

Market Penetration	Scenario	Average Throughput (veh/hr)			
		No Control	Fixed Rate	Fuzzy	Enhanced Fuzzy
	AV + ACC (unstable)	2184	2186	2188	2190
	AV + ACC (stable)	2206	2208	2211	2212
	AV + CACC	2211	2214	2215	2217
	CDA + CACC	2223	2224	2227	2229
75%	AV + HV	2209	2211	2213	2215
	AV + ACC (unstable)	2187	2189	2191	2193
	AV + ACC (stable)	2212	2214	2214	2214
	AV + CACC	2217	2219	2219	2221
	CDA + CACC	2227	2228	2230	2232
100%	AV + HV	2213	2214	2215	2218
	AV + ACC (unstable)	2190	2192	2193	2196
	AV + ACC (stable)	2218	2218	2220	2222
	AV + CACC	2224	2224	2225	2226
	CDA + CACC	2234	2234	2235	2238

HV = Human Driven vehicles; AV = Automated Vehicles; ACC = Adaptive Cruise Control; CACC = Cooperative Adaptive Cruise Control; CDA = Cooperative Driving Automation.

Table 7. Average Volume by Market Penetration and Control Type (Mainline Flow=2,100 vphpl; Ramp Flow=750 vphpl).

Market Penetration	Scenario	Average Throughput (veh/hr)			
		No Control	Fixed Rate	Fuzzy	Enhanced Fuzzy
0%	HV + HV	2078	2102	2134	2162
25%	AV + HV	2160	2189	2215	2233
	AV + ACC (unstable)	2055	2069	2077	2090
	AV + ACC (stable)	2170	2217	2254	2289
	AV + CACC	2162	2206	2269	2311
	CDA + CACC	2472	2475	2477	2479
50%	AV + HV	2204	2210	2226	2248

Market Penetration	Scenario	Average Throughput (veh/hr)			
		No Control	Fixed Rate	Fuzzy	Enhanced Fuzzy
	AV + ACC (unstable)	2079	2087	2102	2109
	AV + ACC (stable)	2196	2224	2266	2315
	AV + CACC	2224	2249	2298	2336
	CDA + CACC	2477	2479	2482	2484
75%	AV + HV	2226	2242	2262	2280
	AV + ACC (unstable)	2084	2108	2118	2124
	AV + ACC (stable)	2242	2257	2281	2323
	AV + CACC	2258	2283	2330	2348
	CDA + CACC	2481	2483	2487	2490
100%	AV + HV	2242	2264	2287	2305
	AV + ACC (unstable)	2118	2131	2153	2164
	AV + ACC (stable)	2250	2269	2306	2342
	AV + CACC	2261	2295	2338	2363
	CDA + CACC	2484	2484	2493	2504

HV = Human Driven vehicles; AV = Automated Vehicles; ACC = Adaptive Cruise Control; CACC = Cooperative Adaptive Cruise Control; CDA = Cooperative Driving Automation.

Further examination of the results in Table 7 indicates that throughput did not reach capacity in many of the scenarios with high levels of automation and cooperation since the simulated throughput is close to the total demand. Therefore, it was decided to increase the demands further until reaching the maximum possible throughput among all modeled scenarios. Using the input volume to the simulation at this throughput level will ensure that we are able to measure the capacities (maximum throughputs) of all scenarios. The highest throughput is expected with the CDA+CACC traffic scenarios. Thus, an additional analysis was performed to increase the demand with the CDA+CACC until the system reaches capacity. Multiple simulation runs were performed with increasing volume on the mainline starting from 2,100 vphpl up to 3,300 vphpl (in increments of 300 vphpl), and an on-ramp volume of 750 vphpl for each scenario. Table 5 shows that at a demand level of 3,375, (3,000 vphpl on the mainline, and 750 vphpl on the on-ramp), the throughput is slightly below demand (the simulated throughput is 3,364 vphpl and the input demand is 3,375 vphpl), and in the scenario with 3,300 vphpl on the mainline and 750 vphpl on the ramp, the throughput is significantly lower than the demand (the simulated throughput is 3,394 vphpl and the input demand is 3,675 vphpl). Table 8 also shows that the maximum throughput achieved for these scenarios was 3,449, therefore, it can be determined that the capacity of the system is about 3,450 vphpl with cooperative merging and CACC on the mainline, which is about 66% above the base case (human driven scenario) that has a capacity of 2,078 vphpl.

Table 8. Capacity Determination for the CDA+CACC Scenario.

Mainline Demand (vphpl)	Ramp Demand (vphpl)	Total Demand (vphpl)	Throughput (vphpl)
2100	750	2475	2484
2400	750	2775	2778
2700	750	3075	3076
3000	750	3375	3364
3300	750	3675	3449

Given the above results and to allow the determination of the maximum throughput for each scenario, the simulation was repeated for all scenarios with volume input that exceeds the maximum capacity that could be achieved with CDA+CACC scenario (3,450 vphpl). The volumes used is this set of simulations are 3,075 vphpl on the mainline and 750 vphpl on the one-lane on-ramp. The results from this analysis are shown in Table 8. Figures 29 to 32 show a visualization of some of the results in Table 8 to allow a better comparison of the results for different scenarios. Table 8, Figure 29, and Figure 30 show the change in capacity with market penetration of automation and cooperation with and without metering. The capacity increased except in the scenarios with the unstable ACC. For example, in Figure 29, with no ramp metering and 100% market penetration, autonomous merge with human driving on mainline (AV+HV) and autonomous merge with stable ACC on mainline (AV+ACC) increased capacity by 13.3% (2,346 vphpl vs. 2,070 vphpl) and 12.7% (2,333 vphpl vs. 2,070 vphpl), respectively. The corresponding increases with autonomous merge combined with CACC on mainline (AV+CACC) and cooperative merge combined with CACC on mainline were 44.4% (2,989 vphpl vs. 2,070 vphpl) and 65.7% (3,432 vphpl vs. 2,070 vphpl), respectively. Another example, in Figure 30, with enhanced fuzzy logic metering and 100% market penetration, autonomous merge with human driving on mainline (AV+HV) and autonomous merge with stable ACC on mainline (AV+ACC) increased capacity by 14.1% (2,453 vphpl vs. 2,149 vphpl) and 9.2% (2,347 vphpl vs. 2,149 vphpl), respectively. The corresponding increases with autonomous merge combined with CACC on mainline (AV+CACC) and cooperative merge combined with CACC on mainline were 42.9% (3,071 vphpl vs. 2,149 vphpl) and 61.8% (3,478 vphpl vs. 2,149 vphpl), respectively.

Table 9. Average Volume by Market Penetration and Control Type (Mainline Flow=3,075 vphpl; Ramp Flow=750 vphpl).

Market Penetration	Scenario	Average Throughput (veh/hr)			
		No Control	Fixed Rate	Fuzzy	Enhanced Fuzzy
0%	HV + HV	2078	2102	2134	2162
25%	AV + HV	2137	2142	2185	2234
	AV + ACC (unstable)	2011	2021	2005	2107
	AV + ACC (stable)	2110	2122	2129	2194
	AV + CACC	2329	2345	2382	2432
	CDA + CACC	2565	2584	2622	2662
50%	AV + HV	2214	2302	2313	2340
	AV + ACC (unstable)	1985	1996	2012	2037
	AV + ACC (stable)	2147	2160	2167	2201
	AV + CACC	2526	2546	2579	2612
	CDA + CACC	2717	2742	2774	2792
75%	AV + HV	2290	2294	2344	2389
	AV + ACC (unstable)	1881	1890	1901	1922
	AV + ACC (stable)	2246	2252	2257	2270
	AV + CACC	2735	2742	2771	2773
	CDA + CACC	2842	2930	2947	3012
100%	AV + HV	2346	2351	2368	2453
	AV + ACC (unstable)	1735	1738	1740	1756
	AV + ACC (stable)	2333	2336	2339	2347
	AV + CACC	2989	3021	3042	3071
	CDA + CACC	3432	3473	3475	3478

HV = Human Driven vehicles; AV = Automated Vehicles; ACC = Adaptive Cruise Control; CACC = Cooperative Adaptive Cruise Control; CDA = Cooperative Driving Automation.

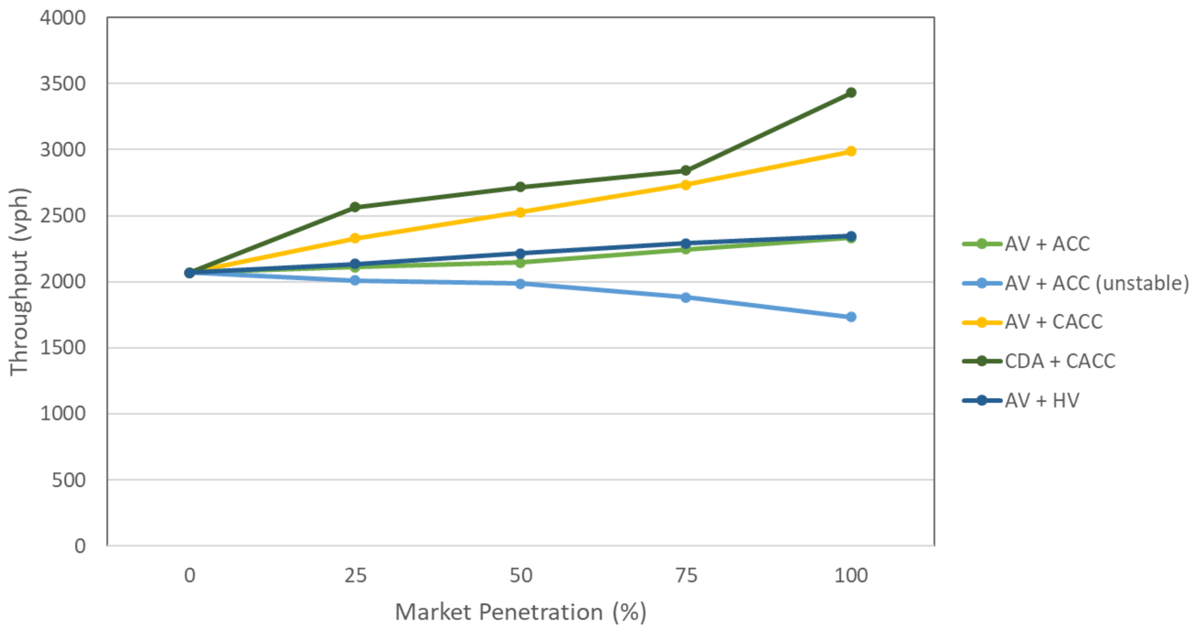


Figure 30. Average throughput without ramp metering with different market penetrations of automation and cooperation (Mainline Flow=3,075 vphpl; Ramp Flow=750 vphpl).

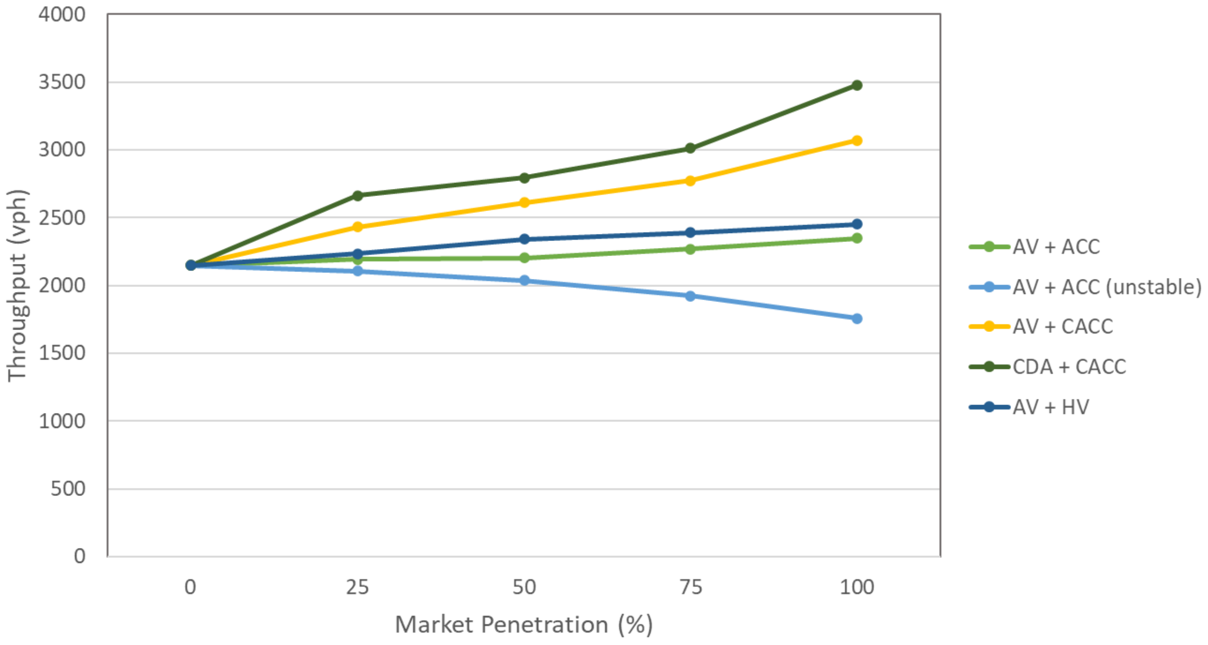


Figure 31. Average throughput with enhanced fuzzy metering control with different market penetrations of automation and cooperation. (Mainline Flow=3,075 vphpl; Ramp Flow=750 vphpl).

