Cooperative Automation Research: CARMA Proof-of-Concept TSMO Use Case Testing: Traffic Incident Management Concept of Operations

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FOREWORD

The Federal Highway Administration's (FHWA) Cooperative Driving Automation (CDA) Program, formerly known as the CARMA Program, is an initiative to enable collaboration for research and development of CDA technologies. The CDA Program develops and maintains an ecosystem of open-source software tools, which together are known as the CARMA Ecosystem, to enable CDA research. The CARMA Ecosystem uses communication between vehicles and roadside infrastructure devices to support coordinated movement to improve safety, traffic throughput, and energy efficiency of the transportation network.

In 2015, the FHWA's Office of Operations Research and Development developed a cooperative adaptive cruise control proof-of-concept prototype that was installed in five research vehicles. From there, the CARMA Ecosystem further evolved through testing and integration. At the time of this writing, the CDA Program is advancing into automated driving systems (ADS) that leverage infrastructure to support cooperative automation strategies. This project expands CARMA functionality to include transportation systems management and operations (TSMO) strategies on surface arterials with intersections.

This concept of operations is the seventh in a series of nine focused on TSMO use cases (UC) and capabilities. It focuses on traffic incident management UCs where traffic and incident response vehicles are actively managed by CARMA tools through advanced signal operations. The intended audience for this report is CDA stakeholders such as system developers, analysts, researchers, application developers, and infrastructure owners and operators.

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Research and Development

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16. Abstract
Cooperative driving automation (CDA) aims to improve the safety, traffic throughput, and energy efficiency of the transportation network by allowing vehicles and infrastructure to work together to coordinate movement. The CARMA Ecosystem is utilized to research CDA and leverage emerging capabilities in automation and cooperation to advance transportation systems management and operations (TSMO) strategies. The objective of this project is to develop the CARMA Ecosystem to enhance infrastructure performance, improve network efficiency, strategically reduce arterial traffic congestion, and enable CDA participants with further capabilities to interact with road infrastructure. The concept of operations (ConOps) discussed in this report focuses on TSMO traffic incident management (TIM) use cases where traffic and incident response vehicles are actively managed by CARMA tools through signal optimization and signal coordination. The strategies in this ConOps are expected to help reduce travel time delay caused by traffic signals, improve safety, and reduce incident response travel time for incident response vehicles. The proposed approach for the use cases has two components. First, local traffic signal optimization using CARMA Streets to improve safety and reduce delay for one or more incident response vehicle. Second, corridor-coordinated TSMO TIM using CARMA Cloud to optimize signal timing in a corridor.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

ACC	standard adaptive cruise control
ADS	automated driving system
BAT	basic arterial travel
BSM	basic safety message
CACC	cooperative adaptive cruise control
C-ADS	cooperative automated driving system
CDA	cooperative driving automation
ConOps	concept of operations
C-V2X	cellular vehicle-to-everything
DSRC	dedicated short-range communication
ETA	estimated time of arrival
EVA	emergency vehicle alert
EVRT	emergency vehicle response time
EVSP	emergency vehicle signal preemption
FHWA	Federal Highway Administration
GPS	Global Positioning System
HRDO	Office of Operations Research and Development
Hz	hertz
I2V	infrastructure-to-vehicle
ID	identifier
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IOO	infrastructure owner and operator
ISO	International Organization for Standardization
MMITSS	Multimodal Intelligent Traffic Signal System
MRP	MMITSS roadside processor
MUTCD	*Manual on Uniform Traffic Control Devices*
NHTSA	National Highway Traffic Safety Administration
NTCIP	Transportation Communications for Intelligent Transportation System Protocol
OBU	onboard unit
PREEMPT	traffic signal preemption in use cases
RSE	roadside equipment
RSU	roadside unit
SPaT	Signal Phase and Timing
SRM	signal request message
SSM	signal status message
STOL	Saxton Transportation Operations Laboratory
TFHRC	Turner-Fairbank Highway Research Center
TIM	traffic incident management
TSMO	transportation systems management and operations
UC	use case
USDOT	U.S. Department of Transportation
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle

V2X	vehicle-to-everything
VSP	vehicle-side processor
WSN	wireless sensor network

CHAPTER 1. INTRODUCTION

IDENTIFICATION

This document is a concept of operations (ConOps) for a transportation systems management and operations (TSMO) use case (UC) on arterials. This ConOps focuses on traffic incident management (TIM).

DOCUMENT OVERVIEW

Background

The Office of Safety and Operations Research and Development (HRSO) performs transportation operations research and development for the Federal Highway Administration (FHWA). On-site research and development are conducted at the Saxton Transportation Operations Laboratory (STOL) established at Turner-Fairbank Highway Research Center (TFHRC). HRDO conducts operations research and development based on the transportation needs of the United States.

In 2015, FHWA designed, built, and installed a cooperative adaptive cruise control (CACC) proof-of-concept prototype system in a fleet of five vehicles. The CACC system was built on the CARMA Platform, as an advancement of standard adaptive cruise control (ACC) systems. It utilized vehicle-to-vehicle (V2V) dedicated short-range communications (DSRC) to automatically synchronize the longitudinal movements of many vehicles within a string. This proof-of-concept system was the first in the United States to demonstrate the capabilities of this technology with a five-vehicle CACC string.

A subsequent task order sought to develop a new reference platform, CARMA2, using the Robot Operating System to enable easy sharing and integration of research outcomes into industry research vehicles.(1) The project advanced CACC functionality and led to the development of a proof-of-concept platooning application that enabled leader-follower behavior and allowed vehicles to begin to negotiate with one another. Additionally, the project led to the development of the Integrated Highway Prototype 1, which integrated speed harmonization, lane changing and merging, and platooning into one trip.

Following CARMA2, a current task order is producing the third iteration of the CARMA Ecosystem, CARMA3, which enters into the world of automated driving systems (ADSs) with SAE International (SAE) Level 3 and above automation.(2) The approach takes advantage of an open-source ADS platform, Autoware®, to enable the use of ADS functionality for cooperative automation strategies.

In addition to CARMA Platform, CARMA Messenger, CARMA Streets, and CARMA Cloud are also being developed. CARMA Messenger represents the capability of moving but not automated entities (e.g., first-responder vehicles, pedestrians, and buses) to communicate with CARMA-equipped vehicles and infrastructure to improve the performance of the network. CARMA Streets represents the infrastructure piece of cooperative driving automation (CDA) at conflict areas (e.g., intersections). It provides an interface to roadside units (RSUs), supports two-way communication between vehicles and infrastructure, and enables CDA by using edge computing to optimize travel through conflict areas. CARMA Cloud further supports regional TSMO through the cloud-based management of transportation systems, data exchange, and multiple simultaneous remote services. All CARMA software products (i.e., CARMA Platform, CARMA Cloud, CARMA Messenger, and CARMA Streets) are open source and are built with the goal of benefitting CDA research. Table 1 lists the various projects associated with this development.

Table 1. Projects associated with this development effort.

Task Order	Product	Title
STOL I T-13005	CARMA	Development of a Platform Technology for Automated Vehicle Research
STOL II 0013	CARMA2	Development of Connected and Automated Vehicle Capabilities: Integrated Prototype I
STOL II 693JJ318F000225	CARMA3	Development of Cooperative Automation Capabilities: Integrated Prototype II
STOL II 693JJ319F000369	CARMA IHP2	Cooperative Automation Research: CARMA Integrated Highway Prototype II

Objective

This ConOps extends the research from Prototype II by utilizing CARMA Streets, CARMA Platform, and CARMA Cloud to enable further capabilities of CDA participants to interact with road infrastructure, including traffic signal controllers. All TSMO TIM UCs in this ConOps consider CDA operations on at-grade intersections. This ConOps discusses TSMO TIM Basic Arterial Travel (BAT) UCs that focus on active traffic management by incorporating signal optimization, signal coordination, and incident response vehicle management. This project addresses two high-level objectives: improving safety and improving incident response vehicle travel time. This project investigates to what extent these objectives can be achieved for the different CDA cooperation classes defined by the SAE standard *Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles* J3216_202107.(3)

Audience

The intended audience for this ConOps is as follows:

- U.S. Department of Transportation (USDOT) and cooperative automation program stakeholders, including the Federal Transit Administration and Federal Emergency Management Agency.
- Academia stakeholders, including faculty, researchers, and students.
- Private sector stakeholders, including consultant companies and original equipment manufacturers.

- System developers, including those who create and support CDA algorithms based on the system concepts described in this document.

- Analysts, researchers, and CDA application developers.

Document Structure

The structure of this document is generally consistent with the System Operational Concept described in Annex A of *2011 International Standard—Systems and Software Engineering—Life Cycle Processes—Requirements Engineering* ISO [International Organization for Standardization]/IEC [International Electrotechnical Commission]/IEEE [Institute of Electrical and Electronics Engineers] 29148: 2011.(4) A document conforming to this structure is called a ConOps in U.S. transportation systems engineering practice, and that title is retained for this document. Some sections of this ConOps have been enhanced to accommodate more detailed content than is described in the ISO/IEC/IEEE 29148: 2011. Titles of some sections may have been edited to capture details more specifically.

Chapter 1 defines the scope of the ConOps.

Chapter 2 describes the current situation and identifies needs for changes with respect to processes and systems to be affected by the ConOps.

Chapter 3 describes the concept for the new TSMO TIM BAT system capabilities and their operations and presents detailed descriptions of operational concepts.

Chapter 4 describes operational scenarios of TSMO TIM BAT at signalized intersections.

Chapter 5 provides an analysis of expected improvements, operational and research impacts, validation plans, disadvantages, and limitations.

The reference section provides a list of reference documents.

CHAPTER 2. CURRENT SITUATION AND OPPORTUNITIES FOR CHANGES

This chapter discusses existing approaches to TIM on signalized arterials using traffic signal preemption. TIM is an exception to normal traffic operations. Incident response vehicles are traveling to an incident location to save lives—travel time is key, but safety is the highest priority. This chapter will highlight the advantages and disadvantages of existing solutions that motivate the development of new CDA solutions to address efficiency and safety of incident response vehicles at signalized intersections.

BACKGROUND AND CURRENT SITUATION

Various roadway facilities intersect through the roadway network to give commuters access, causing conflicts among vehicles from various movement traffic streams. Inappropriate operations at conflict areas (e.g., signalized or unsignalized intersections and merging roadways) result in unstable traffic flow (i.e., stop-and-go traffic), which may exacerbate travel delay, energy consumption and emissions, driving discomfort, and safety risks. Operations of conflict movements at a common conflict area may change in the advent of CDA technology. Cooperative automated driving system- (C-ADS-) equipped vehicles have communication and automation technologies that enable vehicles to coordinate with each other and with infrastructure to improve safety and maximize network efficiency.

C-ADS-equipped infrastructure components such as CARMA Streets enable infrastructure to actively participate in the coordination of vehicle needs—especially special classes of vehicles, including incident response vehicles. C-ADS-equipped vehicles and intersections are part of a connected ecosystem that relies on V2V, vehicle-to-infrastructure (V2I), and infrastructure-to-vehicle (I2V) communications. In this ecosystem, each component plays a role in helping to improve the network. For example, facilities at a common conflict area can be equipped with traffic sensors, edge processors, and communication networks (e.g., DSRC systems) to help support C-ADS-equipped vehicle coordination.

A connected ecosystem combined with the current level of vehicle automation provides opportunities for traffic flow improvements at common conflict areas. Such improvements may produce mobility, increase safety, and improve mobility. These emerging technologies can further help to improve the passing sequence of C-ADS-equipped vehicles at an intersection with proper coordination (e.g., allowing movements without conflict to occur simultaneously instead of allowing only one vehicle at a time to proceed at an intersection) to increase traffic throughput.

Vehicles can be aware of downstream traffic and conflict area conditions to determine the approximate time they can enter a conflict area. Special classes of vehicles, including incident response vehicles (e.g., fire response, ambulance, and law enforcement units), may receive preferential treatment by clearing queues or crossing the stop bar earlier than they would have without preferential treatment. Among CDA applications related to conflict areas, control strategies near signalized intersections have received attention due to increased capabilities to communicate with traffic signal controllers and receive real-time Signal Phase and Timing (SPaT) information. These control strategies usually have two aspects. First, the traffic signal timing plan can be optimized to efficiently serve different traffic approaches according to their demands. Second, C-ADS-equipped vehicles can be controlled simultaneously to improve safety and increase mobility.

Traffic signal control is responsible for regulating traffic flow in a signalized intersection and for improving traffic mobility and safety. Traffic signal control can also be operated to provide right-of-way priority to incident response vehicles such as ambulances, fire trucks, and police cars. According to the *Manual on Uniform Traffic Control Devices* (*MUTCD*), a traffic signal controller can alter the regular signal timing and phasing to provide right-of-way for incident response.(5) The alternative signal timing and phasing may either extend the currently displayed green interval or replace the entire set of signal phases and timing depending on the emergency vehicle's requested signal phase (i.e., approach). An incident response vehicle sends a preemption request to a traffic signal controller by using optical, acoustic, special inductive loop, or Global Positioning System (GPS) technology.(6) Traffic signal cabinets are equipped with an emergency vehicle preemption device to receive the preemption request. In 1970, Long developed a preemption system in which incident response vehicles transmit an optical signal and a receiver detects the presence of incident response vehicles.(7) The detector then commands the signal controller to flash a green light for requested phases.

Incident response vehicles need to respond to emergency incidents as quickly as possible. Statistics indicate that slow responses to emergency calls increase casualty rates. About 10 percent of casualties occur within a few minutes or even seconds after a crash.(8,9) Survival rates fall 7–10 percent with every elapsed minute following a crash.(10) Incident response vehicles experience delays at intersections due to waiting in long queues and stopping at traffic signals to ensure safe right-of-way.

To improve the mobility of incident response vehicles, especially fire response vehicles, an emergency vehicle signal preemption (EVSP) system was developed by Gordon, Tighe, and Siemens.(11) The EVSP system provides a wave of green lights to incident response vehicles when the first responders manually push a button as they depart for an incident. The green wave remains active along the response route until the incident response vehicle passes each intersection. The traffic signal returns to its normal state after a fixed amount of time. Qin and Khan modified the EVSP system to implement a real-time control strategy instead of fixed-time phase holds.(12) The real-time control strategy detects the presence of an incident response vehicle using connected vehicle technology and allocates a maximum green time required for the response vehicle to pass through an intersection.

