Applying Bundled Speed-Harmonization, Cooperative Adaptive Cruise Control, and Cooperative-Merge Applications to Managed-Lane Facilities

PUBLICATION NO. FHWA-HRT-21-008 MARCH 2021

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

The Turner-Fairbank Highway Research Center performs advanced research in several areas of transportation technology for the Federal Highway Administration (FHWA). FHWA's Office of Operations Research and Development (HRDO) focuses on improving operations-related technology through research, development, and testing.

This report summarizes the second phase of continuing research, sponsored by HRDO, evaluating the effects of speed harmonization on traffic flow through common bottleneck locations. During phase 1 of this research, researchers simulated, analyzed, and field-tested speed harmonization in an area of recurring congestion. During this second phase, researchers bundled speed-harmonization, cooperative-adaptive-cruise-control, and cooperative-merge applications onto a vehicle-control platform. Simulations of the three bundled applications were performed using a calibrated network, and a limited field study was performed in a managed lane to confirm the results of the simulation. Promising results from the simulation and field study provide an excellent justification for the implementation of vehicle-to-vehicle and vehicle-to-infrastructure technology that would appeal to roadway owners, operators, and users alike. It is these groups that have a stake in the future of transportation who would benefit most from the findings presented in this report.

Brian P. Cronin, P.E.
Director, Office of Safety and Operations
Research and Development

TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.
FHWA-HRT-21-008</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Applying Bundled Speed-Harmonization, Cooperative Adaptive Cruise Control, and Cooperative-Merge Applications to Managed-Lane Facilities</td><td colspan="2">5. Report Date
March 2021</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Jiaqi Ma (ORCID: 0000-0002-8184-5157), Ed Leslie (ORCID: 0000-0002-1711-2661), Amir Ghiasi (ORCID: 0000-0002-0986-9840), Yi Guo (ORCID: 0000-0002-4778-1823), Sonika Sethi (ORCID: 0000-0002-5236-0003), David Hale (ORCID: 0000-0001-5486-9367), Steve Shladover (ORCID: 0000-0002-3207-0084), Xiao-Yun Lu (ORCID: 0000-0001-6491-3990), and Zhitong Huang (ORCID: 0000-0003-2871-6302)</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Leidos, Inc.
11251 Roger Bacon Drive
Reston, VA 20190</td><td colspan="2">10. Work Unit No.</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
DTFH61-12-D-00020; Task Order 26</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Highway Administration
1200 New Jersey Avenue, SE
Washington, DC 20590</td><td colspan="2">13. Type of Report and Period Covered
Final Report; August 2016–July 2018</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
HRDO-20</td></tr>
<tr><td colspan="4">15. Supplementary Notes
Robert Ferlis (HRDO-20; ORCID: 0000-0003-3099-4037) served as the Government Task Manager on this contract. For more information, contact Taylor Lochrane at Taylor.Lochrane@dot.gov.</td></tr>
<tr><td colspan="4">16. Abstract
The purpose of this document is to describe the research, including simulations and a field experiment, involving the operation of connected and automated vehicles (CAVs) on managed lanes. The scenarios associated with this concept were chosen and designed to facilitate rapid and successful deployment of a solution that is not yet in use. The proposed operation involves deploying platoons of CAV-equipped vehicles that are governed by an integrated set of speed-harmonization, cooperative-merge, and cooperative-adaptive-cruise-control (CACC) applications. The concept accounts for CACC-vehicle behaviors in the vicinity (both upstream and downstream) of managed-lane entry ramps. The concept further addresses platooning and cooperative merging on the managed lane. The concept was simulated, and potential improvements were quantified. The results were then implemented in a small number of real vehicles and tested on a real roadway under controlled conditions and in mixed traffic.</td></tr>
<tr><td colspan="2">17. Key Words
Speed harmonization, cooperative adaptive cruise control, and cooperative-merge applications, managed lanes, traffic smoothing, connected vehicle, connected and automated vehicle, platoon</td><td colspan="2">18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.
http://www.ntis.gov</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
116</td><td>22. Price
N/A</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

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 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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 (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

ACC	adaptive cruise control
CACC	cooperative adaptive cruise control
CAMP	Crash Avoidance Metrics Partnership
CAN	Controller Area Network
CARMA℠	Cooperative Automation Research for Mobility Applications
CAV	connected and automated vehicle
CCTV	closed-circuit television
ConOps	concept of operations
CV	connected vehicle
DSRC	dedicated short-range communications
ETL	electronically tolled lane
FHWA	Federal Highway Administration
GPS	global positioning system
HOT	high-occupancy toll
HOV	high-occupancy vehicle
HTTP	hypertext transfer protocol
I2V	infrastructure-to-vehicle
ID	identity
ITS	intelligent transportation systems
OBU	onboard unit
PATH	Partners for Advanced Transit and Highways
PID	proportional-integral-derivative
REST	representative state transfer
RSE	roadside equipment
RSU	roadside unit
SAE	SAE International
SOV	single-occupancy vehicle
TMC	traffic-management center
TO	task order
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VAD	vehicle-awareness device
VDOT	Virginia Department of Transportation
VF	virtual follower
VL	virtual leader
VSL	variable speed limit

Symbols

a_{des}	desired acceleration
a_{merge}	acceleration of the on-ramp vehicle
a_{sv}	acceleration recommended by the adaptive-cruise-control controller to the subject vehicle
D	distance between the subject vehicle's front bumper and the preceding vehicle's front bumper
D_{cur}	distance between the current position and boundary of speed-harmonization area
D_{GR}	minimum gap-regulation distance
d_l	deceleration of the preceding vehicle
D_{merge}	relative distance to the merge point
d_{REQ}	deceleration required to avoid a rear-end collision
e_k	time gap error
$\dot{e}_k$	change in time gap error
g_{REQ}	required gap to avoid a rear-end collision
k_1	gain in the speed difference between the free-flow speed and the subject vehicle's current speed
k_2	gain on position difference between the preceding vehicle and the subject vehicle
k_3	gain on speed difference between the preceding vehicle and the subject vehicle
k_d	second gain coefficient for adjusting the time gap between the subject vehicle and preceding vehicle
k_p	first gain coefficient for adjusting the time gap between the subject vehicle and preceding vehicle
L	length of the preceding vehicle
L_{seg}	total length of the speed-harmonization area
M	moving-average parameter
n_{test}	number of experimental runs
n_{veh}	number of paired vehicles
p_{merge}	merge point
$p_{release}$	release point
t	time
t_1	the constant time gap between the last vehicle of the preceding CACC-vehicle string and the subject vehicle
t_2	intrastring constant time gap
t_3	duration for the merge vehicle to accelerate to the gap leader's speed
t_{hw}	desired time gap of the adaptive-cruise-control controller
T^m	time needed for vehicle to merge into the platoon
T^P	period of time required for vehicles to adjust their spacings and headways
v_{CACC}	desired speed for the specific cooperative adaptive cruise control mode
v_{Coop}	desired speed calculated by the cooperative-merge module
v_{cur}	current speed of the subject vehicle
v_{des}	desired speed
$vehMode$	operation mode
v_f	free-flow speed
v_{field}	speed of the field-observed vehicle
v_L	speed of the gap leader

v_l	current speed of the preceding vehicle
v_{pre}	prevailing speed in the merge area
v_{SH}	desired speed determined by speed-harmonization application
$v_{simulation}$	speed of the simulated vehicle
v_{sv}	current speed of the subject vehicle
Δt	time step for each update
Φ^h	threshold parameter for headway
φ^h	threshold parameter for headway rate
Φ^s	threshold parameter for spacing
φ^s	threshold parameter for absolute spacing
ζ	binary coefficient that reflects whether the preceding vehicle has a non-zero speed

CHAPTER 1. INTRODUCTION

BACKGROUND

Typical sources of traffic congestion include oversaturation of a roadway with vehicles, poor weather, vehicle crashes, work zones, poor signal timing, and special events. Oversaturation occurs when more vehicles use a road than the road is designed to accommodate (i.e., demand is greater than supply). Congestion leads to breakdowns in traffic flow and bottlenecks. These congestion events bring unwanted impacts, including wasted fuel, increased emissions, decreased travel-time reliability, delays to emergency vehicles, and decreased productivity (e.g., gross domestic product). Now that the Nation's transportation system has matured, the focus has shifted from constructing new lanes to improving the operational efficiency of existing lanes.

