Concept of Operations for CARMA Integrated Highway Prototype 2

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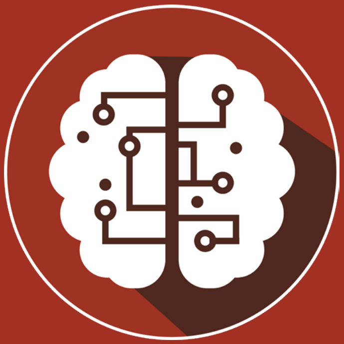

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Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
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McLean, VA 22101-2296

FOREWORD

The Federal Highway Administration's (FHWA's) 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 are known as the CARMA Ecosystem, to enable CDA research. The CARMA Ecosystem is a research environment that enables 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, 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 that leverage infrastructure to support cooperative automation strategies. This project expands previous functionality to include three key feature groups on freeways—cooperative lane follow (platooning and cooperative adaptive cruise control), cooperative lane coordination (cooperative lane change, merge, and weave), and cooperative traffic management (speed and gap control, lane assignment, and queue management). 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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16. Abstract

Cooperative driving automation aims to improve the safety and flow of traffic and facilitate road operations by supporting the movement of multiple vehicles in proximity to one another. This outcome is accomplished by sharing information that can be used to influence dynamic driving tasks directly or indirectly by one or more nearby road users. Vehicles and infrastructure elements engaged in cooperative driving automation may share information, such as state (e.g., vehicle position, signal phase) or intent (e.g., planned vehicle trajectory, signal timing), or they may seek agreement on a plan (e.g., coordinated merge). Cooperation among multiple participants in traffic can improve safety, mobility, situational awareness, and operations. For Integrated Highway Prototype 2 (IHP2), three key feature groups included cooperative lane follow (platooning and cooperative adaptive cruise control), cooperative lane coordination (cooperative lane change, merge, and weave), and cooperative traffic management (speed and gap control, lane assignment, and queue management). The combination of these feature groups to form IHP2 provides benefits to both the individual traveler and the overall traffic system.

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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 ACRONYMS

ACC	adaptive cruise control
ACK	acknowledge
ADS	automated driving systems
AMS	analysis, modeling, and simulation
CACC	cooperative adaptive cruise control
C–ADS	cooperative automated driving system
Caltrans	California Department of Transportation
CAV	connected automated vehicle
CDA	cooperative driving automation
CLC	cooperative lane coordination
CLF	cooperative lane follow
ConOps	concept of operations
CTM	cooperative traffic management
DDT	dynamic driving task
DOT	department of transportation
DSRC	dedicated short-range communication
FHWA	Federal Highway Administration
HOV	high-occupancy vehicle
HRSO	Office of Safety and Operations Research and Development
ID	identification
IHP	Integrated Highway Prototype
IHP1	Integrated Highway Prototype 1
IHP2	Integrated Highway Prototype 2
IOO	infrastructure owner and operator
ITS	intelligent transportation system
N/A	not applicable
NACK	not acknowledged
OBU	onboard unit
R&D	research and development
RSU	roadside unit
SOV	single-occupancy vehicle
STOL	Saxton Transportation Operations Laboratory
TCD	traffic control device
TMC	Traffic Management Center
TSMO	Transportation Systems Management and Operations
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VSL	variable speed limit

CHAPTER 1. SCOPE AND SUMMARY

IDENTIFICATION

This document serves as a concept of operations (ConOps) for the basic travel use case to include SAE International® Level 3 and above automated driving systems (ADS), with and without connectivity and cooperation. The basic travel use case, as part of the Integrated Highway Prototype 2 (IHP2) project, includes cooperative lane follow (CLF), cooperative lane coordination (CLC), and cooperative traffic management (CTM) in a general-purpose freeway facility.

DOCUMENT OVERVIEW

Background

The Office of Safety and Operations Research and Development (HRSO) performs transportation operations research and development (R&D) for the Federal Highway Administration (FHWA). Onsite R&D is conducted at the Saxton Transportation Operations Laboratory (STOL) established at Turner-Fairbank Highway Research Center. HRSO conducts safety and operations R&D based on a national perspective of the transportation needs of the United States.

In 2015, HRSO 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 CARMA Platform℠ as an advancement of standard adaptive cruise control (ACC) systems by using vehicle-to-vehicle (V2V) dedicated short-range communications (DSRC) to automatically synchronize the longitudinal movements of many vehicles within a string. The CACC 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 developed a new reference platform, CARMA2℠, to enable research to be easily shared and integrated into industry research vehicles. The project advanced the CACC functionality and developed a proof-of-concept platooning application that enabled leader-follower behavior and allowed vehicles to begin to negotiate with one another. The project also developed the Integrated Highway Prototype 1 (IHP1), which integrated speed harmonization, lane change/merge, and platooning into one package. This research focused on developing the understanding around negotiations among entities and how this negotiation can be done efficiently to help improve traffic flow based on cooperative tactical maneuvers.

A current task order is producing the third iteration of CARMA℠. CARMA3℠ takes the platform into the world of ADS with SAE Level 3, and above, automation. The approach takes advantage of an open-source ADS platform to enable ADS functionality to be used for cooperative automation strategies.

CARMA Cloud℠, CARMA Messenger, and CARMA Streets are also being developed. CARMA Cloud represents the infrastructure piece of cooperative driving automation (CDA), where vehicles and other entities may communicate with infrastructure to increase the safety and efficiency of the transportation network. CARMA Messenger represents the capability of moving, non-automated entities (e.g., first-responder vehicles, pedestrians, buses) to communicate with CARMA-equipped vehicles and infrastructure to improve the performance of the network. CARMA Streets enables vehicles to communicate with the infrastructure at intersections and provides an interface to traffic signal controllers to optimize travel through an intersection. CARMA Platform, CARMA Cloud, CARMA Messenger, and CARMA Streets are open source and are built with the goal of benefiting CDA research. Table 1 lists the projects associated with this development.

Table 1. Projects associated with this CARMA 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: Prototype II
STOL II 693JJ319F000360	CARMA TSMO	Cooperative Automation Research: CARMA Proof-of-Concept TSMO Use Case Testing

TSMO = transportation systems management and operations.

Objective

The objective of this project, Automated Driving Systems (ADS) OEM-Industry Research Collaboration and Integrated Highway Prototype (IHP), is to advance the basic travel use case using the CARMA ecosystem to enable further interaction of CDA vehicles with the road infrastructure to enhance infrastructure, improve efficiency, and reduce traffic congestion through transportation systems management and operations (TSMO).

This work builds on the research from the current CARMA3 project that developed CARMA Platform and CARMA Cloud. This project will focus on migrating the IHP on CARMA3 to enable further cooperative automation research, leading toward deployment. A team of CARMA users supported development and testing using their own CARMA-enabled vehicles.

The objective of this document is to describe the use of CDA as it applies to the basic travel use case in general freeway operations. CDA in the basic travel use case is focused around the ability to test and evaluate cooperative automation transportation strategies during recurring congestion on freeways. These transportation strategies/features, developed using automated driving technology and communications, tactically address two high-level objectives: reducing traffic congestion and increasing infrastructure efficiency. As part of the CARMA IHP2 project, this ConOps focuses on three categories of features: CLF (platooning, CACC), CLC (merge, weave, lane change), and CTM (speed control, lane assignment).

Audience

The intended audience for this document includes:

- U.S. Department of Transportation connected automated vehicle (CAV) and cooperative automation program stakeholders.
- System developers who will create and support CDA algorithms based on the system concepts described in this document.
- Managed lane owners and operators.
- Analysts, researchers, and CDA application developers.

Document Structure

The structure of this document is generally consistent with the outline of a system operational concept document described in annex A of *ISO/IEC/IEEE Standard 29148:2011* (IEEE 2011). In U.S. transportation systems engineering practice, this structure is called a ConOps, and that title is included in this document. Some sections have been enhanced with more detailed content than that described in the standard, and titles of some sections may have been edited to capture those enhancements more specifically.

- Chapter 1 defines the scope of the ConOps.
- Chapter 2 reviews the concepts of IHP1 systems and identifies the need for changes from the current situation on highways.
- Chapter 3 describes the concept for the new IHP2 system capabilities and their operations and presents a detailed description of operational concepts.
- Chapter 4 describes IHP2 operational scenarios for managed lane operations.
- Chapter 5 provides an analysis of the expected improvements, operational and research impacts, a validation plan, disadvantages, and limitations.

CHAPTER 2. CURRENT SITUATION AND OPPORTUNITIES FOR CHANGES

This chapter discusses the existing IHP, describes the functionalities of IHP1 (e.g., Level 1 automation), and describes the limited infrastructure and operational scenarios used in the project and field testing.

EXISTING IHP FEATURES

This section discusses IHP1 features on the vehicle and infrastructure sides.

IHP1 Background and Scope

In 2017, STOL conducted research to develop a new reference platform, CARMA2, to enable research capabilities to be easily shared and integrated into industry research vehicles. This project advanced the CACC functionality and developed a proof-of-concept platooning application that enabled leader-follower behavior and allowed vehicles to begin to negotiate with one another within an existing platoon. This project also developed the IHP1, which integrated speed harmonization, cooperative merge, and platooning into one application for the first time.

The goal of IHP1 was to demonstrate the potential of relying on SAE Level 1 automation (i.e., longitudinal control, which is the control of throttle and braking) for early benefits of ADS and CDA deployments (SAE International 2020). All lateral maneuvers were still controlled by human drivers, which may reduce overall system efficiency due to the uncertainties of human behavior and safety considerations. IHP1 only addressed operational decisions in local traffic (i.e., immediate operations in a freeway merge area). Tactical decisions that can further enhance system performance on a larger scale (e.g., a freeway corridor), such as lane assignment and comprehensive platoon formation where vehicles begin in different lanes, were not part of IHP1.

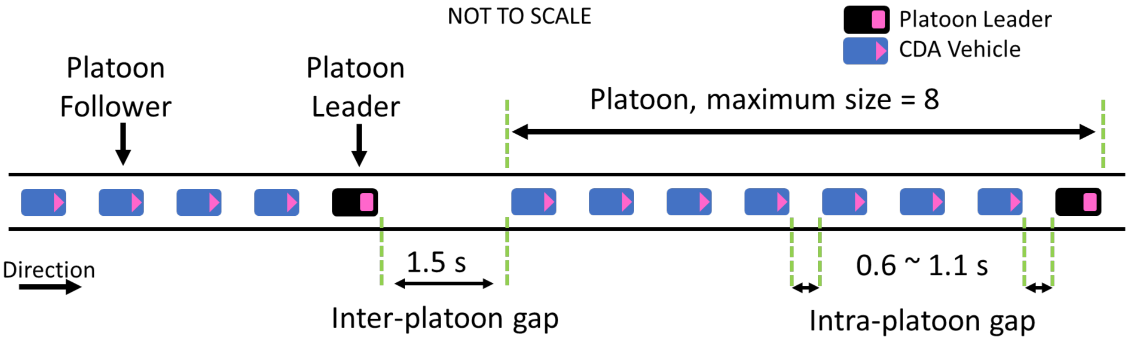
From the infrastructure perspective, IHP1 featured two key assumptions. First, IHP1 assumed that roadside units (RSU), which are connected to a traffic management center (TMC), play a role in coordinating longitudinal maneuvers, such as setting traveling speeds by considering downstream traffic conditions and coordinating longitudinal movements of merging and mainline vehicles. For this assumption, IHP1 operations require 100 percent vehicle connectivity in the traffic stream, although human-driven and CDA vehicles may coexist in the traffic stream. The second assumption was that IHP1 was designed for a managed lane scenario with dedicated ramps as an early-deployment location. This assumption facilitated the IHP1 design to form high-performance traffic streams along freeway facilities (similar to a recent FHWA exploratory advanced research project) (Liu et al. 2018). As a result, CDA vehicles, whether on mainline managed lanes or onramps, are observed by, and receive commands from, the roadside infrastructure to ensure minimum disturbances to mainline traffic when the onramp vehicles merge into the mainline managed lane.

The operational concepts of the three IHP1 component features are discussed separately in the subsections that follow. This report does not aim to provide a comprehensive literature review of all academic studies on CDA. Instead, the focus of this report is on reviewing the operational concepts of each IHP1 feature and showing how each feature is integrated with others, with findings from the most relevant, well-recognized studies.