Shaaban et al. proposed an effective signal preemption and path selection strategy.(13) An optimal path is selected from the starting location of an incident response vehicle to the destination of the emergency call. This system uses V2V and V2I technology to notify other vehicles about the incident response vehicle information, which may help to clear any traffic queue before the incident response vehicle arrives at the intersection. C.Y. Chen, P.Y. Chen, and W.T. Chen claim that the shortest path cannot ensure the earliest arrival time.(13) The incident response vehicles can respond to the emergency call more quickly by traveling through the path with better traffic conditions. Subsequently, an incident response vehicle path selection algorithm which considers current and historical traffic information was developed by C.Y. Chen, P.Y. Chen, and W.T. Chen.(14)

Emergency vehicle response time (EVRT) is another traffic signal control method for emergency vehicle preemption. The EVRT strategy utilizes connected vehicle technology to predict queue length and provide early green lights to clear queues at downstream intersections to improve the mobility of emergency vehicles.(15) To predict queue length, the EVRT strategy assumes 100 percent penetration of connected vehicles.

Most traffic signal preemption control methods generally serve only one approach to an intersection, for one or more emergency vehicles that are traveling on the same path. When multiple emergency vehicles simultaneously arrive from different approaches, current traffic signal control generally follows first-come-first-serve rules.(16) However, there are some mechanisms where one vehicle can override others.

There have been crashes where two incident response vehicles collided in an intersection.(17,18) D. Gross and J. Gross proposed a system that provides early warnings of incident response vehicle arrival and departure and direction of approach.(19) The incident response vehicle uses a transceiver to transmit its travel direction. The transceiver also receives the travel direction messages of other incident response vehicles within range of the transceiver. This system allows incident response vehicle drivers to determine the possibility of collisions with other incident response vehicles.

Goel, Ray, and Chandra developed an intelligent traffic signal system where a wireless sensor network (WSN) is employed to communicate between intersections.(20) The WSN detects the incident response vehicle based on its emitted sounds. The sensor sends the information to the next intersection over the WSN. If multiple incident response vehicles are approaching from different directions, the intersection follows first-come, first-serve rules.

In the United States, it is challenging for traffic engineers to ensure the safe passage of incident response vehicles. From 1996 to 2015, an average of 355 fatalities per year occurred in crashes related to police vehicle pursuits.(21) According to Fahy and Bui et al., from 1997 to 2006 approximately 94 fatalities resulted from collisions between fire response vehicles and other vehicles, pedestrians, and bicyclists. (22,23) The National Highway Traffic Safety Administration (NHTSA) released a report that analyzed ambulance crashes from 1992 to 2011.(21) The report found that ambulances are involved in approximately 6,500 crashes each year. The report also found that nearly 60 percent of ambulance crashes occur while the vehicles are in emergency use.

Incident response vehicles alert pedestrians and vehicles using horns, sirens, and flashing lights to avoid collisions.(24) However, excessive use of lights and sirens during emergency driving may cause crashes.(25,26) The lights and sirens can limit the auditory capability of emergency vehicle drivers and impede the vision of adjacent road users. Smith, Davidson, and Pfister developed a warning system that alerts vehicles and pedestrians to the direction emergency vehicles are approaching from.(27) Buchenscheit et al. used V2V and V2I communication systems to notify nearby vehicles about the presence, location, and speed of emergency vehicles.(28) Bui et al. suggested that comprehensive emergency vehicle driver training and risk management strategies may be effective in reducing emergency vehicle crashes.(25)

Traffic signal preemption cannot directly address some safety concerns. However, it may reduce delay and disruption to logical traffic signal control at intersections and along response routes, which may improve safety. Current traffic signal preemption generally overrides other traffic signal control strategies, such as coordination, to force off current phases and immediately display green signal indications ahead of emergency vehicles. One potential scenario occurs when other vehicles, such as freight trucks or other heavy vehicles, are also approaching a preempted intersection. The operating characteristics of freight trucks are different from passenger cars. Heavy vehicle deceleration depends on the mass, tire-pavement friction, braking efficiency, and reaction time of the drivers. Gates and Noyce found that, due to low deceleration capability, heavy vehicles are 3.6 times more likely to run red lights than passenger vehicles.(29)

Crashes may occur when the traffic signal controller attempts to terminate the current signal phase without considering the presence of vehicles in the dilemma zone. Tarko, Li, and Laracuente developed a probabilistic algorithm that identifies the optimal green extension for the vehicles in the dilemma zone.(30) McCoy and Pesti developed an advanced detection and warning system to improve dilemma-zone protection.(31) Zimmerman et al. designed a detection-control system, which determines the phase termination time based on the number of vehicles in the dilemma zone and the waiting time of vehicles at conflicting phases.(32) None of these systems consider the dilemma zone during a preemption event.

Incident response vehicle preemption systems disrupt normal traffic operations to provide right-of-way to incident response vehicles. Studies have analyzed the impact of traffic signal preemption on traffic flow. Bullock, Morales, and Sanderson; Nelson and Bullock; and Collura and Chang found that preemption systems can negatively impact the arterial travel time of responding vehicles. (33,34,35) Paruchuri developed an adaptive preemption of the traffic system that considers real-time traffic data to reduce vehicle delay of nonemergency vehicles.(36)

Traffic signal preemption systems aim to reduce travel time for emergency vehicles, but the operations and benefits are not always clear. When a vehicle requests preemption, the quick change in control priorities can significantly disrupt traffic flow and may create confusion that could impact safety. The current approach to preemption makes control decisions that are independent of the current traffic situation. This may lead to undesirable outcomes when multiple emergency response vehicles are present. For example, if the signal controllers along an arterial are changing to create a green pathway for a fire response vehicle without considering conflicting traffic, other emergency vehicles on other approaches or perhaps a freight vehicle (e.g., a gasoline tanker truck) may be caught in the dilemma zone and may be unable to safely stop.

Das et al. presented a connected emergency vehicle application that ensures smooth progression of single or multiple emergency vehicles through corridors, allows safe passage of heavy vehicles in the dilemma zone, and improves the overall performance of traffic signals.(37) The system is based on the priority model described in Zamanipour et al., which is implemented in the Multimodal Intelligent Traffic Signal System (MMITSS) project.(17) MMITSS focuses on connected vehicle traffic signal applications based on V2V and V2I wireless communication technologies.

OPPORTUNITIES FOR CHANGE

CDA that leverages V2V and V2I communications to enable vehicles to share information and cooperate provides opportunities to improve TIM on arterial roadways. SAE has standardized how cooperation between vehicles is regarded. Similar to the levels of automation defined in the SAE standard *Taxonomy and Definitions for Terms Related To Driving Automation Systems for On-Road Motor Vehicles* (J3016_202104), the newer standard, SAE J3216_202107, defines the classes of cooperation.(1) Vehicles equipped with cooperative automated driving systems (CADS) can share their status and driving intent (classes A and B) and seek and enter cooperative driving agreements (classes C and D). Figure 1 summarizes the cooperation classes in relation to the levels of vehicle automation.

SAE INTERNATIONAL

RELATIONSHIP BETWEEN CLASSES OF COOPERATIVE DRIVING AUTOMATION (CDA) J3216 AND LEVELS OF AUTOMATION J3016

			Partial Automation of DDT		Complete Automation of DDT		
		SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
		No driving automation (human does all driving)	Driver assistance (longitudinal OR lateral vehicle motion control)	Partial driving automation (longitudinal AND lateral vehicle motion control)	Conditional driving automation	High driving automation	Full driving automation
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)		
CDA CLASSES							
SAE CLASS A STATUS SHARING	Here I am and what I see	E.g., Brake lights, traffic signal	Potential for improved object and event detection¹		Potential for improved object and event detection²		
SAE CLASS B INTENT SHARING	This is what I plan to do	E.g., Turn signal, merge	Potential for improved object and event detection¹		Potential for improved object and event detection²		
SAE CLASS C AGREEMENT SEEKING	Let's do this together	E.g., Hand signals, merge	N/A		C-ADS designed to attain mutual goals through coordinated actions		
SAE CLASS D PRESCRIPTIVE	I will do as directed	E.g., Hand signals, lane assignment by officials	N/A		C-ADS designed to accept and adhere to a command		

1. Improved object and event detection and prediction through CDA Class A and Class B status and intent sharing may not always be realized given that Level 1 and 2 driving automation features may be overridden by the driver at any time, and otherwise have limited sensing capabilities compared to Level 3, 4, and 5 ADS-operated vehicles.
2. Class A and B communications are one of the many inputs to an ADS's object and event detection and prediction capability, which may not be improved by the CDA message.

Figure 1. Table. "Relationship Between Classes of Cooperative Driving Automation (CDA) J3216 and Levels of Automation J3016."(3)

Table 2 shows examples of CDA features relating to cooperative traffic signals at intersections and considering different cooperation classes. A number of these examples are taken from SAE J3216_202107. However, the effects of different cooperation classes defined in SAE J3216_202107 have not been investigated.

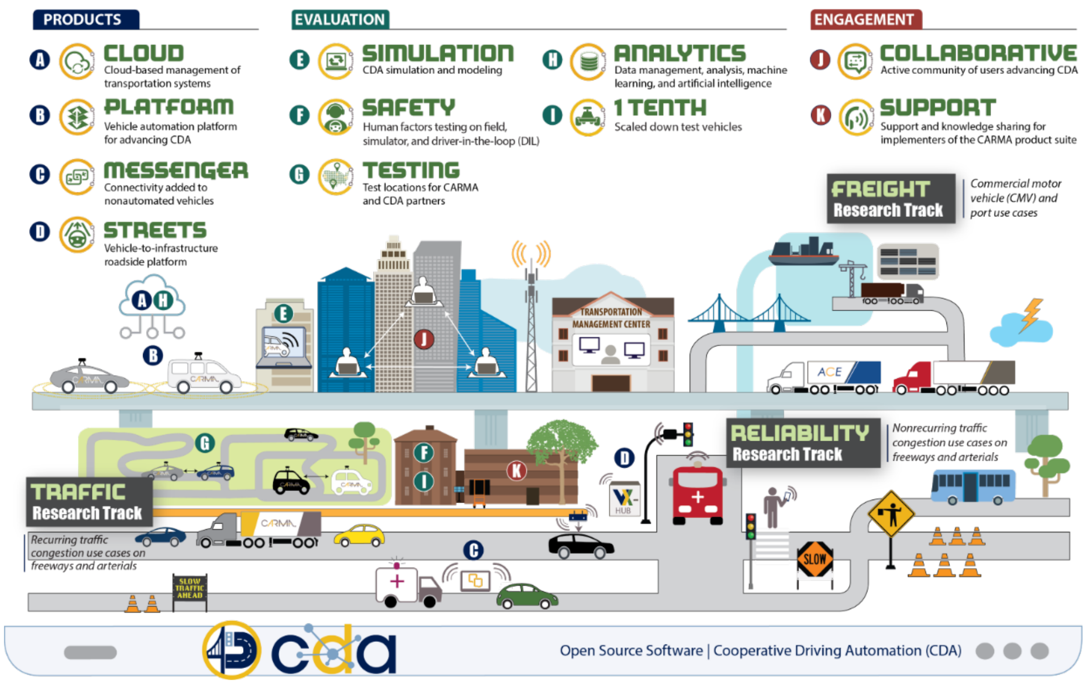
Table 2. Examples of cooperative signalized intersection features.

Feature	Class of CDA	CDA Device Transmission Mode and Directionality	Information Exchanged	Level of Functionality
Signal priority	A) Status sharing	One way: C-ADS-equipped vehicles → RSE	Vehicle location, speed, and priority status (e.g., incident response vehicle en-route to an incident).	Enabling signal timing changes based on the approaching vehicle.
Eco-approach and departure	A) Status sharing B) Intent sharing	One way: RSE→ C-ADS-equipped vehicles	SPaT messages	Enabling C-ADS equipped vehicles to plan their motions based on knowledge of a future signal phase that would otherwise be unavailable.
Tandem approach and departure	C) Agreement seeking	Two way: C-ADS-equipped vehicles → RSE RSE → C-ADS-equipped vehicles C-ADS-equipped vehicles → C-ADS-equipped vehicles	SPaT messages Velocity profile Negotiation results	Enabling SPaT changes based on the approaching vehicle. Enabling C-ADS-equipped vehicles to plan their motions and optimize their velocity based on future (and possibly optimized) signal phases and the status of the other vehicle. Supporting more efficient motion plans with increased reliability and look-ahead distance to reduce energy consumption and emissions.

RSE = roadside equipment.
Note: In practice, one-way transmission will typically send the message to multiple CDA devices in the vicinity.

To fill in existing research gaps, this ConOps proposes an edge computing-based cooperative control framework for C-ADS-equipped vehicles, including passenger vehicles and incident response vehicles, at a signalized intersection in the TSMO context. This ConOps is part of the CDA framework and distinguishes between levels of vehicle automation and classes of vehicle cooperation.