Because managed lanes have evolved into sophisticated roadways, managed-lane operators have a unique opportunity to leverage their facilities as real-world test beds and preliminary deployment sites for connected and automated vehicles (CAVs), thereby increasing the return on investment of these lanes. CAVs may be equipped with a suite of technologies ranging from preliminary vehicle automation (i.e., automated/autonomous decisionmaking at the vehicle level using onboard sensors) to a connected ecosystem in which vehicles and roadside infrastructure communicate wirelessly among themselves. The preliminary levels of automation are shown in figure 1, whereas the complete set of all levels may be viewed online. (FHWA 2018)

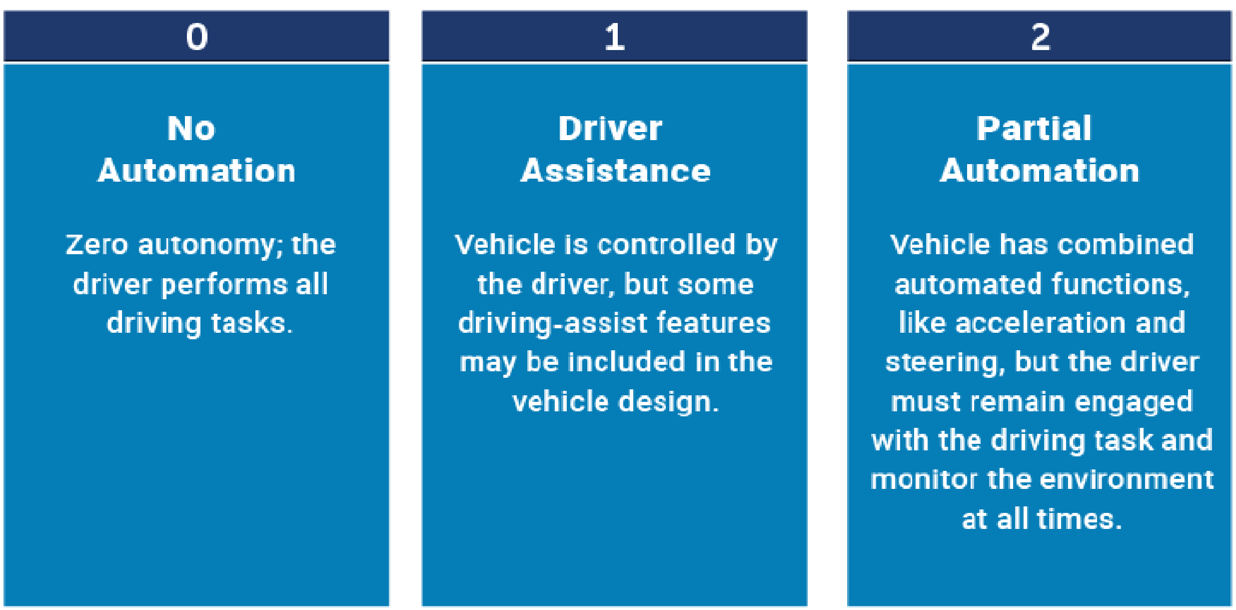


Figure 1. Illustration. Preliminary levels of automation based on SAE International's definitions. (NHTSA)

Managed-lane facilities are frequently equipped with traffic sensors, communication networks, and tolling equipment, all of which can be leveraged to support CAV initiatives. With rapid advancements in CAV technology, priced managed lanes can benefit directly from emerging communication technologies (e.g., dedicated short-range communications (DSRC) systems) and in-vehicle innovations. When combined with current levels of vehicle automation, modern managed lanes present an opportunity for incremental traffic-flow improvements that may produce widespread mobility, safety, and environmental benefits.

These vehicle-connectivity and -automation technologies could allow vehicles to maintain consistent speeds throughout the roadway facility, thereby increasing the traffic levels that a roadway can support. Increased throughput and capacity of managed lanes could also benefit parallel general-purpose lanes as traffic shifts to these managed lanes. Consistent, optimized speeds would facilitate a reduction in fuel consumption, harmful emissions, and highway crashes.

To date, more than 30 CAV applications and concepts have been developed, many through prototyping and demonstration. Among these applications, three technologies show the most promise for early deployment at managed lanes: speed harmonization, cooperative adaptive cruise control (CACC), and cooperative merge.

Speed Harmonization

Generally, speed harmonization involves gradually lowering speeds upstream of a heavily congested area to reduce the stop-and-go traffic that contributes to driver frustration and crashes. Because this strategy reduces vehicle speeds, it may either delay or prevent the onset of traffic congestion. To date, a related strategy, known as variable speed limits (VSLs), 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 obtained positive results in terms of improving traffic-flow stability, reducing crashes and injuries, and decreasing emissions. (FHWA 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, driver responses to suggested speeds have not been consistent. Dynamic adjustments to speed limits are less efficient than dynamic adjustments to recommended and/or actual speeds communicated directly to CAVs (in which case, the speeds are automatically adjusted unless drivers intervene). In an ideal scenario, speed commands are generated by effective algorithms based on real time–traffic monitoring. Different commands are then communicated to and automatically implemented by vehicles on different segments of the roadway. Such dynamic speed-harmonization systems may successfully manage upstream and bottleneck (e.g., merge 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.
- Disseminating such information to upstream vehicles rapidly in a manner that achieves an effective rate of compliance.

Some recent studies assessed infrastructure-to-vehicle (I2V)-based speed-harmonization applications, in which speed guidance is communicated directly to vehicles. These simulations demonstrated 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, which concurred with other simulation-based studies. (Talebpour et al. 2013)

Compared to segment-based speed harmonization (which provides the same speed recommendation or command for all traffic on a freeway segment), trajectory-based speed harmonization is a more advanced approach that controls an individual vehicle's trajectory and coordinates it with other vehicles. Speeds of individual vehicles can be controlled in real time, depending on each vehicle's location on the roadway segment, to enable vehicles to smoothly pass downstream bottlenecks. Recent simulation studies and field experiments suggest the potential of such an approach to enhance traffic smoothness and, therefore, improve efficiency and safety. (Ghiasi et al. 2017, Ma et al. 2016) In particular, trajectory control can facilitate freeway merging. Regarding freeway merging, a central controller (e.g., traffic-management center (TMC)) coordinates the trajectories of upstream managed-lane vehicles and merge vehicles such that smooth and efficient merging with minimal impact on mainline traffic can be guaranteed.