CACC and Platooning

Adding V2V communications to an ACC system is one way to turn it into a CACC system. As a result, an ADS vehicle will leverage its ability to communicate with surrounding vehicles to maintain an optimal following distance. The ADS vehicle can slow down when it gets too close to another vehicle, speed up to maintain the desired headway, or communicate with other vehicles about speed/trajectory changes while in ACC mode. The primary motivation for the development of CACC is to reduce traffic congestion by improving highway capacity and throughput and attenuating traffic flow disturbances. The use of V2V communication could allow the mean following time gap to be reduced from about 1.4 s when the vehicle is driven manually to approximately 0.6 s when CACC is used, resulting in an increase in highway lane capacity (Nowakowski et al. 2010). Several highway traffic simulations showed that autonomous ACC alone, even at high market penetration rates, had little effect on lane capacity (Nowakowski et al. 2010; Shladover, Su, and Lu 2012). On-the-road experiments showed that a stream of autonomous ACC vehicles is string unstable, resulting in a negative impact on lane capacity (Milanés et al. 2014). However, with the shorter following gaps enabled by CACC systems, lane capacity could be increased from the typical 2,200 vehicles per hour to almost 4,000 vehicles per hour at 100 percent market penetration. See Wang, Wu, and Barth (2018) and Wang et al. (2020) for a review of existing efforts on CACC algorithms and limited testing.

IHP1 adopts the concept of platooning, which gives special responsibilities to platoon leaders to coordinate platoon formation, dissolution, and rear-join for vehicles external to the platoon (e.g., a merge vehicle). This project advanced the CACC functionality and developed a proof-of-concept platooning application (referred to as all-predecessor following) that enabled leader-follower behavior and allowed vehicles to begin to negotiate with one another within an existing platoon (Bujanovic 2018). However, platooning in IHP1 can be further extended to enable a true hierarchical control structure, with the platoon leader coordinating platooning membership with vehicles within the platoon and on nearby lanes. Figure 1 illustrates a platoon in which the platoon leader controls the platoon size, intraplatoon gaps, and interplatoon gaps.



Source: FHWA.

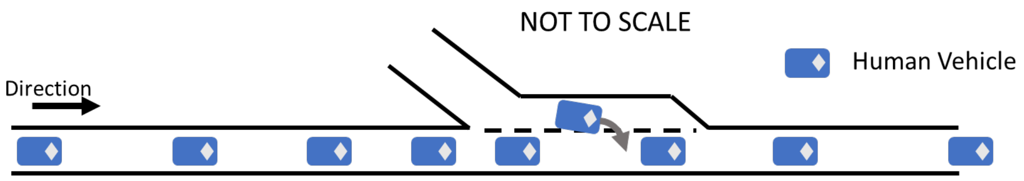
Figure 1. Illustration. Vehicle platoon.

Cooperative Merge

Cooperative merging leverages V2V and vehicle-to-infrastructure (V2I) communications to enable an ADS vehicle to signal to other vehicles (e.g., via DSRC) its intention to merge into a traffic stream. Using signaled information, merging vehicles may identify upcoming acceptable gaps on the mainline and make lane changes when possible. In addition, upstream managed lane vehicles may cooperate by adjusting their speeds or changing lanes to create a gap for the requesting vehicle. The trajectories of merging vehicles are then optimized such that the disturbance created in the traffic stream is minimized. The merge movement can then occur safely and with minimal impact on the platoon and upstream traffic.

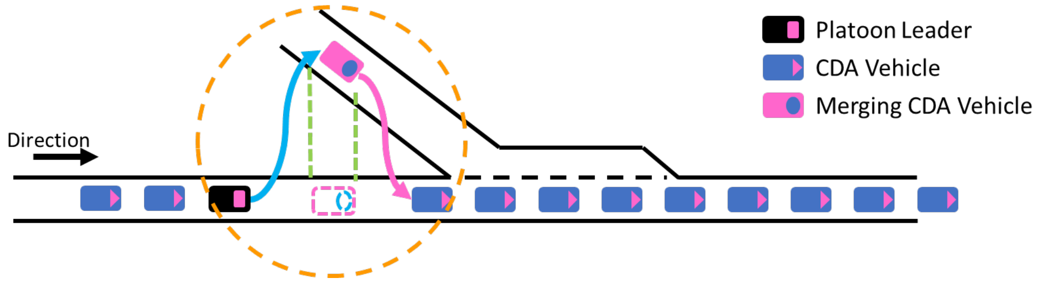
A recent study described developing a vehicle control platform to successfully conduct a proof-of-concept field experiment of a cooperative lane change maneuver driven by a simple algorithm (Raboy et al. 2017). This demonstration was executed using automated speed control, V2V communications, and vehicle-based radar systems. Experimental results showed the effectiveness of the platform and successful proof of the new concept of cooperative lane change. Chou, Shladover, and Bansal (2016) tested two cooperative automated merging strategies for highway entry: one using V2I communication and the other using V2V communication in a microscopic simulation. The results showed that V2I reduced travel time in the merging section when the traffic flow was high, and the V2V case supports a significant increase in traffic flow without increasing travel times. The results indicate the potential advantages of using cooperative automation to relieve the bottleneck in the merging section.

These studies only target limited merging areas with simple algorithms. The effectiveness of cooperative merging cannot be isolated from other CDA operations, such as platooning. Additionally, the combination of cooperative merging with speed harmonization (by controlling and coordinating arrivals of upstream managed lane vehicles to create gaps for merging) can further improve merging area performance. To solve the two challenges of separate and simple algorithms, IHP1 extended the isolated cooperative merge by allowing merging vehicles to join the mainline managed lane platoon from the rear of the platoon. As shown in figure 2, the merging vehicle will form a virtual platoon with the two mainline vehicles, with one being the last vehicle of the first platoon and the second, the immediate follower of the mainline platoon (a vehicle or leader of the second platoon). This virtual platoon will be coordinated by the roadside infrastructure and will last until the merge vehicle makes a lane change to the mainline.



Source: FHWA.

A. Scenario 1.



Source: FHWA.

B. Scenario 2.

Figure 2. Illustrations. Comparison between regular human merge and cooperative merge.

Speed Harmonization

Speed harmonization involves gradually lowering vehicle speeds upstream of a heavily congested area to reduce stop-and-go traffic, which contributes to driver frustration and crashes. This strategy may also be used to reduce vehicle speeds, to either delay or prevent the onset of traffic congestion. To date, a related strategy known as variable speed limits (VSL) has been applied at several locations in Europe and a few locations in the United States. Installations in Europe, some of which date back to the 1970s, have shown positive results in improving traffic flow stability, reducing crashes and injuries, and decreasing emissions using VSL (Fuhs and Brinckerhoff 2010). Current VSL systems use changeable speed limit signs posted over each lane to regulate freeway speeds based on prevailing traffic conditions. Although VSL systems may achieve speed harmonization when successful, they were not considered to be a connected vehicle application by IHP1. The reason they are not is because dynamic speed limit adjustments are less efficient than dynamic adjustments of recommended and/or actual speed limits communicated directly to CDA vehicles. In an ideal scenario, speed commands are generated by effective algorithms based on real-time traffic monitoring. Different commands are then communicated to vehicles on different segments of the roadway and automatically implemented by the vehicles. Such dynamic speed harmonization systems may successfully manage upstream and bottleneck (e.g., merging area) traffic flow through the following actions:

- Reliably detecting the location, type, and intensity of downstream congestion (or other relevant) conditions.

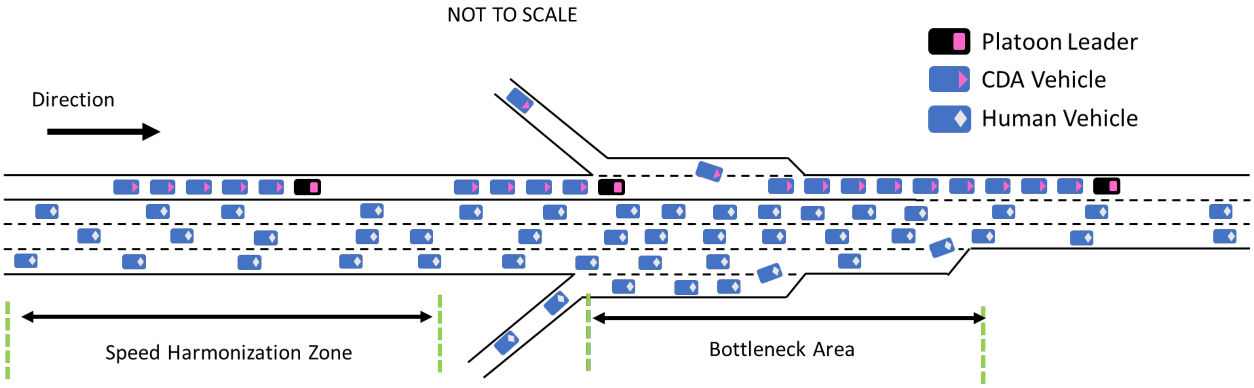
- Formulating an appropriate response plan (i.e., vehicle speed and/or lane recommendations) for approaching vehicles.

- Rapidly disseminating such information to upstream vehicles in a manner that achieves an effective compliance rate.

Some recent studies assessed V2I-based speed harmonization in which speed commands were directly communicated to vehicles (Learn et al. 2017; Talebpour, Mahmassani, and Hamdar 2013; Ghiasi, Li, and Ma 2019; Yang and Rhaka 2017). These simulations found significant travel time reductions (e.g., a 10 percent reduction corridor-wide and a 35 percent reduction on localized bottleneck segments) at CAV penetration rates of 10 percent or higher. This finding concurred with those of other simulation-based studies (Talebpour, Mahmassani, and Hamdar 2013). See Ma et al. (2016) for a comprehensive review of algorithms for VSL and speed harmonization.

In IHP1, segment-based traffic speed harmonization was considered. This harmonization refers to the control strategy, which divides the roadway into segments and generates the same speed commands or recommendations across each segment of a roadway. The goal is to ensure all vehicles travel at similar speeds, thereby minimizing conflicts among vehicles and improving efficiency and safety of the system.

As shown in figure 3, in the case of a downstream speed drop in the bottleneck area, if the congestion is moderate, the algorithm will seek to smooth the traffic in the speed harmonization zone, let the queue at the bottleneck dissipate, and then allow the upstream traffic to pass the bottleneck smoothly at a reasonable speed. Otherwise, if the traffic is too congested and the queue is not anticipated to dissipate in a short time, the CDA vehicles will be guided by the infrastructure to approach and join the queue smoothly and, in turn, avoid hitting the downstream queue at a sudden full stop.



Source: FHWA.

Figure 3. Illustration. Infrastructure-to-vehicle speed control algorithmic logic.

IHP1 implemented speed harmonization in response to downstream bottleneck conditions, recurring capacity constraints, or non-recurring events (e.g., work zones) by sending corresponding general speed commands for certain roadway segments. The longitudinal speed commands can be extended to better integrate with cooperative merging at merge areas to effectively create gaps for merging vehicles. However, this level of integration results in more computational burden due to the attempt to control and coordinate all individual vehicles in real time. The combination of a segment-based algorithm at basic segments and a trajectory-based algorithm at merging areas can be considered as a feasible compromise.

IHP1 Infrastructure

IHP1 was designed for a managed lane scenario with dedicated ramps to form high-performance traffic streams along freeway facilities; therefore, CDA vehicles, eligible to use managed lanes, can be fully observed and controlled by the roadside infrastructure to ensure minimum disturbance to the mainline traffic when the onramp vehicles merge into the mainline managed lane.

Two major factors tie managed lanes to IHP operations. First, although ADS technologies offer opportunities to advance safety, mobility, and reliability on the Nation's roadways, market penetration will be low at first, and the potential benefits may not be fully realized. Managed lane facilities will support realizing these benefits at early deployment stages by attracting and concentrating the equipped vehicles in proximity to each other so they can gain the benefits of V2V cooperation. IHP1 focused on deployment stages during low market penetration and addressed how the proposed bundling of speed harmonization, cooperative merge, and platooning is operated to improve existing system performance. For early deployment, single-lane, controlled-access facilities equipped with existing intelligent transportation system (ITS) and communication devices (e.g., DSRC RSUs) offer the opportunity to begin integrating ADS vehicles into traffic. Because the facilities are single lane, the presence of a small number of CDA vehicles can still impact operations on the managed lanes and, therefore, improve system performance and the individual traveler's experience.

Second, IHP1 presented strategies to increase the efficiency of available managed lane capacity and to improve traffic performance without significant capital investment (e.g., construction of lanes or management of reversible lanes). These strategies are an attractive solution for managed lane operators seeking to meet Federal and local performance requirements, or those seeking innovative solutions to growing travel demand. More efficient data collection through CDA technologies may also be mutually advantageous for managed lane facilities to meet performance management and reporting requirements.