Table 8, Figure 31, and Figure 32 show the change in capacity due to different ramp metering strategies and market penetrations of automation and cooperation. Ramp metering increases capacity with the enhanced fuzzy logic algorithm producing the highest increase in capacity. For example, with no ramp metering and human driven vehicles (HV+HV), the maximum increase in capacity achieved with the enhanced fuzzy logic was 4.4% (2,162 vphpl with metering vs. 2070 vphpl without metering). The increase in capacity with the traditional fuzzy logic algorithm was 3.1% (2,134 vphpl with metering vs. 2070 vphpl without metering). With 25% and 100% autonomous merge with stable ACC on the mainline (AV+ACC), the enhanced fuzzy logic ramp metering increased capacity by 4.0% (2,194 vphpl vs. 2,110 vphpl) and 0.6% (2,347 vphpl vs. 2,332 vphpl), respectively. With 25% and 100% cooperative merge with CACC on the mainline (CDA+CACC), the enhanced fuzzy logic ramp metering increased capacity by 3.7% (2,662 vphpl vs. 2,565 vphpl) and 1.3% (3,478 vphpl vs. 3,432 vphpl), respectively. This indicates that the impact of ramp metering on capacity or maximum throughput decreases with the higher levels of market penetrations of automation and cooperation. Note that there is a difference in scale between Figure 31 and Figure 32, due to the higher range of throughput in Figure 31.

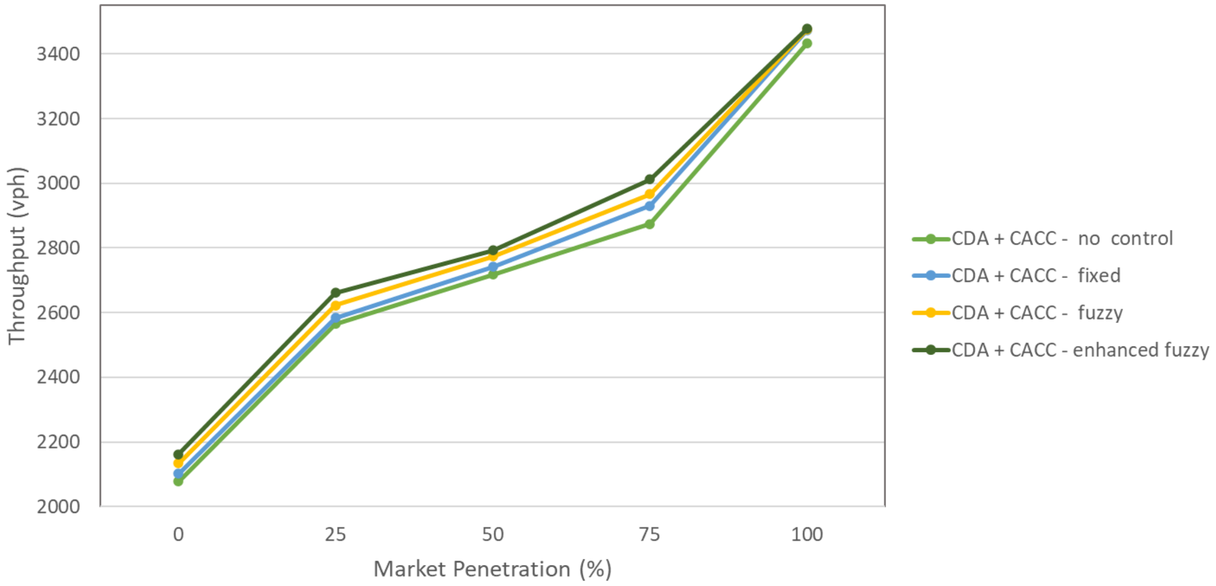


Figure 32. Average throughput by metering control type and market penetration for the CDA+CACC scenario. (Mainline Flow=3,075 vphpl; Ramp Flow=750 vphpl).

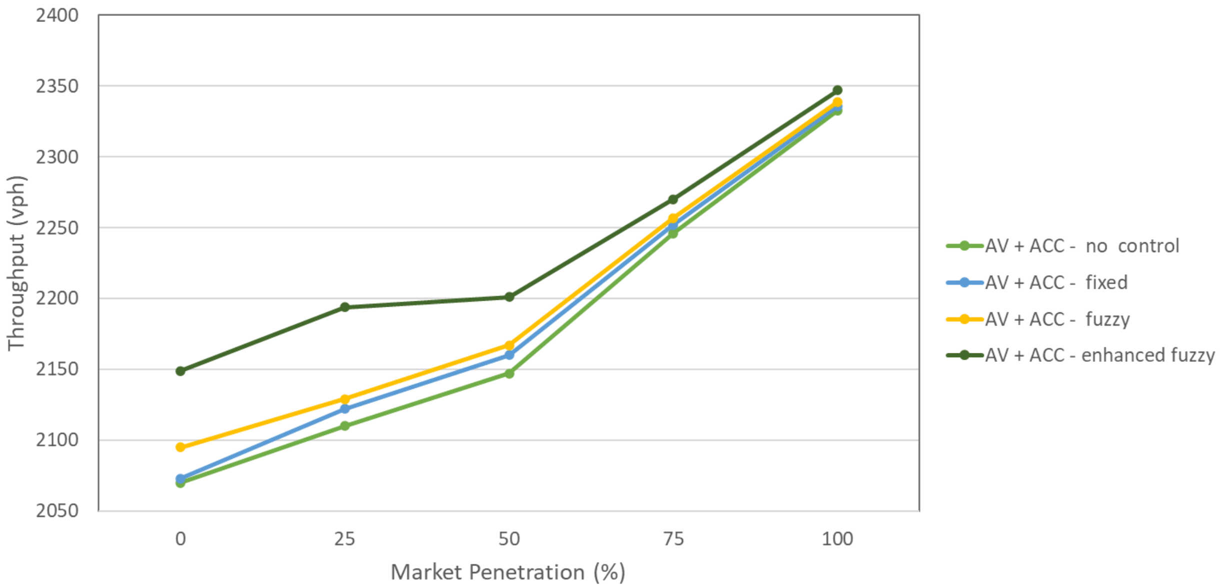


Figure 33. Average throughput by metering control type and market penetration for the AV+ACC scenario. (Mainline Flow=3,075 vphpl; Ramp Flow=750 vphpl).

Vehicle-Level Assessment Results

This study also utilizes a co-simulation platform (OpenCDA) to assess the vehicle-level performance of the cooperative merging operations under different scenarios. Utilizing a co-simulation environment provides a realistic approach for modeling vehicle dynamics and vehicle sensors that cannot be achieved using traffic simulation models by themselves. The co-simulation tool was used to assess vehicle-level measures identified in the test plan developed in this study and presented above. These vehicle-level measures include Time to Complete Merge, Average Merging Speed, and Speed and Acceleration Deviations.

In the co-simulation, a test case featuring a two-lane freeway with an on-ramp merge. To ensure realism, the traffic scenario was carefully constructed, including a combination of vehicles: 7 CDA vehicles on the mainline and 3 CDA vehicles merging from the on-ramp, as well as background traffic. In addition, the test case was set to emulate normal driving conditions, specifically sunny weather with good visibility.

Table 10 shows the results of the vehicle-level measures produced using co-simulation when cooperative merging operation is implemented at a freeway on-ramp merge. The table shows the performance of the merging of three human driven vehicles and three cooperatively merging vehicles. The results show significant improvements in terms of the time required to complete the merging operation and average merging speed with cooperative merging when compared with human-driven merging vehicles due to the smoother and more efficient merge operations. In terms of merge stability, the standard deviations of speed and acceleration were found to be smaller with cooperative merging compared with human-driven vehicles.

Table 10. Vehicle-Level Performance Measures under Cooperative Merging Operations.

Vehicle-level performance measures	CDA merging vehicles				Human-Driven merging vehicles			
	Car 1	Car 2	Car 3	Average	Car 1	Car 2	Car 3	Average
Time to complete merge (sec)	6.4	2.2	2.1	3.6	15.6	4.1	16.9	12.3
Average merging speed (mph)	50.5	51.0	54.2	51.9	44.1	59.4	44	49.2
Speed standard deviation (within merge area)	1.4	1.0	1.9	1.5	3.7	0.1	3.1	2.8
Acceleration standard deviation (within merge area)	3.0	2.2	3.3	2.9	7.0	2.6	5.4	5.3

Figure 33 below illustrates the vehicle trajectories obtained from the co-simulation platform. The purpose of this visualization is to compare the merging maneuvers of on-ramp CDA vehicles against the on-ramp human-driven vehicles. The smoother merging operation of CDA vehicles can be observed through the trajectory paths of the on-ramp CDA vehicles. This is because the mainline CDA vehicles cooperated with the merging vehicles by decelerating or accelerating. Another notable observation is the merged locations of the on-ramp vehicles. The merged locations refer to the points at which the vehicles have successfully completed the merging on to the mainline freeway. In the case of the CDA vehicles, examining the merged locations indicate a significantly faster merging process compared to the human-driven vehicles from the on-ramp.

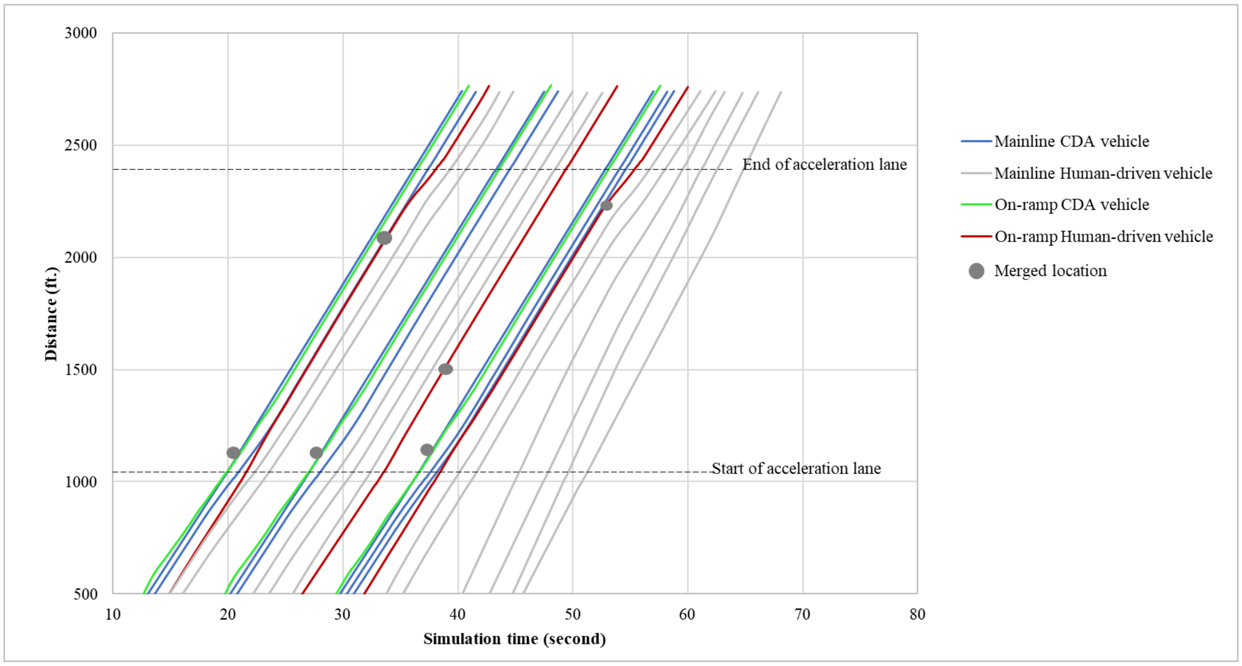


Figure 34. Vehicle trajectories of CDA and human-driven vehicles on the mainline freeway and on-ramp roadway.