CACC

A CAV's adaptive cruise control (ACC) can become CACC by adding vehicle-to-vehicle (V2V) communications. This enhancement means the CAV would leverage its ability to communicate with surrounding vehicles to maintain the optimal following distance. The CAV could slow down when it gets too close to another CAV, speed up to maintain the desired headway, or communicate with other vehicles about speed and trajectory changes while in cruising 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. Vehicles that use V2V communication could allow the mean following-time gap between vehicles to decline from about 1.4 s when driving manually to approximately 0.6 s when using CACC, resulting in an increase in highway lane capacity. (Nowakowski et al. 2010) Several highway-traffic simulations conducted by the California Partners for Advanced Transportation Technology showed that autonomous ACC alone, even at high market-penetration rates, had little effect on lane capacity, and recent on-the-road experiments have shown that streams of autonomous ACC vehicles have a negative impact on lane capacity and safety. (Nowakowski et al. 2002, Shladover et al. 2012, Milanés et al. 2014) However, at a market-penetration rate of 100 percent, CACC systems could help increase lane capacity from the typical 2,200 vehicles per h to almost 4,000 vehicles per h by engendering shorter following gaps and greater flow stability.

In addition to V2V-based CACC, Shladover et al. (2015) proposed the concept of CACC systems that use I2V communication, though they did not investigate the concept in detail. Theoretically, the CACC system reduces the potential for congestion at bottleneck locations by automatically reducing the speeds of upstream vehicle strings using I2V communication to set speed values, thus reducing speed differentials and allowing the traffic flow to be maintained at peak throughput. This strategy is similar to the proposed concept of the bundled application of

CACC and speed harmonization: by controlling the lead vehicle's speed and trajectory, the vehicle strings will arrive at bottleneck locations at an ideal point in time, allowing them to pass the location smoothly. This bundled application should also be coordinated with cooperative merging so that vehicles that attempt to merge into the managed lane will be integrated without a breakdown in traffic flow.

Cooperative Merging

The concept of cooperative merging leverages V2V and vehicle-to-infrastructure (V2I) communications to enable CAVs to signal (via DSRC or an equivalent wireless technology) their intention to merge into traffic streams containing other vehicles. Using information sent through V2V and V2I communications, merging CAVs may identify upcoming acceptable gaps on the mainline and make lane changes when possible. In addition, upstream managed-lane CAVs may cooperate by adjusting their speeds to create a gap for the requesting CAV. The trajectories of merging CAVs are then optimized. The merge movement can then occur safely and with minimal impact on the platoon's mobility.

A recent Federal Highway Administration (FHWA) study describes an effort to develop an innovative vehicle-control platform to successfully conduct a proof-of-concept field experiment to validate 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 show the effectiveness of the proposed platform and successfully prove the new concept of cooperative lane change. Chou et al. (2016B) tested two cooperative automated merging strategies, one using I2V and the other using V2V communications, for highway entry in a microscopic simulation. The results show I2V communication reduced travel time in the merging section when the traffic flow was high, and V2V communication supports a significant increase in traffic flow without increasing travel times. The results indicate the potential advantages of using cooperative automation to relieve bottlenecks in the merging section.

All these existing studies, however, target only limited merge areas with simple algorithms. The effectiveness of cooperative merging cannot be isolated from other CAV operations, such as platooning. Additionally, the combination of cooperative merging and speed harmonization (by controlling and coordinating arrivals of upstream managed-lane vehicles to create gaps for merging) can further improve merge-area performance. Therefore, the bundling of the algorithms proposed in this study addresses such integration of three applications (i.e., speed harmonization, CACC, and cooperative merge).

MANAGED-LANE OVERVIEW AND RELEVANCE FOR CAV APPLICATIONS

FHWA's 2012 *Priced Managed Lanes Guide* states, "Managed lanes are designated lanes or roadways within highway rights-of-way where the flow of traffic is managed by restricting vehicle eligibility, limiting facility access, and in some cases collecting variably priced tolls." (Perez et al. 2012)

Several types of managed lanes are in use today. The two types most relevant to the deployment of V2I protocols are described as follows:

- Restricted-use lanes: One of the most commonly used lane-management tools is restricting use based on vehicle eligibility. Eligibility can be defined in terms of vehicle type (i.e., bus-only, truck-only, motorcycle-only, or hybrid-only lanes) or by the number of occupants in a vehicle (i.e., high-occupancy vehicle (HOV) lanes; for example, lanes that require two or more (HOV 2+) or three or more (HOV 3+) people in a vehicle).

- Priced-managed lanes: Various types of priced-managed lanes are in operation including the following:

    - Variable tolls on entire roadways: Fees are levied on toll roads and bridges as well as existing toll-free facilities during rush hour.

    - Variably priced lanes: Variable tolls are levied on separated lanes within a highway, such as express toll lanes or high-occupancy toll (HOT) lanes. These lanes typically charge a flat fee for use. As congestion on the managed lane increases, the cost to use the lane also increases to discourage additional users from entering the lane, thus maintaining free-flow conditions on the managed-lane facility.

Managed lanes offer several features that are favorable and, in many respects, critical to the testing and implementation of CAV technology. Further, many managed-lane facilities have the design, operational, and institutional infrastructure that would be necessary to implement V2I protocols without the need for expensive updates—one of the first steps toward broader adoption and penetration of CAV technology.

Managed lanes are separated from general-purpose lanes, either through barriers or markings, and provide the opportunity for active management of traffic through access control, vehicle eligibility restriction, pricing, or a combination thereof. Managed lanes also offer operational flexibility because the operating agency can proactively manage demand and capacity of the facility by applying new strategies or modifying existing strategies. The infrastructure and associated investment required to implement several V2I communication protocols is either already available or more readily installed on several types of managed-lane facilities versus general-purpose lanes. These and other synergies are discussed in detail in chapter 2.

The goals of managed-lane operations overlap with the goals of CAV applications. While each managed-lane project is implemented with individual goals and performance measures, in general, all managed-lane operations aim to provide superior traffic performance (typically measured in terms of travel speeds and travel-time reliability) to that of adjacent general-purpose lanes, which are not subject to the same level of active management. Through a variety of strategies, operating agencies of managed lanes seek to restrict vehicle-flow rates to provide an acceptable level of service. These strategies result in significant, measurable benefits, including time savings, improved reliability, and increased operational efficiency of the roadway. Federal statutes recommend a minimum average operating speed of 20 m/s (45 mph) for 90 percent of the time in HOV+ facilities (i.e., ones that combine HOV with single-occupancy vehicles (SOVs) or low-emission or energy-efficient vehicles) during morning or evening weekday peak-hour periods throughout an evaluation period 180 consecutive days. While this minimum is considered a de facto test for HOV-only facilities, it is not mandated.

Operationally, a suite of strategies, including restrictions, access limitations, and tolling, are applied to managed lanes. These strategies are designed to achieve the following goals:

- Enhancing lane efficiency and use in underused areas and efficiently reallocating capacity in over-used lanes.
- Providing travel-time reliability by enabling superior traffic performance, which is achieved by maintaining reliable speeds and unimpeded travel for transit.
- Yielding revenue to offset lifecycle costs (in the case of toll lanes) by taking in enough income from use fees to fund operations and maintenance activities.