Existing managed lanes are better equipped to support IHP1 operations than general purpose lanes with existing sensors (e.g., radar detectors) and communication infrastructure (e.g., fiber optic). Managed lanes are composed of various systems, subsystems, and components. Subsystems commonly found in managed lanes include real-time traffic management and communications subsystems, which connect the other subsystems. The communication subsystem can be an important asset for CDA operation, as it can support needed V2I systems. For instance, a direct fiber-optic connection can be leveraged for transmitting data to the TMC while saving the upfront costs to set up a fiber-optic cable on a general-purpose facility. Other relevant infrastructure considerations include the roadside communications network, roadside electrical power availability, and toll system maintenance. Electronically tolled lanes are typically equipped with a variety of sensor technologies that support tolling. These technologies can be used and enhanced in a CDA environment to support speed harmonization, vehicle platooning, and cooperative merging.

IHP STAKEHOLDERS

Stakeholders' actions influence travel in the transportation environment, which may include road users traveling across publicly accessible roadways, emergency responders, and infrastructure owners and operators (IOOs). This section identifies two types of IHP stakeholders and their corresponding needs: road users and IOOs.

Road Users

A road user is a traffic participant on, or adjacent to, an active roadway for the purpose of traveling from one location to another. For IHP, human-driven or connected motorized vehicles are the main users of the freeway systems. Road user needs include:

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

From the transportation user's perspective, IHP supports and enhances the following benefits:

- **Smoother and faster travel with less stress**—Vehicle platooning and merge coordination can reduce the friction in traffic flow, increase lane capacity, and improve vehicle-following stability, thereby increasing the capacity of highway bottleneck locations.

- **Greater operational efficiency and travel-time reliability**—The combination of speed harmonization, cooperative merge, and vehicle platooning can substantially reduce uncertainty in travel times by smoothing traffic and enabling real-time prediction of travel times.

- **More productive travel experience**—Several features of CDA technology, including speed harmonization, can help improve the travel experience. These features include stop-and-go movement elimination, travel time reliability improvement, proactive congestion management, and access control.

Table 2 lists four categories of road users and defines the characteristics and needs for each category.

Table 2. Road user characteristics and needs.

Driver	Road User Categories	User Characteristics and Needs
Human driving	Regular human driver	Regular human drivers do not have connectivity or automation capability. They have uncertain driver behavior. Their needs align with general user needs.
	Connected human driver	Connected human drivers receive additional traveler information and can make better, informed travel decisions. Their needs align with general user needs.
Automated driving	Nonconnected ADS vehicle	Nonconnected ADS vehicles operate independently, rely on local sensor information and automated control software, and usually have conservative behavior to provide increased comfort and safety margin. Their needs include accurately sensing local traffic conditions and actuating control of vehicles to ensure safety and travel efficiency.
	CDA vehicle	Compared with ADS, CDA vehicles partner with other cooperative vehicles and infrastructure in the traffic stream to improve overall traffic performance. Their needs include availability of other vehicles to perform cooperative actions and improving overall system safety and efficiency while guaranteeing individual vehicle travel experiences.

IOOs

An IOO is a traffic participant who provides, operates, and maintains roadways and supporting infrastructure that enable the mobility needs of road users. IOOs include public, public-private, or private entities that operate in accordance with Federal, State, and local laws.

The goal of an IOO is safe and efficient traffic management, which includes monitoring and managing traffic and the factors affecting traffic flow (e.g., incidents, weather, work zones, dissemination of routing information, and other actions that improve traffic flow efficiency). Operator goals may also include:

- Reducing recurring congestion on urban freeways.
- Improving reliability and safety.
- Reducing travel times, fuel consumption, and emissions.
- Maintaining and increasing the use of alternative and emerging transportation modes (e.g., car-sharing options).

Many State departments of transportation (DOTs) and public agencies have developed roadmaps for incorporating connected vehicles, ADS, and CDA into future TSMO practices (Virginia DOT CAV program, Pennsylvania DOT CAV initiative, California Department of Transportation (Caltrans) CAV Infrastructure Development Branch) (VDOT 2021; Pennsylvania DOT 2022; Caltrans 2021). Based on State and agency plans and indepth engagement with Virginia DOT and Transurban, the following benefits of IHP are summarized from the IOO perspective (Transurban n.d.):

- **Meeting efficiency goals.** Early adoption of CDA on an existing managed lane allows greater congestion management ability for facility operators, increased throughput, enhanced safety, and improved driver experience. These benefits will be based on the relatively higher fraction of CDA vehicles concentrated in the managed lane facility compared with the number of vehicles using the entire highway.

- **Improving highway resource utilization.** Traditional approaches to managing congestion, such as capacity expansion, are increasingly becoming obsolete due to funding constraints and limitations of these approaches in alleviating transportation problems. CDA technologies can be considered as strategies for TSMO that offer potential for innovative solutions to congestion and travel time reliability.

- **Gaining first-mover advantage.** If operators currently primed to accommodate CDA vehicles on their facilities do not voluntarily test and advance this technology, third parties may fill that role and dictate the direction of CDA technology development. This direction may or may not be aligned with an agency's goals or organizational capacity.

- **Evolving to accommodate the future of mobility technology.** Organizations that respond to rapid technological change may be more likely to thrive in this era of 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, ubiquitous sensing using automated vehicle sensors). A key question is, what additional capabilities and possibilities can be expected from ADS as more advanced sensing and computing capabilities are integrated with ADS?

Data from these systems become a key resource because an ADS that shares its perception information could significantly improve situational awareness of surrounding ADS. If an ADS can share tactical or operational plans in the future 5 s, 20 s, or even 1 min, and negotiate with other ADS to jointly perform certain maneuvers, transportation disutilities such as crash risks, delay, and excessive emissions can be reduced.

From the infrastructure end, upgrading existing infrastructure and software may not be sufficient. Advanced infrastructure concepts may instead be necessary, such as cloud services that provide digital information (e.g., work zones, incidents, weather, congestion) or management rules (e.g., speed or gap control) in a format that can be directly sent to, and processed by, ADS vehicles.

For freeway control, CDA presents opportunities and new TSMO strategies. Unlike IHP1, the IHP2 concepts are enabled by higher SAE levels of automation and various classes of cooperation (SAE International 2020). IHP2 aims to fully utilize shared data between vehicles, and between vehicles and infrastructure, to create better dynamic world models, referred to as cooperative perception, that enable CDA vehicles to navigate traffic streams more safely and efficiently. Also, CDA vehicles not only act on additional information, but also actively engage with surrounding CDA vehicles under a cooperative control paradigm. For example, CDA vehicles can negotiate with each other to obtain optimal trajectories preferred by the vehicles themselves and also taking into account the traffic system performance. These capabilities create more possibilities for CTM and vehicle coordination to improve the performance of vehicle behavior, local traffic, and transportation systems.

Driving automation and connectivity provide opportunities to deploy multiple cooperative automation strategies. Successful deployment also depends on coordination among diverse stakeholders, including IOOs, ITS technology providers, ADS and ADS-equipped vehicle manufacturers and suppliers, and ADS-dedicated vehicle fleet operators. IHP2 provides the opportunity to use CDA for freeway system management and congestion reduction.

CHAPTER 3. INTEGRATED HIGHWAY PROTOTYPE 2 OPERATIONAL CONCEPT

This chapter details the operational concepts of IHP2 by laying out the vision for IHP and discussing different IHP2 features. IHP2 is a concept in which the automated driving technology can work together with automated vehicles and with roadway infrastructure to improve the performance of the transportation system. This chapter describes how automated driving technology can be used in a cooperative manner, starting when ADS or CDA vehicles enter the freeway until they exit the freeway. This chapter also discusses the role of infrastructure in supporting and enabling automated driving technology to help manage the transportation system to address congestion and improve safety during normal travel.

CDA

This section provides an overview of the concept and framework of CDA. The key discussion points include the different levels of automation and various classes of cooperation.

SAE International J3216

CDA technologies enable mobility applications that are not achievable by individual ADS operating independently of each other. These ADS operate by sharing information that can be used to increase safety, efficiency, and reliability of the transportation system and accelerate deployment of driving automation. Driving automation and connectivity present opportunities to deploy multiple cooperative automation strategies, but successful deployment depends on coordination among diverse stakeholders. These public and private stakeholders are preparing for, and deploying, different use cases at different temporal and spatial scales. For example, vehicle strategies—such as speed harmonization—and TSMO strategies—such as basic travel, traffic incident management, weather management, and work zone management data sharing—are key use cases supported by CDA.

CDA aims to improve the safety and flow of traffic and facilitate road operations by supporting the movement of multiple vehicles in proximity to one another. This aim is accomplished, for example, by sharing information that can be used to influence dynamic driving task (DDT) performance directly or indirectly by one or more nearby road users. Vehicles and infrastructure elements engaged in cooperative automation may share information, such as state (e.g., vehicle position, signal phase) and intent (e.g., planned vehicle trajectory, signal timing), or seek agreement on a plan (e.g., coordinated merge). Cooperation among multiple participants and perspectives in traffic can improve safety, mobility, situational awareness, and operations.

Similar to SAE J3016 levels of automation, a new standard, SAE J3216, defines classes of cooperation (SAE International 2020, 2021). The classes address different capabilities of a CDA vehicle that would affect its ability to cooperate with other CDA vehicles. These classes are summarized in table 3.

Table 3. Overview of SAE International cooperation classes and automation levels (SAE International 2020).

No Automation		**Partial Automation of DDT**			**Complete Automation of DDT**		
		Level 0: No Driving Automation (human does all driving)	**Level 1: Driver Assistance (longitudinal or lateral vehicle motion control)**	**Level 2: Partial Driving Automation (longitudinal and lateral vehicle motion control)**	**Level 3: Conditional Driving Automation**	**Level 4: High Driving Automation**	**Level 5: Full Driving Automation**
No Cooperative Automation		e.g., signage, TCD	Relies on driver to complete DDT and supervise feature performance in real time		Relies on ADS to complete DDT under defined conditions (fallback condition performance varies between levels)		
SAE class A: Status Sharing	**Here I am, and what I see**	e.g., brake lights, traffic signal	Potential for improved object and event detection*		Potential for improved object and event detection**		
SAE class B: Intent Sharing	**This is what I plan to do**	e.g., turn signal, merge	Potential for improved object and event prediction*		Potential for improved object and event prediction**		
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		

*Improved object and event detection prediction through CDA class A and 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 with Level 3, 4, and 5 ADS-operated vehicles.

**Class A and B communications are one of many inputs to an ADS object and event detection and prediction capability, which may not be improved by the CDA message.

C–ADS = cooperative automated driving system; N/A = not applicable; TCD = traffic control device.

CARMA3

The purpose of CARMA is to transform transportation and improve efficiency and safety through automated vehicles working together and working with roadway infrastructure.

CARMA Platform is open-source software that enables researchers and engineers to develop and test CDA features on properly equipped vehicles to set the foundation for interoperability across vehicle make and model and safely introduce the technology on the Nation’s roads. The most recent version enables R&D capabilities to support TSMO. CARMA Platform enables cooperative research functionality to an ADS, and CARMA Cloud enables the roadway to provide information to support safe operation for new TSMO strategies. CARMA is built on a flexible framework designed to be easily shared and integrated into several vehicle types, including passenger cars and heavy trucks.

CARMA technology facilitates cooperation among vehicles and roadway infrastructure through communication. By providing information about what is ahead with CARMA Cloud (such as basic travel, traffic incident management, road weather management, and work zone management), CARMA Platform enables automated vehicles to interact and cooperate with infrastructure and other vehicles, thereby increasing the performance of the existing transportation system.

This ConOps serves as part of the CARMA3 framework (Nallamothu et al. 2020) and distinguishes between levels of vehicle automation and classes of vehicle cooperation. Four classes of cooperation are defined as follows (SAE International 2020):

- **Status-sharing (class A):** Perception information about the traffic environment and the state of the sending entity are provided by the sending entity for potential use by receiving entities.

- **Intent-sharing (class B):** Information about planned future actions of the sending entity are provided by the sending entity for potential use by receiving entities.

- **Agreement-seeking (among CDA vehicles) (class C):** A sequence of collaborative messages among specific CDA devices is intended to influence local planning of specific DDT-related actions.

- **Prescriptive (class D):** A party has determined a course of action is necessary or optimal for its own operations and communicates with other road users with the intention of directing their actions.

This ConOps addresses the feature groups that are part of the CARMA IHP2, including CTM, CLF, and CLC. These groups correspond to the following use cases and situation groups identified in the CARMA3 TSMO ConOps that was developed in a parallel project.