5. ACTION PLAN, TRAINING PLAN, AND ALTERNATIVE ANALYSIS PLAN

This chapter includes the proposed plan to identify the action items required to establish and advance the practices needed for the infrastructure support of the CDA. The proposed action plan are based on required actions to achieve different levels of capabilities in technical and institutional dimensions and subdimensions, identified based on a review of the capability maturity models and frameworks developed for TSM&O, CAVs, and other active traffic management and transportation strategies and processes. In addition, the chapter includes a training plan that proposes training modules for the purpose of building the workforce required for the incorporation of CDA consideration in TSM&O based on the identified action plan. Finally, the chapter proposes methods to select and prioritize strategic and tactical actions to build the capabilities required for the TSM&O support of CDA.

5.1 RELATED FDOT PLANS

This section presents a review of the FDOT TSM&O program plans that provide the goals, objectives, performance measures, and actions of TSM&O and associated advanced strategies and technologies in Florida. These plans will form important inputs to the selection and prioritization of strategies and actions related to infrastructure interaction with emerging vehicle technology in general and specifically, CDA. The action items presented later in this document will need to be coordinated with the action items in the other TSM&O plans to meet the overall goals, objectives, and performance metrics targets.

In addition, the FDOT plans should be updated as needed to consider CAV and CDA, as specified in the action plan developed in this project. In addition to the three plans reviewed in this section (FDOT TSM&O Strategic Plan, CAV Business Plan, and Statewide Arterial Management Program (STAMP) Action Plan), other FDOT programs, initiatives, and plans will need to be considered for potential updates, including but not limited to the Florida Transportation Plan (FTP), Smart Work Zone Initiative, Transportation Technology Strategic Plan, Strategic Highway Safety Plan (SHSP), Strategic Intermodal System (SIS) Policy Plan, Florida's Aging Road Users Strategic Safety Plan (Safe Mobility for Life Coalition), and Traffic Incident Management (TIM) Plan.

5.1.1 FDOT TSM&O Strategic Plan

The FDOT TSM&O Division developed the 2017 Update of the TSM&O Strategic Plan (FDOT 2017), which includes the vision, mission, goals, objectives, and priority focus areas of the TSM&O program. It also identifies an action plan to be accomplished over three to five years.

The plan identifies paths to achieve the goals of the TSM&O program, including active arterial management (AAM), adaptive signal control, incident management, standard operation procedure changes, and performance monitoring. The selected performance metrics for mobility include planning time index (PTI), throughput, and delay reduction for all users, in addition to all lanes cleared times. Districts may select other performance metrics to supplement the PTI. The crash rate and severity are selected as the measures for safety in congested urban areas. The targets for safety and mobility performance metrics include at least a 5% improvement in throughput, PTI, and speed due to the application of strategies selected to improve mobility. Target thresholds for crash rate and severity improvements will be set in a future update to the plan.

The Strategic Plan identifies six TSM&O strategies as statewide focus areas: TSM&O Mainstreaming, Arterial Management, Connected Vehicles, Express Lanes, Freeway Management, and Information Systems. Task 1 of this project developed a concept of operation for the consideration of CDA for these focus areas. It is recommended that CAV and CDA are added to the focus areas (this is one of the action items proposed in Phase 1 of the action plan proposed in this study).

5.1.2 Connected and Automated Vehicles Business Plan

The 2019 Business Plan of the CAV Program of the FDOT (FDOT 2019) includes an institutionalized framework and timeframes to support statewide deployment goals. The plan identifies specific CAV short-term to long-term action items. The Business Plan addresses the preparation of Florida's infrastructure for CAV deployment, including:

- Identify policies and governance for planning, designing, and deploying CAV.
- Identify education and outreach programs.
- Develop industry outreach to implement outcome-based CAV technologies.
- Identify and develop technical standards and specifications.
- Establish a platform for CAV implementation readiness in terms of technology implementation, infrastructure improvements, and needs identification.
- Move towards full-scale CAV deployment and prioritized implementation to achieve the benefits.

The action plan proposed in this project builds on the CAV business plan and provides inputs to this plan.

5.1.3 STAMP Action Plan

The Statewide Arterial Management Program (STAMP) Action Plan (FDOT 2021) provides outcome-based actions intended for arterial management. The plan has five (5) Focus Areas and twenty-five (25) Action Items to guide the implementation process. The five focus areas and overview of the actions are discussed below.

- Infrastructure Upgrades Update the TMC central software and servers to support Advanced Traffic Controller (ATC)–enabled data and arterial management strategies.
- Data Management - Initiate development of collective requirements for the data analytics engine requirements in terms of a data analytics engine that includes data archival, access, security, and user interface.
- Performance Assessment – Develop common goals and objectives for historical and real-time performance measures to be captured in a standardized dashboard.
- Operations and Maintenance – Develop and circulate tutorials on programming requirements and funding options for STAMP communication, controllers, central systems,

management strategy implementation, operations, and maintenance, and develop a plan to identify staffing needs in arterial management programs.
- Emerging Technologies - Continue to deploy advanced detection technologies, such as Automated Traffic Signal Performance Measures (ATSPM) applications, and share lessons learned to support arterial operations and management decisions on priority corridors.

5.2 The Enhancement Categories Proposed in the ConOps

Another basis for the action plan suggested in this study is the ConOps developed in this study. To understand the action plan presented in the next section, it is important to understand the concepts presented in the ConOps. Thus, a summary of these concepts is presented in this section for convenience.

The vision for the incorporation of CDA in TSM&O is for the FDOT to start implementing infrastructure interfaces required for CDA by extending their current and planned traffic management strategies and CV infrastructure deployment applications to accommodate the CDA needs in an evolutionary manner, considering the abovementioned challenge. With the limited market penetration of CDA vehicles in the traffic stream in the near future, the extension of the existing capabilities is recommended to be implemented in an evolutionary manner that will provide support to the existing applications and provide improvements to the system's performance as they are implemented. As the CDA vehicles begin to be incorporated in the transportation system, the already introduced enhancements to the system's operations can be used to support the CDA and make use of the CDA in improving TSM&O. At this future stage, the additional extension of the capabilities will be implemented as needed.

The following enhancement management categories are recommended in the proposed concept of operations.

- **Enhancement Management Category 1 – Data Support of Management**: This category of enhancements improves existing operational strategies by utilizing data from CV (Enhancement 1-a) and vehicles equipped with CDA Class A and higher capabilities (Enhancement 1-b). This will involve using additional data collected from CV, connected automated vehicles (CAV), and CDA, which can improve existing freeway, arterial, and integrated corridor management strategies, such as ramp metering, signal control, incident and work zone management, and managed lanes.

- **Enhancement Management Category 2 – Information and Guidance Provision**: This category involves providing additional infrastructure information that can be used by CV and CDA. Current CV applications involve the provision of information according to Society of Automotive Engineers (SAE) J2735 and various SAE J2945 standards, including Signal Phase and Timing Messages (SPaT), Geometry MapData Messages (MAP), Traffic Information Messages (TIM), and Road Safety Messages (RSM). However, additional messages will need to be specified to support CDA, such as vehicle speed, gap setting, lane changing parameters, platooning parameters, and dynamic merge parameters. These messages, although required for CDA vehicles, can also be used by CV vehicles that are equipped with onboard units that are capable of receiving this information. CDA with Level 1 or Level 2 of automation and Class 1 and 2 of cooperation can receive broadcasted information and use it for longitudinal and lateral control, but with no cooperation with the infrastructure. Higher levels of automation and classes of collaboration can use this information in a similar manner and can also participate in Enhancement Management Category 3. The information from the infrastructure can improve CDA safety and mobility and expand the Operational Design Domain (ODD) by providing data that supplements the information gathered by vehicle sensors, such as cameras, LiDAR, and radar. This level may include the provision of recommended strategic, tactical, and operational actions that can be used by both connected vehicles and CDA vehicles. For example, the infrastructure can provide recommendations to alter driving behavior, such as increasing the car-following gaps on wet pavement, reducing speeds, or merging ahead of lane closures. This information could be provided to human-driven connected vehicles for use by the driver, as well as to CDA-equipped vehicles to be used by the CDA.

- **Enhancement Management Category 3 – Fully Cooperative Operations and Management:** Enhancement Management Category 3 includes operational strategies that require the collaboration between the infrastructure and individual vehicles of automation level 3 and above and cooperation class 3 and 4. This involves vehicle-specific guidance from the infrastructure. In addition to status and intent sharing, as more CDA vehicles are introduced into the traffic stream, the FDOT can further enhance their operational strategies and implement new collaborative infrastructure strategies that require the collaboration between the infrastructure and the vehicles using CDA-specific communications. These enhancements will include the provision of guidance information and feedback from CDA vehicles to support Class C (agreement seeking) and Class D (prescriptive) of cooperative driving, according to the SAE J3216 Standards. The provided information will build on the information presented in Enhancement Management Category 2. Initially, all provided guidance will not be prescriptive, but will be suggested actions, as they support SAE J3216 Class 3 Cooperation (Agreement Seeking) rather than Class 4 (Prescriptive). This is considered Enhancement Category 3-a. The CDA vehicles will have full authority on deciding on the final actions. In the next step in Enhancement Category 3-b, the infrastructure will provide prescriptive actions for Class 4 vehicles in some of the applications.

The vision for the incorporation of CDA in TSM&O is for the FDOT to start implementing infrastructure interfaces required for CDA by extending their current and planned traffic management strategies and CV infrastructure deployment applications to accommodate the CDA needs in an evolutionary manner, considering the abovementioned challenge. With the limited market penetration of CDA vehicles in the traffic stream in the near future, the extension of the existing capabilities should be implemented in an evolutionary manner that will provide support to the existing applications and provide improvements to the system's performance as they are implemented. As the CDA vehicles begin to be implemented, the already introduced enhancements to the system's operations can be used to support the CDA and make use of the CDA in improving TSM&O. At this future stage, the additional extension of the capabilities will be implemented as needed.

Considering the implementation plan above, the following enhancement management categories are recommended for this concept of operations for TSM&O.

- Enhancement Management Category 1 – Data Support of Management: This category of enhancements improves existing operational strategies by utilizing data from CV (Enhancement 1-a) and vehicles equipped with CDA Class A and higher capabilities (Enhancement 1-b). This will involve using additional data collected from CV, CAV, and CDA, which can improve existing freeway, arterial, and integrated corridor management strategies, such as ramp metering, signal control, incident and work zone management, and managed lanes.