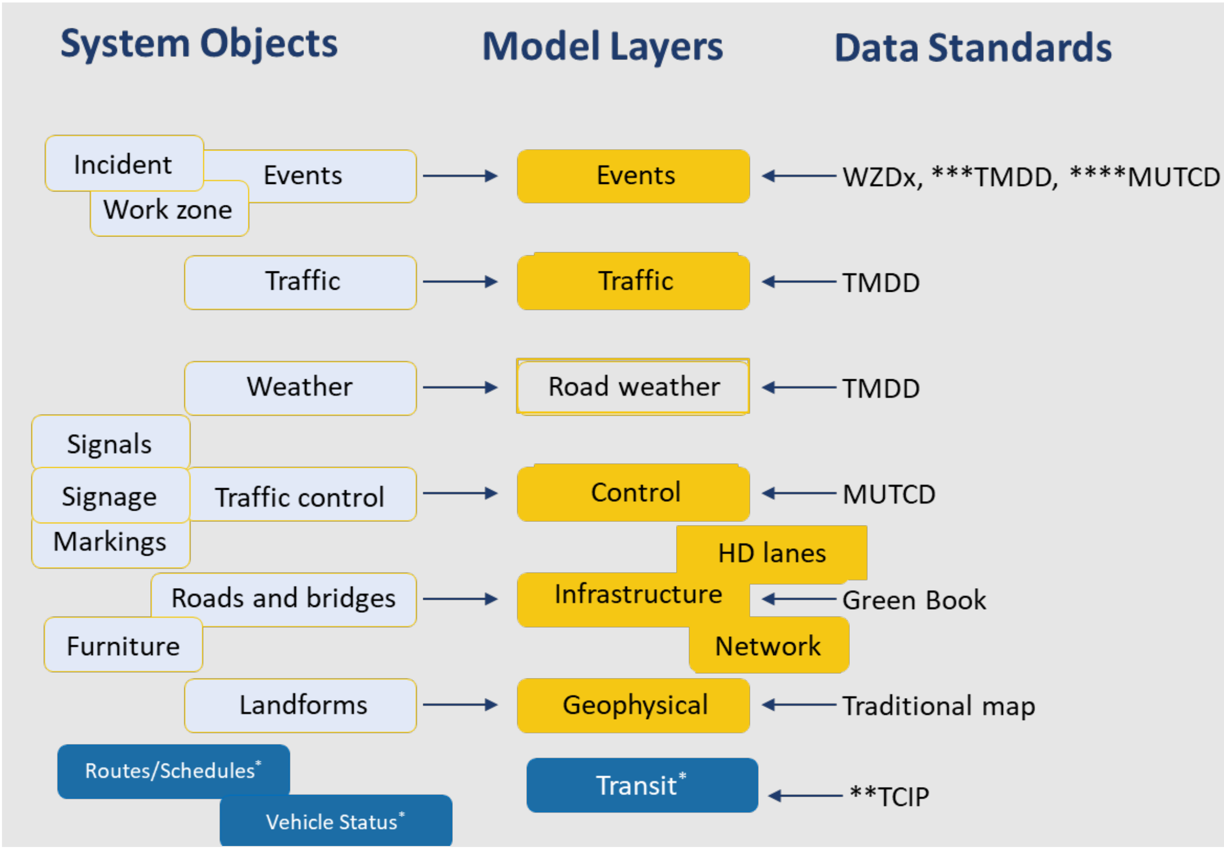
The CDA framework is a platform for the research and development of emerging automated driving and vehicle-to-everything (V2X) communications. Figure 2 illustrates the CARMA Ecosystem, which is comprised of open-source software, tools to support evaluation and testing, and an engagement and support community.



Source: FHWA.

Figure 2. Schematic Diagram. CARMA Ecosystem.[38]

CARMA tools provide a framework for CDA application development. CARMA Cloud provides an overall system-level capability to integrate TSMO strategies utilizing information from a variety of different systems. Figure 3 illustrates the system objects and layers that represent different critical TSMO systems, including work zones, traffic conditions, weather, traffic control, roads and bridges, and landforms. Each TSMO system contains a collection of system objects, which represent key entities and capabilities that create model layers of information. Many of the system objects are created based on standards that have been developed to support interoperability and uniformity across the different systems. Utilizing a cloud-based platform for this information integration provides capability for the development of CDA applications for other transportation needs, such as TIM.



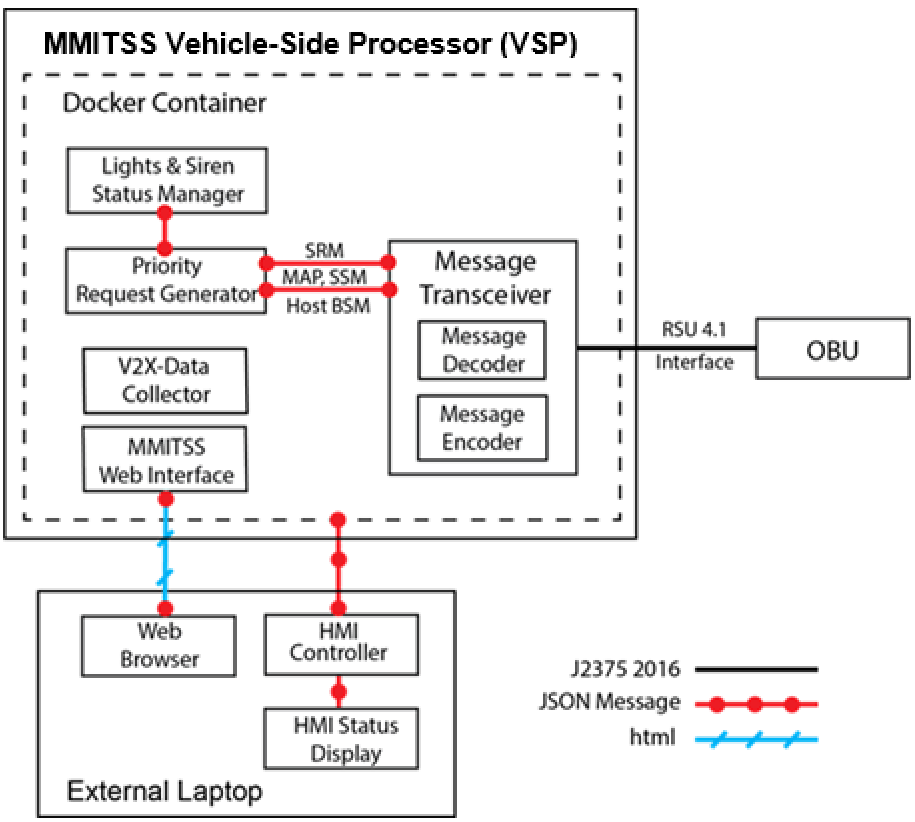
Source: FHWA.
*Potential new system objects for transit management.
**Transit communications interface protocol (TCIP).
***Traffic Management Data Dictionary (TMDD)[39].
****MUTCD[5].
WZDx = work zone data exchange; HD = high definition; Green Book = *A Policy on the Geometric Design of Highways and Streets*.[40]

Figure 3. Diagram. CARMA Cloud components.

CARMA Streets is a relatively new addition to the CARMA Ecosystem. It provides roadside edge computing that integrates communication between infrastructure and CDA-equipped vehicles, as well as other connected but nonautomated vehicles. CARMA Streets provides the capability for real-time applications as part of CDA applications. CARMA Platform is a research and testing platform for vehicle automation. It has been applied to demonstrate advanced CDA capabilities such as CACC, eco-driving, and other automated capabilities. CARMA Messenger is a vehicle platform for communicating with nonautomated but connected vehicles.

In addition to CDA and the CARMA Ecosystem, the Connected Vehicle Pooled Fund has led to the development of MMITSS, which provides intelligent and priority-based traffic signal control using data from connected vehicles.[41] Figure 4 and figure 5 show the software architecture of MMITSS. MMITSS has components that are deployed on the roadside (i.e., roadside processor [MRP]), on the vehicle (i.e., vehicle-side processor [VSP]), and on a server that supports data archiving and a web-based user interface. The VSP and MRP both have message transceivers that encode the protocol for talking to the RSU and onboard unit (OBU) devices, as well as a message library that can pack and unpack the Unaligned Packed Encoding Rules (UPER)-encoded messages in the SAE standard *Dedicated Short Range Communications (DSRC) Message Set Dictionary* (J2735_201603).(42)

The VSP hosts a priority-request generator that is responsible for locating the vehicle on the map (based on local GPS position and map messaging received by the OBU) and broadcasting a signal request message (SRM). The VSP has special lights and a siren manger component that can sense the lights and siren circuit on an incident response vehicle such as a fire truck, ambulance, or police car. In addition, there is a data-capture component called V2X data client that archives data from the other VSP components. Since the VSP does not have a persistent internet connection, the V2X data compressor manages the captured data by compressing and deleting the oldest data to ensure device storage is adequate. Figure 4 shows the VSP architecture of the MMITSS software.

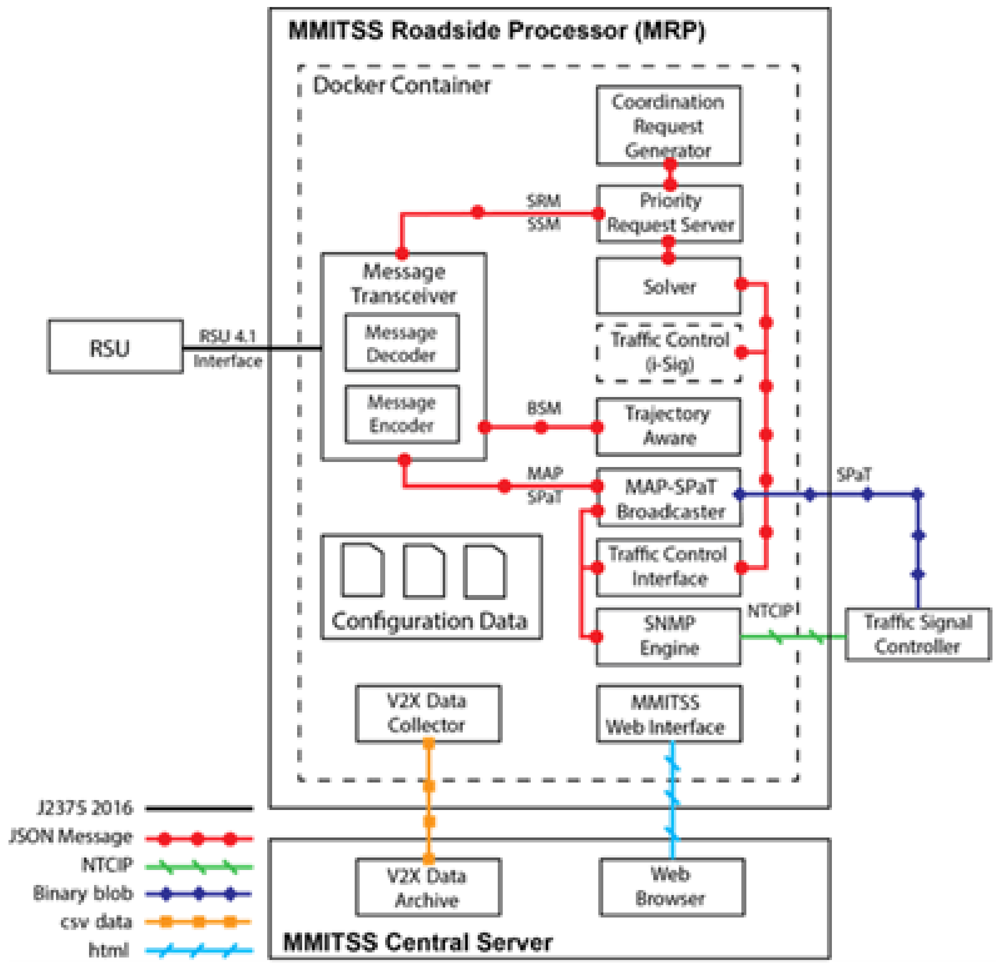


SSM = signal status message; BSM = basic safety message; HMI = Human-Machine Interface; HTML = Hypertext Markup Language; JSON = JavaScript Object Notation; CSV = comma-separated values; SNMP = Simple Network Management Protocol.

Figure 4. Flowchart. Software architecture of MMITSS VSP.(41)

The MRP hosts the algorithms that realize the MMITSS intelligent priority control using the connected vehicle data. When a vehicle broadcasts an SRM, the MRP message transceiver forwards it to the priority request server, which is responsible for collecting and managing requests from multiple vehicles and from the coordination request generator since MMITSS implements coordinated traffic signal control as a form of priority. Given a set of active priority requests, the priority request solver will solve an optimal scheduling problem to determine the desired traffic control schedule. Figure 5 shows the MRP architecture of the MMITSS software.

This schedule is sent to the traffic control interface for implementation on the traffic signal controller though National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) objects (e.g., call, hold, force off, and omit). The traffic signal controller provides SAE SPaT message data that are modified by the MAP-SPaT broadcaster to include the MMITSS control schedule.(42) Currently, the trajectory-aware and intelligent traffic signal control applications are not utilized in MMITSS. They require a minimum of 20–30 percent market penetration of connected vehicles to be effective.



MMITSS phase 3 development, DOT Dynamic Mobility Application Program.
SSM = signal status message; BSM = basic safety message; HMI = Human-Machine Interface; HTML = Hypertext Markup Language; JSON = JavaScript Object Notation; CSV = comma-separated values; SNMP = Simple Network Management Protocol.

Figure 5. Flowchart. Software architecture of MMITSS Roadside Processor (MRP).(41)

MMITSS implements both traffic signal preemption and traffic signal priority. In MMITSS, the flow of information from incident response vehicles is identical to other modes including transit and trucks. The vehicle, or another source, generates a request for priority that is added to the list of active requests in the MMITSS priority request server. For incident response vehicles (referred to as emergency vehicles in MMITSS), the priority request solver will omit phases that are not required for serving the active requests. For example, if an incident response vehicle requests priority for the major through movement at an intersection and the signal is currently serving the side street through movements, phases serving all the turning movements as well as the through movement opposing the incident response vehicle will be omitted.

Omitting these phases limits the flow of vehicles in conflicting movements and provides green for the through and left-turn movements to serve the approaching incident response vehicle. If more than one incident response vehicle approaches the intersection from different approaches—for example, during phase two and phase six—and phase four is active, then phases one, three, five, and seven will be omitted. Traffic signal priority does not consider omitting phases since it is intended for serving transit and trucks, which are considered a normal part of the traffic stream rather than exceptions to normal conditions.

The emergence of CDA, the CARMA Ecosystem, and MMITSS provides a case for creating a new and effective TIM system for signalized arterials.

TSMO STAKEHOLDERS

Stakeholders are entities whose actions influence travel in the transportation environment; these may include transportation users engaged in travel on publicly accessible roadways, emergency responders, transit vehicles, transit riders, bicyclists, pedestrians, and infrastructure owners and operators (IOOs). This section discusses transportation users and IOOs and their corresponding needs.

Transportation Users

A transportation user is a traffic participant on or adjacent to an active roadway for the purpose of traveling from one location to another. For TSMO, motorized vehicles, including incident response vehicles, whether human-driven or automated, are the main users of traffic systems at intersections. Transportation user needs include the following:

- Safe trips.
- Smooth, low-stress, and fast travel.
- Reliable travel times.
- Energy efficiency.
- Accurate information to help them make optimal decisions about driving tasks (i.e., decision support systems).

Integrating CDA technology into TSMO, from the transportation user's perspective, may support and enhance the following benefits:

- Safer travel: Providing traffic signal preemption for incident response vehicles can improve safety by reducing the number of vehicles involved in conflicting movements at a signalized intersection.

- Greater operational efficiency and travel-time reliability: Traffic signal preemption can improve travel time reliability by reducing traffic signal delay and allowing one or more incident response vehicles to pass through the intersection more efficiently.

- Improved traffic safety: Reducing crashes can be a potential benefit of CDA technology. NHTSA estimates combined use of V2V and V2I communications has the potential to significantly reduce unimpaired driver crashes.(43)

Table 3 identifies four transportation user categories and the characteristics and needs of each category.

Table 3. Transportation user characteristics and needs.