Use Case: Basic Travel

The TSMO situation groups for the basic travel use case are given as follows:

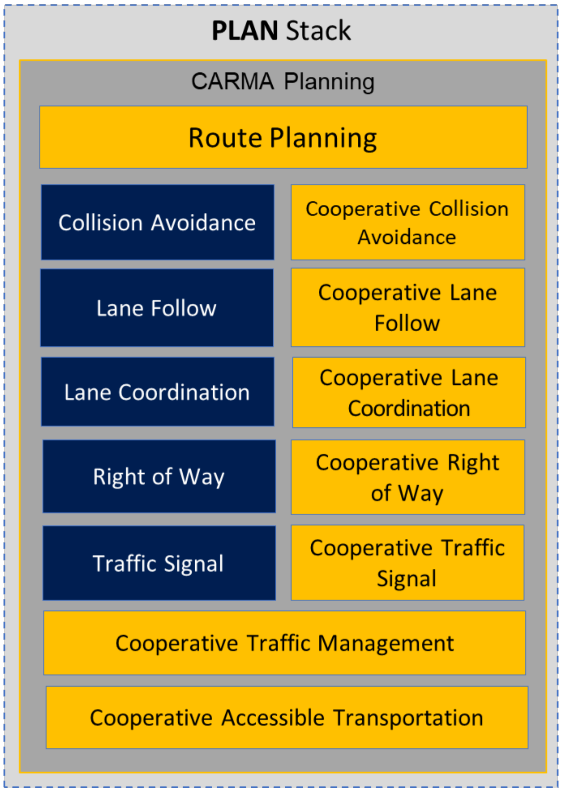
- **Situation Group A-1: Basic Travel Operations for All Roadway Types**—Nonspecialized vehicle situations applicable to all roadway types:
    - A-1.1: Managing vehicle platooning (joining, formation, operation, and dissolution).
    - A-1.2: Managing vehicle strings CACC.
    - A-1.3: Implementing cooperative lane changes (when not platooning).
    - A-1.5: Identifying vehicle by capabilities (e.g., automation level and cooperation class).
    - A-1.10: Navigating managed lanes facilities (high-occupancy toll lanes).
- **Situation Group A-2: Basic Travel Operations for Highways—**Nonspecialized vehicle situations applicable to roadways with intersections that are not at grade to other roadways, which include interstates and most freeways and expressways:
    - A-2.1: Merging on/diverging off highway (when not platooning).
    - A-2.2: Merging on/diverging off highway with platoon.
    - A-2.3: Managing active traffic (e.g., speed harmonization).
    - A-2.4: Ramp metering with/without traffic signal prompt.

TECHNOLOGICAL FRAMEWORK FOR IHP2

This section describes the functionality needs for IHP2. The focus is to discuss IHP2 enabled by higher levels of automation and classes of cooperation. Other lower levels of automation and cooperation scenarios will also be discussed.

In IHP1, three features were developed separately and then integrated: platooning, cooperative merge, and speed harmonization. IHP1 relies on SAE Level 1 automation and integration done only for longitudinal (speed/acceleration) control (SAE International 2020). Higher levels of automation offer a larger number of possible CDA scenarios, and, therefore, IHP2 adopts a different feature definition that better aligns with regular highly automated vehicle functional modules.

Figure 4 shows a list of the planning module stack of CARMA3. The boxes with a dark background on the left are for regular noncooperative ADS modules/features. They are used when one ADS vehicle cannot find other vehicles or infrastructure with which to engage for cooperative maneuvers. Consideration of noncooperative ADS modules is key when the market penetration of CDA vehicles is low during initial deployment stages. The boxes with a lighter background are cooperative feature groups to enable various cooperative maneuvers. Other than conventional module types at the vehicle level, such as lane follow and lane change, two lighter yellow boxes are added for system-level management: CTM and cooperative accessible transportation.



Source: FHWA.

Figure 4. Illustration. CARMA planning modules.

For IHP2, the three relevant feature groups are CLF (platooning and CACC), CLC (cooperative lane change, merge, and weave), and CTM (speed and gap control, lane assignment, and queue management). Table 4 defines each feature within the three feature groups. Each of the three IHP2 feature groups not only includes IHP1 features, but also covers additional features (e.g., cooperative lane change, gap control) to present a comprehensive package for integrated freeway management with CDA.

Table 4. IHP2 features and descriptions.

Feature Group	IHP2 Feature	Description
CLF	CACC (strings)	Allows two or more vehicles to communicate with one another and, therefore, follow in a string, closer than would be possible without communication. However, each vehicle still behaves independently of other vehicles and has no responsibility toward the rest of the string.
	Platooning (groups)	Allows two or more vehicles to closely travel together as a single unit, where each vehicle agrees to abide by the group rules to proceed safely through traffic and realize maximum benefits.
CLC	Cooperative lane change	Plans a smooth lateral motion from the current lane into an adjacent lane by first checking for collision risk with neighboring vehicles in the target lane and initiating cooperative agreements with one or more of them, as necessary, to plan a safe lane change within the physical constraints of the situation.
	Cooperative merge	Plans a smooth lateral motion from the current lane, which is either ending or combining with another (e.g., when two highways merge), to the lane into which the current lane merges. Uses cooperative agreements with neighboring vehicles, as necessary, to ensure safety and efficiency.
	Cooperative weave	Allows two or more cooperative driving automation vehicles to plan simultaneous or near-simultaneous lane changes where each vehicle will be changing lanes into the lane of the other vehicle.
CTM	Speed control	Allows a vehicle to adjust its speed based on communication/rules from other vehicles, the cloud, or another entity (e.g., pedestrian).
	Gap control	Allows a vehicle to adjust its gap to its preceding vehicle, whether part of a string, group, or neither, based on the communication/rules provided from other vehicles or the cloud.
	Lane assignment	Accepts a request from the cloud regarding which lane the vehicle should plan to be in, and, if necessary, when appropriate, calls for the lane change and/or merge features to be executed.
	Queue management	Allows vehicles to accept speed control and lane assignment command such that the downstream bottleneck queue can be minimized.

CLF

The CLF feature group contains two distinct features: CACC and platooning. CACC allows two or more vehicles to communicate with one another and follow in a string closer than would be safely possible without communication. However, each vehicle still behaves independently of other vehicles and has no responsibility toward the rest of the string. Platooning allows two or more vehicles to closely travel together as a single unit, where each vehicle agrees to abide by the group rules to safely proceed through traffic and realize maximum benefits. Table 5 summarizes the differences between CACC and platooning.

Table 5. Differences between platooning and CACC.

Category	Platooning	CACC
Control hierarchy	Hierarchical control with special responsibilities for platoon leader.	Decentralized control with no special responsibilities for the string leader.
Membership	Coordinated platoon/group membership.	Ad hoc string membership and vehicles behave independently.
Spatial scope	Operates in a single lane or in multiple lanes for a platoon lane change, search for partners, and so on.	Operations in a single lane with small following gaps.

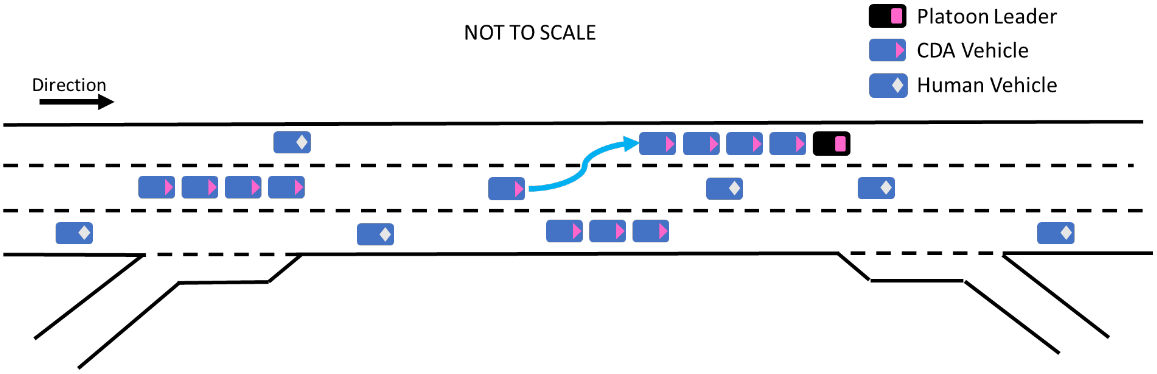
Platooning is an organized behavior where each vehicle in a platoon has a responsibility toward the rest of the platoon to abide by agreed-upon rules. The focus is on organized behavior. With platooning, a group of vehicles, coordinated by the platoon leader, aim to move through traffic as safely and efficiently as possible. With CACC, independent vehicles can receive the front vehicles' real-time information and, thus, can follow more closely compared with conventional ACC.

With platooning, the vehicles behave freely before joining and after leaving the platoon. Once they have agreed to join the platoon, and then subsequently join, the vehicles must follow certain rules and protocols. The rules are commonly set by the platoon leader. A platoon leader may set rules by passing on the rules it receives from infrastructure (e.g., maximum amount of vehicles allowed in a platoon or speed limit) or by its own volition (e.g., joining allowed only from the side or just from the rear, and, if joining is allowed from the side, how additional space will be created).

Because platooning is a group activity, it does not need to be confined to a single lane. A platoon may change lanes together, and vehicles would coordinate how this is done. For example, they might coordinate the last vehicle changing lanes first and then each subsequent vehicle changing lanes in reverse order, from last to first. Platooning protocols can also help with looking for platooning partners and agreeing where to meet, as these are part of the team activity.

In this ConOps, platooning and CACC coexist as CLF features because of the different classes of cooperation. CACC vehicles belong to class A (status sharing), while vehicle platooning can vary with class B (intent sharing), class C (agreement seeking), or class D (prescriptive).

Figure 5 illustrates the CLF. A five-vehicle platoon is operating in the left-most lane, and the platoon leader coordinates the intraplatoon gaps and longitudinal maneuvers. In the middle lane, one CDA vehicle has completed negotiating with the platoon leader and is allowed to change the lane to join the platoon from the rear of the platoon. This maneuver may be allowed because this CDA vehicle might share the same (or nearby) destination off-ramp with other platoon members, and vehicles joining together in a platoon is operationally preferred. This concept will be further discussed in the CTM section. In the middle lane and the right-most lane are a four- and three-vehicle CACC string, respectively. The intrastring gaps between vehicles are different from each other, and this value is set by the independent CDA vehicles themselves. In the platoon, the intraplatoon gap can be set as the same or different among platoon members, but the platoon leader must approve it.



Source: FHWA.

Figure 5. Illustration. IHP2 CLF.

CLC

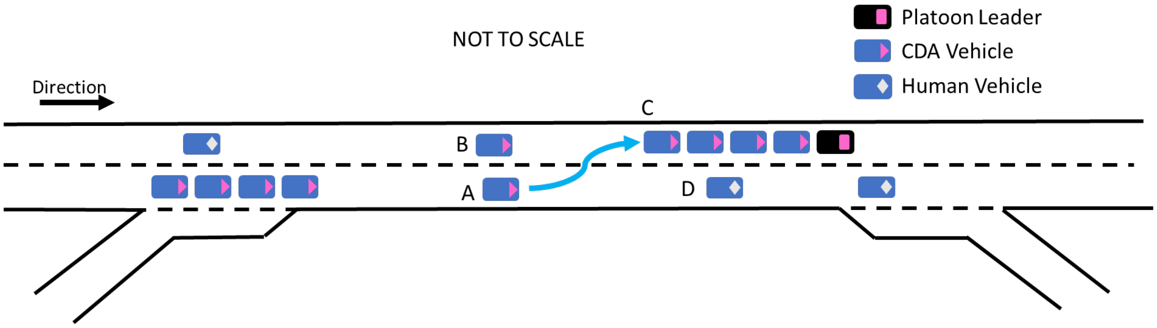
Unlike IHP1, which only uses Level 1 automation, IHP2 focuses on benefits from using functionalities of Level 3, or higher, automation. A major distinction is the potential for both longitudinal and lateral vehicle coordination. Three features are included in the CLC feature group: cooperative lane change, cooperative merge, and cooperative weave.

Cooperative Lane Change

Cooperative lane change plans a smooth lateral motion from the current lane into an adjacent lane. It first checks for collision risk with neighboring vehicles in the target lane and initiates cooperative agreements with one or more of them to plan a safe lane change within the physical constraints of the situation.