- Enhancement Management Category 2 – Information and Guidance Provision: This category involves providing additional infrastructure information that can be used by CV and CDA. Current CV applications involve the provision of information according to Society of Automotive Engineers (SAE) J2735 and various SAE J2945 standards, including Signal Phase and Timing Messages (SPaT), Geometry MapData Messages (MAP), Traffic Information Messages (TIM), and Road Safety Messages (RSM). However, additional messages will need to be specified to support CDA, such as vehicle speed, gap setting, lane changing parameters, platooning parameters, and dynamic merge parameters. These messages, although required for CDA vehicles, can also be used by CV vehicles that are equipped with onboard units that are capable of receiving this information. CDA with Level 1 or Level 2 of automation and Class 1 and 2 of cooperation can receive broadcasted information and use it for longitudinal and lateral control, but with no cooperation with the infrastructure. Higher levels of automation and classes of collaboration can use this information in a similar manner and can also participate in Enhancement Management Category 3. The information from the infrastructure can improve CDA safety and mobility and expand the Operational Design Domain (ODD) by providing data that supplements the information gathered by vehicle sensors, such as cameras, LiDAR, and radar. This level may include the provision of recommended strategic, tactical, and operational actions that can be used by both connected vehicles and CDA vehicles. For example, the infrastructure can provide recommendations to alter driving behavior, such as increasing the car-following gaps on wet pavement, reducing speeds, or merging ahead of lane closures. This information could be provided to human-driven connected vehicles for use by the driver, as well as to CDA-equipped vehicles to be used by the CDA.

- Enhancement Management Category 3 – Fully Cooperative Operations and Management: Enhancement Management Category 3 includes operational strategies that require the collaboration between the infrastructure and individual vehicles of automation level 3 and above and cooperation class 3 and 4. This involves vehicle-specific guidance from the infrastructure. In addition to status and intent sharing, as more CDA vehicles are introduced into the traffic stream, the FDOT can further enhance their operational strategies and implement new collaborative infrastructure strategies that require the collaboration between the infrastructure and the vehicles using CDA-specific communications. These enhancements will include the provision of guidance information and feedback from CDA vehicles to support Class C (agreement seeking) and Class D (prescriptive) of cooperative driving, according to the SAE J3216 Standards. The provided information will build on the information presented in Enhancement Management Category 2. Initially, all provided guidance will not be prescriptive, but will be suggested actions, as they support SAE J3216 Class 3 Cooperation (Agreement Seeking) rather than Class 4 (Prescriptive). This is considered Enhancement Category 3-a. The CDA vehicles will have full authority on deciding on the final actions. In the next step in Enhancement Category 3-b, the infrastructure will provide prescriptive actions for Class 4 vehicles in some of the applications.

The enhancement categories in the above list will take advantage of the capabilities of connected and CDA vehicles to enhance TSM&O and accommodate the needs of CDA. The modified and new functions in the three categories will need to consider that various levels of vehicle automation according to SAE J3016 and the cooperation classes according to SAE J3216 will operate in the system simultaneously for a long period of time with changing levels of market penetrations. The first two categories (Data Support of Management and Information Guidance and Provision) can provide benefits, even with no or limited CDA functions, but they are required to support the enhancements of the third category (Fully Cooperative Management and Operations). It is recommended that FDOT will start with implementing Category 1 enhancements and some of Category 2 enhancements, considering the limited availability of higher classes of the CDA in the early phases of the deployment. However, this implementation can be conducted in a manner that accommodates further enhancements to achieve the remaining Category 2 and Category 3 enhancements.

The Concept of Operation presents a comprehensive list of potential applications in each of the enhancement areas as related to the focus traffic management areas of the FDOT TSM&O Strategic Plan. These focus areas are Information Technology, Freeway Management, Express Lane Management, and Arterial Management.

5.3 Required Capabilities as a Basis for Action Plan

The action plan in this document will be developed based on identified required capability dimensions and subdimensions. The dimensions of the capability maturity models (CMM) developed for TSM&O and connected vehicles were used as a starting point for identifying the dimensions and subdimensions.

The Second Strategic Highway Research Program (SHRP2) Reliability program developed a capability maturity model (CMM) for transportation system management and operations (TSM&O) (Gettman et al., 2017). The TSM&O CMM applies concepts that are popular for various applications in information technology. The FDOT has successfully used the CMM to assess and identify actions of their TSM&O programs. Building on the original TSM&O CMM, the FHWA has developed capability maturity frameworks (CMFs) that focus on agency capabilities in specific areas, including Road Weather Management, Planned Special Events, Traffic Incident Management, Traffic Management, Traffic Signal Management, Work Zone Management, Integrated Corridor Management, Connected and Automated Vehicles (CAV), Traffic Analysis, and Active Demand Management. The FHWA has developed these frameworks for use by agencies and regions to self-assess their current strengths and weaknesses and to develop targeted action plans for program area improvements. These frameworks, and in particular including the one developed for CAV (Gettman et al., 2017), can be used as a basis to establish an action plan for infrastructure support of CDA. The original CMM utilized six dimensions of capability: Business Process, Performance Measurements, Systems and Technology, Organization and Workforce, Culture, and Collaboration. The FHWA CAV CMF dimensions are Business Process, Systems and Technology (both Field and Back Office), Performance Measures Collaboration, Culture, and Organization and Staffing.

The selected dimensions to develop the action plan in this study are listed below:

- Business Process: This dimension includes the revision of plans, guidance, policies, and standards, and the planning and programming of CAV and CDA infrastructure support.
- System and Technology: This dimension involves the development of basis for CAV and CDA infrastructure support, and the deployment of the supporting infrastructure and implementation of enhancements to traffic management.
- Data and Performance Measurement: This dimension involves data collection, sharing, management, utilization and performance measurements.
- Culture and Collaboration: This dimension covers participation in national effort, building partnership, and building culture.
- Workforce and Organization: This dimension focuses on recruitment, hiring, development, and retention, as well as organizational structure, roles and responsibilities.

5.4 CDA Infrastructure Support Action Plan

The action plan is proposed to be developed in four phases, which corresponds to four potential capability maturity levels. These phases/maturity levels are listed below.

- Awareness and Exploration Phase
- Initialization Phase
- Action Suggestion Integration Phase
- Optimized Cooperation Phase

This section presents the suggested actions for each of the capability building dimensions and their subdimensions for the above four phases of the action plan.

5.4.1 Phase 1: Awareness and Exploration Phase

During this phase, FDOT and partner agencies are aware of the existing and potential CAV and CDA applications and begin exploring the required infrastructure support. This phase involves initially utilizing CV data in traffic management (Enhancements Category 1-a in the ConOps developed in this study) in preparation for utilizing CAV and CDA (Enhancement Category 1-b). In this phase, the FDOT will start updating their plans, standards, policies, guidance, system engineering process, manuals, and demand forecasting and simulation practices, and guidance with the consideration of CAV and CDA. The FDOT will identify methods to justify the investment in the CDA infrastructure and start updating the associated requirements, specification, design procedures, and management platforms. This phase will also include the review, update, development, and implementation plans and specification for data and performance measures, with the consideration of CV, AV, and CDA data. The FDOT will participate in national efforts and start initializing the building of the required partnerships, culture, organization, and training programs. Table 11 lists the potential actions for the Awareness and Exploration phase for each maturity capability dimension by subdimension.

Examples of pilot projects are listed below. More details can be found in the ConOps document.

- Merge area management: CV data can be used in the identification of the need for geometric improvements, in supporting the decision to activate metering, and providing additional inputs to ramp metering rate calculations in traffic adaptive ramp metering algorithms.
- Incident management support: CV data can be used to allow for quicker detection, crash location identification, and crash severity information. The data can be used to improve onsite monitoring and site management practice. In addition, it will provide a better understanding of driver behavior in the vicinity and ahead of incidents.
- Work zone management: The involves using CV data for detecting unplanned work, identifying work zone configuration, performance monitoring and prediction, providing a better understanding of driver behaviors ahead and in the vicinity of the work zone, and identifying the difficulties of automated vehicles in work zones.
- Speed management: CV data allow measuring the location and attributes of the bottleneck, shockwaves, and queues that are used as inputs to speed management algorithms.
- Lane and shoulder management: This involves the use of data to support decisions to open and close the shoulder and lanes and to identify safety and mobility issues associated with lane and shoulder management.
- Car-following and platoon management: This includes collecting information about the gaps between the vehicles under different traffic, geometry, and environmental conditions to identify the need for enforcement, management, or advisory strategies.
- Safety management: This includes collecting information about wrong-way driver (WWD) and “near”-WWD. In addition, the enhancements collect information about the queues, crash occurrence, and near misses, and allow for the prediction of unsafe conditions and geometry in off-line and real-time operations.
- Express lanes: The collected data can be used to support dynamic pricing based on vehicle attributes, number of occupants, automation level, and cooperation class. The collected data can also allow better access control by identifying the difficulty in weaving and merging/diverging maneuvers to/from the express lane.
- Signal management: This action uses CV data to support signal retiming, activation of special signal timing plans, and adaptive signal control.
- Priority and preemption support: This action uses CV data to support signal priority and preemption.

- Integrated corridor management: This action includes the use of the additional data to obtain more detailed measures for better signal plan optimization and activation on alternative routes and incident events, as well as for integrating signal control with downstream ramp meters.

Table 11: The Potential Actions for the Awareness and Exploration Phase for Each Maturity Capability Dimension by Subdimension.

Capability Dimension	Capability Subdimension	Exploration Phase Action
Business Process	Revision of Plans, Guidance, Policies, and Standards	Action 1-A-1: Identification of needed updates to the TSM&O Strategic Plan, CV Business Plan, STAMP Action Plan, and other FDOT Plans. Action 1-A-2: Identification of cybersecurity, privacy, and liability risks associated with guidance provision to CV and CDA vehicles. Action 1-A-3: Identify potential future updates to highway standards, guidance, and procedures. Action 1-A-4: Incorporate AV CAV, and CDA in the long-range plans.
	Planning and Programming of CAV CDA Infrastructure Support	Action 1-B-1: Identification of and communicating the business case, constraints, and funding needs of CDA incorporation in TSM&O. Action 1-B-2: Approve methods to select between alternative investment options considering CDA.
System & Technology	Development of Basis for CDA Infrastructure Support	Action 1-C-1: Adoption of concept of operations, requirements, and other system engineering documents; building on and considering the three enhancement categories of the concept of operation developed in this study. Action 1-C-2: Update the requirements, specifications, and design of SunGuide, Vehicle to Everything (V2X) Data Exchange, and Signal Control Software for Use of CV Data (Enhancement 1-a).

Capability Dimension	Capability Subdimension	Exploration Phase Action
		Action 1-C-3: Develop Standard Operating Guidance (SOG) for CV data use.
	Deployment of Supporting Infrastructure and Implementation of Enhancements to Traffic Management	Action 1-D-1: Update the SunGuide software, V2X Data Exchange, and signal control software for use of CV data pilot projects. Action 1-D-2: Implementation of pilot projects for CV data use in management (Enhancement Level 1a). Examples of potential projects were provided earlier in this section.
Data and Performance management	Data Collection, sharing, and management	Action 1-E-1: Develop and implement plans and specifications for data exchange, archiving, and utilization related to CV, Autonomous vehicles, and CAV data utilization.
	Performance Measurements and Utilization	Action 1-F-1: Review and update the performance measures of the plans and processes of the FDOT, considering measures based on the availability of CV and eventually, CAV data. This includes measures that are currently used for transportation system operations, management, and planning; and new measures for use in traffic management. Action 1-F-2: Update the demand forecasting models (the FSUTMS models in Florida) and sketch planning tools to incorporate CDA Action 1-F-3: Update simulation guidance for CDA modeling
	Data Utilization	Action 1-G-1: Utilize CV data for off-line monitoring of traffic operations Action 1-G2: Utilize CV data for real-time monitoring of traffic operations
Culture and Collaboration	Participation in National Effort	Action 1-H-1: Participation in national and peer-exchange efforts

Capability Dimension	Capability Subdimension	Exploration Phase Action
	Building Partnership	Action 1-I-1: Identification and development of outreach and involvement plan of state and regional planning, design, and operations partners. This includes: • Identification of key public and private stakeholders and participants in CDA • Dissemination of information and coordinate with the stakeholders and participants • Coordination with the stakeholders identified in ConOps of the pilot projects on anticipated project activities. • Coordination with national and other state efforts regarding key aspects of CDA development and applications. • Coordination and involvement in dialogues with private-sector providers • Establish a CDA coordination task group with participation from partner agencies.
	Building Culture	Action 1-J-1: Develop a plan to promote a culture that appreciates the value of CDA and investing in infrastructure support of CDAs.
Workforce Development and Organization	Recruitment, Hiring, Development, and Retention	Action 1-K-1: Confirm the core knowledge, skills and abilities (KSAs) needed for CDA. Action 1-K-2: Review and utilize information from the Training Plan suggested in this project in the next section, NCHRP 20-102(20) project "Preparing the Transportation Workforce for the Deployment of Emerging Technology", and NCHRP Project No. 20-07/Task 408 "Transportation Systems Management and Operations (TSM&O) Workforce Guidebook

Capability Dimension	Capability Subdimension	Exploration Phase Action
		Action 1-K-3: Approve a program for training to obtain the KSAs required for infrastructure support of the CDA building on CV and AV training of the FDOT. Action 1-K-4: Deliver initial modules that focus on CV and AV topics that can be extended in the future for CDA training.
	Organizational Structure, Roles, and Responsibilities	Action 1-M-1: Examine the current FDOT organizational structure, roles, and responsibilities, and determine if any updates are needed.