Despite significant potential for customization in managed-lane operational policy at State and local levels, managed-lane facilities face several challenges in meeting their performance goals. Agencies face limitations, such as capacity limitations, demand increases (due to demographic patterns), time-of-day variations (due to weather and events), and organizational or regulatory restrictions (such as policies that limit HOV+ requirements and toll rate increases that could effectively respond to changing traffic patterns). Challenges operators of managed lanes face also include issues related to data collection and performance management.

The CAV strategies proposed in this study present a mechanism to increase the efficiency of managed-lane capacities and to improve traffic performance without significant capital investment. These strategies pose an attractive solution to managed-lane operators struggling to meet Federal and local performance requirements or those seeking innovative solutions to growing travel demand. Synergies may also be gained through more efficient data collection through the use of CAV technologies to meet the performance-management and reporting requirements of managed-lane facilities. These are explored in detail in chapter 4.

AUDIENCE

The intended audience for this document includes the following:

- USDOT CAV-program stakeholders.
- System developers who will create and support CAV algorithms based on the system concepts described in this document.
- Managed-lane owners and operators.
- Analysts, researchers, and CAV-application developers.

DOCUMENT OVERVIEW

Chapter 1 defines the scope of the study and describes the background.

Chapter 2 provides a concept of operations (ConOps) and describes the current situation with respect to processes and systems to be affected by the ConOps, describes the need for changes to the current situation, describes a concept for new system capabilities and their operations, and presents detailed description of operational concepts and an example operational scenario.

Chapter 3 describes CAV applications that are included in the bundle and corresponding algorithms for vehicular control. Simulation scenarios, platforms, and results are introduced to demonstrate the effectiveness of this bundled application in managed lanes.

Chapter 4 describes the field experiment conducted at the Saxton Transportation Operations Lab, including experimental preparation, the vehicle platform used, infrastructure deployment possibilities, the experimental design, and data analysis.

Chapter 5 provides conclusions of the research.

CHAPTER 2. CONOPS

JUSTIFICATION FOR AND NATURE OF CHANGES

As managed-lane infrastructure advancements have evolved from simple restriping and signage improvements to more sophisticated intelligent transportation systems (ITS) and toll-system deployments, managed lanes are ideal test sites for V2V and V2I technology and potential first locations for CAV deployments.

Separated from general-purpose lanes, managed lanes allow for the partial isolation and segregation of CAVs during the initial market-penetration phase of deployment. They also provide a more controlled traffic environment than general-purpose lanes. Besides having necessary physical infrastructure that includes power and communications networks, other elements of managed lanes—such as ITS, signage, and toll technologies—also support CAV deployment. Managed-lane developers and operators also often have the institutional frameworks required to implement innovative technologies, such as CAVs. Institutional frameworks include familiarity with a systems-engineering approach and the existence of a performance-management system to meet the increased accountability needs of a managed facility. Further, many of the challenges related to meeting performance requirements and data management can be addressed through enhanced V2I technologies. These technologies largely support the objectives of providing superior traffic performance through better traffic management and increased use.

This chapter presents justification for deploying CAV technologies on managed lanes from the users' and facility operators' perspectives.

Transportation Users' Perspective

Deploying CAVs on managed lanes will support the following needs of transportation users:

- Safety: Crash reduction is one of the most significant potential benefits of CAV technology. The National Highway Traffic Safety Administration estimates that the combined use of V2V and V2I communications has the potential to significantly reduce crashes involving unimpaired drivers. (Harding et al. 2014)

- Smooth, low-stress, and fast travel: CACC and merge coordination can reduce friction in traffic flow and increase the capacity of highway bottleneck locations by increasing lane capacity and improving vehicle-flow stability.

- Reliable travel times: The combination of speed harmonization, cooperative merging, and CACC can substantially reduce uncertainty in travel times by smoothing traffic and enabling real-time prediction of travel times.

- Decision-support systems: such systems provide accurate information to help drivers make optimal decisions about driving tasks.

- Minimal distraction from the driving task: Several features of CAV technology, including speed harmonization, can help improve the travel experience. These include but are not limited to elimination of stop-and-go movements, improvement of travel-time reliability, proactive congestion management, and access control.

Transportation Operators' Perspective

Broadly speaking, the goal of transportation operators is efficient traffic management. This goal includes monitoring and managing traffic and factors affecting traffic flow, including incidents, weather, work zones, dissemination of routing information, and other factors that affect traffic-flow efficiency. Operators' goals may therefore include the following:

- Reducing recurring congestion on urban freeways: Early adoption of CAV technology on existing managed lanes allows operators to gain access to greater congestion management due to increased throughput, enhanced safety, and an improved driver experience. These benefits will be dependent on a relatively high percentage of total drivers using CAV-enabled vehicles using the managed-lane facility.

- Improving travel-time reliability and safety: Traditional approaches to managing congestion, such as capacity expansion, are increasingly becoming obsolete due to funding constraints as well as inherent limitations of these approaches in alleviating transportation problems. CAV technologies can be considered operational strategies that offer the potential for innovative solutions to the hard problems of congestion and travel-time variability that continue to plague facilities.

- Reducing travel times, fuel consumption, and emissions: CAV applications, such as speed harmonization, CACC, and cooperative merge, are capable of smoothing vehicle trajectories, reducing speed oscillations, and avoiding severe braking. These applications lead to a more uniform set of driver behaviors, thus diminishing unnecessary delays and accelerations.

- Maintaining and increasing the use of alternative and emerging transportation modes (e.g., car-sharing options): CAVs are considered a separate mode by travelers according to a recent survey. (Krueger et al. 2017)

Additionally, these operators would gain first-mover advantage; if operators who are currently primed to accommodate CAV on their facilities do not make the voluntary move to test and advance this technology, outside actors are likely to fill that role and dictate the direction of CAV-technology development. This direction may or may not be in line with a specific agency's goals or organizational capacity. Organizations that learn to respond to rapid technological change will be more likely to thrive in this era of rapid technological enhancement in the transportation field.

NATURE OF CHANGES

This section of the ConOps describes several categories of changes relevant to the deployment of CAV applications on managed lanes.

Organizational and Institutional Changes

To facilitate deployment of CAV applications on managed lanes, recommended organizational and institutional changes include the following:

- Adopt a systems-engineering approach. A systems-engineering process is essential for developing operational scenarios to accommodate CAV applications in managed-lane facilities. ConOps must be developed for the system (regional level) as well as for the local facility in question.

- Develop a performance-management system. CAVs should be aligned with agency performance standards and holistic data requirements so that transportation agencies can leverage data sources across the organization. A performance-measurement system will collect and process relevant data to determine whether system goals and performance targets for all CAV applications and operational alternatives are being achieved.

- Develop a data-collection and -management system. This system will obtain all of the relevant data in real time from the various vehicles, onboard sensors, wireless devices, roadway traffic sensors, weather systems, message boards, and other related systems. These data should be placed in or be accessible from a common data environment.

  - Include rich, accurate data sources. Critical data will come from a variety of sources and should include the following:

    - Real-time traffic data: Real-time traffic data include vehicle speed and location data collected and disseminated by vehicles in the connected system plus traditional detection sources (e.g., inductive loop detectors, overhead radar, closed-circuit television (CCTV) cameras) that provide traffic data for the system.