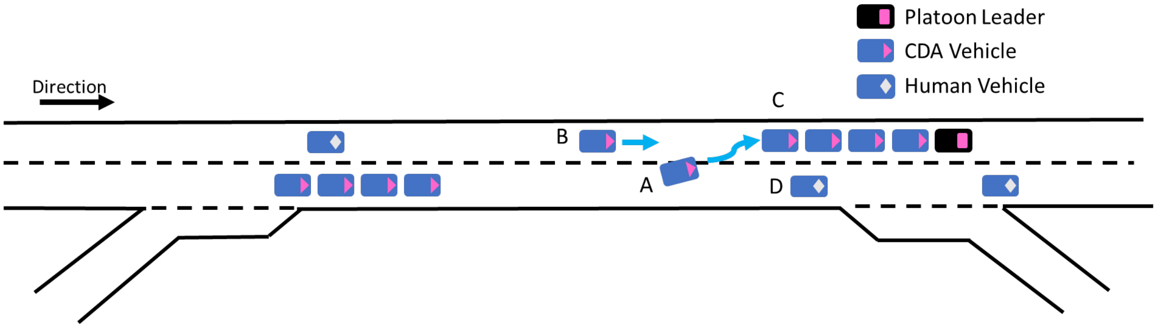
This process occurs any time a lane change needs to be initiated. Ideally, CDA vehicles can receive the current status and intent of surrounding vehicles and negotiate with them, depending on the surrounding vehicles' cooperation classes, to complete the maneuvers. When nonconnected, human-driven vehicles are nearby, CDA vehicles rely on onboard sensors to detect, estimate, and predict human-driven vehicle behavior.

Figure 6 illustrates one example where the ego CDA vehicle A in the right lane intends to change the lane and join a platoon in the left lane from the rear. Vehicle A constantly checks collision risks with the vehicles in the front in the current lane (vehicle D), the last vehicle in the platoon (vehicle C), and a nearby CDA vehicle in the left lane (vehicle B). If vehicle B can negotiate with vehicle A, vehicle B may control its longitudinal maneuvers to leave a gap that is sufficiently safe for vehicle A to change the lane and join the front platoon. If vehicle B only shares the current status or intent, it is still beneficial for vehicle A to plan the trajectory better to smoothly change the lane to the left.



Source: FHWA.

A. Step 1.



Source: FHWA.

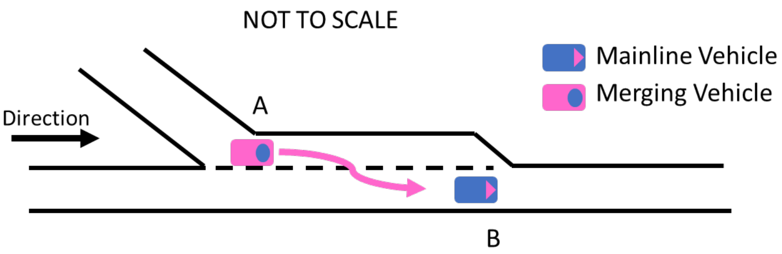
B. Step 2.

Figure 6. Illustrations. Cooperative lane change.

Cooperative Merge

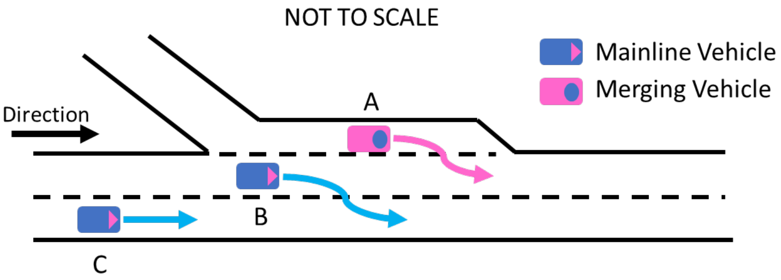
Cooperative merge plans a smooth lateral motion from the current lane, which is either ending or combining with another (e.g., when two highways merge), to the lane into which the current lane merges. Cooperative merge seeks cooperative agreement with neighboring vehicles to ensure safety and efficiency.

When a vehicle intends to merge into the mainline, it can potentially encounter four cases that will activate the cooperative merge. Figure 7 shows a typical example of different scenarios during a merge process and the corresponding cooperative driving logic. A cooperative merge can be applied in a V2V or V2I environment or both. An approach that includes V2I is beneficial because it can facilitate, through the use of roadside infrastructure or a cloud service, the cooperative merge process by allowing the cooperation process to start earlier, resulting in a higher level of benefit. The following four cases can activate cooperative merge:



Source: FHWA.

A. Case 1.



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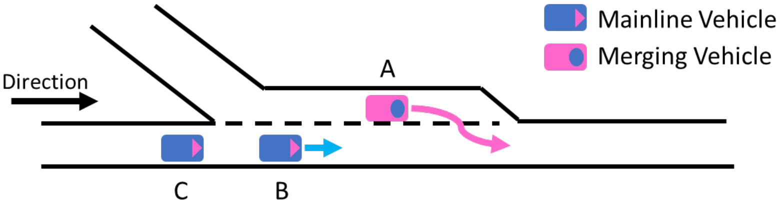
B. Case 2.



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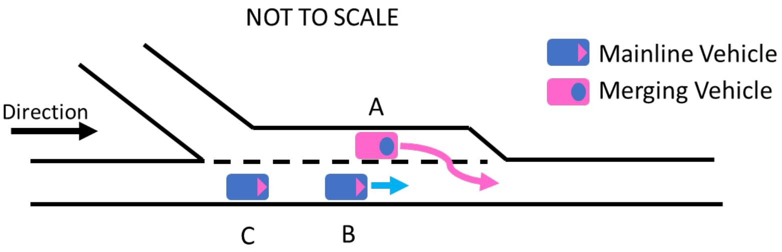
C. Case 3.



Source: FHWA.

D. Case 4.

Figure 7. Illustrations. Cooperative merge.

- Case 1: In figure 7-A, vehicle B is in the target lane in front of the merging vehicle A. If vehicles A and B have similar speed (i.e., small speed difference), the merging vehicle A slows down slightly and merges into the mainline.
- Case 2: As shown in figure 7-B, if vehicle A intends to merge into the mainline and vehicle B in the target lane is behind vehicle A, then vehicle B will be advised to move cooperatively over to the adjacent lane to create a safe and acceptable gap for vehicle A to merge into. This cooperative merge can be activated under certain conditions, such as when the new lane will not affect vehicle B's ability to complete its original route and when the speed difference between vehicle A and vehicle B is less than maximum speed difference threshold.

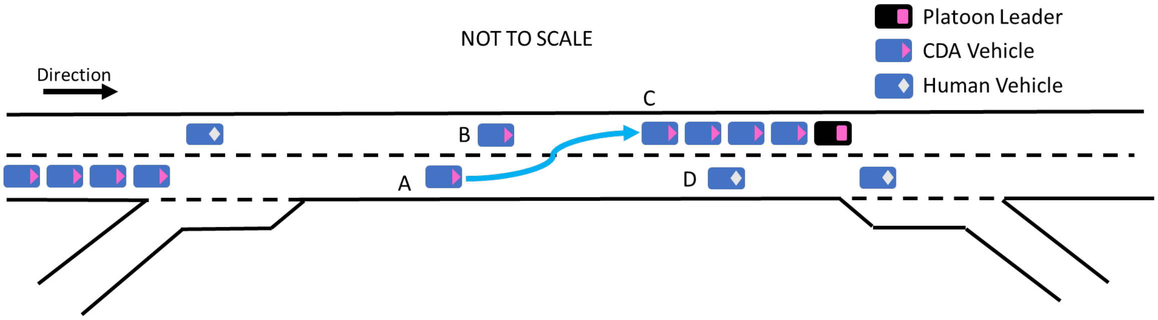
Case 3 and case 4 are scenarios in which the mainline vehicle cannot move over into the adjacent lane because the requirements in case 2 cannot be met. Therefore, the mainline vehicle needs to reduce speed to create a gap and allow the merging vehicle to enter the mainline.

- Case 3: As shown in figure 7-C, vehicle A on the onramp intends to merge into the mainline, and mainline vehicle B is behind vehicle A. In this case, vehicle B will slow down to create an acceptable gap to let vehicle A merge into the mainline from the onramp. Meanwhile, the following vehicle C will also cooperatively slow down to keep a safe following distance from vehicle B. Vehicles B and C can be independent vehicles and can also possibly be part of a platoon.
- Case 4: Figure 7-D shows that when vehicle A requests to merge into traffic from the onramp, mainline vehicle B is too close to slow down. In this case, vehicle B will take no action and keep its speed. The following vehicle C will slow down and let vehicle A merge into the mainline.

Although the existence of human-driven vehicles is not discussed in the four cases, any ADS vehicle can complete the merge maneuver independently through noncooperative modules, relying on onboard sensing and ADS software. However, it is always possible for any CDA vehicle to sense, estimate, and predict human-driven vehicle trajectories to enable cooperative driving with human-driven vehicles.

Cooperative Weave

Cooperative weave allows two or more CDA vehicles to plan simultaneous or near-simultaneous lane changes, where each vehicle changes lanes into the lane of the other vehicle. Involved CDA vehicles will either receive information from, or negotiate with, surrounding vehicles and plan their own trajectories to complete the weave maneuver smoothly. For example, as shown in figure 8, vehicle A intends to make a lane change to the left to join the platoon (figure 8-A), while vehicle B intends to change lanes to the off-ramp (figure 8-B). If no cooperation is enabled, one or both vehicles may need to accelerate or brake heavily to ensure safety as they start to get close to each other. With CDA, it is possible the two vehicles can negotiate and codevelop optimal smooth trajectories that eliminate the need for large accelerations and minimize the impact on the upstream traffic. In this example, vehicle A slightly accelerates and changes the lane by knowing vehicle B agrees to slow down slightly and make the lane change after vehicle B completes the maneuver.



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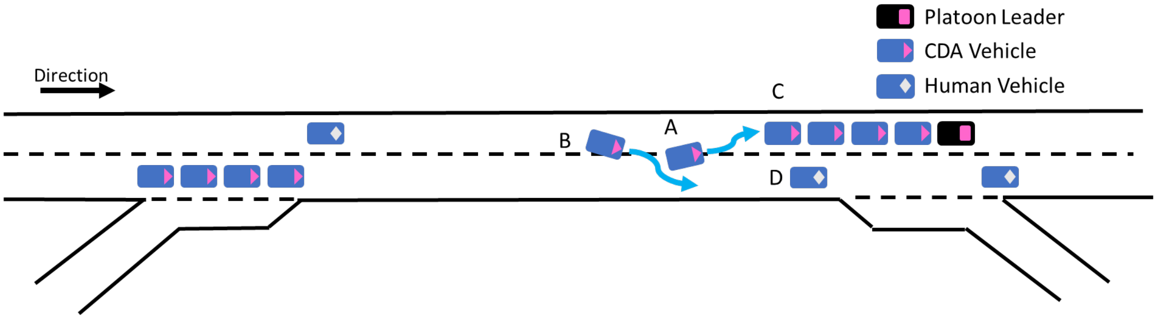
A. Step 1.



Source: FHWA.

B. Step 2.

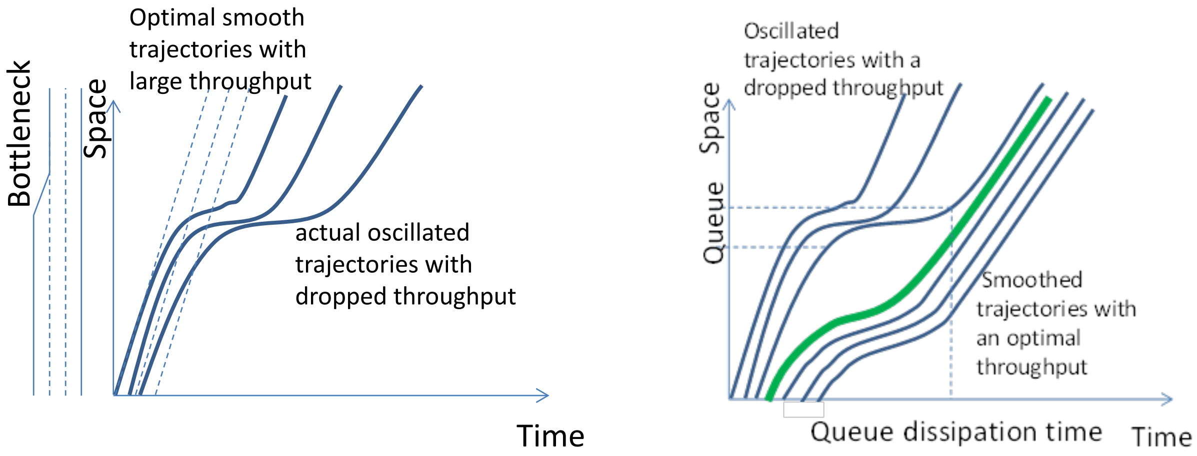
Figure 8. Illustrations. Cooperative weave.

CTM

Both CLF and CLC are mainly V2V cooperation features. CTM includes three features: speed control, gap control, and lane assignment. CTM focuses on cooperation between vehicles and infrastructure. Since TMCs collect data from all connected vehicles and infrastructure detectors and have better estimates of dynamic traffic states, the TMC can make better informed decisions to improve traffic system performance.