5.4.2 Phase 2: Initialization

This phase initializes the incorporation of CDA in TSM&O and explores some basic capabilities in pilot projects, including the provision of information and guidance to manage the maneuvers of connected vehicles (assuming that the market penetration of CAV and CDA is low at this stage). This is referred to in the ConOps document of this study as Enhancement Category2. For example, this disseminated information and guidance can be used in speed harmonization, red light violation warning, eco approach, and lane selection ahead of work zones and incidents. This information can be used as a basis for the provision of information to CDA vehicles. Depending on CAV/CDA technology adoption, this phase will also include the use of CAV/CDA vehicle data (Enhancement Level 1b), in addition to CV data in traffic management (Enhancement Level 1a). This phase involves updating policies, standards, test plans, standard operating guidance, and security management System with CDA consideration. This phase also involves beginning the updates to the SunGuide software, V2X Data Exchange Platform, and signal control software, and the implementation of new data engineering, performance measurement, and data analytic techniques to support the decision processes. The FDOT will continue participating in national efforts and start initializing the building of the required partnerships, culture, organization, and training programs. Table 12 lists the potential actions for the Initialization phase for each maturity capability dimension by subdimension.

In the Initialization phase (Phase 2), the use of CV data for traffic management (piloted in Phase 1) becomes a mainstream TSM&O strategy. If data starts to become available from CAV/CDA vehicles according to the standards that are currently being developed by the SAE, the use of this data will be piloted in Phase 2. Pilot projects could potentially include the provision of suggested actions to CV that can also be used for CDA when CDA vehicles are introduced to the traffic stream. Potential examples of such actions are listed below. Additional details can be found in the ConOps document.

- Merge area management: This action recommends changing lanes to mainline traffic ahead of the merge area and/or changing speed for mainline and merging traffic ahead of the merge area, considering the geometry, weather conditions, and vehicle type.
- Incident management: This action provides guidance on route selection, lane selection, and speed ahead of an incident location. The information can also include providing approaching emergency vehicle information and geofencing of an incident scene to reduce vehicle intrusion and provide alerts to responders about safety risks. In addition, it can also include determining and disseminating the optimal routing, site location, and lighting status to emergency vehicles.
- Work zone management: The suggested actions can include worker safety alerts, recommended routing and merge locations, and warning of any unexpected events, including intruding vehicles.
- Speed management: This can include speed harmonization, with recommended speeds on a segment-by-segment level, with consideration of traffic and environmental conditions.
- Lane and shoulder management: This involves the provision of lane changing guidance in advance of the closure, opening, and restrictions of shoulders and lanes, including selecting the lanes that improve the performance, discourage discretionary lane changes, and provide lane change advisory ahead of off-ramps or opened lanes or shoulders.

- Car-following and platoon management: This includes disseminating warnings regarding the gaps left by vehicles under different traffic and environmental conditions.
- Safety applications: These are actions such as those provided to wrong way driving vehicles, vehicles approaching the back of queues, vehicles approaching, rules of practice, and segment level safe speed under different conditions.
- Express lane management: This involves the provision of information to facilitate express lane selection and lane change recommendations ahead of the express lane access points.
- Signal management: This involves providing SPaT and MAP information, intersection blocking warnings, red-light violation warnings, and pedestrian on crosswalk information to vehicles with the aim to impact vehicle trajectory to improve safety and mobility.
- Adaptive signal control: The provided information could include SPaT and MAP information to vehicles, pedestrians, and bicyclists, in conjunction with adaptive signal control.
- Priority and preemption: The provision of information to inform priority vehicle's drivers that their priority requests will be met and the provision of routing information to emergency vehicles and buses to avoid recurrent and non-recurrent congestion. This provision of routing information can be integrated with preemption and priority.
- Integrated corridor management: These enhancements include the provision of information regarding the performance on alternative routes and predicted travel time information provision, mode shift during severe highway or transit incidents, and restricting, rerouting, and delaying commercial vehicles.

Table 12: The Potential Actions for the Initialization Phase for Each Maturity Capability Dimension by Subdimension.

Capability Dimension	Capability Subdimension	Initialization Phase Action
Business Process	Revision of Plans, Guidance, Policies, and Standards	Action 2-A-1: Update highway design policies and standards (e.g., geometric design standards, manual of uniform control devices, etc.). Action 2-A-2: Develop a framework and policies for ensuring privacy, security, legal and regulatory requirements for CDA.
	Planning and Programming of CAV CDA Infrastructure Support	Action 2-B-1: Development of five-year deployment road map and funding plan for the development of infrastructure update plan with consideration of CDA.
System and Technology	Development of the Basis for CDA Infrastructure Support	Action 2-C-1: Start updating SunGuide, V2X Data Exchange, signal control central software, and field equipment for use of CAV and CDA data and provision of guidance.

Capability Dimension	Capability Subdimension	Initialization Phase Action
		Action 2-C-2: Extend the standard operation guidance (SOG) to cover the provision of action suggestions to CV (Enhancement 2). Action 2-C-3: Adoption of CDA infrastructure support test plan.
	Deployment of Supporting Infrastructure and Implementation of Enhancements to Traffic Management	Action 2-D-1: Implementation of pilot Projects for Enhancement 1b (using data from CDA/CAV vehicle in management) and Enhancement 2 (provision of guidance information to CV and CDA vehicles). See potential enhancements presented earlier. Action 2-D-2: Expansion and mainstreaming of the use of CV data in traffic management (Enhancement 1-a). Action 2-D-3: Update the Security Management System, considering the guidance provision and CAV/CDA Consideration.
Data and Performance Management	Data Collection, Sharing, and Management	Action 2-E-1: Extending the plans and specification for the V2X data exchange, archiving, and utilization including SunGuide and V2X Data Exchange with the Consideration of CAV and CDA data.
	Performance Measurements and Utilization	Action 2-F-1: Review and update the performance measures of the processes of the FDOT and partner agencies with CAV and CDA vehicle performance considerations. Action 2-F-2: Identify and refine the performance metrics for pre-deployment and post-deployment assessments of CDA infrastructure support.

Capability Dimension	Capability Subdimension	Initialization Phase Action
		Action 2-F-2: Conduct evaluation of the impacts of the new data utilization and Action Suggestion Provision.
	Data Utilization	Action 2-G-1: Update the measures utilized in off-line and real-time decision support tools.
Culture and Collaboration	Participation in National Effort	Action 2-H-1: Continue the participation in national and peer-exchange efforts.
	Building Partnership	Action 2-I-1: Establish state-wide and regional task groups for CDA support.
	Building Culture	Action 2-J-1: Implement a plan to promote a culture that appreciate the value of CDA and investing in infrastructure support of CDAs.
Workforce Development and Organization	Recruitment, Hiring, Development, and Retention	Action 2-K-1: Implementation and delivery of a program for training to obtain the KSAs required for infrastructure support of CDA building on the current CV and automated vehicle training of the FDOT and national organizations (see further discussion in the Training action plan section). Action 2-K-2: Establish a professional development plan for the TSM&O workforce and the foundation of certificates for the infrastructure support of CDA that are specific to different functions (planning, highway design, operation, and management, etc.). Action 2-K-3: Identifying and implementing strategies for recruitment and hiring for positions including when an agency is ready to hire including: When is the position needed? What knowledge, skills, and abilities are required for the position? Where and

Capability Dimension	Capability Subdimension	Initialization Phase Action
		how should agencies recruit for the position? Action 2-K-4: Apply best practices for TSM&O workforce retention through improvements to training and professional development, human resource benefits, and workplace culture.
	Organizational Structure, Roles & Responsibilities	Action 2-M-1: Start any needed refinement for the FDOT organizational structure, roles, and responsibilities and determine if any updates are needed.

5.4.3 Phase 3: Action Suggestion Integration

This phase will see the FDOT mainstreaming and integration of the Action Suggestions in TSM&O for use by both CV and CDA. However, the provided actions are not prescriptive but suggested actions, as they support SAE J3216 Class 3 Cooperation (Agreement Seeking) rather than Class 4 (Prescriptive). This is Enhancement Category 3-a. The CDA vehicles will have full authority to decide on the final actions. This phase will also involve full utilization of CV and CAV/CDA data in traffic management and include applying the necessary extension of cybersecurity protection; extending the SOG; and updating the SunGuide, V2X Data Exchange Platform, and signal control software. It will also involve extending the standard approach to device testing, procurement, and deployment based on technology advancements and lessons learned. Furthermore, this phase will involve the use of data platforms with full consideration of CDA, implementation of the calculations of the performance measures of the processes of the FDOT and partner agencies with CDA vehicle performance considerations, and working with peer states and research entities to develop approaches for monitoring, data collection, tracking performance, forecasting, and evaluating the impacts of CDA. The FDOT will continue participating in national efforts and start initializing the building of the required partnerships, culture, organization, and training programs. Table 13 lists the potential actions for the Action Suggestion Integration phase for each maturity capability dimension by subdimension.

In the Action Suggestion Integration Phase, traffic management agencies will support the operations of CDA vehicles and other connected vehicles by providing suggested actions integrated with traffic management strategies to improve the performance at the vehicle level, traffic stream level, and network level. Potential examples of such actions are listed below. More details can be found in the ConOps document.

- Merge area management: These actions will involve infrastructure support of dynamic merge control initially coexisting with ramp metering. Actions will be suggested regarding the speeds, gaps, and accepted gaps of the vehicles on the mainline and ramps infrastructure to improve performance, taking into account geometric and weather conditions.

- Incident management: This includes providing information for optimized lane utilizations, vehicle speeds, car-following gaps, and dynamic lane change and merge support ahead of the incidents. In addition, these actions provide optimal routings of emergency vehicles and instruct lane and route clearance to allow emergency vehicle passing.
- Work zone management: These actions provide approaching vehicles with optimized lane utilizations, dynamic speed harmonization that involves vehicle-specific (trajectory-based) speeds, car-following gap recommendations for cooperative adaptive cruise control (CACC) at and ahead of the work zone, and trajectory optimization. They will also include cooperative dynamic merge, cooperative construction vehicle access points, cooperative truck-mounted attenuators such as the automated truck-mounted attenuator (ATMA) and alternating one-way operations on a two-lane roadway.
- Speed management: These actions involve speed harmonization, which includes communicating vehicle-specific (trajectory-based) speed to CDA vehicles. The application can obtain feedback about the utilization of these speeds to achieve optimal operations of the freeway segment.
- Lane and shoulder management: These actions will include implementing a cooperative lane-balancing strategy to balance the traffic across lanes. They can also include supporting cooperative dynamic lane changing with consideration of CACC and platooning.
- Car following and platoon management: These actions include providing vehicle-specific gaps; specifying platoon size; and coordinating platoon formation, dissolution, and rear-join for vehicles external to the platoon. It can also set the intra-platoon and within platoon gaps and speeds.
- Safety applications: These are actions such as those provided to wrong way driving vehicles, vehicles approaching the back of queues, vehicles approaching, rules of practice, and segment level safe speeds under different conditions. Arterial safety applications involve cooperative gap acceptance of permissive left-turn and right-turn on red, cooperative red light violation protection, cooperative gap acceptance at unsignalized intersection operation, cooperative pedestrian conflict resolution, cooperative railroad crossings, and cooperative oversized vehicle restrictions.
- Express lane management: These actions involve providing recommendations about the lane utilization, speed, lane changing, car-following gaps, and platooning parameters in the express lane itself, upstream of the ingress to and downstream of the egress from the express lane, taking into account vehicles with different levels of automation and classes of cooperation.
- Signal management: Signal management in this phase will involve the infrastructure provision of vehicle-specific information to pass through multiple traffic signals, taking into account the CACC and platooning of vehicles. It can also include supporting the gap acceptance of the permissive left turns and right turns on red.
- Adaptive signal control: This involves a multi-objective optimization of the combination of signal control and vehicle trajectories, with the consideration of CACC, platooning, and the Traffic Optimization for Signalized Corridors (TOSCo) efforts.
- Priority and preemption: This includes cooperative clearance of lanes and routes ahead of emergency vehicles and cooperative bus lanes.