Driving Mode	Transportation User Category	User Characteristics and Needs
Human driving	Nonconnected human driver	Nonconnected human drivers have neither connectivity nor automation capability, and they have uncertain driver behavior. Needs align with general user needs.
Human driving	Incident response vehicle driver	Incident response vehicle operators who are highly trained and skilled drivers and are expected to follow agency operating policies.
Human driving	Connected human driver	Connected human drivers receive additional traveler information and can make better-informed travel decisions than nonconnected. Needs align with general user needs.
Automated driving	Nonconnected ADS-equipped vehicle	Nonconnected, ADS-equipped vehicles operate independently, relying on local sensor information and automated control software, and usually have conservative behavior to provide an increased margin of comfort and safety. Needs include accurately sensing local traffic conditions and actuating control of vehicles to ensure safety and travel efficiency.

Driving Mode	Transportation User Category	User Characteristics and Needs
Automated driving	C-ADS-equipped vehicle	Similar to ADS-equipped vehicles, C-ADS-equipped vehicles partner with other CDA participants in the traffic stream, including the infrastructure, to improve overall traffic performance. Needs include availability of other vehicles to perform cooperative actions, improving overall system safety and efficiency while guaranteeing individual vehicle travel experiences.

IOOs

IOOs are traffic participants who provide, operate, and maintain roadways and supporting infrastructure for the mobility needs of transportation users. IOOs include public, public-private, or private sector entities that operate in accordance with applicable laws at the Federal, State, or local level. Incident response vehicles can be from public, public-private, or private sector agencies that provide a variety of services, such as fire response, ambulances, police, and towing and recovery.

The goal of IOOs is safe and efficient traffic management. This includes monitoring and managing traffic and the factors affecting traffic flow, such as incidents, weather, intersections, the dissemination of routing information, and other actions that increase traffic flow efficiency. Goals of IOOs may also include the following:

- Reducing congestion that reoccurs.
- Improving reliability and safety.
- Reducing travel times, fuel consumption, and emissions.
- Maintaining and increasing use of alternative and emerging transportation modes, such as transit or car-sharing options. (CAVs are considered a separate mode by travelers).

From the perspective of IOOs, TSMO may provide the following benefits:

- Faster realization of efficiency goals: Timely adoption of CDA at existing intersections may provide faster incident response and greater congestion management abilities to increase throughput, enhance safety, and improve driver experience. These benefits may increase as the fraction of C-ADS-equipped vehicles using the intersection, out of the total number of users, increases.
- Maximized resource utilization for more efficient solutions: Traditional approaches to managing congestion, such as capacity expansion, are increasingly facing funding constraints and inherent limitations in alleviating transportation problems. CDA technologies can be considered operational strategies that offer potential innovative

solutions to congestion and travel time variability at intersections. CDA technologies can be used to clear traffic congestion to allow incident response vehicles to travel faster and more safely.

- First-mover advantage: If operators currently primed to accommodate C-ADS-equipped vehicles on their roadways do not voluntarily move to test and advance this technology, outside actors may fill that role and dictate the direction of CDA technology development. This direction may or may not be in line with a specific agency's goals or organizational capacity. Incident response agencies have an advantage since they manage their vehicle fleets and have close partnerships with traffic operation departments and agencies.

- Organizational evolution to accommodate the future of mobility technology: Organizations that respond to rapid technological change may be more likely to thrive in this era of rapid technological enhancement in the transportation field.

JUSTIFICATION FOR AND NATURE OF CHANGES

The transportation industry is moving toward improving safety with ADS by enhancing various vehicle technologies (e.g., levels of automation and ubiquitous sensing using automated vehicle sensors). As more advanced sensing and computing capabilities are integrated with ADS, a key consideration is what changes must take place to enable CDA system deployment and what additional capabilities and possibilities can be expected, including the deployment of smarter infrastructure systems that are based on CDA technologies. This section discusses the nature of those changes.

Organizational and Institutional Changes

The following organizational and institutional changes can be implemented to enable the deployment of CDA systems:

- Adopt a systems-engineering process: A systems-engineering process is important for developing operational scenarios to accommodate CDA applications on intersection facilities. A ConOps can be developed for the system (regional level) and for the corridor in question.

- Develop a performance management system: C-ADS-equipped vehicles aligned with agency performance standards and holistic data requirements can help transportation agencies leverage data sources across the organization. A performance management system collects and processes relevant data to determine whether system goals and performance targets for all CDA applications and operational alternatives are being achieved.

- Develop a data collection and management system: All relevant data are obtained—in real time—from the various vehicles, onboard sensors, wireless devices, RSUs, roadway traffic sensors, weather systems, message boards, incident response management systems, and other related systems. These data can be placed in or be accessible from a common data environment.

- Include a rich assortment of data: Tap into rich, accurate data from a variety of sources, potentially including the following:

    - Real-time traffic data—Includes vehicle speed and location data collected and disseminated by vehicles as part of a connected system. Also includes traditional detection sources (e.g., inductive loop detectors, overhead radar, and closed-circuit television cameras) that provide traffic data for the system.

    - Traffic signal plan data—Includes planned SPaT data from traffic signal controllers at signalized intersections.

    - Traffic signal timing data—Includes actual SPaT data from traffic signal controllers at signalized intersections. Differs from planned data if control methods include actuated, adaptive, and priority.

    - Incident response system data—Includes current location and status of incident response vehicles. Provides their readiness to respond to new incidents.

    - Emergency dispatch system data—Includes time and location of incidents, response units assigned, and other law enforcement and fire/emergency medical services data.

    - Weather condition data—Provides infrastructure-based road weather information system and third-party weather data feeds that can supplement vehicle-acquired weather data.

    - Pavement condition data—Provides real-time pavement surface condition data (e.g., dry, wet, snowy, iced, and salted) from in-pavement sensors.

    - Crowdsourced data—Includes data collected from platforms that have large installed user bases. Supplements data from other sources.

    - Historical data—Includes historical data used for the improvement of traffic analysis accuracy and the prediction of traffic conditions.

Technical and Technological Changes

The following technical and technological changes can be implemented to enable the deployment of CDA systems.

Procuring new hardware to support technology, as follows:

- Enabling connectivity of infrastructures at intersections through DSRC or other communication technologies, such as cellular vehicle-to-everything (C-V2X) and improving the computing power of infrastructures by installing hardware, such as edge processors, to support algorithms that enable CDA applications.

- Equipping vehicles that use CDA systems with communication radios (e.g., OBUs and vehicle awareness devices), cameras, light detection and ranging technology, radar sensors, and other computational resources to implement the new control software.

Developing and acquiring new software, as follows:

- Making use of the frequently collected and rapidly disseminated multisource data drawn from connected travelers, vehicles, and infrastructure.

- Including a vehicle awareness application (e.g., an OBU installed by the vehicle manufacturer or as an aftermarket integrated device); a personal wireless application (e.g., smartphone or other handheld device); or an application that can collect, receive, and disseminate needed CDA data.

- Enabling systems and algorithms that can generate traffic condition predictions, alternative scenarios, and solution evaluations in real time.

- Containing microscopic and macroscopic traffic simulations.

- Incorporating real-time and historical data.

- Utilizing traffic optimization models.

- Encouraging the constant evaluation, adjustment, and improvement of traffic optimization models (this requires an increase in computational capability and the long-term storage of historical data).

- Evolving and improving algorithms and methods based on performance measurements.

- Including emerging communication technology (e.g., DSRC or C-V2X) and software elements that enable the developed CDA system to act upon the received information.

Operational Policy Changes

The operational policies of intersections are generally designed to accommodate traffic operations that meet the goals of operators. Key questions to determine proper operational policies of intersections include:

- Who are the stakeholders and users of the system?
- What are the elements and capabilities of the system?
- Where are the affected systems?
- When and where will activities be performed?
- Why are the strategies being used?
- How will the system be operated and maintained?
- How will the performance of the system be measured?

Stakeholders can create agreements or compacts to set expectations, establish incentives to participate, encourage investments, and measure performance. Improved throughput and smoother travel experience are shared goals between IOOs and CDA applications.

Facility Infrastructure Changes

Depending on the facility type, configuration, operations, and existing equipment, the following categories of facility infrastructure changes may be needed:

- I2V infrastructure (e.g., roadside equipment [RSE] including connected vehicle RSUs [wireless] and edge processing devices) to transmit central information to all vehicles within the communication area. If nonequipped vehicles are allowed, traditional dynamic message signs convey public traveler information.

- Roadside sensors (e.g., video cameras, radars, and loop detectors) to detect or estimate real-time vehicle trajectories of nonequipped vehicles upstream of intersections.

- Striping and pavement markings.

- Appropriate signage to convey relevant information to all drivers (both equipped and nonequipped).

For the early stages of CDA deployment, infrastructure equipped with existing communication devices offers the opportunity to begin integrating CDA systems into traffic. Due to the enabled cooperation capabilities, even a small number of C-ADS-equipped vehicles may impact traffic operations at intersections, and therefore improve system performance and the individual traveler’s experience. Incident response fleets are attractive candidates as early adopters of CDA technologies.

CHAPTER 3. OPERATIONAL CONCEPT OF THE PROPOSED SYSTEM

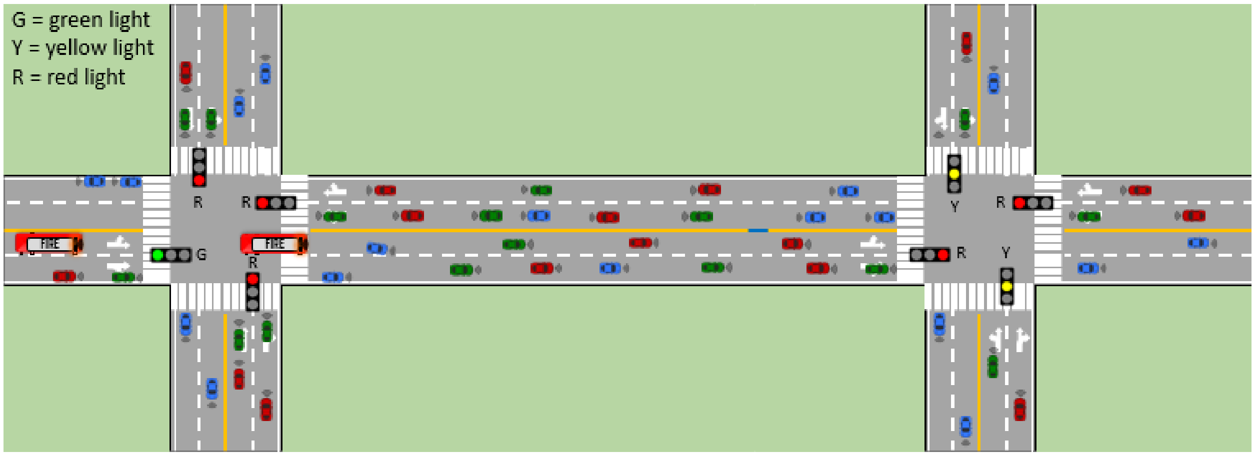
This chapter details the operational concept of the TSMO TIM BAT UCs. The chapter describes how automated driving technology can be used in a range of cooperative manners to reduce delays and improve safety. The discussion covers from when C-ADS-equipped incident response vehicles enter the communication area of signalized intersections to when traffic signal preemption is provided. The development of the CARMA Ecosystem and MMITSS are key technological advances that enable a CDA approach to TSMO TIM of BAT using traffic signal preemption (PREEMPT).

TECHNOLOGICAL FRAMEWORK FOR TSMO TIM BAT UCS

This section describes the algorithm framework for an active traffic management feature to be used for the TSMO TIM BAT UCs. Many TSMO strategies can be used for TIM. This framework focuses on an arterial with several signalized intersections and one or more active incident response vehicles, as illustrated in figure 6. At any time, there may be one or more incident response vehicles en route to an incident. Having active incident response vehicles is an exception to the assumption of “normal” traffic operating conditions, and special considerations are made for traffic signal operations, including traffic signal preemption.

It is assumed that all incident response vehicles are equipped with CDA technologies. It is also assumed that each intersection is equipped with an RSU, an edge processor, and a traffic signal controller that provides SPaT data and can provide preemption for incident response vehicles when requested. CDA-capable incident response vehicles have high-definition maps used to determine vehicle approach, desired time of service, or estimated time of arrival (ETA) at intersection stop bar.

The decision to provide preemption can depend on several factors, including the presence of a queue. When an incident response vehicle sends a request for traffic signal priority (i.e., preemption), an RSU forwards the message to the appropriate edge processor, where it is considered along with requests from other priority-eligible vehicles. At any single intersection, several incident response vehicles may request priority within a short amount of time.



Source: FHWA.

Figure 6. Illustration. Arterial traffic signal corridor with incident response operations.

The traffic signals in an arterial network are generally operated in a coordinated mode that provides progression for vehicles traveling along the primary direction of movement. Generally, traffic analysts design coordinated signal timing (e.g., cycle length, offset, and phase splits) in consideration of normal general passenger vehicle flow along the route and not to assist incident response vehicles. Traffic signal preemption can alter traffic signal timing significantly. During preemption timing, some phases (e.g., movements) may be skipped, shortened, extended, and reordered. These changes deviate from the normal traffic signal timing and control, and human drivers (SAE Levels 1–2) may require additional response time. The presence of an incident response vehicle with active lights and siren can help reduce uncertainty. The goal of the altered signal timing is to improve response time and reduce the number of vehicles moving in the intersection to enhance safety.

CDA technologies can enhance situational awareness when incident response vehicles are active. Two V2V UCs based on the SAE J2735_201603 emergency vehicle alert (EVA) message that improve situational awareness are as follows:[(42)]

- TSMO UC EVA-1: Move over where vehicles are alerted to the presence of an incident response vehicle on the roadside and the vehicles are required to provide a safety barrier.
- TSMO UC EVA-2: Yield the right-of-way where an incident response vehicle is upstream from vehicles and the vehicles are required to move to the right side of the roadway to clear a pathway for the incident response vehicle to travel. This UC can improve safety and response time.