Speed control allows a vehicle to adjust its speed based on communication/rules from other vehicles, the cloud, or another entity. Speed control is similar to the speed harmonization concept in IHP1 for bottleneck reduction (e.g., capacity constraints, work zones). Additionally, speed control for IHP2 also concerns speed control of CDA vehicles to improve local traffic smoothness and stability. For example, at key freeway locations, such as merge and weave (as shown in figure 7 and figure 8), the longitudinal speed of vehicles A and B can be controlled by the infrastructure to achieve system-level performance, not just the vehicle-level performance for vehicles A and B.

Speed control of each CDA vehicle results in coordinated space-time trajectories of each vehicle to achieve optimal system performance. Recent simulation studies (Ghiasi, Li, and Ma 2019) and field experiments (Ma et al. 2016) prove the potential of such an approach in enhancing traffic smoothness and, thus, improving efficiency and safety. For example, as shown in figure 9, when detecting an imminent downstream speed drop at a bottleneck, to avoid hitting the downstream queue at a sudden full stop, a CDA vehicle (the thicker green curve) should moderately slow down and pass the bottleneck smoothly at a reasonable speed just as the downstream queue dissipates. This trajectory-control strategy not only smooths the CDA vehicle's trajectory, but also helps any type of following vehicles (CDA or human-driven vehicles) to move in a similarly smooth manner. As a result, vehicles following this CDA vehicle will pass the bottleneck with a larger throughput rate due to reduced time headway at a high speed, less fuel consumption due to smoothed trajectories, and less collision risk due to harmonized vehicle speed.



Source: FHWA.

Source: FHWA.

A. Benchmark without trajectory smoothing.

B. Harmonized trajectory.

Figure 9. Charts. Projected trajectories with and without smoothing.

Gap control allows a vehicle to adjust its gap to its preceding vehicle, whether it is part of a string, group, or neither, based on the communication and rules provided by other vehicles or from the cloud. Gap control is another key longitudinal control parameter to enhance system efficiency. For example, at merge areas, the infrastructure can instruct CDA vehicles to follow closely (i.e., create smaller gaps), in combination with speed control, to create additional large gaps for merge vehicles. Gap control may also be instructed by the infrastructure based on current weather conditions or unique roadway geometry, which may influence wireless communications' reliability, to ensure safe CDA operations.

In terms of lateral control, lane assignment accepts a request from the infrastructure regarding which lane the vehicle should plan to be in. Also, if necessary and when appropriate, it accepts calls for the lane change or merge features to be executed. For example, similar to the single-lane operations in figure 9, speed control and lane assignment commands are for minimizing downstream bottleneck queues. Also, when a downstream lane is closed due to a work zone, it is possible to assign CDA vehicles to the lanes that are not closed before the vehicles approach the work zone. This step is similar to the effect of early lane change advisories, but with CDA vehicles, it is possible to perform a system-level optimal control with the flexibility of CDA lane assignment.

INFRASTRUCTURE CONFIGURATION AND NEEDS

This section describes technological and institutional infrastructure and explains the use of CARMA Cloud and the role of IOOs in developing the strategies for addressing congestion.

A key feature of CDA operations is the dynamic vehicle-infrastructure interactions, particularly the exchange of real-time vehicular and roadway information that ADS can understand and share. IHP2 considers a cloud-based service that can be used to emulate a TMC for traffic monitoring, environmental monitoring, operations control and event injection, and road segment control definitions (e.g., dynamic speed limits). Such cloud services can communicate with CDA vehicles through roadside points of presence, irrespective of the particular communications technology, using the appropriate protocols. CDA vehicles can also share their statuses and what they sense about the surrounding dynamic traffic environment for better static and dynamic world models. The two-way information exchange constitutes the foundation of CDA, which includes both cooperative perception and cooperative vehicle control/traffic management. CDA device agents, vehicles, and infrastructure may use this information to improve situational awareness and expand their operational design domain.

There is a limited set of user needs relevant to the TMC-vehicle/operator-traveler interactions. Travelers are primarily the beneficiaries of these interactions but can also be information providers. Traffic operators, working on behalf of the infrastructure, are primarily the service and information providers but can also be informed by travelers using V2I communication. Table 6 lists the needs of road users and IOOs. In this table, road users are vehicles with connectivity capability, such that one-way or two-way information exchanges can occur between road users and IOOs. From the communication perspective, traffic management services, or TMC cloud services, can rely on DSRC or other communication channels (e.g., cellular services) that are subject to small communication delays and few packet drops. As long as the information is communicated between vehicles and the TMC cloud within a reasonable amount of time (on the order of seconds), the information maintains its value for guiding vehicles and informing TMCs.

Table 6. Infrastructure needs for road users and IOOs.

Road Users	IOOs
• Get maps for navigating to their destination, including detours. • Get information on traffic conditions ahead. • Get information on incidents. • Get information on lane use restrictions. • Get information on work zones. • Get information on weather conditions. • Get information on current local speed limits. • Get information on any special rules currently enforced. • Get information on toll pricing. • Get information on parking availability. • Inform IOOs of observed incidents. • Inform IOOs of observed work zones. • Inform IOOs of observed weather conditions. • Inform IOOs of their status, intent, and what they see.	• Monitor traffic conditions, including the presence of incidents. • Monitor environmental conditions. • Characterize incidents (location; vehicles, people, and objects involved; lanes blocked). • Inform emergency services of incidents. • Change traffic signal timing plans. • Control access to roadways. • Control speed limits. • Control (restrict) lane use. • Inform travelers of incidents. • Inform travelers of lane use restrictions. • Inform travelers of work zones. • Inform travelers of weather conditions. • Inform travelers of current local speed limits. • Inform travelers of any special rules currently enforced. • Receive traffic condition information from travelers.

The vehicle-to-everything communications environment is dynamic and not assumed to be perfectly reliable. Therefore, it cannot be expected that every transmitted message is received. In many cases this situation is acceptable, but guaranteed delivery may be desirable during complex negotiations among vehicles and with the infrastructure. One example of this need for guaranteed delivery is the CARMA3 mobility message specification and the protocol with which it is normally used, which allow negotiations based on requests and responses in the form of ACK (acknowledge) or NACK (not acknowledged) replies. For example, a vehicle broadcasting a request to merge waits until an ACK reply is received to confirm the merge will be accepted. If the requesting vehicle receives a NACK reply, or no reply at all, it adjusts its plans accordingly and attempts a different proposed merge (e.g., at a later time), or does not attempt to merge at all. In this way, if the request message is corrupted due to an error introduced by the communications medium, it would not result in an unsafe merge because the recipient would not send the necessary ACK reply. In other cases where messages are repeated regularly, such as speed or gap recommendations, guaranteed delivery is not as important because there will be many other opportunities to receive missed messages.

CARMA Cloud acts as a virtual TMC that receives information about the transportation system behavior, determines appropriate traffic behavior, and provides traffic direction and traveler information messages to vehicles to maintain safety and mobility across the system. To build those messages, CARMA Cloud gathers the needed data from external data sources (e.g., an agency’s own sensor networks or third-party and emerging data providers) that provide traffic, incident, work zone, and road weather data, as well as any other relevant data. In many cases, these data may be provided by ITS operated by a transportation agency in a TMC. As such, CARMA Cloud generally supplements existing TMC capabilities with the specific intent to provide messaging for V2I applications. Because not all roadways are managed through a TMC, the platform is data agnostic (i.e., does not use a specific type of data) and can manage the data and interfaces needed to provide V2I messaging independent of a TMC.

To enable IHP2, CARMA Cloud or other selected cloud services can also provide infrastructure rules to CDA vehicles, as shown in table 7.

Table 7. Exchanges and rules between CDA vehicles and the cloud.

Exchange Type	Information Type
Mapping rules	• Updates to lane configuration. • Updates to dynamic world models.
Planning rules	• Speed rules. • Speed harmonization. • Minimum gap rules. • Platooning statues (allowed or not). • Platooning limitations (two-, three-, or four-car, and so on).
Cooperative perception	• Vehicle current status, intent, and so on. • Local world information sensed by each CDA vehicle.

SUMMARY OF IHP2 NEEDS

Table 8 lists operational needs for key features of IHP2 and provides information for future development of the IHP2 system.

Table 8. Vehicle-side operational needs for IHP2.

Key Feature	ID No.	Operational Need
General	IHP-N01	Improve safety and efficiency of freeway traffic at the basic segment, merge, and weave areas.
	IHP-N02	Maintain situational awareness, i.e., accurate dynamic world models, including infrastructure (e.g., roadway geometry, roadway diet) and surrounding traffic (e.g., vehicles, pedestrian, bicyclists).
	IHP-N03	Detect vehicles incapable of cooperating with other vehicles.
	IHP-N04	Gather, integrate, process, and disseminate data.

Key Feature	ID No.	Operational Need
CDA Vehicle System: CLF	IHP-N05	Location, speed, and other status information from other CDA vehicles in the vicinity, on the same lane or adjacent lanes, of the ego CDA vehicles.
	IHP-N06	Location, speed, and other status information from human-driven vehicles in the vicinity, on the same lane or adjacent lanes, of the ego CDA vehicles.
	IHP-N07	Reliable, low-latency wireless communication to enable close lane following for platooning and CACC.
	IHP-N08	Negotiate with platoon members or nearby vehicles with the intention to join, if the ego vehicle is a platoon leader.
CDA Vehicle System*:* CLC	IHP-N09	Merge/lane-change vehicle speeds, locations, and other status information from nearby vehicles.
	IHP-N10	Negotiate with merge/lane-change vehicle and create gaps, along with other mainline/target lane vehicles, to facilitate merge.
	IHP-N11	Mainline/target lane vehicle speeds, locations, and other status information from nearby vehicles.
	IHP-N12	Negotiate with the mainline/target lane vehicles for gap creation to facilitate merge/lane change.
	IHP-N13	Reliable, low-latency wireless communication during the gap creation and lane change.
CDA Vehicle System*:* CTM	IHP-N14	Capability for CDA vehicles sharing information of the ego vehicles and surrounding CDA and non-CDA vehicles with the traffic management service.
	IHP-N15	Capability for CDA vehicles to process various information sent from the traffic management service.
	IHP-N16	Execute CTM commands or respond with appropriate control based on information sent from the traffic management service.
Non-ADS (Connected Human Driver)	IHP-N17	Information from surrounding vehicles.
	IHP-N18	Share real-time status information with nearby vehicles and the traffic management service.
	IHP-N19	User interface to present information to human drivers.
	IHP-N20	User interface to show the intent of vehicles in the vicinity to merge into the highway or change lanes into the ego vehicle lane.

Key Feature	ID No.	Operational Need
Traffic Management Service (Cloud Service)	IHP-N21	Gather and process data from infrastructure ITS devices to monitor current traffic conditions.
	IHP-N22	Gather and process data from CDA-equipped vehicles and connected non-CDA vehicles to monitor current traffic conditions.
	IHP-N23	Gather dynamic information on various traffic events (e.g., incidents, work zones, weather, lane restrictions, dynamic speed limits) from conventional infrastructure owner and operator data sources.
	IHP-N24	Gather dynamic information on various traffic events (e.g., incidents, work zones, weather, lane restrictions, dynamic speed limits) from CDA vehicle and connected non-CDA vehicle observation.
	IHP-N25	Set mapping rules and update dynamic world models for CDA vehicles.
	IHP-N26	Set planning rules, including speed rules, gap rules, platooning rules (e.g., size limitations).

ID = identification.

PERFORMANCE METRICS

The effectiveness of IHP2 needs to be evaluated for its capability to positively impact vehicle behavior and traffic flow performance metrics.

Performance Metrics for Vehicle Behavior

Key performance metrics for monitoring and evaluating operations include:

- Separation distances—Longitudinal distances between the vehicles in the test; used to determine safe distances and the frequency of infringement of those distances.

- Disengagements—Occurrence frequency when safety drivers deactivate the ADS feature being tested and take manual control of the vehicles.

- Travel speeds driven—Speeds driven by each vehicle during the tests used to create an accurate picture (playback) for evaluating the driving within the vehicle travel areas.

- Speed changes—Changes in speeds of the vehicles above or below a threshold in response to interactions between ADS vehicles (reduction in speeds by the ramp vehicle moving onto the highway and reductions/maintenance of the mainline vehicles' speeds).

- Data exchanges during negotiation (cooperation class C)—All data exchanges between two cooperation class C ADS vehicles to determine whether the maneuver negotiations took place as designed. Exchanges include the following data types:

- Total duration of the negotiation process.
- Frequency of negotiation success/failure (NACK replies from neighboring vehicles).
- Number of attempts before a plan is accepted by all affected neighbors.
- Message latency, which is the time difference between message origination from vehicle A to message reading by vehicle B. The latency time includes the following: the time to compose the message; the time to send the message from vehicle A's guidance computer to vehicle A's onboard unit (OBU); the queuing time on vehicle A's OBU; the radio transmission from vehicle A to vehicle B; the message constitution and queuing on vehicle B's OBU; sending the message from vehicle B's OBU to vehicle B's guidance computer; and the time for vehicle B's decomposition and reading.