    - Weather-condition data: Infrastructure-based road-weather information systems and third-party weather-data feeds can supplement vehicle-acquired weather data.

    - Pavement-condition data: Information on real-time pavement-surface conditions (e.g., dry, wet, snowy, iced, salted) can be provided by in-pavement sensors.

    - Vehicle data: Vehicle data (e.g., status, location, movement) can be acquired from the vehicles themselves and disseminated to other vehicles, applications, and systems using V2V and V2I communications.

    - Crowd-sourced data: Crowd sourced–data platforms enable data collection from large installed user bases, which can supplement data gathered from other sources.

    - Historical data: In addition to real-time data, historical data will be a critical input to applications. Historical data can improve the accuracy of traffic analysis and the prediction of traffic conditions. Examples of such data include probe data (supplied by many vendors) and sensor and/or volume data, which are often archived by State agencies. Even relatively new forms of data, such as automated traffic-signal performance measures, are now being archived.

Technical and Technological Changes

To facilitate deployment of CAV applications on managed lanes, recommended technical changes include the following:

- Procure new hardware, such as the following, to support technology:
  - Managed-lane facilities may already have a significant amount of communications infrastructure in place to support tolling operations. This infrastructure would need to be enhanced with the installation of DSRC technologies (e.g., roadside equipment (RSE)) and algorithms that support CAV applications.
  - The vehicles that use the system will need to be equipped with ACC, DSRC or equivalent radios (e.g., onboard units (OBUs) and vehicle-awareness devices (VADs)), and the computational resources to implement the new control software.
- Develop or acquire new software. The application(s) should do the following:
  - Make use of the frequently collected and rapidly disseminated multisource data drawn from connected travelers (e.g., cyclists and pedestrians), vehicles, and infrastructure.
  - Include a VAD (e.g., an OBU, which is installed either by the vehicle manufacturer or as an aftermarket integrated device); a personal wireless application (e.g., a smartphone or other handheld device); or another application capable of collecting, receiving, and disseminating movement/location information.
  - Enable systems and algorithms that can generate traffic-condition predictions, alternative scenarios, and solution evaluations in real time.
  - Contain microscopic and macroscopic traffic simulations.
  - Incorporate real-time and historical data.
  - Use traffic-optimization models.
  - Encourage the constant evaluation, adjustment, and improvement of traffic-optimization models (these modeling changes require an increase in computational capability as well as long-term storage of historical data).
  - Evolve and improve its algorithms and methods on the basis of performance measurement.
  - Include DSRC and software elements that enable the CACC system to act upon receipt of speed recommendations from the V2I speed-harmonization algorithm.

Because no operational CACC implementations currently exist, CACC is reliant upon yet-to-be-deployed connected-vehicle (CV) technologies and new in-vehicle software.

- Incorporate a cooperative-merge system that will rely on the same technologies as CACC, namely DSRC or equivalent and software elements that enable the CACC system to act upon receipt of speed recommendations from the V2I speed-harmonization algorithm. The concept of a cooperative-merge system relies on CACC system functions that have not been commercially deployed yet.

Operational Policy Changes

The operational policies of managed lanes are generally designed to accommodate traffic operations that meet the goals of operators. This subsection discusses the various types of operational policies and the potential for including CAVs in those operational scenarios. These scenarios include the option of allowing CAVs on existing HOV or express lanes, the extension of toll-free or reduced-toll privileges to strings of CVs, and other CAV operations that align with managed-lane objectives (e.g., reduced congestion and increased travel-time reliability).

The key questions to ask to determine operational policy include the following:

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

What are the net financial implications for the managed-lane operator?

All stakeholders must have clear expectations and incentives to participate. Improved use of existing capacity is a shared goal of both managed-lane operators and CAV applications. There also needs to be an agreement or compact with roadway users to set expectations, encourage investments, and measure performance.

Operational policies encouraging CAV operation on managed lanes should be flexible, particularly so they can evolve as the market-penetration rate of equipped vehicles increases. The operational scenarios at low market-penetration rates are likely to be different from those at higher rates. Most current managed-lane operations allow for some flexibility, such as periodically revisiting and updating HOV-restriction and toll rate–setting policies. However, a CAV operational scenario would require a more deliberate incremental approach potentially linked to factors, such as demand and market-penetration rate of OBU-equipped vehicles, automated vehicles, evolution of technology, and traffic-operations solutions. Details on operational policies of early CAV deployments are discussed in chapter 4.

Facility Infrastructure Changes

Facility infrastructure changes will depend upon the configuration and operations of the existing facility. Depending upon the type of facility and existing equipment, the following categories of infrastructure changes may be needed:

- Infrastructure-based sensors (e.g., radar detectors).
- Dedicated ramps (e.g., entry and exit points).
- Lane entry barriers and separation from general-purpose lanes.
- Striping and pavement markings.
- Appropriate signage to convey relevant information to all drivers (both equipped and unequipped).

OPPORTUNITIES AND DESIRED CHANGES

The emergence of CAV technologies offers extensive opportunities to advance safety, mobility, and reliability on the Nation's roadways. Market-penetration rates, however, are anticipated to remain low during the next decade, and the potential benefits may not be fully realized. The use of managed-lane facilities will support the realization of these benefits at early stages of deployment by attracting and concentrating the equipped vehicles in proximity to each other so they can gain the benefits of V2V cooperation. The concept described in this chapter focuses on deployment stages that have low market-penetration rates and addresses how the proposed bundled application is operated to improve existing system performance.

For early CAV deployment, single-lane, controlled-access facilities that are equipped with existing communication infrastructure, DSRC or an equivalent wireless technology, and roadside units (RSUs) offer the opportunity to begin integrating CAVs into standard traffic. Because the facilities are single lane, the presence of a small number of CAVs can significantly impact operations on the managed lanes and, therefore, improve system performance and the individual traveler's experience. A detailed system framework for implementing the bundled application on managed lanes will be discussed.

CONCEPTS FOR THE PROPOSED SYSTEM

This section of the ConOps presents the concepts and framework of the proposed system with two focuses—CAV technologies and managed-lane operational strategies. In this section, the bundled application is applied to the integrated CAV system, including but not limited to the speed-harmonization, CACC, and cooperative-merge applications. In this study, implementation of VADs on all nonautomated vehicles (i.e., manually driven vehicles) is assumed. VAD-equipped vehicles have wireless-communication capability. They can broadcast real-time information regarding their operation status and route choice. Although these vehicles do not have an automated controller to perform the car-following task, they can serve as leaders of CACC-vehicle strings and provide data for speed harmonization and cooperative merging.

Managed-Lane Configuration with a Bundled CAV Application

Transportation networks and their host organizations carry a wide variety of characteristics across States and cities. Naturally, some physical and social conditions are more amenable to CAV managed-lane applications than others. This section discusses numerous criteria for assessing the suitability and practicality of the proposed system for one or more candidate locations.

Managed Lane–Configuration Requirements

Several aspects of a managed-lane facility may render it suitable for CAV operations. A simple network topology with long distances, controllable entry points, and limited entry and exit points facilitates access control and measurement and prediction of traffic flow as required for the CAV applications presented in this chapter. Several types of managed lanes exhibit these features to a greater or lesser extent.