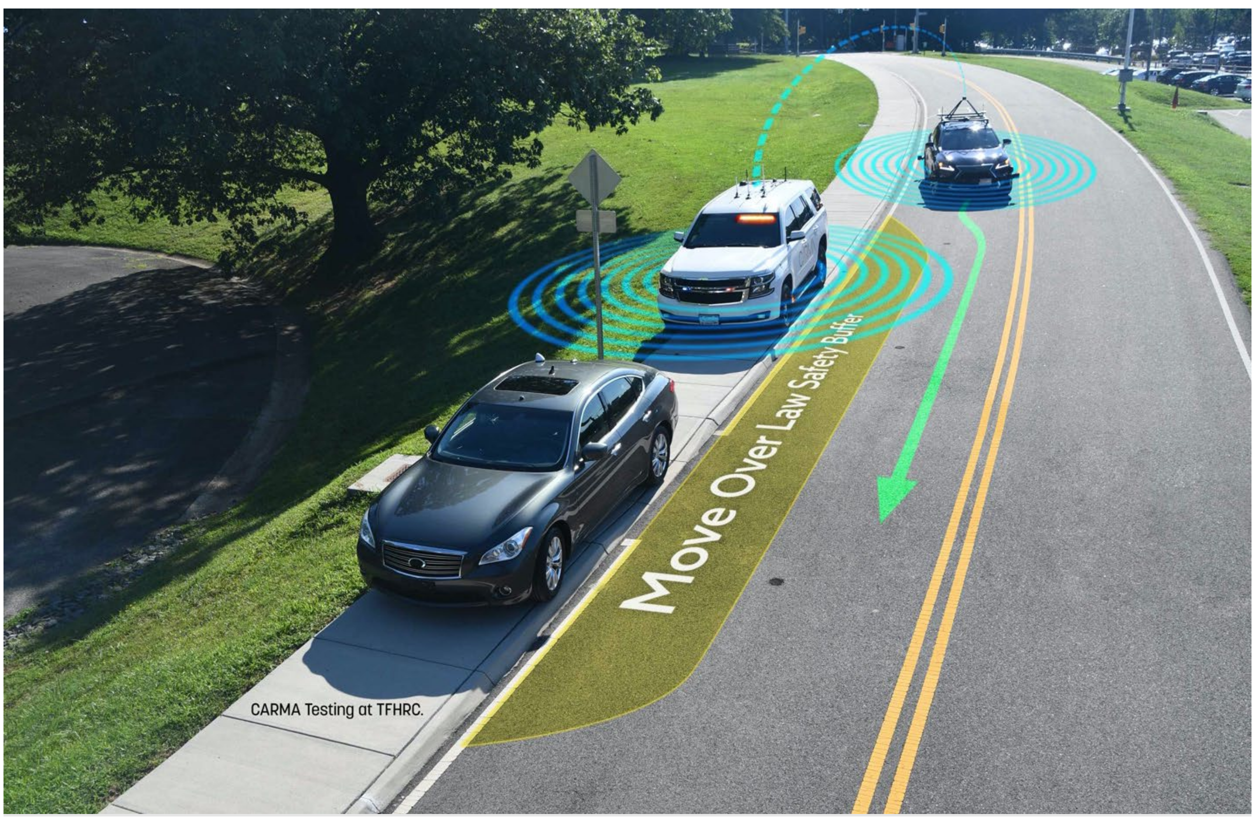
Traffic signal preemption is a TSMO tool that can be used to provide several potential benefits. The TSMO TIM BAT UCs include the following:

- TSMO UC PREEMPT-1: Single-intersection, single incident response vehicle traffic signal preemption.

- TSMO UC PREEMPT-2: Single-intersection, multiple incident response vehicle traffic signal preemption.
- TSMO UC PREEMPT-3: Multiple-intersection along the same route, multiple incident response vehicle traffic signal preemption.
- TSMO UC PREEMPT-4: Queue clearance.
- TSMO UC PREEMPT-5: Single-lane queue clearance.

TSMO UC EVA-1: Move Over

The move-over UC is illustrated in figure 7. CDA-equipped vehicles are alerted to the presence of an incident response vehicle on the roadside, and they are required to provide a safety buffer. Vehicles are required to move over a lane or to reduce their speed to a threshold below the posted speed limit. CDA technology can alert vehicles as they approach an incident response vehicle on the roadside and can monitor the safety buffer during the passing event. This is SAE Class A and/or SAE Class D cooperative driving behavior for SAE Level 3–5 vehicles. The vehicles can be informed about the presence of the incident response vehicle or directed to move over or slow their speed.

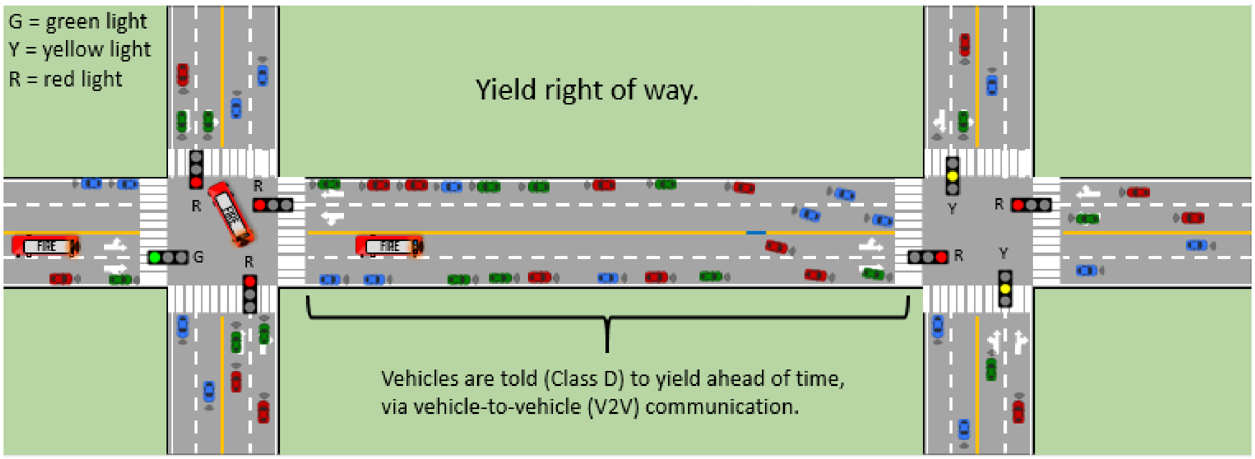


Source: FHWA.

Figure 7. Illustration. TSMO UC EVA-1: Move over.

TSMO UC EVA-2: Yield the Right-of-Way

The yield-the-right-of-way UC utilizes the EVA message to alert nonemergency connected vehicles about an incident response vehicle approaching them in the roadway. When a vehicle is aware of an incident response vehicle approaching, the vehicle is required to move to the right side of the road and stop to clear a pathway for the incident response vehicle to travel. This UC can improve safety and response time. This UC is illustrated in figure 8. This is SAE Class A or SAE Class D cooperative driving behavior.(3) Vehicles can either be made aware of the approaching incident response vehicle or directed to move to the right.

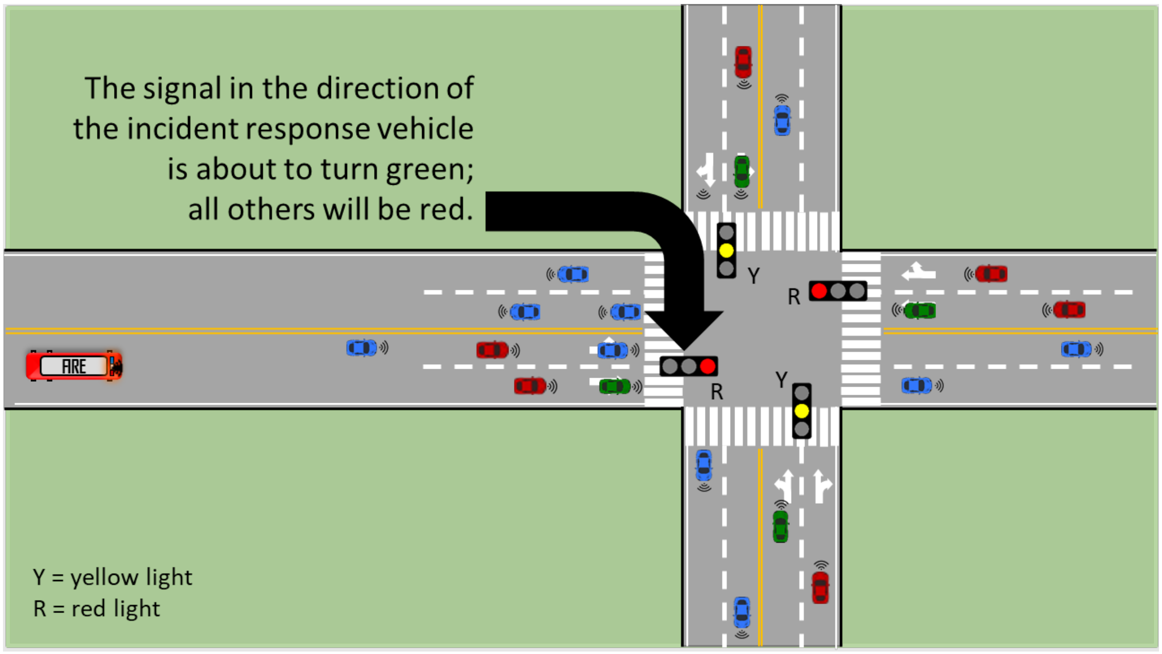


Source: FHWA.

Figure 8. Illustration. TSMO UC EVA-2: Yield the right-of-way.

TSMO UC PREEMPT-1: Single-Intersection, Single Incident Response Vehicle Traffic Signal Preemption Requests

This UC captures the most basic preemption behavior. A CDA incident response vehicle is approaching a signalized intersection (illustrated in figure 9). The vehicle communicates its ETA at the intersection, position, and speed. The traffic signal controller terminates phases that are currently green, with consideration for minimum green, pedestrian walk, pedestrian clearance, yellow change, and red clearance time. The signal will then hold the green indication for the incident response vehicle until it passes the stop bar and clears the intersection. The traffic signal will then return to normal signal timing. This is SAE Class B cooperative driving behavior. When the traffic signal controller becomes aware of the approaching incident response vehicle, it will change to green as quickly as possible. The traffic signal preemption behavior can be realized using the traffic signal controller's preemption capability or using the MMITSS emergency vehicle priority capability.

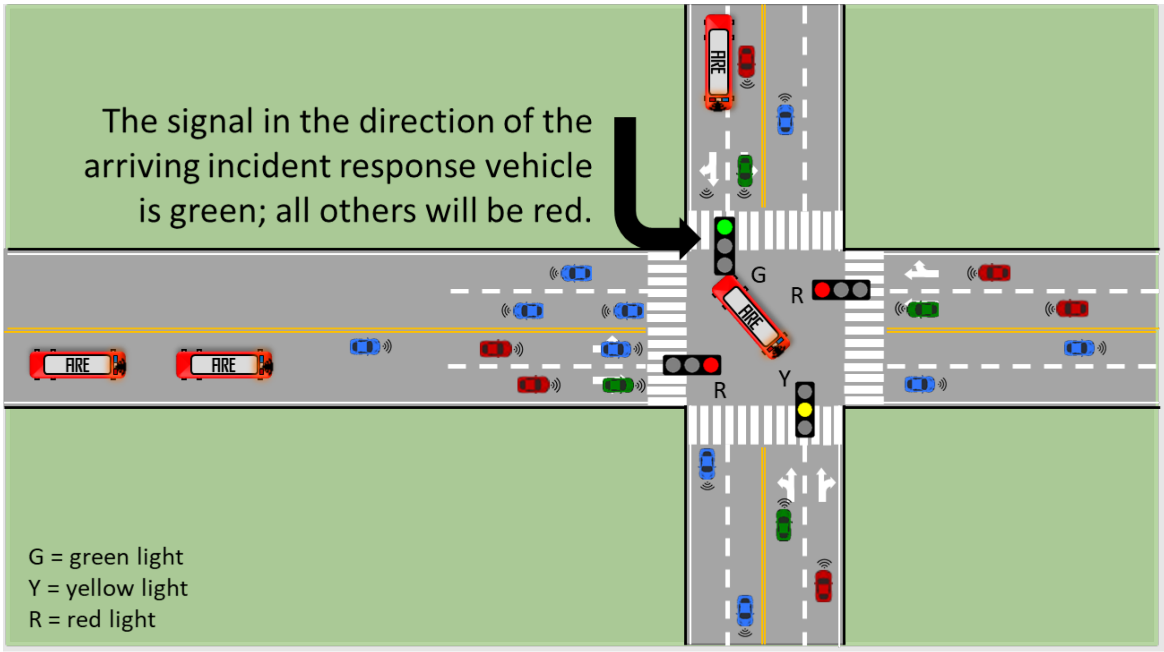


Source: FHWA.

Figure 9. Illustration. TSMO UC PREEMPT-1: Single-intersection, single incident response vehicle traffic signal preemption.

TSMO UC PREEMPT-2: Single-Intersection, Multiple Incident Response Vehicle Traffic Signal Preemption

Figure 10 illustrates the UC at a single intersection where multiple incident response vehicles are approaching, perhaps from different directions. Traditional traffic signal preemption serves the requests for preemption on a first-come-first-serve basis. CDA provides the ability to have additional information about the number, approach direction, and ETA. MMITSS considers the collection of multiple active preemption requests simultaneously and determines the best traffic signal control that will reduce the total delay rather than using a first-come-first-serve protocol. Single-intersection, multiple incident response vehicle traffic signal preemption is SAE Class B cooperative behavior. The traffic signal control uses the information from the vehicles to determine the best traffic signal control within the constraints of the traffic signal controller, including minimum green, pedestrian walk, pedestrian clearance, yellow change, and red clearance times.

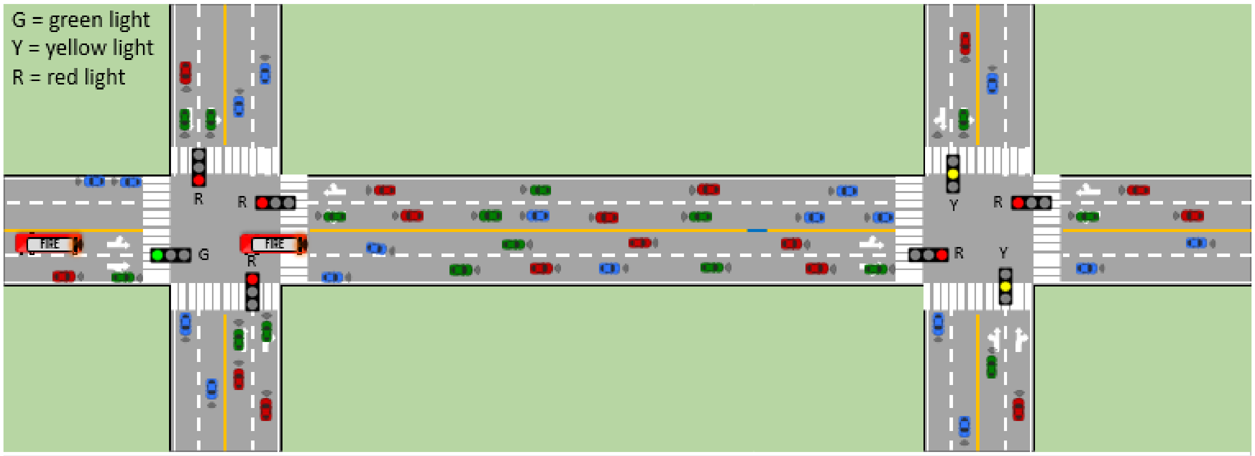


Source: FHWA.