Performance Metrics for Traffic Performance

This subsection identifies performance metrics for traffic performance to evaluate the IHP2 impacts on traffic flow. As shown in table 9, the five categories of impacts are safety, throughput, flow stability, flow breakdown and reliability, and sustainability (Mahmassani 2016). The impacts can be investigated using analysis, modeling, and simulation (AMS) tools and real-world studies.

Table 9. Traffic performance measures for IHP2 evaluation.

Category	Impact	Performance Measure
Safety	Reduction in number of crashes	Number of crashes
	Improvement in outcome of crashes	Severity of crashes
Throughput	Increase in traffic flow volume	Number of vehicles per hour per lane
	Smoothness of traffic flow	Variability of speeds within traffic stream
Flow stability	Improved local stability	Local flow stability index
	Improved string stability	Mixed-flow string stability index
Flow breakdown and reliability	Occurrence of traffic shock waves	Number of significant shock waves formed
	Severity of shock waves	Propagation speed of formed shock waves relative to wave front
		Duration of shock wave-induced queues
Sustainability	Impact on greenhouse gas emissions	Level of carbon dioxide, nitrogen oxide, and particulate matter-equivalent emissions
	Reduction in energy consumption	Amount of energy consumed

Safety

Because the majority of crashes are due to human error, automated vehicles have the potential to significantly decrease the number of crashes, specifically at high market penetration levels. One way to quantify safety improvements is by calculating the number of crashes and the crash severity. Other factors, such as safety surrogate measures (e.g., time to collision), are also useful.

Throughput

CDA technologies are expected to increase the flow throughput of transportation facilities by increasing flow densities. However, such impacts are dependent on the market penetration of those technologies. Throughput can be quantified by measuring the number of vehicles passing through per hour and the variability of speeds within a facility segment.

Flow Stability

There are two types of traffic stabilities: flow stability and string stability. Flow stability refers to the traffic stream's ability to recover its steady-state properties (density-speed) after incurring a perturbation. String stability refers to intervehicular spacing along the platoon. If disturbances in vehicle spacings do not grow as the disturbance propagates along the platoon, the platoon is string stable. There are several stability indexes developed in the literature that can be used in the AMS tool (Darbha and Rajagopal 1999; Zhou and Peng 2005).

Flow Breakdown and Reliability

Flow breakdown is a traffic phenomenon in which throughput/capacity drops due to a perturbation (e.g., accident or sudden braking). CDA vehicles are expected to improve traffic flow reliability by providing smoother, safer, and more responsive vehicle operations. The AMS tool can use multiple measures to quantify CDA impact on flow breakdown and reliability, such as the occurrence of shock waves and the severity of shock waves formed.

Sustainability

The environmental impact of CDA is uncertain. However, smoother operations associated with CDA can lead to lower greenhouse gas emissions and energy consumption due to reduced acceleration and braking.

CHAPTER 4. OPERATIONAL SCENARIOS

This chapter identifies IHP2 operational scenarios to enhance TSMO. The focus IHP enabled on any highway in general purpose lanes and understanding the impact as early deployment benefits of CDA enter the system are discussed. An end-to-end use case is described where a vehicle enters the freeway, engages in CDA features described in the prior chapters (including actions by both the CDA-enabled vehicle and roadway infrastructure using mapping and planning rules), and exits the freeway.

END-TO-END CDA OPERATIONS FROM FREEWAY ENTERING TO EXITING

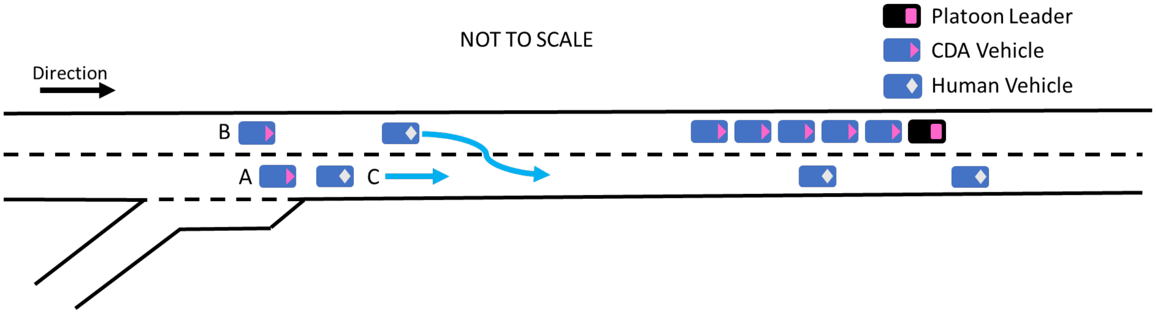
This section describes possible CDA operations for a CDA vehicle from the time it enters a freeway from an onramp to when it exits the freeway using an off-ramp. This scenario is designed to cover all key features of IHP2, including CLF, lane coordination, and traffic management.

As shown in figure 10-A, CDA vehicle A aims to enter the freeway from the onramp. When vehicle A approaches the onramp, it receives information from the cloud that there are multiple vehicles nearby, and that two of them—vehicle B (a CDA vehicle) and vehicle C (a human connected vehicle)—will impact vehicle A's trajectory of merging. In this scenario, vehicle A and vehicle B both belong to cooperation class C. Vehicle C is a human-driven vehicle and can share its own status with the cloud and with vehicles A and B. The negotiation is coordinated between vehicles A and B with the purpose of ensuring minimum disturbance to the mainline traffic. The result of the negotiation is for vehicle B to make a lane change to the left to create a gap for vehicle A to merge into the mainline. All other vehicles can be either nonconnected ADS vehicles or nonconnected human-driven vehicles. The nonconnected vehicles will perform perception and decisionmaking independently without any communication and data sharing with other vehicles. CDA vehicles will need to use onboard sensors to detect the nonconnected vehicles, regardless of the nonconnected vehicle's status as ADS or human driven, and plan corresponding trajectories to avoid any conflict.

In figure 10-B, the merge process of vehicle A has been completed. Because of the shared information of vehicle C, vehicle A is able to follow vehicle C closely and forms a short CACC string in the short term. In the meantime, as shown in figure 10-C, vehicle A negotiates with vehicle E, the leader of the platoon in front of vehicle A, to join the platoon from the rear. Vehicle A will be a platoon member until it reaches near the off-ramp as its destination.

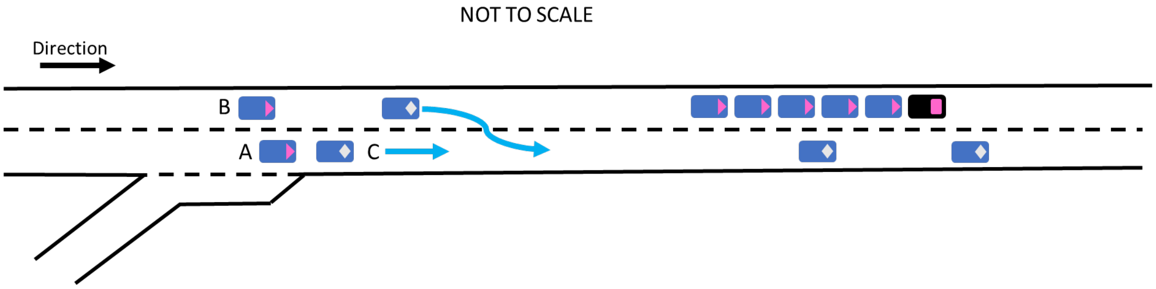
After a certain period, vehicle A and the platoon approach another merge with reduced traffic performance because of heavy merge traffic. The cloud considers the necessity to perform CTM, including speed control/harmonization, and lane assignment. In figure 10-D, all platoon members are first instructed not to move to the right lane at or upstream of the bottleneck merge area (geofenced). Second, the platoon leader also receives speed commands from the cloud to slow down to perform speed harmonization of the upstream traffic. Vehicle A, as a member of the platoon, receives commands directly from the cloud, but gives priority to the platoon leader and slows down with all other members of the platoon.

In figure 10-E, vehicle A informs the platoon leader, vehicle E, of its intent to leave the platoon. Vehicle E will provide instructions to vehicle A and the platoon member vehicles behind vehicle A to create larger gaps so that vehicle A could smoothly change lanes to the right. The lane change maneuver of vehicle A conflicts with planned trajectories of vehicle D, which intends to make a lane change to the left. Vehicle A identifies this conflict and negotiates with vehicle D, which first slows down and then proceeds with making the lane change. These moves are parts of a multiparticipant cooperative maneuver. Vehicle A eventually reaches the destination off-ramp and completes the trip. Vehicle A benefits from multiple CDA features in this process, including cooperative merge, CACC, platooning, cooperative lane assignment, speed control, and cooperative weave. The combination of cooperation among vehicles and with the cloud not only improves individual vehicle travel experiences, but also enhances overall traffic system performance.



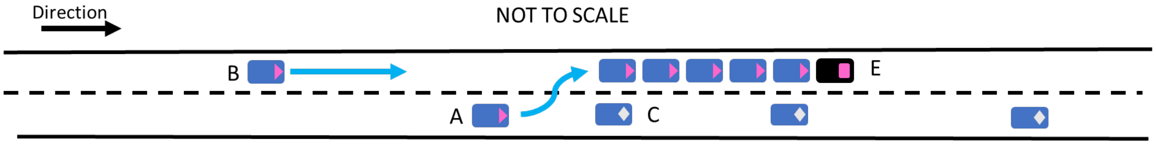
Source: FHWA.

A. Vehicle B moves to the left lane to facilitate the merge of vehicle A.



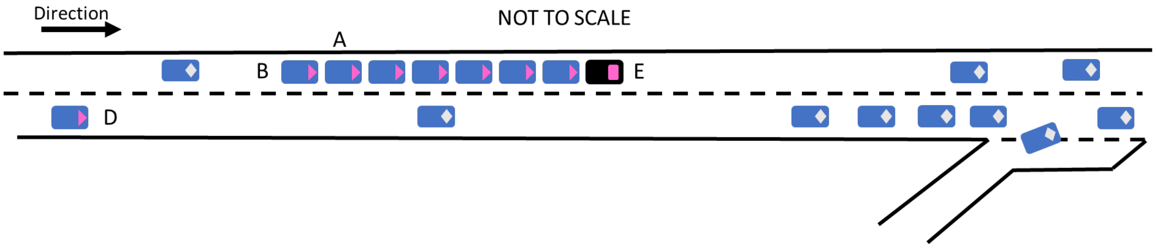
Source: FHWA.

B. Vehicle A forms a CACC string with human-driven vehicle C.



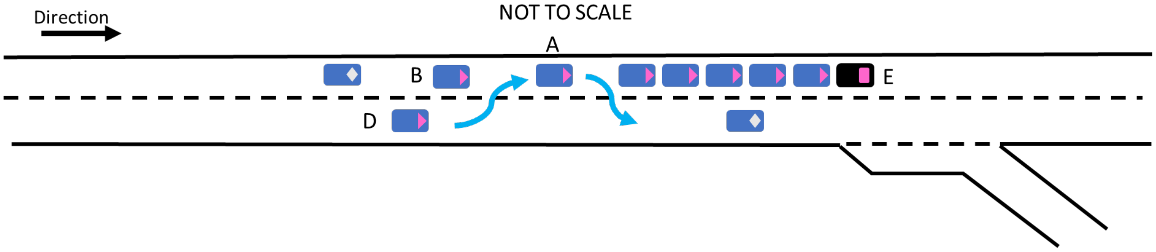
Source: FHWA.

C. Vehicle A seeks to join the existing platoon in the left lane.



Source: FHWA.

D. Platoon vehicles remain in formation as they approach a bottleneck.



Source: FHWA.

E. Vehicle D enters the platoon while vehicle A leaves the platoon.

Figure 10. Illustrations. End-to-end CDA operations.

CTM WITH LANE ASSIGNMENT AND SPEED CONTROL

This section describes how TMCs (i.e., CARMA Cloud) use mapping and planning rules for downstream bottleneck reduction and queue management. This scenario describes how and what decisions are made from the cloud and TMC side.

As illustrated in figure 10-D, mixed traffic of platoons, individual CDA vehicles, and human-driven vehicles are approaching a bottleneck area caused by heavy merge traffic. The cloud continuously monitors the traffic conditions by receiving information from all connected vehicles (CDA and connected human-driven vehicles) and infrastructure detectors, if any. The cloud fuses all received data and estimates that there is currently a long queue of stop-and-go traffic in the right lane and a slightly better condition in the left lane. The cloud runs the CTM features to develop rules for speed, gap control, lane use, and other strategies to reduce the bottleneck conditions.