- Integrated corridor management: This provides cooperative vehicle rerouting; cooperative restriction, rerouting, and delaying of commercial vehicles; optimizing route guidance in combination with signal control optimization considering CACC and platooning; and cooperative integration of signal control with ramp metering/cooperative dynamic merge.

Table 13: The Potential Actions for the Action Suggestion Integration Phase for Each Maturity Capability Dimension by Subdimension.

Capability Dimension	Capability Subdimension	Action Suggestion Integration Phase Action
Business Process	Revision of Plans, Guidance, Policies, and Standards	Action 3-A-1: Implementation of updates to FDOT highway design policies and standards (e.g., geometric design standards, manual of uniform control devices, etc.). Action 3-A-2: Implement a framework and policies for ensuring privacy, security, legal and regulatory requirements for CDA. Action 3-A-3: Update the FDOT project development process to incorporate CDA consideration.
	Planning and Programming of CAV CDA Infrastructure Support	Action 3-B-1: Implementation of a five-year deployment road map and funding plan for the development of the infrastructure update plan with consideration of CDA.
System and Technology	Development of the Basis for CDA Infrastructure Support	Action 3-C-1: Produce operational versions of SunGuide, V2X Data Exchange, signal control software, and field equipment for the provision of action suggestion to CDA. Action 3-C-2: Extend the standard operation guidance (SOG) to cover the provision of action suggestions to CDA (Enhancement 3).

Capability Dimension	Capability Subdimension	Action Suggestion Integration Phase Action
	Deployment of Supporting Infrastructure and Implementation of Enhancements to Traffic Management	Action 3-D-1: Mainstream the use of CV/CAV/CDA data in traffic management and the provision of suggested actions to connected vehicles. Action 3-D-2: Implement the Security Management System with guidance provision and CDA consideration. Action 3-D-3: Implement a standard approach to device procurement, deployment, and testing with consideration of lessons learned. Action 3-D-4: Expansion and mainstreaming of the use of CAV and CDA data. Action 3-D-5: Initiate projects that involve the provision of Suggested Actions to CDA vehicles.
Data and Performance management	Data Collection, Sharing, and Management	Action 3-E-1: Extend the plans and specification for the V2X data exchange, archiving, and utilization, including SunGuide and V2X Data Exchange, with the consideration of CAV and CDA data.
	Performance Measurements and Utilization	Action 3-F-1: Review and update the performance measures of the processes of the FDOT and partner agencies with CAV and CDA vehicle performance considerations. Action 3-F-2: Conduct post-deployment assessment of CDA infrastructure support. Action 3-F-3: Work with peer states and research entities to develop approaches for monitoring, data collection, tracking performance, forecasting, and evaluating impacts of CDA.

Capability Dimension	Capability Subdimension	Action Suggestion Integration Phase Action
	Data Utilization	Action 3-G-1: Refine and mainstream the use of off-line and real-time decision support tools to assess and manage performance with CDA consideration.
Culture and Collaboration	Participation in National Efforts	Action 3-H-1: Continue the participation in national efforts and peer-exchange effort.
	Building Partnership	Action 3-I-1: Continue the state-wide and regional task groups for CDA infrastructure support.
	Building Culture	Action 3-J-1: Continue the promotion of a culture that appreciates the value of CDA and investing in infrastructure support of CDAs.
Workforce Development & Organization	Recruitment, Hiring, Development, and Retention	Action 3-K-1: Expand and extend the program for training to obtain the required KSAs for CDA. Action 3-K-2: Implement the certification program of the infrastructure support of CDA. Action 3-K-3: Expand the implementation of strategies for retention and recruitment.
	Organizational Structure, Roles, and Responsibilities	Action 3-M-1: Implement any needed refinement for the FDOT organizational structure, roles, and responsibilities, and determine if any updates are needed.

5.4.4 Phase 4: Optimized Cooperation

This phase involves the full collaboration between the infrastructure and the CDA vehicles, along with the infrastructure providing suggested actions, as well as prescriptive actions in some of the applications. The CDA vehicles still have full authority to decide actions, except for the specific circumstances in which it is designed to accept and adhere to a prescriptive communication. This phase will build on the actions conducted in the previous phases to advance the capabilities in the institutional and technical sub dimensions. The actions will consider additional opportunities for optimizing the performance of the transportation system for specific actions of the vehicles based on the latest findings from testing these applications at the national level with consideration of all the issues and constraints and solutions to address these issues and constraints. Table 14 lists the potential actions for the Action suggestion for the optimized cooperation phase for each maturity capability dimension by subdimension.

Table 14. The Potential Actions for the Optimized Cooperation Phase for Each Maturity Capability Dimension by Subdimension.

Capability Dimension	Capability Subdimension	Optimized Cooperation Phase Action
Business Process	Revision of Plans, Guidance, Policies, and Standards	Action 4-A-1: Continue updating FDOT highway design policies and standards based on lessons learned from full cooperation. Action 4-A-2: Update the framework and policies for ensuring privacy, security, legal and regulatory requirements for CDA considering the full cooperation.
	Planning and Programming of CAV CDA Infrastructure Support	Action 4-B-1: Update the five-year deployment road map and funding plan for the development of the infrastructure update plan with consideration of full cooperation.
System and Technology	Development of the Basis for CDA Infrastructure Support	Action 4-C-1: Produce operational versions of SunGuide, V2X Data Exchange, signal control software, and field equipment with consideration of full cooperation. Action 4-C-2: Extend the standard operation guidance (SOG) with consideration of full cooperation.

Capability Dimension	Capability Subdimension	Optimized Cooperation Phase Action
	Deployment of Supporting Infrastructure and Implementation of Enhancements to Traffic Management	Action 4-D-1: Mainstream the vehicle-infrastructure cooperation. Action 4-D-2: Implement the Security Management System with consideration of full cooperation. Action 4-D-3: Implement a standard approach to device procurement, deployment, and testing with consideration of full cooperation. Action 4-D-4: Initiate projects that involve the provision of full cooperation.
Data and Performance management	Data Collection, Sharing, and Management	Action 4-E-1: Extend the plans and specification for the V2X data exchange, archiving, and utilization, including SunGuide and V2X Data Exchange, with the consideration of full cooperation.
	Performance Measurements and Utilization	Action 4-F-1: Review and update the performance measures of the processes of the FDOT and partner agencies with consideration of full cooperation. Action 4-F-2: Continue conducting post-deployment assessment of CDA infrastructure support. Action 4-F-3: Continue working with peer states and research entities to develop approaches for monitoring, data collection, tracking performance, forecasting, and evaluating impacts of CDA.
	Data Utilization	Action 4-G-1: Continue refining and mainstreaming the use of off-line and real-time decision support tools to assess and manage performance with CDA consideration.

Capability Dimension	Capability Subdimension	Optimized Cooperation Phase Action
Culture and Collaboration	Participation in National Efforts	Action 4-H-1: Continue the participation in national and peer-exchange efforts.
	Building Partnership	Action 4-I-1: Continue the state-wide and regional task groups for CDA infrastructure support.
	Building Culture	Action 4-J-1: Continue the promotion of a culture that appreciates the value of CDA and investing in infrastructure support of CDAs.
Workforce Development and Organization	Recruitment, Hiring, Development, and Retention	Action 4-K-1: Continue and update the program for training to obtain the required KSAs for CDA. Action 4-K-2: Continue the certification program of the infrastructure support of CDA. Action 4-K-3: Expand the implementation of strategies for retention and recruitment.
	Organizational Structure, Roles, and Responsibilities	Action 4-M-1: Implement any additional refinement needed for the FDOT organizational structure, roles, and responsibilities, and determine if any updates are needed.

5.5 Training Plan

This section identifies a set of modules to satisfy the training needs for the FDOT in cooperative driving automation based on the resources needed to implement the action plan suggested in the previous section. The program is expected to build on the existing and planned FDOT training activities, such as those of the TSM&O program, demand forecasting programs, and simulation programs. The FDOT TSM&O program has training modules, with some of these modules available only to FDOT staff, and others available to the public. The publicly available modules are classified as TSM&O Computer Based Trainings, Intelligent Transportation Systems (ITS) Construction, Engineering, and Inspection (CEI) Computer-Based Trainings, and Statewide Arterial Management Computer Based Trainings.

The training program should also consider and use and/or learn from the training programs and modules available from national resources. National organizations that have provided training modules related to TSM&O and transportation technologies include the American Association of State Highway and Transportation Officials (AASHTO), Consortium for Innovative Transportation Education (CITE), USDOT, FHWA, Professional Capacity Building (PCB) Partnership, Connected Vehicle Trade Association/Mobile Comply/Society of Automotive Engineers (SAE), Institute of Transportation Engineers, National Highway Institute (NHI), and Transportation Tech.

Two important projects that address TSM&O and transportation technology workforce development (including training, recruitment, and retention) are listed below and can be used as important resources in establishing the training efforts of TSM&O and emerging transportation system technology.

- National Cooperative Highway Research Program (NCHRP) Project 20-102(20) "Preparing the Transportation Workforce for the Deployment of Emerging Technology": This is ongoing research to develop a guide for transportation agency recruitment, hiring, development, and retention of a workforce proficient in developing and deploying complex transportation technologies and systems. It will address short-term and long-term strategies for workforce development, including consideration of how and when to outsource, in addition to or in place of building capacity internally.

- NCHRP Project No. 20-07/Task 408 "Transportation Systems Management and Operations (TSM&O) Workforce Guidebook" (Szymkowski et al., 2019). This guidebook focuses on the hiring and workforce development, including specific job position requirements, the knowledge, skills, and abilities required for those job positions, and recommendations for hiring each position. The final report of the project presents information on training and professional development is presented, including specifics on training providers and courses, in addition to recommendations to maximize workforce retention.

The deliverables of the above two projects can be used as companions to the Training Plan recommended in this document when establishing the training program and the plan for advancing the workforce development efforts with consideration of CAV and CDA.

The training program for the development of a workforce to support the action plan presented in the previous section is recommended to be conducted in three phases.

- Phase 1: This phase will involve activities that confirm the core knowledge, skills, and abilities (KSAs) needed for CDA, assess the national training and workforce development efforts for possible adoption, approve a program for training, and deliver or adopt from other organizations' initial modules that cover CV and AV topics that can be extended in the future for CDA training.

- Phase 2: This phase will involve the implementation and delivery of a program for training to obtain the KSAs required for infrastructure support of CDA building on the training provided by the FDOT and other organizations mentioned above. This phase will also establish the foundation for (or use based on national efforts) certificates for the infrastructure support of CDA that are specific to different functions (planning, modeling, highway design, operation and management, etc.).
- Phase 3: This phase sees the expansion and extension of the training program based on the lessons learned from the deployment and the implementation of a certification program of the infrastructure support of CDA.

Table 15 includes the recommended training modules mapped to the required KSAs to accomplish the actions associated with each capability subdimensions in the action plan presented in the previous section. The following is a list of these modules.