The following are the main types of managed lanes that have been defined and recognized by the National Cooperative Highway Research Program, American Association of State Highway and Transportation Officials, and FHWA:

- HOV lane: Managed lane restricted primarily to HOVs (no tolling applied).
- HOT lane (also referred to as "value-priced lane"): HOV lane tolled electronically for single- or low-occupancy vehicles and free to HOVs.
- Truck or bus lane: Dedicated lane for trucks or managed lane dedicated to buses.
- Express lane: Managed lane that restricts access. According to the *Manual on Uniform Traffic Control Devices*, an express lane is defined as a managed lane that employs electronic tolling in a freeway right-of-way with or without access restrictions. (FHWA 2009)
- Express toll lane (or road): Managed lane tolled electronically that charges users a fee for use (with some exceptions).

Attributes of managed-lane facilities (table 1) that make them suitable for CAV operations include the following:

- Access design: The design of access and egress points impacts the operating conditions within a managed-lane facility and affects an agency's ability to readily modify operating strategies to accommodate CAV operation. Continuous access facilities, or those with multiple access and egress points, increase the complexity of operations but provide more flexibility for drivers using the facility. Managed lanes with limited access and egress points greatly simplify CAV research but create operational challenges because they concentrate the lane-changing maneuvers needed for access and egress in a way that can degrade operation of general-purpose lanes. The spacing of ramp connections and weaving section lengths are also important as they could impact safety and operating conditions. Controlled-access facilities are generally preferable for CAV operation. The following access characteristics are favorable to CAV operational scenarios:

  - Direct access ramps for CAV managed lanes.
  - Limited entry and exit points over the managed segment (less effective when there are multiple managed lanes for CAVs and weaving effects may be created).

- Barrier separation: Barrier separations that are favorable to CAV operation include the following:
  - Concrete barriers.
  - Pylons (flexible delineators).
  - Separate roadways (alongside or outside right-of-way, or elevated/depressed around general-purpose lanes).
- Lane configuration/placement: The number and width of lanes and characteristics of shoulders can impact the feasibility of CAV deployment. Single-lane facilities offer a simple topology to implement longitudinal control through speed harmonization and vehicle platooning using CACC, but they are vulnerable to blockage when incidents occur. Multilane facilities can enable complex lateral maneuvers involved in cooperative lane change. Note that at early stages of deployment, only one lane may be needed for CAV operation, and the additional lane(s) can continue to serve as regular managed lane(s).
- Operational policies: Several operational aspects of managed-lane facilities can impact their ability to accommodate CAV operations. Variable or time-of-day access policies, presence of tolling, and lane use—particularly during peak periods—have an impact on facility and driver readiness for CAV operational scenarios. For instance, a facility with existing dynamic signage and variable time-of-day policies should have the necessary infrastructure—and institutional and driver readiness—to implement, convey, and follow complex operational policies required for CAV operation.

Table 1. Favorability of managed lanes for CAV operation.

Type of Facility	Access*	Barrier Separation*	Lane Configuration/ Placement*	Overall Favorability for CAV Operation
HOV lane (no tolling)	Concurrent flow; Direct access ramps	Continuous access with no physical barrier separation	Single directional lane next to the median	Low
HOT lane	Direct access ramps; Limited entry and exit points	Physical barrier separation	Single or dual directional lane next to the median	High
Truck or bus lane	Different access characteristics exist	Physical barrier separation	Different lane configurations exist	Low
Express lane/ express toll lane	Dedicated ramps or weaving lanes	Physical barrier separation in some deployments	Single or dual directional lane next to the median	High
Dynamic shoulder use	No direct access ramps	No physical barrier separation	Right side of freeway	Low

*Typical managed-lane design/configuration attributes.

Express, express toll, and HOT lanes are likely to be more suitable for CAV applications than HOV lanes and truck- or bus-only lanes. In addition to a favorable network topology, these types of managed lanes are associated with the facility, technology, and institutional infrastructure needed to implement a CAV-deployment program. While deployment of CAV programs can also be undertaken at some of the other types of managed-lane facilities, it would require significant effort.

Technological- and Facility-Infrastructure Requirements

Managed lanes are comprised of various systems, subsystems, and components. Real-time traffic management and communication subsystems, which connect various other subsystems, are commonly found in managed-lane facilities. The communication subsystem is an important asset for CAV operation as it can support V2I and I2V systems. For instance, an existing direct fiber-optic connection can be leveraged for transmitting data to the TMC while saving the upfront costs required to set up a fiber-optic cable in a general-purpose facility. Other relevant infrastructure considerations include the roadside communications network, roadside electrical power availability, and toll-system maintenance. Electronically tolled lanes (ETLs) are typically equipped with a variety of sensor technologies that support tolling. These technologies can be used and enhanced in a CAV environment to support speed harmonization, CACC, and cooperative merging.

Technologies typically in place on managed lanes include the following:

- A data or a telecommunications network that allows computers or components to exchange data with each other using a data link. Components could include network interfaces, repeaters, hubs, bridges, switches, routers, modems, and firewalls.

- Traffic-detection technologies, such as cameras, light curtains, pavement sensors, CCTV systems, and license plate recognition.
- Driver messaging systems, such as dynamic message signs and lane-control signals.
- ETLs that have access to a toll-collection system. Several subsystem components of a toll collection system can be leveraged for CAV operations. These components include the following:
    - In-vehicle transponders (toll tags) or smart phone–based toll apps.
    - Toll gantries over the lanes with transponder readers mounted.
    - Vehicle detection and classification systems, violation enforcement systems, and lane controllers to manage all lane equipment.
    - Telecommunications to a back office for administration and a host computer system to serve as a central database to manage accounts in the back office.
    - An express lane or HOT lane facility with a dynamic pricing system.

These systems can be used directly, repurposed, or leveraged to meet the technological requirements of CAV applications. The following specific technology requirements are relevant for CAV applications:

- Speed-harmonization algorithms: A managed-lane facility would require a method of conveying speed information to vehicles equipped with communications and automatic speed-control technology as well as nonequipped vehicles that may be allowed on managed lanes in certain deployment scenarios. A managed-lane facility would require the following:
    - A TMC to host speed-harmonization algorithms based on traffic operations and safety considerations.
    - Communication technology, such as DSRC or cellular, to communicate target speeds directly to vehicles equipped with an OBU and to transmit data back to RSE and the TMC.
    - VSL signs to communicate speed limits to drivers of nonequipped vehicles if allowed to travel on managed lanes.
- CACC and cooperative-merging system: For cooperative merging, predicting gaps at merge points based on traffic entering the system and conditioned by the TMC is necessary. Predicting such gaps requires real-time communication between OBU-equipped vehicles with RSE/TMCs and roadside detectors to identify the unequipped vehicles. If RSE or OBUs are not available, traditional traffic detectors (e.g., loop or radar detectors) installed at multiple locations upstream of the merge area can be used to estimate locations and speeds of all vehicles.

For vehicles attempting to merge and enter managed lanes, algorithms must be developed to predict or create gaps between or within strings of CACC vehicles. A virtual ramp-metering system may be used to release vehicles waiting at on-ramps based on the predicted arrival time of gaps. If needed, CACC vehicles in the managed lane may create a gap for the merge vehicle. A gap between strings of CACC vehicles can be realized by slowing down the upstream string of CACC vehicles so the merge vehicle can join either at the end of the downstream string or at the front of the upstream string. In some cases, long strings of CACC vehicles may disconnect into two strings, thereby creating a gap for the merge vehicle. If merge vehicles are operating in CACC mode throughout the merging process—starting at release and then continuing through the merge area and as they join the platoon—it is expected that the merge maneuver will be facilitated. Developing capabilities to predict wait times for CACC vehicles attempting to enter at on-ramps is necessary, and this information should be ideally reported to drivers as a key component of public traveler information.