Figure 10. Illustration. TSMO UC PREEMPT-2: Single-intersection, multiple incident response vehicle traffic signal preemption.

TSMO UC PREEMPT-3: Multiple-Intersection, Multiple Incident Response Vehicle Traffic Signal Preemption

Effective traffic signal preemption requires time before an incident response vehicle arrives at the intersection to change from the current phase to the desired service phase (i.e., minimum green, pedestrian walk, pedestrian clearance, yellow change, and red clearance). Traffic signal preemption also requires time for the vehicles to be discharged to create a clear travel path for the incident response vehicle. If the route the incident response vehicle will travel is known, the traffic signals along the path can be preempted well in advance to create a clear path. This is especially true when there are multiple incident response vehicles traveling to an incident. This UC is illustrated in figure 11.



Source: FHWA.

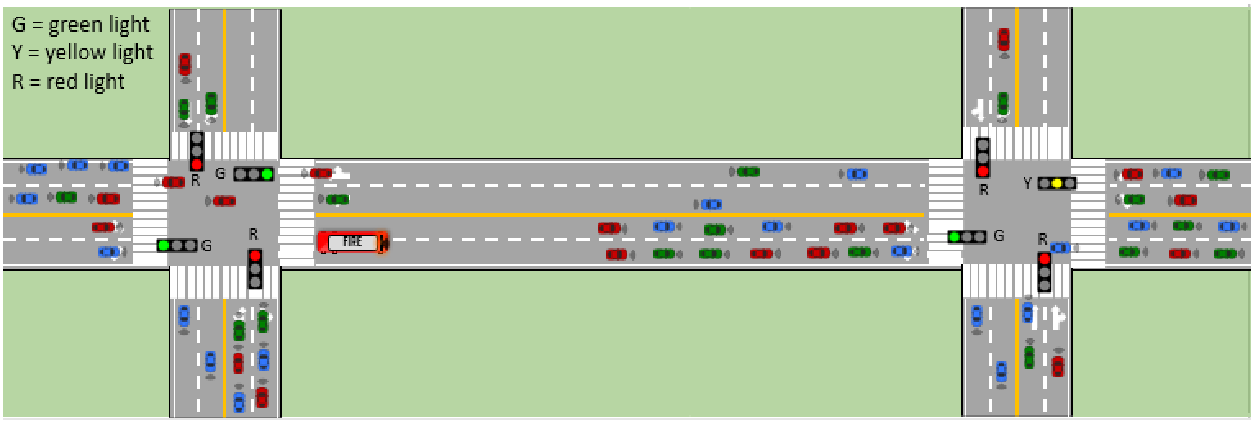
Figure 11. Illustration. TSMO UC PREEMPT-3: Multiple-intersection, multiple incident response vehicle traffic signal preemption.

Route information, location of incident response vehicles, and number of incident response vehicles traveling could be acquired from an emergency dispatch system using CARMA Cloud to coordinate travel along the route. To implement this coordination control strategy, priority requests can be scheduled in the MMITSS priority request server and the arrival times can be adjusted based on vehicle progress. MMITSS has a peer-to-peer capability that allows requests for priority to be forwarded from an upstream intersection to a downstream intersection. The forwarded requests will provide coordination and could be used as confirmation of vehicle arrival along a defined route. Multiple-intersection (route), multiple incident response vehicle traffic signal preemption is SAE Class B cooperative behavior.

TSMO UC PREEMPT-4: Queue Clearance

When the transportation network is congested, or even when there is significant traffic demand, the existence of queues can be an impediment to incident response vehicles. Traffic signal priority and preemption can be used to clear the queues at downstream intersections to create a clear travel path for incident response vehicles. This UC is illustrated in figure 12.

CDA vehicle information can be used to measure queues at intersections along the travel route. The time required to clear a standing queue can be accommodated by using MMITSS traffic signal priority (a less aggressive approach to traffic signal preemption). The queue can be cleared and then preemption can be used to serve the incident response vehicles. MMITSS preemption allows traffic signal phases to be omitted if they are not directly used to serve the approaching incident response vehicles. Queue clearance using traffic signal priority and traffic signal preemption is SAE Class B cooperative behavior.



Source: FHWA.

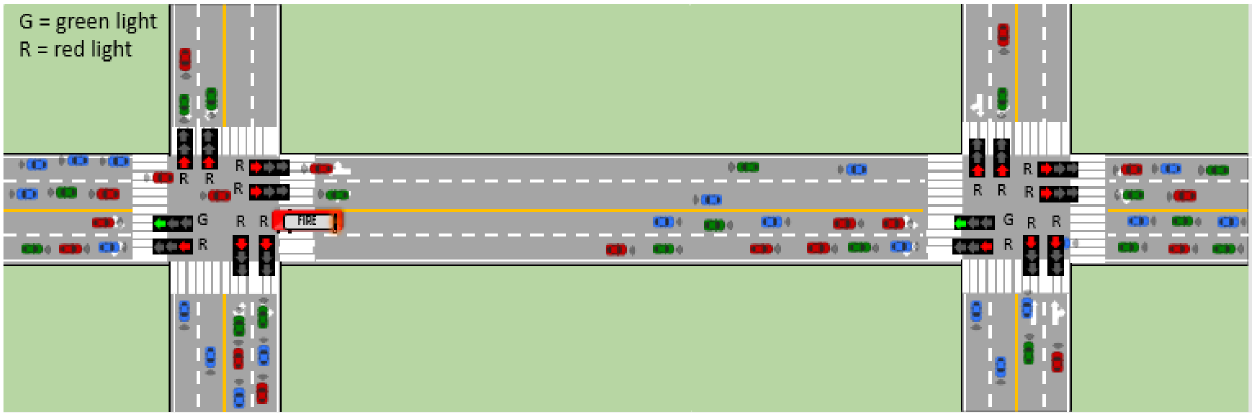
Figure 12. Illustration. TSMO UC PREEMPT-4: Queue clearance.

TSMO UC PREEMPT-5: Single-Lane Queue Clearance

Queue clearance is an effective strategy for improving the travel time of incident response vehicles. However, queue clearance can also cause additional queuing and congestion at downstream signals by releasing a large queue of vehicles that will then travel downstream and enter another queue. If this occurs at multiple intersections along a route, the downstream intersections can become significantly congested. To address this situation, single-lane queue clearance can be used, but requires lane control signals for each of the travel lanes. This is a new concept not directly addressed in the *MUTCD*.[5] However, research has been conducted on the use of lane control signals for daily operations in Harris County, Texas.[44]

Figure 13 illustrates the concept of using lane control for traffic signal operations. Each lane has a traffic signal indication. According to the *MUTCD*, the traffic signals over each lane should be required to have supporting signage and lane markings that are clear to the vehicles. CDA vehicles are ideal for these advance traffic signal control concepts. As shown on the left side of figure 12, at the upstream intersection, the incident response vehicle passes through the intersection on a green traffic signal indication on the inside lane while the queue of vehicles in the right lane is held. At the downstream intersection, the left-hand lane is served by a green lane control indication to clear the queue ahead of the arriving incident response vehicles.

Traffic signal preemption and traffic signal priority can provide a clear path for the incident response vehicle, and traffic congestion can be better managed using lane-based controls. Queue clearance using lane-based traffic signal priority and traffic signal preemption is SAE Class B cooperative behavior.



Source: FHWA.

Figure 13. Illustration. TSMO UC PREEMPT-5: Single-lane queue clearance.

INFRASTRUCTURE CONFIGURATION AND NEEDS

This section describes technological and institutional infrastructure and explains the role of IOOs in developing the CDA TIM operating policies and procedures.

A key feature of CDA operations is the dynamic vehicle-infrastructure interactions, particularly the exchange of real-time vehicular and roadway information that an ADS-equipped vehicle can understand and share. This project considers RSE, an edge processor, and a traffic signal controller used to adapt traffic signal timing. The RSE can communicate to C-ADS-equipped vehicles, irrespective of the particular communication technologies, using the appropriate protocols. C-ADS-equipped vehicles can also share their status and raw sensor data or objects that are sensed in the surrounding dynamic traffic environment to provide accurate world models of static and dynamic objects. The two-way information exchange constitutes the foundation of CDA, which includes both cooperative perception and cooperative vehicle control.

For TIM, cooperative perception is also a key part of the automation. CDA participants, vehicles, and infrastructure may use shared perception information to improve situational awareness and expand their operational design domain. The algorithms for several of these UCs leverages CARMA Cloud to support sharing information between the incident management system and the traffic signal control system. However, many of the UCs can be effective without the cloud-based information.

There are limited user needs relevant to operator-traveler interactions. Travelers are the primary beneficiaries but can also be information providers. Traffic operators, working to support the infrastructure, are the primary service and information providers. They receive information from C-ADS-equipped vehicles, process and analyze the information with all other available information, make appropriate changes to traffic signal timing, and send the resulting information back to C-ADS-equipped vehicles. Table 4 lists the infrastructure needs of road users and IOOs. In this table, road users are C-ADS-equipped and passenger vehicles, such that one-way or two-way information exchanges can occur between them and IOOs.

Table 4. Infrastructure needs and responsibilities for road users (i.e., CDA vehicles) and IOOs.

Road Users (C-ADS-equipped vehicles)	IOOs
N/A.	Monitor traffic conditions.
Inform IOOs of observed traffic conditions.	Receive traffic condition information from travelers.
Get information on traffic conditions downstream. Get maps that contain incident response vehicle routes and incident locations. Get information on incident response vehicle status.	Inform travelers of traffic conditions.
Get information on weather conditions.	Inform travelers of weather conditions.
Inform IOOs of observed weather conditions.	Receive weather condition from road users (optional).
Inform IOOs of statuses, intents, and what they see.	Estimate queues.
N/A	Control traffic signal timing.
Inform IOOs of statuses, intents, and what they see.	Optimize signal timing with consideration for various incident response vehicle types and statuses.
Get SPaT information.	Inform travelers of planned SPaT.
N/A	Control lane use.
Get information on accessible and assigned lanes.	Inform travelers of accessible lanes and assigned lanes.

N/A = not applicable.

Based on the proposed control algorithm for specific UCs, the edge processor and intersection controller will exchange information for requesting and granting traffic signal priority for incident response vehicles, as shown in table 5.

Table 5. Exchanges between RSE and vehicles.

RSE-to-vehicle	Vehicle-to-RSE
Priority status and signal timing	**Cooperative perception**
• Signal status message (SSM) (e.g., SRM acknowledgement). • SPaT plan. • Information from other vehicles.	• SRM (e.g., request for signal priority). • Current status of incident response vehicles.

SUMMARY OF TSMO NEEDS AND REQUIREMENTS

To summarize key features of this TSMO TIM ConOps and inform future development of TSMO TIM system requirements, this section describes operational needs and functional requirements for C-ADS-equipped vehicles and infrastructure. These needs and requirements are specified for different CDA cooperation classes and different components of the proposed control algorithm. For all these operational needs and functional requirements, the following applies:

- Static infrastructure data may include high-definition maps, speed limits, and lane restrictions.
- Dynamic transportation system information may include morning, evening, and off-peak traffic volumes; road closures; work zones; and traffic control system operations.
- C-ADS-equipped vehicle status and intent data may include vehicle identifier (ID) (e.g., license plate or a temporary anonymous ID), vehicle type, location, speed, braking status, heading, priority position, desired time of service (i.e., ETA), intersection approach, lane, and vehicle role (e.g., active fire response, ambulance, and police). These data sets may vary across different cooperation classes.
- RSE advisory data may include acknowledgement information from a vehicle request for priority for each C-ADS-equipped vehicle and RSE signal data including SPaT plan. An edge processor and RSEs are needed in all cooperation classes because C-ADS-equipped vehicles need to receive the SPaT plan. However, they might not be used for transferring information from one C-ADS-equipped vehicle to another if V2V communication range is sufficient in the control area.

Table 6 lists operational needs for vehicles and infrastructure.

Table 6. Operational needs for vehicles and infrastructure in TSMO TIM BAT UCs.

Actor	ID	Operational Need
CARMA Cloud, CARMA Platform, CARMA Messenger	TSMO TIM BAT UC-N01	Communicate incident location to incident response vehicle(s).
CARMA Platform, CARMA Messenger	TSMO TIM BAT UC-N02	Store and broadcast vehicle status and intent information (e.g., location, speed, and route).
CARMA Platform, CARMA Messenger	TSMO TIM BAT UC-N03	For incident response vehicle, send SRM to RSE once it is within range of RSE.
CARMA Cloud, CARMA Streets	TSMO TIM BAT UC-N04	CARMA Streets needs to receive static infrastructure data (e.g., high-definition maps, speed limits, and lane restrictions) from CARMA Cloud.

Actor	ID	Operational Need
CARMA Platform, CARMA Messenger	TSMO TIM BAT UC-N05	Receive static infrastructure data, vehicle-specific advisory data, and SPaT. Receive priority request status information from incident response vehicles.
RSE	TSMO TIM BAT UC-N06	Receive vehicle status and intent information from C-ADS-equipped vehicles.
RSE	TSMO TIM BAT UC-N07	Receive SRM from incident response vehicles.
RSE–CARMA Streets	TSMO TIM BAT UC-N08	RSE needs to relay received data to CARMA Streets.
RSE–CARMA Streets	TSMO TIM BAT UC-N09	RSE needs to receive static infrastructure data, vehicle-specific advisory data, and SPaT from CARMA Streets and broadcast this information.
RSE–CARMA Streets–RSE	TSMO TIM BAT UC-N10	CARMA Streets needs to send signal status message information to RSE for broadcast to incident response vehicles to acknowledge receipt of SRM.
CARMA Streets	TSMO TIM BAT UC-N11	Receives and stores SPaT data.
CARMA Streets	TSMO TIM BAT UC-N12	Stores data from various sources (e.g., incident response vehicles, C-ADS-equipped vehicles, and traffic sensors).
CARMA Streets	TSMO TIM BAT UC-N13	Processes data and calculates traffic signal preemption-related variables (e.g., preemption status, signal adaptation, queue length and dissipation estimation, and speed advisory).
CARMA Cloud, CARMA Streets	TSMO TIM BAT UC-N14	CARMA Cloud needs to relay work zone data to CARMA Streets.
CARMA Streets, signal controller	TSMO TIM BAT UC-N15	CARMA Streets needs to communicate with the signal controller to adapt the signal timing.
CARMA Streets	TSMO TIM BAT UC-N16	Aggregates traffic information received from individual vehicles and sensors.
CARMA Cloud, CARMA Streets	TSMO TIM BAT UC-N17	CARMA Streets needs to send aggregate traffic information to CARMA Cloud.
CARMA Cloud, CARMA Platform, CARMA Messenger, CARMA Streets, RSE, signal controller	TSMO TIM BAT UC-N18	All must have proper cybersecurity platforms and strategies to protect them from and help them recover from cyber threats.