First, the cloud implements speed rules by sending corresponding optimal speed commands to all CDA vehicles, including platoons, in geofenced areas. The purpose of the speed rules is to slow down the CDA vehicles and reduce the speed rate of the vehicles entering the bottleneck area. This process is also referred to as speed harmonization. Second, the cloud assigns the left lane as the desired lane for CDA vehicles and connected human-driven vehicles (via onboard devices) because the merge traffic from the right side of the onramp caused a long queue in the right lane.

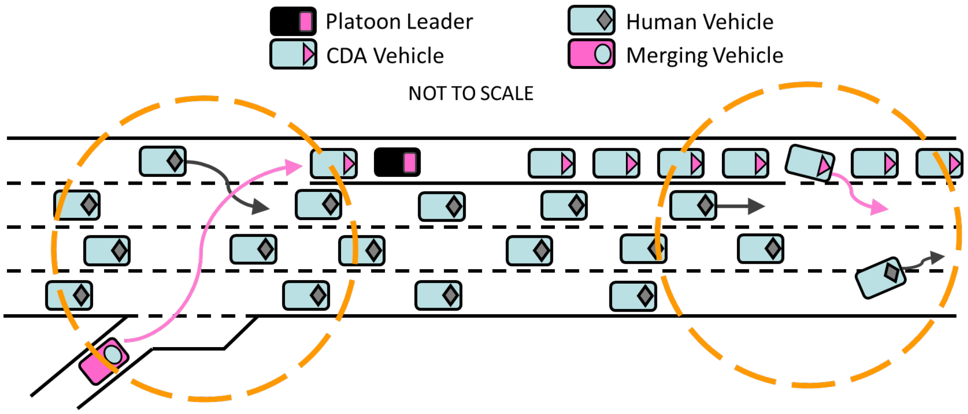
For vehicles that will exit the freeway via the next off-ramp, the cloud assigns the right lane as the desired lane early, before the vehicles are in the diverge or weave area. This lane use rule is expected to help improve the traffic flow for the freeway diverge or weave areas. As traffic volume increases, the traffic flow density will become high, which makes it more difficult to change lanes approaching the off-ramp. When a vehicle is close to the exit but still cannot change lanes into the off-ramp, vehicles make aggressive lane changes to force their way into the target lane or to stop at certain points. This action potentially causes great disturbances in the traffic flow. If the lane assignment rules are used early and at the appropriate time, the vehicles can start making lane changes at a greater distance upstream from the exit. In this case, a vehicle will have a better chance to find an acceptable gap or negotiate with other CDA vehicles to create gaps for lane changes

DEDICATED FACILITY OPERATIONS FOR EARLY DEPLOYMENT

This section describes a scenario in which a dedicated facility (i.e., managed lanes, dedicated ramps) is used for early deployment benefits. As illustrated in figure 11-A**,** the managed lane strategy has been widely used to serve high-occupancy vehicles (HOV), or drivers willing to pay a toll, to improve overall efficiency of the highway system. The CDA-dedicated managed lane can adopt a similar operational concept that only allows CDA vehicles to enter the managed lane. The managed lane physically separates the CDA traffic stream from regular traffic. As the CDA vehicles concentrate in the managed lane, they will have a higher probability of traveling in vehicle platoons or CACC strings, thereby improving highway performance. It is also possible to allow special purpose human-driven vehicles (e.g., HOV vehicles) to use the managed lane in very early stages to make best use of the managed lane capacity. Simulation studies have demonstrated feasibility and system performance enhancement, even with mixed traffic (Ma et al. 2016).

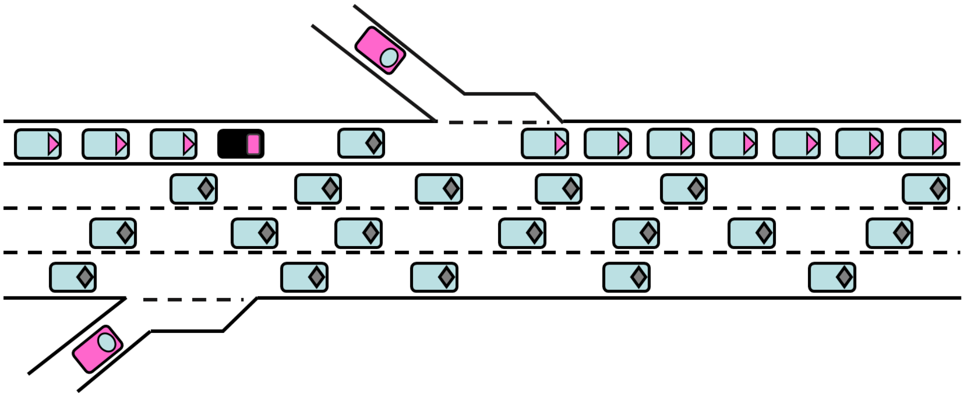
Another possible dedicated infrastructure is the left-side dedicated ramp connected to the managed lane, as illustrated in figure 11-B. Because more vehicles will have access to the left-side managed lane as the CDA market penetration increases, vehicles entering the freeway from the right-side ramp may make multiple lane-change maneuvers to access the managed lane. This action creates a weaving section (shown as two dashed circles in figure 11-A representing the start and end of the managed lane) that can reduce highway capacity and increase safety risks. Constructing dedicated ramps with direct access to the left-side managed lane can reduce such negative effects and can be considered as a part of the dedicated infrastructure strategy.

In this scenario, a limited-access, barrier-separated managed lane next to the median of a freeway with limited entry and exit ramps running alongside general-purpose lanes is considered. Only the CDA vehicles and connected human-driven vehicles are eligible to use the dedicated facility. Human single-occupancy vehicles (SOV) can also pay the tolls to use the managed lane.



Source: FHWA.

A. Managed lane without dedicated CDA ramp.



Source: FHWA.

B. Managed lane and dedicated ramp.

Figure 11. Illustrations. Two dedicated facility operational scenarios.

Congestion starts to form at multiple merging areas. The cloud monitors traffic flow conditions via roadside equipment and infrastructure-based sensors (e.g., radar traffic detectors), including traffic flow, density, and speed data, and transmits the information to the TMC. In addition, CDA vehicles transmit basic location and status (e.g., speed, direction) to the infrastructure devices, which then convey that information to the cloud for subsequent decisionmaking. The daily managed lane operations process for this scenario is as follows:

- CDA and connected human-driven vehicles enter the managed lane at one end of the segment on dedicated ramps. CDA vehicles may form vehicle platoons based on onboard vehicle platooning algorithms subject to rules set by the cloud, such as maximum string length. Certain vehicles may seek to exit the facility at certain exit points. The vehicle platooning algorithm may also govern this process by, for example, splitting a long platoon into shorter platoons with the exiting vehicle at the end of one platoon and then letting the exiting vehicle disconnect itself from the platoon to exit via an off-ramp. If desirable, the two separate platoons can recombine once the exiting vehicle completes its departure.

- The cloud aggregates, organizes, and summarizes streaming data received from connected vehicles and infrastructure-based systems. The cloud monitoring and detection systems identify flow breakdown events based on real-time received data.

- On the basis of current traffic demand and congestion level, the cloud will use existing pricing algorithms to calculate dynamic tolls and, via the infrastructure-based communications systems, send this updated information to all users to indicate that the cost of using the facility is changing. Some human SOVs may be discouraged from using the facility, thus reducing the demand. The reduced demand would improve the service quality for HOVs, CDA vehicles, and connected human-driven vehicles.

- On the basis of bottleneck traffic conditions, the cloud speed control/harmonization algorithm generates recommended speeds for all vehicles. Connected human-driven vehicles receive recommended speed commands for each freeway subsegment. CDA vehicles receive recommended speed profiles that are automatically followed.

- At merge areas, the cloud or roadside equipment receives merge requests from merge vehicles at the onramps. The cloud speed control algorithm generates speed commands for CDA vehicles on the managed lane for gap creation. The cloud cooperative speed control may also generate speed commands for the merge CDA vehicles to ensure the merging vehicles can use the created/assigned gaps to merge into the managed lane.

CHAPTER 5. ANALYSIS OF THE PROPOSED SYSTEM

This chapter provides an analysis of the benefits, advantages, limitations, and disadvantages of IHP2. 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. Driving automation and connectivity present opportunities to deploy multiple cooperative automation strategies, but successful deployment depends on coordination among diverse stakeholders.

CDA aims to improve the safety and flow of traffic and facilitate road operations by supporting the movement of multiple vehicles in proximity to one another. This result is accomplished by sharing information to influence DDT performance by one or more nearby road users. Vehicles and infrastructure elements engaged in cooperative automation may share information such as state and intent or seek agreement on a plan. Cooperation among multiple participants and perspectives in traffic can improve safety, mobility, situational awareness, and operations.

For IHP2, three feature groups include CLF, CLC, and CTM. The three IHP2 feature groups not only include IHP1 features, but also cover additional features to present a comprehensive package for integrated freeway management with CDA. The concept of IHP is evolutionary, and new freeway applications not currently considered by researchers and developers are intended to be incorporated as they are conceived. Cooperation among vehicles and with the cloud not only improves individual vehicle travel experiences but also enhances the overall traffic system performance.

SYSTEM VALIDATION PLAN

This section describes system validation methods that will be used in the development of IHP2 algorithms and software systems. The purpose of the validation testing is to ensure that the developed IHP2 system can meet all the operational needs listed in table 8 of chapter 3.

Simulation Testing

The simulation can be designed to test IHP2 using the performance metrics identified in chapter 3 in terms of vehicle behavior and traffic system performance. Different types of simulation can be used and combined for testing purposes.

ADS simulators offer the potential benefit of testing control algorithms embedded in real software because they support simulation of different vehicles with vehicle dynamics, sensor suites, environmental conditions, control software, and map generation that enable automated vehicle simulations. These capabilities enable more detailed testing of IHP2 software directly in the simulation environment under different critical scenarios. Performance metrics related to vehicle behavior can be extracted to understand if vehicle behavior meets the needs of the IHP2 systems.

Traffic simulators offer the possibility to scale up the evaluation to a highway corridor/network level (compared with the limited number of vehicles and length of the roadway for ADS simulators) to study the CDA impact on transportation system performance, as measured by traffic performance metrics such as safety, efficacy, stability, and sustainability. The traffic simulators can evaluate different scenarios, including various market penetration of CDA vehicles, traffic demand, various control strategies, and different infrastructure alternatives (e.g., dedicated ramps). Usually, the CDA control algorithms will be simplified from real software and will be parsimonious. However, calibrated/validated CDA behavioral models/algorithms (e.g., platooning vehicle following behavior as compared with the human driver following behavior) will be implemented for large-scale testing.

Field Testing

Field testing can be conducted on a closed test track or selected open public road with different levels of live traffic. Depending on participation by partners, five or more CARMA vehicles loaded with IHP2 software can be instructed to run loops on the test track to represent continuous driving. End-to-end driving scenarios discussed in chapter 4 can be tested. These scenarios include cooperative merging, lane changing, joining a platoon, cooperative weaving, and CTM (via sending rules such as speed and gap control to CDA vehicles). The purpose of testing is to collect vehicle behavior performance measures and validate whether the IHP2 software meets the needs established in chapter 4 of this report.

Similar to IHP1 testing, IHP2 could also be tested on a public road with live traffic. Selected scenarios from the test track testing can also be applied. One key difference is the existence of live traffic, which will dynamically interact with all CDA vehicles. This testing would offer an opportunity to collect further data on human driver behavior in response to CDA vehicles.

Data collected from both test track and public road testing can be used not only to calculate vehicle behavior performance metrics, but also to calibrate traffic simulation CDA behavior models and human models in response to CDA behavior. This research can enable better validated evaluation of CDA's traffic impacts in simulations.

SUMMARY OF IMPACTS

IHP2 offers a holistic approach for optimally managing transportation systems and reducing disutilities. The benefits of IHP2 can only be realized when the cooperative control can be enabled by effective algorithms, including those for CLF, CLC, CTM, and a combination of different features. The need for controlling each individual CDA vehicle calls for highly scalable algorithms—possibly a mixture of distributed and centralized approaches—to guide all CDA vehicles in the transportation system. IHP2 presents changes to how TSMO is conducted. ITS infrastructure systems need to be upgraded to accommodate CDA system needs, such as cloud services and supporting information technologies. Agencies also need to evaluate and build capabilities for operating such systems. The conventional process of transportation system performance monitoring and reporting can be revolutionized with the prevalence of CDA vehicles and advanced sensors.

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