- Module 1: Highway Design Standards and Policies with Consideration of AV and CDA
- Module 2: Long Range Planning with Consideration of AV and CDA
- Module 3: CDA Cybersecurity, Privacy, and Liability Considerations for Decision Makers
- Module 4: Connected, Automated, and Cooperative Vehicles for Decision Makers
- Module 5: Pre-Deployment Alternative Analysis with Consideration of AV and CDA
- Module 6: Update of the FDOT Systems Engineering Course to Incorporate CDA
- Module 7: CDA Message Standards
- Module 8: Testing of Infrastructure-Support of CDA
- Module 9: Real-Time Operation and Management of Freeway Operations Considering Vehicles with Different Levels of Connectivity, Automation, and Cooperation
- Module 10: Real-time Management of Arterial Operations Considering Vehicles with Different Levels of Connectivity, Automation, and Cooperation
- Module 11: Central and field hardware and software to support CDA
- Module 12: Security Management System
- Module 13: Basics of Data Science and Engineering for TSM&O Staff
- Module 14: Utilization of CV, AV, and CDA Data for System Level and Vehicle Level Performance Estimation
- Module 15: Demand Forecasting with CV, AV, and CDA Consideration
- Module 16: Simulation Modeling with CV, AV, and CDA Consideration
- Module 17: Post-Deployment Evaluation of CDA Projects
- Module 18: Machine Learning, Artificial Intelligence, and Decision Support Systems for TSM&O Staff
- Module 19: Recent Findings from National and International CDA Practices and Research
- Module 20: Building Partnerships for CDA
- Module 21: Organizational structure, roles, and responsibilities related to CDA

Table 15. The Recommended Training Modules Mapped to the Required KSAs to Accomplish the Actions Associated with Each Capability Subdimension.

Capability Dimension	Capability Subdimension	Function Supported by the Required KSA	Training Module
Business Process	Revision of Plans, Guidance, and Standards	Understanding TSM&O Strategic Plan, and CV Business Plan. FDOT Highway design policies and standards (e.g., geometric design standards, manual of uniform control devices, etc.) and project development process for AV and CDA consideration. Cybersecurity, privacy, and liability risks associated with guidance provision to CV and CDA vehicles. Incorporating CDA/CAV in the long-range plans.	Module 1: Highway Design Standards and Policies with Consideration of AV and CDA Module 2: Long Range Planning with Consideration of AV and CDA. Module 3: CDA Cybersecurity, Privacy, and Liability Considerations for Decision Makers.
	Planning and Programming of CDA	Understanding TSM&O Strategic Plan and CV Business Plan	Module 4: Connected, Automated, and

Capability Dimension	Capability Subdimension	Function Supported by the Required KSA	Training Module
	Infrastructure Support	Identification and communicating the business case, constraints, and funding needs. Methods for selection between alternative investment options considering CDA. Development of Five-Year Deployment Road Map and Funding Plan including Development of Infrastructure Update Plan.	Cooperative Vehicles for Decision Makers. Module 5: Pre-Deployment Alternative Analysis with Consideration of AV and CDA.
System and Technology	Development of Basis for CDA Infrastructure Support	Adoption of concept of operations and requirements and other system engineering documents. Developing and implementing Standard Operating Guidance (SOG) with Consideration of CV, AV and CDA. Adoption and implementation of the CDA Infrastructure Support Test Plan.	Module 6: Update of the FDOT Systems Engineering Course to Incorporate CDA. Module 7: CDA Message Standards. Module 8: Testing of Infrastructure-Support of CDA. Module 9: Real-Time Operation and Management of Freeway Operations with Vehicles with Different Levels of Connectivity, Automation, and Cooperation. Module 10: Real-time Management

Capability Dimension	Capability Subdimension	Function Supported by the Required KSA	Training Module
			of Arterial Operations with Vehicles with Different Levels of Connectivity, Automation, and Cooperation.
	Deployment of Supporting Infrastructure and Implementation of Enhancements to Traffic Management	Extending/updating SunGuide, V2X Data Hub, and signal control software. Software for Use of CV Data pilot projects. Implementation of TSM&O projects with CDA Consideration. Updating the Security Management System with CDA Consideration.	Module 9: Real-Time Operation and Management of Freeway Operations with Vehicles with Different Levels of Connectivity, Automation, and Cooperation. Module 10: Real-time Management of Arterial Operations with Vehicles with Different Levels of Connectivity, Automation, and Cooperation. Module 11: Central and field hardware and software to support CDA. Module 12: Security Management System.
Data and Performance management	Data Collection, sharing, and management	Data exchange, archiving, and utilization related to CV, Autonomous vehicles, and CAV.	Module 13: Basics of Data Science and Engineering for TSM&O Staff.

Capability Dimension	Capability Subdimension	Function Supported by the Required KSA	Training Module
	Performance Measurements and Utilization	Utilizing performance measures to support FDOT considering measures based on the availability of CV, CAV, and CDA Utilizing updated demand forecasting models to incorporate CDA. Utilizing multi-resolution modeling with CDA consideration. Pre-deployment and post-deployment assessment of CDA.	Module 14: Utilization of CV, AV, and CDA Data for System Level and Vehicle Level Performance Estimation. Module 15: Demand Forecasting with CV, AV, and CDA Consideration. Module 16: Simulation Modeling with CV, AV, and CDA Consideration. Module 17: Post-Deployment Evaluation of CDA Projects.
	Data Utilization	Utilize CV data for off-line monitoring of traffic operations. Utilize CV data for real-time monitoring of traffic operations.	Module 18: Machine Learning, Artificial Intelligence, and Decision Support Systems for TSM&O Staff.
Culture and Collaboration	Participation in National Effort	Understand recent findings from national efforts.	Module 19: Recent Findings from National and International CDA Practices and Research.
	Building Partnership	Building regional, state, and national partnerships.	Module 20: Building Partnerships for CDA.

Capability Dimension	Capability Subdimension	Function Supported by the Required KSA	Training Module
	Building Culture	Develop a plan to promote a culture that appreciates the value of CDA and investing in infrastructure support of CDAs.	Module 4: Connected, Automated, and Cooperative Vehicles for Decision Makers.
Workforce Development and Organization	Recruitment, Hiring, Development, and Retention	Develop modules that support the decisions, planning, design, operation, and management associated with CDA.	All modules
	Organizational Structure, Roles, and Responsibilities	Understanding the organizational structure, roles, and responsibilities related to CDA.	Module 21: Organizational structure, roles, and responsibilities related to CDA.

5.6 Alternative Analysis Plan

With the increasing interest in CV and AV and more recently, CAV and CDA, there is a need to identify methods for the pre-deployment alternative analysis of infrastructure support of these technologies and associated strategies and applications, compared to the more traditional highway and intelligent transportation systems (ITS) improvements. Such methodologies can be used to support the decisions of transportation agencies to invest in the infrastructure, with consideration of advanced vehicle technologies. This section presents three methods that could be used as standalone methods or in various combinations for this purpose. The first method (Risk and Reward method) is a simplified method utilized in the USDOT ITS Artificial Intelligent (AI) Plan (Vasudevan et al., 2020), which compares the risks and rewards of investing in AI applications in transportation systems, with the purpose of prioritizing the applications for potential investments. This method can be used at a high level to prioritize the actions presented in the action plan and the potential application used in pilot projects, as presented in the previous section. The remaining two methods were previously described and utilized in a FDOT research titled “Connected Vehicle Vehicle-to-Infrastructure Support of Active Traffic Management” (Hadi, Iqbal, et al., 2019). These two methods are the stochastic return on investment (ROI) analysis and a multi-criteria decision-analysis (MCDA) procedure utilizing the Analytical Hierarchy Process method. There are advantages of these methods, and they can be used in different combinations. These two methods can be used for more detailed analysis of a subset of potential pilot projects identified based on initial screening using the Risk and Reward method.

5.6.1 Risk and Reward Method

This methodology was utilized in the development of the USDOT ITS AI Plan (Vasudevan et al., 2020) and was based on estimates of the alternative risks and rewards obtained in stakeholder workshop sessions. The stakeholders rated the investment risk and potential reward of each AI application. Based on the results, the stakeholders were asked the following day to select their top six high priority applications. Reward-Risk Scores were obtained for 49 potential applications of AI in transportation, representing the ratio between reward and risk. In addition, "Prioritization Scores" were also calculated based on the prioritization ratings from stakeholders. The higher the number, the better for both the Reward-Risk Score and Prioritization Score, as shown in Figure 34 and Figure 35.

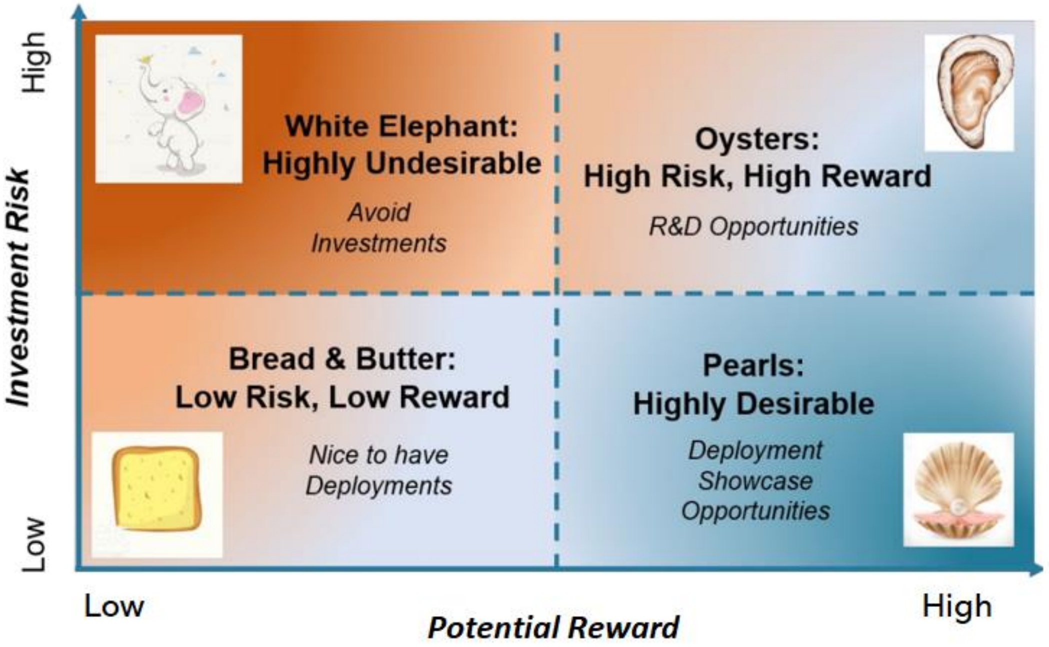


Figure 35: Concept of reward-investment risk chart as presented in the USDOT ITS AI Plan (USDOT 2020).

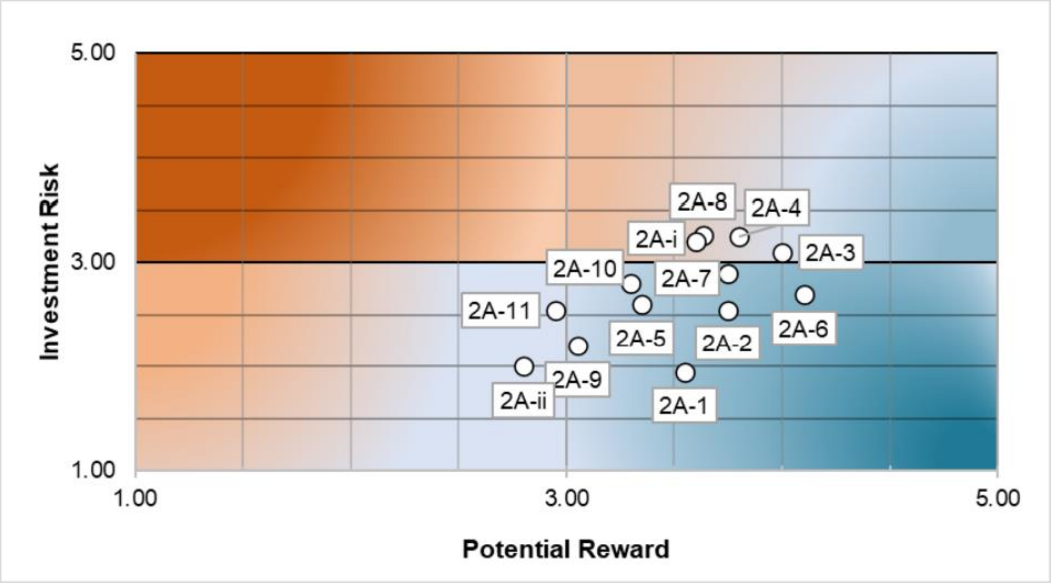


Figure 36: Example reward-investment risk chart as presented in the USDOT ITS AI Plan (USDOT 2020).