Table 7 lists functional requirements for C-ADS-equipped vehicles, RSEs, and a central computer. These requirements are also specified for different cooperation classes.

Table 7. Functional requirements for vehicles and infrastructure in TSMO TIM UCs.

ID	Functional Requirement	Cooperation Class
TSMO TIM BAT UC-R01	A C-ADS-equipped incident response vehicle with at least cooperation Class A has an onboard computer with storage and computing functions.	A, B, C, and D
TSMO TIM BAT UC-R02	A C-ADS-equipped incident response vehicle with at least cooperation Class A has an alert system with lights and a siren that provides statuses to an onboard computer.	A, B, C, and D
TSMO TIM BAT UC-R03	A C-ADS-equipped incident response vehicle with at least cooperation Class A broadcasts its location, speed, and heading. The communication frequency is approximately 10 hertz (Hz) or more.	A, B, C, and D; status data only for Class A
TSMO TIM BAT UC-R04	A C-ADS-equipped incident response vehicle with at least cooperation Class A determines the distance and time to the intersection stop bar and sends an SRM when traffic signal preemption is desired. The vehicle will determine if the lights and siren system is active to qualify to send an SRM.	A, B, C, and D
TSMO TIM BAT UC-R05	A C-ADS-equipped incident response vehicle with at least cooperation Class A determines that the lights and siren system is active and then broadcasts an EVA message.	A, B, C, and D
TSMO TIM BAT UC-R06	Each intersection has an edge processor that is capable of running traffic signal preemption algorithms (i.e., MMITSS) and communicating NTCIP to a traffic signal controller.	A, B, C, and D
TSMO TIM BAT UC-R07	The central computer provides incident information—such as the location of the incident, the location of the assigned response vehicle, and the route the vehicle will travel to the incident—to the edge processor at a signalized traffic intersection.	A, B, C, and D
TSMO TIM BAT UC-R08	The central computer provides downstream traffic congestion information to the intersection's edge processor.	A, B, C, and D

ID	Functional Requirement	Cooperation Class
TSMO TIM BAT UC-R09	RSE receives status and intent data from C-ADS-equipped vehicles with at least cooperation Class A within the communication range. The communication frequency is approximately 10 Hz or more.	A, B, C, and D
TSMO TIM BAT UC-R10	RSE broadcasts traffic signal status and intent data among C-ADS-equipped vehicles within the communication range using DSRC or C-V2X. The communication frequency is approximately 10 Hz or more.	A, B, C, and D; optional for when CDA communication range is too short, and data needs to be relayed using RSEs.
TSMO TIM BAT UC-R11	RSE sends vehicle-specific advisory data and determined SPaT within the communication range using DSRC or C-V2X. The communication frequency is approximately 10 Hz or more.	A, B, C, and D
TSMO TIM BAT UC-R12	RSE rebroadcasts EVA messages received from incident response vehicles.	A, B, C, and D

PERFORMANCE METRICS AND TARGET TRAFFIC FLOW

The effectiveness of TSMO TIM BAT UCs can be evaluated by measuring their capability to positively impact performance. Performance metrics in this ConOps are presented from two perspectives: incident response vehicle travel experience and traffic flow.

Performance Metrics for Traveler Experience

Performance metrics for monitoring and evaluating vehicle operations during the execution of these use cases include the following:

- Safety—Number of crashes or near crashes (conflicts) that incident response vehicles are involved in while actively responding to incidents.
- Incident response travel time—Time for a collection of incident response vehicles to travel from their origins to the incident location. In a corridor, this would include the time from control corridor entry to the time of corridor exit or of arrival at the incident location.
- Travel time of other road users—Time for a vehicle to travel from an origin to a destination in the control corridor.
- Incident response vehicle queueing delay—Time that an incident response vehicle is delayed due to nonincident response vehicle obstruction or queueing.
- Incident response vehicle traffic signal delay—Time an incident response vehicle is stopped at a traffic signal, including time waiting for a traffic queue to clear.

- Nonincident response vehicle traffic signal delay—Time a nonincident response vehicle is stopped at a traffic signal, including time in a traffic queue.
- Data exchanges during communication/negotiation—All data exchanges from V2V, V2I, and I2V are used to determine if communication and maneuver negotiations took place as designed. Data exchanges include the following data types:
    - Number of vehicles that request traffic signal priority.
    - Number of SRMs that require requests per vehicle.
    - Number of attempts needed before a plan is accepted by all affected neighbors.
    - Frequency of packet loss.
    - Latency of message: The time difference between message origination on vehicle A and the reading of the message by infrastructure and vice versa. Latency time includes the time it takes to compose the message and send it from vehicle A's guidance computer to vehicle A's OBU, the queuing time on vehicle A's OBU, the radio transmission time from vehicle A to infrastructure, the message constitution and queueing time on infrastructure's RSE, the transformation time from infrastructure's RSE to infrastructure's computer, the time required for retransmission in the case of message loss, and the time for infrastructure's decomposition and reading.

Performance Metrics on Traffic Performance

Performance metrics on traffic performance evaluate the impact of TSMO TIM BAT UCs on traffic flow in corridors. Table 8 summarizes two categories of impacts: throughput (nonincident response vehicles) and traffic congestion (level of service).

Throughput

CDA technologies are expected to increase the vehicle throughput of transportation facilities by increasing the number of vehicles served. Throughput can be quantified by measuring the number of vehicles passing through a corridor per hour and the variability of speeds within a facility segment.

Traffic Congestion

CDA technologies are applied to improve incident response performance. Since traffic signal preemption is an exception to normal traffic operations, the impacts of these technologies could be significant. Traffic congestion can be measured by level of service, as defined in the *Highway Capacity Manual*.(45)

Table 8. Summary of performance metrics for TSMO TIM BAT UC evaluation.

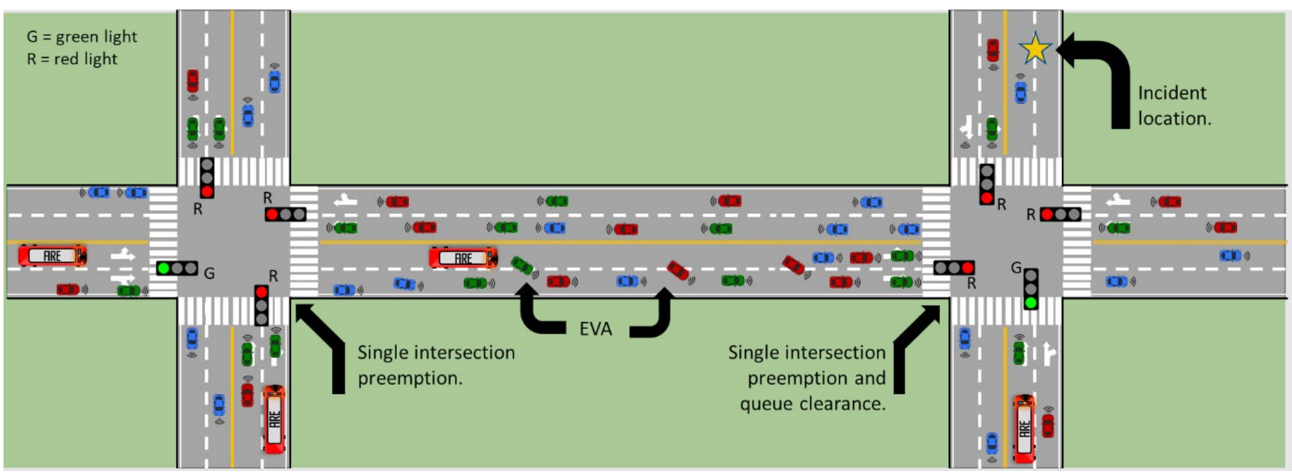
Category	Impact	Performance Metric
Safety	Safety of incident responders is the highest priority.	Crashes and conflicts. Surrogate safety measures of conflicts can be used to characterize the level of safety. Some surrogate safety measures include time to collision, modified time to collision, post-encroachment time, and speed differential.
Throughput	Increase in number of vehicles that can be served in a corridor.	Number of vehicles passing through the corridor per hour.
Throughput	Potential increase in delay for nonincident response vehicles when traffic signal preemption is given to incident response vehicles.	Average traffic signal delay for nonincident response vehicles.
Traffic congestion	Potential impact in quality of service by shifting priority to incident response vehicles.	Level of service.[44]

CHAPTER 4. OPERATIONAL SCENARIOS

This chapter identifies three TSMO TIM BAT operational scenarios. Each scenario includes one or more of the UCs described in chapter 3. The operational scenarios help to increase understanding of the impact of the potential deployment of certain TIM UCs in early stages of CDA technology development. The first operational scenario considers the use of traffic signal preemption and the issue of yielding the right-of-way in a corridor. The second scenario extends the first scenario to consider route-based preemption and the use of lane-by-lane traffic signal control for queue clearance. The third scenario explores the use of CDA when there is a work zone that can cause response delay for incident response vehicles. These scenarios are designed to cover all the key features of the proposed control framework and illustrate their potential benefits.

SCENARIO 1: ARTERIAL WITH MULTIPLE INCIDENT RESPONSE VEHICLES

This scenario captures incident response operations on a corridor and includes TSMO UC PREEMPT-2 (single intersection, multiple incident response vehicle traffic signal preemption) and TSMO UC EVA-2 (yield the right-of-way). This scenario is illustrated in figure 14. It is assumed that traffic signals in the corridor are operated as a coordinated system and have coordination signal timing plans (e.g., cycle length, offset, and phase spits) that have been selected based on the traffic volumes for the time of day.



Source: FHWA.

Figure 14. Illustration. Scenario 1: Basic arterial with multiple incident response vehicles.

In this scenario, four incident response vehicles are active in the corridor. One of the incident response vehicles has just exited the intersection on the left and is headed toward the intersection on the right; it is requesting traffic signal preemption. Two other incident response vehicles are approaching the intersection on the left; both are requesting traffic signal preemption. The fourth incident response vehicle is approaching the right intersection from the bottom and requesting preemption. Vehicles on the arterial are being alerted to the presence of the incident response vehicles and are moving to the right lane to clear a path.

Scenario 1 captures several key operating characteristics, as follows:

- Multiple incident response vehicles may issue priority requests at any intersection at any given time.
- Traffic signals operate as a coordinated system.
- Incident response vehicles alert other vehicles to their presence.
- Other vehicles yield the right-of-way to incident response vehicles. If the other vehicles are C-ADS vehicles, this communication is SAE Class D cooperation; otherwise, it is SAE Class A cooperation.

Scenario 1 will allow the performance of the system to be evaluated to better understand the following:

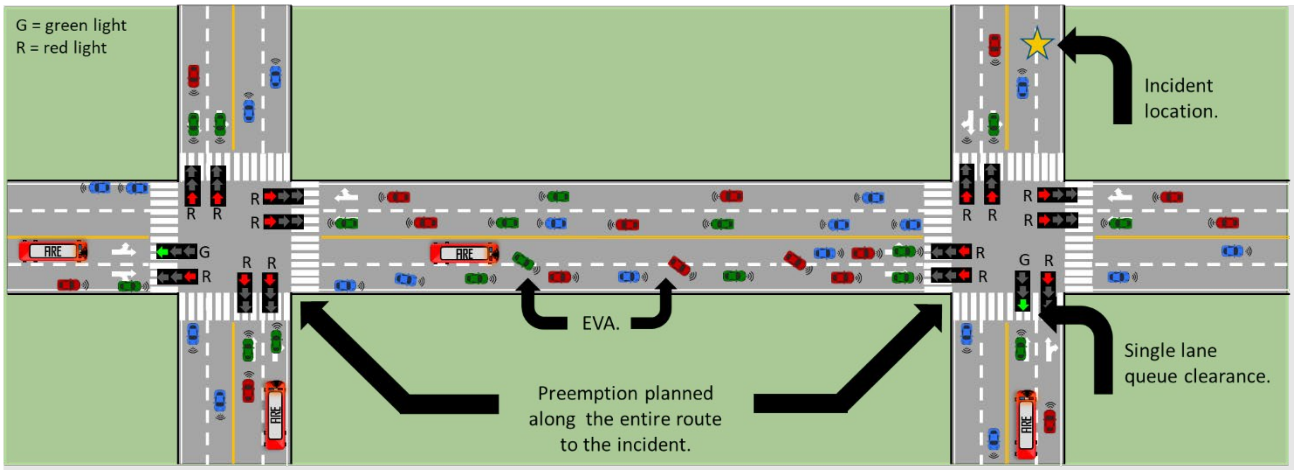
- Benefits for incident response operations of the TSMO TIM, such as incident response vehicle travel time and impact or delay to nonincident response vehicles.
- Impact of number of active incident response vehicles on system performance.
- Impact of conflicting incident response vehicle requests for preemption (e.g., main arterial and cross streets).
- Impact of providing traffic signal preemption in a coordinated system of traffic signals.

Scenario 1 highlights several important features. First, the ability to use CDA data to make preemption signal timing decisions with an algorithm that can accommodate multiple active incident response vehicles is valuable. Next, the EVA message is valuable in its ability to alert other vehicles to the presence of incident response vehicles so they can clear a path. Both UCs can improve incident response vehicle safety and response time.