Institutional Infrastructure Requirements

To implement a CAV application within the institutional framework of managed lanes, synergies between CAVs and the managed-lane project will need to be established. The institutional framework for a managed-lane operating entity already includes multiple stakeholders and management, operation, and reporting structures that could support CAV use. Identifying these synergies and the common goals of CAV applications and managed-lane operations will play a significant role in bringing more stakeholders onboard with deployment.

Institutional readiness is defined by the character of the management structure for a managed-lane facility. Institutional structures and mapping of operational responsibilities create natural opportunities and barriers for setting up and implementing a CAV program. For example, if a single agency owned and operated all aspects of managed lanes (including the TMC, pricing algorithms and policies, customer-service center, and tolling system), the coordination effort required to implement CAV applications would be low. By contrast, an agency that did not control its own customer-service center or operational-policy decisionmaking would tend to experience more difficulties.

Several synergies between managed-lane operations and institutional frameworks are required to deploy CAV applications. The following are some key areas of managed-lane operations that can be leveraged to support deployment:

- Institutional capability to implement a systems-engineering approach: Most new managed-lane developers have the institutional capability to implement a systems-engineering approach. Managed-lane developers are increasingly following such an approach during project development, including the development of a ConOps.

- Evolved performance-management capabilities: An agency's ability to implement CAV operational scenarios could depend on the type and frequency of performance monitoring as well as the available staff and institutional structures to support performance monitoring. For instance, an organization that continuously monitors speed, volume, travel time, and vehicle occupancy on its managed lanes will have more resources to conduct or assess pilot programs than one collecting only enough data to meet minimum

Federal requirements. Similarly, an operating agency performing in-house monitoring will have more resources than one that depends on a third-party vendor for those services.

Further, CAV applications can enhance and improve managed-lane performance by meeting managed-lane performance goals. U.S. Federal law (23 U.S.C. 166) requires maintaining target speeds of 20 m/s (45 mph) or greater 90 percent of the time on managed lanes. Initial results and simulations show CAV applications have the ability to offer better use of available capacity and improvements in traffic performance that would support managed-lane agencies in meeting this performance goal.

Institutional Constraints

Constraints within existing managed-lane frameworks for CAV deployments are identified from institutional perspectives. Some institutional constraints regarding CAV operation on managed lanes follow:

- Alignment with an existing tolled facility's goals: To move to exclusive CAV operation, the outcomes from implementing CAV applications should be demonstrably in line with the facility and operating agency goals for the managed-lane facility as well as the goals of various stakeholders (including driving public). Thus, if a facility's goal is to maximize throughput and improve safety outcomes, the proposed CAV applications should demonstrate improvements per those metrics.

- Infrastructure-investment requirements: Once project planners have the legislative authority necessary to integrate CAVs into managed lanes, it may be necessary to forge new relationships with partners not previously involved, such as transit authorities and private entities. Entities that can fund and finance installation of additional hardware and software to support CAV deployment and optimization of managed-lane operations may also be necessary. In addition to the costs of acquiring the technology and equipment necessary for CAV applications, infrastructure adjustments and upgrades, such as additional ramp lanes, buffers and barriers between different lanes, signage, and static and dynamic driver-communication mechanisms, are some investment needs that operators may have to consider.

- Business case and toll-revenue implications: Several multilane managed facilities are tolled and have revenue targets. A CAV application that uses an existing right-of-way will most likely have implications for toll revenue in terms of the new toll policies that accommodate and incentivize CAV use and uncertain traffic demand for the dedicated lane. The types of managed-lane configurations most suitable for CAV operation also typically involve tolling and, in several cases, are operated and managed by a private entity. Private developers and operators are governed by long-term contractual agreements that define operational and financial performance metrics for the facility. Any operational policy changes that affect toll revenue may not align with the operating agency's goals. In addition to the impact of CAVs on traffic performance, additional analyses may be needed to determine the impact of CAV operation on tolls based on changing CAV market-penetration rates and user mixes. More comprehensive analysis tools are needed to address the full impacts of a managed-lane or CAV system—including design, access, and operational strategies—based on factors, such as demand management, revenue generation, and air-quality conformity.

Operational Strategies for CAV Operation on Managed Lanes

This section discusses operational concepts and policies for speed harmonization, CACC, and cooperative merging on managed lanes. The concepts are delineated in an evolutionary framework that addresses the operational goals, policies, and constraints of typical managed-lane facilities along with technology evolution and market-penetration rates of CAVs. While managed-lane operational policies follow from specific project goals and use a variety of performance metrics, this concept assumes that the overarching goal of the target facility would be improving traffic performance, reducing congestion, and enhancing safety through active demand management.

For a CAV application to be successful, operational concepts should be synergistically combined with the framework and goals of managed-lane operations. The concepts in Infrastructure Considerations present considerations for CAV operation on a single-lane managed-lane facility in a mixed-traffic environment.

Infrastructure Considerations

The following are relevant aspects of infrastructure considered in the ConOps:

- Roadway Type:
  - 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.
- Facility Type:
  - Peak-period access restriction, toll-based occupancy, CV capabilities (one- or two-way communications and data exchange). About half of all managed-lane projects operate only in peak periods, reverting to general-purpose lanes during other times. (NCHRP 2016) Such facilities are primed to implement a CAV operational

policy that incentivizes CAV operation during peak periods to better manage demand on the facility when congestion is at its worst.

  - All-day access restriction and/or tolling based on occupancy, CV capabilities, and/or other criteria.

- Information Infrastructure:

  - I2V equipment (e.g., RSE) to transmit central information to all vehicles on managed lanes; if nonequipped vehicles are allowed on managed lanes, traditional dynamic message signs are used to convey public traveler information.

  - Roadside sensors (e.g., video cameras, radars, or loop detectors) to detect or estimate real-time vehicle trajectories of all vehicles on the managed lanes.

  - Onboard sensors (radar, light detection and ranging, or vision) that determine range and relative speed to the vehicle in front.

  - Onboard sensors with V2V-communications capabilities (e.g., OBUs) that allow data exchange among vehicles at a high rate using a low-latency medium, such as DSRC or an equivalent wireless technology.

CAVs and Managed-Lane Operational Policy

At low CAV market-penetration rates, a mix of CAVs and regular CVs would be allowed on the managed-lane facility. (Note that CVs are vehicles equipped with onboard communications technologies alone, whereas CAVs are equipped with both communications and automation technologies.) The following operational policies can encourage CAV operation on managed lanes:

- Incentives: Incentives for CAV deployment could include toll discounts and HOV-requirement waivers for low-emissions vehicles with which several managed-lane facilities are familiar. These incentives could be in the form of concessions to restricted-lane policies, such as allowing SOVs that are equipped with DSRC or an equivalent wireless technology to use a restricted lane during specific time periods or in the form of toll concessions or rebates for such vehicles. These incentives could be aimed at better managing peak-period congestion through harnessing the capacity-enhancing benefits of CAV applications in addition to the benefits of minimum occupancy requirements to manage demand.