5.6.2 Stochastics Return-on-Investment Method

The stochastic ROI analysis, as presented in a previous study by (Hadi et al. 2019), is applied using the Monte Carlo simulation to consider the uncertainties of the inputs required in the estimation of the benefits and costs of emerging technology applications. Traditionally, the ROI analysis is conducted by calculating deterministic point estimates of the net present value (NPV) or benefit-cost ratio (BCR) of the project's alternatives. This involves deterministic estimates of the present values of the current and future benefits and costs over the project's economic life. A deterministic discount rate is used to calculate the present values of the cash flows. This conventional method is not able to capture the uncertainty and risks associated with emerging technology projects. There is a significant amount of uncertainty associated with the input parameters to the analyses, including the future CV market penetration, the initial and recurrent costs, the impacts and benefits of the deployments, and the dollar valuations of the benefits.

The stochastic ROI is based on risk analysis to account for uncertainty in ROI by expressing the input parameters as probability distributions rather than deterministic values. As a result, the output BCR also follows a probability distribution. To do this type of analysis, the input parameter distributions must be defined. Commonly used distributions for this purpose are the uniform, normal, and lognormal distributions. A uniform distribution is a probability distribution with equally likely outcomes. A normal distribution follows a symmetrical bell-shaped curve and is simply described using arithmetic mean and standard deviation. However, it is important to consider the skewness of the distribution when analyzing the benefits, and this consideration can be provided by the lognormal distribution. Lognormal distribution becomes especially useful when analyzing the effects of technology when such effects are multiplicative rather than additive. For example, parameters utilized in this model such as market penetration and interest rates are all functions of compounded rates for which the assumption of a normal distribution or uniform distribution would not be appropriate. The lognormal distribution can be used for estimating benefits while considering uncertainty. The parameters of the lognormal distributions can be estimated based on the highest and lowest values of the benefits and market penetration reported in the literature. The costs of deployments can be estimated based on a normal or uniform distribution considering the highest and lowest limits reported in the literature.

The lognormal distribution is described using the median (μ^*) and the multiplicative standard deviation (σ^*) for a given set of data. As described by Limber et al. (*15*), the lower and upper limits of an interval at a given confidence level ($1 - \alpha$) can be expressed as follows:

$$LL_{\alpha/2} = \frac{\mu^*}{(\sigma^*)^{Z_{\alpha/2}}}, \qquad (1)$$

$$UL_{\alpha/2} = \mu^* \times (\sigma^*)^{Z_{\alpha/2}}, \qquad (2)$$

$$\mu = \ln(\mu^*), \qquad (3)$$

$$\sigma = \ln(\sigma^*), \qquad (4)$$

where, μ and $\mu^*$are the mean and median of lognormal distribution, σ and σ^* are the standard deviation and multiplicative standard deviation of the lognormal distribution, $LL_{\alpha/2}$ and $UL_{\alpha/2}$ are the lower and upper limits of the variable at given confidence level α, and $Z_{\alpha/2}$ is the Z-value for the upper and lower limits at given confidence level ($1 - \alpha$).

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

$$m = e^{\mu + \frac{1}{2}\sigma^2}, \qquad (5)$$

$$SD = e^{\mu + \frac{1}{2}\sigma^2} \sqrt{e^{\sigma^2} - 1}, \qquad (6)$$

To calculate the BCR, the upper and lower limits for the benefits and costs need to be calculated first, as discussed in the following subsections.

5.6.3 Multicriteria Decision Analysis (MCDA) Method

The issue of uncertainty in traditional return-on-investment analyses is meant to be addressed by stochastic ROI analysis. However, ROI analyses do not account for changes in key performance indicators (KPIs) that cannot be converted to dollar values. The methods also do not account for the weights that the project stakeholders put on different KPIs, according to their priorities. The multi-criteria decision-analysis (MCDA) methods address these two deficiencies in the ROI. The MCDA methods include but are not limited to Analytic Hierarchy Process (AHP) (Saaty, 1980); best-worst multi-criteria decision-making method (BWM) (Rezaei, 2015); Evaluation Based on Distance from Average Solution (EDAS) (Ghorabaee et al., 2015); Technique for Order of

Preference by Similarity to Ideal Solution (TOPSIS) (Hwang & Yoon, 1981); Stochastic Multi-Criteria Acceptability Analysis (SMAA) (Lahdelma & Salminen, 2001); Potentially All Pairwise Rankings of All Possible Alternatives (PAPRIKA) (Weistroffer & Li, 2016). Macharis (Macharis & Bernardini, 2015) reported that AHP developed by (Saaty 1980) has been used in almost 33% of the literature that applied MCDA in transportation engineering. This method was proposed for utilization in a previous FDOT study (Hadi et al. 2019).

The AHP evaluates the project alternatives against each other and provides the best potential solution to achieve the objectives as assessed by performance measures associated with these criteria. The process requires the input of stakeholders to develop a pairwise comparison between the priorities of different criteria. A typical hierarchical structure consists of the main goal that lies at the top of the hierarchy, criteria and subcriteria in the middle hierarchy levels, and the decision alternatives at the final level (Saaty 1980).

The AHP includes three parts: the hierarchic breakdown structure, prioritization procedure, and ranking alternatives. A typical three-level hierarchical structure (as described earlier) will be used in this study. The prioritization procedure involved assigning weights for each evaluation criterion based on the importance of that criterion in achieving the overall goal. A pairwise comparison matrix was created to compare the importance of criteria relative to each other, and a normalized matrix is derived based on Equation 7. A criteria weight vector is calculated from the averaging of each row in the normalized matrix, based on Equation 8. The prioritization procedure then involves assigning scores to each alternative based on its performance relative to the considered criterion. Finally, a global score is assigned to each alternative allowing the ranking based on the scores.

$$\bar{a}_{ij} = \frac{a_{ij}}{\Sigma_j^m = a_{ij}} \tag{7}$$

$$w_j = \frac{\Sigma_{j=1}^m \bar{a}_{ij}}{m} \tag{8}$$

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

The comparing of alternatives requires subjective judgment from transportation professionals due to the uncertainty of variables and the presence of qualitative measures which is crucial to determine the consistency of the opinions of the decision makers. Saaty (Saaty 1980) proposed a measure called consistency index (CI), as shown in Equation 9, to show the degree of AHP consistency by comparing CI to a predefined index called random consistency index (RI).

$$\mathrm{CI} = \frac{\lambda\mathrm{max} - n}{n-1} \tag{9}$$

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

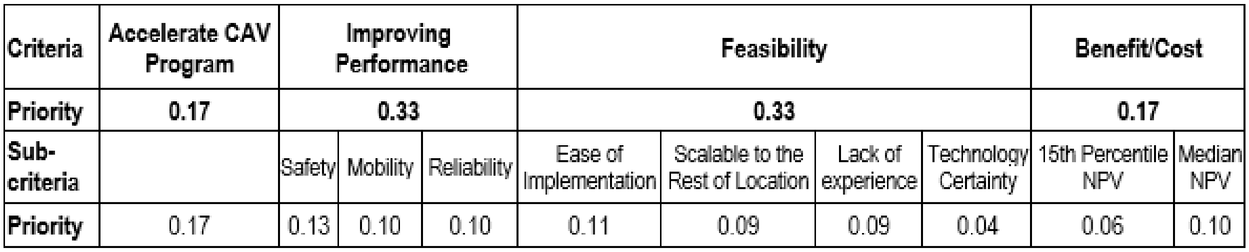
The AHP in the previous FDOT project (Hadi et al. 2019) utilized a four-level decision-making hierarchy. The first level of the decision hierarchy is the main goal of selecting between CV-based solutions and non-CV-based solutions. The second level of the hierarchy includes the high-level objectives that are mapped to the goal. The objectives used were based on those identified in the 2019 Florida's CAV Business Plan program. These objectives were used in the assessment of this project, but other objectives and criteria can be used based on agency priorities and preferences. The next level of the hierarchy includes the sub-criteria required for detailed assessments associated with the objectives at the higher level. The selected criteria can include any outcome performance measures, output measures, economic measures, feasibility, and risks and constraints. The last level in the hierarchy is the available alternatives for performing the upper-level tasks that could include, for example, CV/CAV/CDA-based projects, other ITS/TSM&O projects, highway capacity improvement projects, and so on. The stochastic BCR analysis described in the previous section can be included as one of the selection sub-criteria in the AHP analysis.

Table 16 includes objectives and criteria selected in the previous FDOT Research project (Hadi et al. 2019) based on the criteria presented in the CAV Business Plan of the FDOT. The selected objectives are acceleration of the CAV program, improving performance, solution feasibility, and benefit/cost ratios.

Table 16. Goal, Objectives, and Criteria Based on the Previous FDOT Research Project (Hadi et al. 2019).

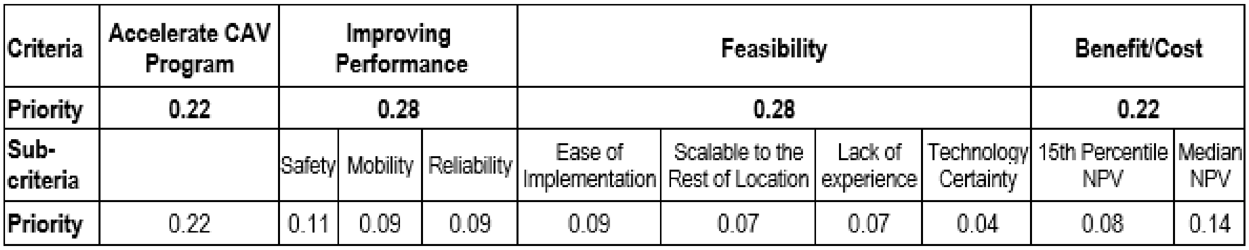
Goal	Objectives	Sub-Criteria
Selecting between CV-based and existing conventional solutions for improving safety on urban arterials	1- Accelerate CAV program	
	2- Improve performance	2.1- Safety 2.2- Mobility 2.3- Reliability
	3- Feasibility	3.1- Ease of Implementation 3.2- Scalable to the Rest of Sate/Region 3.3 - Lack of Experience 3.4 - Technology Certainty
	4- Return-on- Investment	4.1- 15th Percentile Benefit-Cost (B/C) Ratio 4.2- Median B/C Ratio

In the previous FDOT research project mentioned above (Hadi et al. 2019), two decision-makers from the FDOT District 6 in Miami were asked to assign a weight for each criterion relative to each other. The criteria were further decomposed into sub-criteria, and an assigned weight was given for each sub-criteria. The assigned weights for the different criteria and sub-criteria by the two decision makers are shown in Figures 37 and 38.



Criteria	Accelerate CAV Program	Improving Performance			Feasibility				Benefit/Cost	
Priority	0.17	0.33			0.33				0.17	
Sub-criteria		Safety	Mobility	Reliability	Ease of Implementation	Scalable to the Rest of Location	Lack of experience	Technology Certainty	15th Percentile NPV	Median NPV
Priority	0.17	0.13	0.10	0.10	0.11	0.09	0.09	0.04	0.06	0.10

Figure 37. Weights calculated using the AHP process based on the interview of decision maker 1 in the previous FDOT research project (Hadi et al. 2019).



Criteria	Accelerate CAV Program	Improving Performance			Feasibility				Benefit/Cost	
Priority	0.22	0.28			0.28				0.22	
Sub-criteria		Safety	Mobility	Reliability	Ease of Implementation	Scalable to the Rest of Location	Lack of experience	Technology Certainty	15th Percentile NPV	Median NPV
Priority	0.22	0.11	0.09	0.09	0.09	0.07	0.07	0.04	0.08	0.14

Figure 38. Weights calculated using the AHP process based on the interview of decision maker 2 in the previous FDOT research project (Hadi et al. 2019).

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