SCENARIO 2: ROUTE-BASED PRIORITY WITH LANE-BY-LANE TRAFFIC SIGNAL PREEMPTION AND YIELD THE RIGHT-OF-WAY

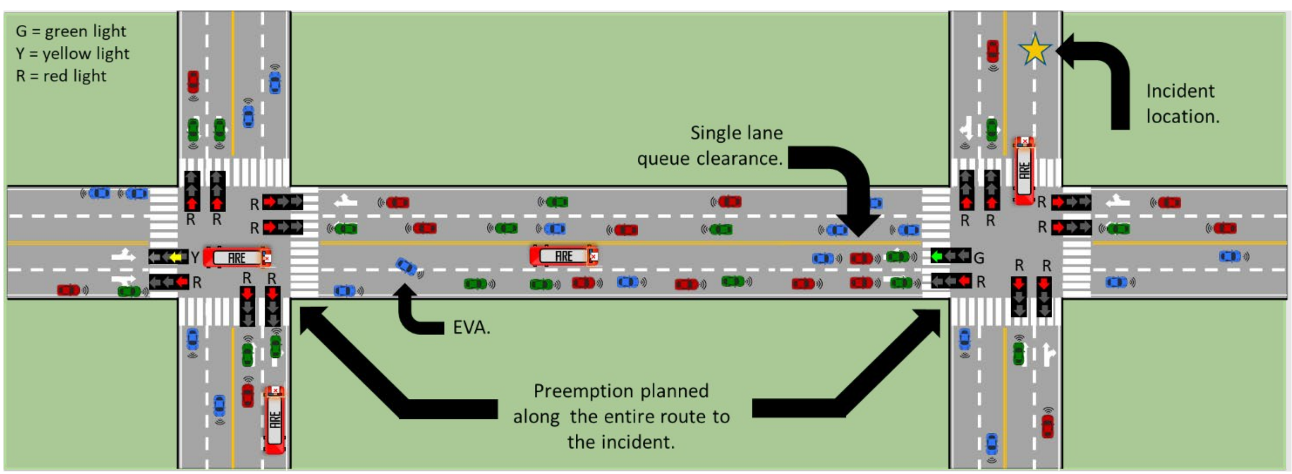
Scenario 2 depicts an incident on the egress leg of the intersection on the right. In figure 15-A at time 1, there are four active incident response vehicles. One incident response vehicle has just exited the left intersection in the center lane, which had provided a green indication when the incident response vehicle requested traffic signal preemption. Two other incident response vehicles are approaching the left intersection. They are each requesting traffic signal preemption. The incident response vehicle approaching from the left will receive the center lane green indication, because the signal was already in that state, even though the incident response vehicle approaching from the bottom is closer and would have arrived sooner. The fourth incident response vehicle is approaching the intersection on the right from the bottom. It is requesting traffic signal preemption and receiving a green signal indication on the inside lane.

In figure 15-B at time 2, the incident response vehicle approaching the left intersection from the left is clearing the intersection. The traffic signal has changed to the yellow interval as it transitions to provide traffic signal preemption for the incident response vehicle arriving from the bottom. The incident response vehicle that approached the intersection on the right from the bottom has cleared the intersection. The traffic signal has already transitioned to the green interval for the vehicle approaching from the left, which is requesting traffic signal preemption. The queue on the inside lane of the left approach to the intersection on the right will have sufficient time to clear before the incident response vehicle arrives. In both intersections, all movements that are not serving incident response vehicles are in a red interval to prevent vehicles from entering the response routes of the incident response vehicles.



Source: FHWA.

A. Time 1.



Source: FHWA.

B. Time 2.

Figure 15. Illustrations. Route-based priority with lane-by-lane traffic signal preemption and yielding of right-of-way.

TSMO UC EVA-2 (yield the right-of-way) supports the CDA capability of directing (SAE Class D cooperation) C-ADS vehicles to yield the right-of-way to incident response vehicles and alerting other CDA vehicles to the presence of active incident response vehicles. TSMO UC PREEMPT-3 (multiple-intersection (route) and multiple incident response vehicle traffic signal preemption) and TSMO UC PREEMPT-5 (single-lane queue clearance) create response "tunnels" for each of the incident response vehicles.

Scenario 2 captures several key operating characteristics, as follows:

- Multiple vehicles may request traffic signal preemption along an incident response route at the same time.
- The traffic signals should operate as a coordinated system.
- Lane-by-lane traffic signal indications will allow the creation of incident response "tunnels" that can accommodate queue clearance and reduce the number of vehicles with conflicting movements in an intersection.
- Incident response vehicles can alert other vehicles to their presence so the other vehicles can yield the right-of-way. If the other vehicles are C-ADS vehicles, this is SAE Class D cooperation; otherwise, it is SAE Class A.

This scenario will allow researchers to evaluate traffic performance to better understand the following:

- Benefits of TSMO TIM on incident response operations.
- Impacts of TSMO TIM on other road users.
- Impact of number of active incident response vehicles on system performance.
- Impact of conflicting incident response vehicle requests for preemption (e.g., main arterial and cross streets).
- Impact of providing traffic signal preemption in a coordinated system of traffic signals.
- Benefits of lane-by-lane traffic signal control to provide queue clearance.

Scenario 2 highlights several important features. First, the ability to use CDA data to make preemption signal timing decisions with an algorithm that can accommodate multiple active incident response vehicles is valuable. Next, the ability to control traffic flow on a lane-by-lane basis to reduce the number of potential conflicts and the flow of queued vehicles to downstream intersections is valuable. Finally, the EVA message's ability to alert other vehicles to the presence of incident response vehicles so they can move out of the way is also valuable. These UCs can improve incident response vehicle safety and response time.

SCENARIO 3: WORK ZONE INCIDENT RESPONSE

Work zones generally have delays due to reduced speed and lane availability. In this scenario, TIM can be used to help incident response vehicles travel through the work zone faster. With the awareness of a work zone on the route to an incident, upstream intersections can be used to meter the volume of traffic entering the work zone ahead of one or more incident response vehicles. This metering may reduce the queue entering the work zone. Many work zones consist of a single lane, but some work zones may have more than one lane. When there is more than one lane, TSMO UC EVA-2 could provide improvements to incident response vehicle travel time. Scenario 3 enables work-zone information to be available for TIM in arterial corridors.

Scenario 3 will allow researchers to evaluate traffic performance to better understand the following:

- Use of traffic signal priority or preemption to meter flow of traffic into a work zone.
- Use of EVA in work zones with multiple travel lanes to direct C-ADS vehicles to move to the right (SAE Class D cooperation) and alert CDA vehicles to the presence of the incident response vehicles so they can also move to the right (SAE Class A cooperation).

CHAPTER 5. ANALYSIS OF THE PROPOSED SYSTEM

This chapter provides an analysis of the benefits, advantages, limitations, and disadvantages of TSMO TIM BAT UCs on signalized arterials using scenario 1, which was discussed in chapter 4. A high-level system validation plan is also discussed.

SUMMARY OF POTENTIAL BENEFITS AND OPPORTUNITIES

CDA technologies enable mobility applications that are not achievable by individual ADS-operated vehicles. They do so by sharing information that can be used to increase the safety, efficiency, and reliability of the transportation system. This information may also serve to accelerate the deployment of driving automation in on-road motor vehicles. CDA aims to improve the mobility of travelers in transportation systems. This is accomplished, for example, by sharing information about incident response vehicle status (location, destination, and route); estimating queues and traffic congestion; and providing preferential treatment on signalized arterials. Cooperation among diverse participants and perspectives in traffic, especially at conflict areas (e.g., intersections, merging roadways), can improve safety, mobility, situational awareness, and operations.

For the TSMO TIM BAT UCs, an integrated control framework is proposed to efficiently manage traffic on signalized arterials. Vehicle capabilities, including generating and sending SRMs, can be processed on CDA-capable vehicles using CARMA Platform. This information can be shared with infrastructure using CDA-enabled wireless communications, regardless of the particular technology. Infrastructure, using CARMA Streets, can provide preemption and priority traffic signal control that specifically accommodates incident response vehicle requests. Information about incident response vehicle location, speed, destination, and route can be made available through CARMA Cloud through integration with incident response management and dispatch systems. For this analysis, only CARMA Platform and CARMA Streets are considered.

SYSTEM VALIDATION PLAN

This section describes methods to validate the developed algorithms and software systems for the TSMO TIM BAT UCs. Validation testing helps ensure that, once developed, the TSMO TIM BAT UC system can meet the operational needs for scenario 1 listed in table 8.

Simulation Testing

Simulations can be designed to test the developed signal control algorithm for the TSMO TIM BAT UCs using the performance metrics, identified in chapter 3, of incident response vehicle and infrastructure behavior and traffic system performance. Different types of simulation can be used and combined for testing purposes.

Traffic simulators offer the possibility to scale up evaluation to an intersection corridor or network level (as compared to a limited number of vehicles and amount of roadway length for ADS simulators) to study CDA's impacts on transportation system performance. For this purpose, these impacts are measured using traffic performance metrics such as safety, efficacy, stability, and sustainability. Traffic simulators can evaluate various scenarios, such as traffic demand, TIM, and intersection geometry (including near-side bus stops). Usually, the CDA control algorithms will be simplified from real software and parsimonious to calibrated and validated CDA behavioral models and algorithms that are implementable for large-scale testing.

Field Testing

To ensure the developed algorithm can be reliably and easily implemented into CARMA Platform, proof-of-concept tests will be conducted on a closed-test track. This can be demonstrated on site at a signalized intersection that is typical of anywhere in the United States. Depending on participation by partners, multiple CARMA vehicles loaded with necessary feature groups can be instructed to run loops on the test track to represent continuous driving. The operational scenarios discussed in chapter 4 can be tested. The purpose of the testing can be to verify the software, collect vehicle behavior performance measures, and validate if the software meets the requirements. Data collected from the test track can be used not only to calculate vehicle behavior performance metrics, but also to calibrate traffic simulation CDA behavior models. This may enable better evaluation of CDA's traffic impacts using validated simulation models.

SUMMARY OF IMPACTS

The proposed control strategy for the TSMO TIM BAT UCs can impact the research and operations of future transportation systems management. From a research perspective, the proposed control strategy offers an approach to efficiently manage transportation systems at signalized intersections and reduce any adverse effects, such as improving safety while reducing excessive delay. The benefits of the TSMO TIM BAT UCs can be demonstrated using CDA incident response vehicles that send SRMs to infrastructure when responding to incidents. The infrastructure components accept the SRMs and adapt the traffic signal timing, within the structure of the traffic signal controller, to provide benefits to the incident response vehicles.

From an operations perspective, the proposed control strategy for the TSMO TIM BAT UCs presents changes to how TSMO is conducted at signalized intersections. Intelligent transportation system infrastructure systems would need to be upgraded to accommodate CDA system needs, such as RSE services and supporting information technologies. Agencies would need to evaluate and build up capabilities for operating such emerging systems. The conventional process of transportation system performance monitoring and reporting could be improved with the prevalence of C-ADS-equipped vehicles and advanced sensors. Conventional strategies for TSMO that agencies may already be familiar with can be enhanced by CDA technologies.

Disadvantages and Limitations

The proposed control strategy for the TSMO TIM BAT UCs provides insights into CDA operations at signalized intersections but may face limitations, such as the following:

- Providing traffic signal preemption for incident response vehicles can impact the performance of other traffic. Incident response is considered an exception to normal operations, but the impact of shifting the capacity should be understood and mitigated if excessive.

- Simulating incident responses can be challenging. Many scenarios can be considered, and it is challenging to select those that are common because incident response is an exception to normal operations. Ideally, safety and mobility will be improved without significant negative impact.

CHAPTER 6. SUMMARY AND CONCLUSION

CDA aims to improve the safety, traffic throughput, and energy efficiency of the transportation network by allowing vehicles and infrastructure to work together to coordinate movement. The FHWA CDA Research Program is utilizing the CARMA Ecosystem to research CDA and leverage emerging capabilities in automation and cooperation to advance TSMO strategies.

The objective of this project is to advance the CARMA Ecosystem to enhance infrastructure performance, improve network efficiency, reduce traffic congestion through TSMO strategies on arterials, and enable further capabilities for CDA participants to interact with the road infrastructure. This ConOps focuses on TSMO TIM use cases, which investigate active traffic management strategies applied to traffic signal corridors. TSMO TIM is a traffic management tool that can help improve safety and reduce travel time delay caused by traffic signals for incident response vehicles. The proposed approach for TSMO TIM has two components: First, local traffic signal optimization to improve safety and reduce delay to one or more incident response vehicles using CARMA Streets. Second, corridor-coordinated TSMO TIM to optimize signal timing in a corridor using CARMA Cloud. The proposed control framework is expected to improve safety and reduce incident response travel time.

CDA technologies can enhance situational awareness when incident response vehicles are active. Table 9 summarizes the TSMO TIM BAT UCs. The UCs are classified as SAE Class B because the incident response vehicle in each UC shares its intent and requests cooperative behavior from infrastructure and other CDA vehicles.

Table 9. Summary of TSMO TIM BAT UCs.

TSMO TIM BAT UCs	Description	SAE CDA J3216_202107 Class Behavior
EVA-1	Vehicles are alerted to the presence of an incident response vehicle on the roadside and are required to provide a safe barrier.	Class B
EVA-2	Vehicles yield the right-of-way to incident response vehicles to provide safer travel and reduce response time.	Class B
PREEMPT-1	Single-intersection, single incident response vehicle traffic signal preemption.	Class B
PREEMPT-2	Single-intersection, multiple incident response vehicle traffic signal preemption.	Class B
PREEMPT-3	Multiple-intersection (route), multiple incident response vehicle traffic signal preemption.	Class B
PREEMPT-4	Queue clearance (approach).	Class B
PREEMPT-5	Single-lane queue clearance.	Class B

The CDA Program team has created two V2V UCs based on the SAE J2735 EVA message.[41] These UCs, which improve situational awareness, are as follows:

- TSMO UC EVA-1: Vehicles are alerted to the presence of an incident response vehicle on the roadside and are required to provide a safety barrier. This UC can improve safety.
- TSMO UC EVA-2: Vehicles are required to yield the right-of-way and move to the right side of the roadway to clear a pathway for incident response vehicles approaching from the rear. This UC can improve safety and response time.

Traffic signal preemption is a TSMO tool that can provide potential benefits. The TSMO TIM UCs include the following:

- TSMO UC PREEMPT-1: Single-intersection, single incident response vehicle traffic signal preemption.
- TSMO UC PREEMPT-2: Single-intersection, multiple incident response vehicle traffic signal preemption.
- TSMO UC PREEMPT-3: Multiple-intersection, multiple incident response vehicle traffic signal preemption.
- TSMO UC PREEMPT-4: Queue clearance.
- TSMO UC PREEMPT-5: Single-lane queue clearance.

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