- Adjusting existing occupancy policies to accommodate additional CAV traffic: Operational policies governing occupancy could also be adjusted to accommodate the additional traffic CAV operation would generate. For instance, an HOV 2+ restriction during peak periods could be raised to HOV 3+ alongside the implementation of concessions for CAV carpools that include two or more passengers. This flexibility is critical at managed lanes where HOV demand is already high and the addition of CAV traffic may cause demand to increase over the managed-lane capacity.

CAV Control and Driver Role

The operational concept in this chapter could apply to SAE International (SAE) level-1 automation with V2V and V2I communications via DSRC or an equivalent wireless technology at low market-penetration rates. The following applications rely on such communications:

- Speed harmonization: The TMC uses speed-harmonization algorithms to determine reasonable speeds by section and conveys this information to communications-equipped vehicles on the lane as advice or, in the case of a CAV, a directive. Recommended speeds are based on safety and traffic-flow considerations. Vehicles equipped with DSRC or an equivalent wireless technology adjust to the recommended speed with manual driving (at SAE level 0) or perform automatic longitudinal control of speed (at SAE level 1). If nonequipped vehicles are allowed on managed lanes, they should follow speed commands displayed on message signs.

- CACC: Multiple consecutive CACC vehicles receive information about the lead vehicle's motion and incorporate it into their control. These vehicles receive information from lead vehicles at high frequency and maintain safety and stability at a close following distance, thus forming a platoon of connected, speed-harmonized vehicles. V2V-only communication allows exchange of data regarding vehicle characteristics, position, speed, acceleration, yaw rate, brake status, throttle position, steering angle, and so forth using DSRC or an equivalent wireless technology.

- Cooperative Merge: Cooperative-merge control requires coordination between managed-lane vehicles and merge vehicles. Ideally, when all vehicles are CAVs, managed-lane vehicles can be automatically controlled to speed up or slow down to create gaps for merge vehicles, the trajectories of which are controlled to accurately merge into the created gaps. If some manually driven CVs (and even nonequipped vehicles) use these lanes, data from OBUs and roadside communication units and sensors can be fused to predict gap arrivals at merging points, and merging CAVs can be controlled accordingly to merge into the managed lane. Ideally, only CAVs will be allowed on dedicated managed lanes. If manually driven CVs are also allowed on dedicated on-ramps, a virtual ramp-metering system is needed to release merge vehicles by considering the predicted manual driving and merging trajectories.

Operational Considerations

The following are relevant aspects of roadway operation considered in the ConOps:

- Limitations of mixed-traffic operation: CAV application in mixed traffic would result in the operation of OBU-equipped vehicles in an environment that could hinder the full realization of its benefits. As vehicles equipped with DSRC or an equivalent wireless technology operate in mixed traffic, some vehicles will receive direct information from surrounding vehicles and infrastructure and will be enabled with automated controls for fast response times. At the same time, driver-operated non-CAVs would rely on different (likely less frequently updated) information sources and would suffer from slower response times. This mismatch could lead to suboptimal traffic outcomes in terms of performance and safety and hinder full realization of benefits of the CAV applications.

- Operation at low market-penetration rates: This operational scenario could be implemented at relatively low-to-moderate (10 to 30 percent) market-penetration rates. Similar to incentives for low-emission vehicles, incentives for CAVs could encourage increased market-penetration rates of equipped vehicles.

Example Scenario for CAV Operation on Managed Lanes

This section presents an example operational scenario for applying bundled speed-harmonization, CACC, and cooperative-merge applications to managed-lane facilities. The scenario is intended to reflect the operation of each application at a high level, indicating how the flow of information should occur among systems, users, and institutions.

A Single-Lane Managed Facility Dedicated Exclusively to CV and CAV Operation in an Environment with Low Market-Penetration Rates of CAVs

A TMC manages a freeway segment that is highly congested, particularly at multiple merge areas. A HOT lane with direct access ramps and limited entry and exit points has been implemented on this freeway. The HOT lane is separated from general-purpose lanes using a physical barrier made of pylons. This HOT-lane capacity is not well used, although the general-purpose lanes are extremely congested during rush hours.

With increasing adoption of onboard communication (i.e., CVs) and vehicle-automation technologies (i.e., CAVs), the TMC decides to use these new technologies to fulfill their operational goals. The overall market-penetration rate of CAV technologies, however, is still low, so spreading CAVs among all lanes may dilute the potential benefits. Therefore, the TMC may decide to dedicate the managed lane exclusively for CAV operations. In this scenario, only vehicles equipped with CV or CAV technologies would be allowed to use the managed lane. In the meantime, all other users, including HOVs and travelers who are willing to pay the toll, need to reregister and install an OBU or VAD. With all users registering in advance and through the use of data from the initial period of deployment, the TMC is able to estimate the demand of the managed-lane facility during peak periods. Additionally, the TMC expects this strategy can promote a shift from some existing longer-distance trips in general-purpose lanes to the managed lane even though, by design, there are few entry and exit points. This shift will also indirectly benefit drivers making shorter trips on general-purpose lanes.

To complete such conversion, the TMC tries to reuse the existing infrastructure as much as possible by, for example, maintaining dedicated entry and exit points and physical barriers. The TMC installs RSUs along the freeway segment every 500 m, depending on terrain, to ensure two-way V2I communication is enabled throughout the segment. Real-time data communicated via DSRC or cellular—along with traditional data from traffic detectors installed upstream and downstream from each merge area—are sent to a central server for storage, processing, and decisionmaking. This central server is located at the TMC and has been upgraded to accommodate new CAV technologies, including processing CAV data and running new CAV algorithms for the bundled applications. A summary of the desired managed-lane features follows:

- Facility features:
  - Urban corridor with peak-period congestion.
  - Existing HOT lanes with dedicated entry and exit points and physical pylon barriers.
  - Existing ITS infrastructure, such as traffic detectors installed before and after each merging point and TMC data center and server for traffic monitoring and management.
- Technological (CAV) features:
  - DSRC-based communication systems (e.g., RSUs and other hardware/software) installed along the freeway to ensure continuous V2I communication.
  - Automated ramp vehicle control with or without closed-loop ramp metering.
- Operational features:
  - CAVs, HOVs, and HOT vehicles are allowed to use the managed lane and dedicated ramps, but all vehicles need to be OBU equipped.
  - Registration is required of all vehicles to use managed lanes and dedicated ramps.
  - Eligibility rules are only for peak periods.
  - Speed limits are higher for the managed lane than general-purpose lanes to further improve throughputs.

In this scenario, congestion starts to form at multiple merge areas. RSE and infrastructure-based sensors (e.g., radar traffic detectors) monitor traffic-flow conditions, including density and speed data, and transmit this information to the TMC. In addition, DSRC-equipped CVs and CAVs transmit basic location and status (e.g., speed, direction) information to infrastructure devices, which then convey that information to the TMC for subsequent decisionmaking. The daily managed-lane operations process for this scenario is as follows:

1. CVs and CAVs enter the managed lane at one end of the segment on dedicated ramps. CAVs may form CACC-vehicle strings based on onboard CACC algorithms subject to system constraints, such as maximum string length. Certain vehicles may exit the facility at certain exit points. The CACC algorithm also governs this process by splitting a long string into short strings, for example, with the exiting vehicle at the end of one string and then letting the exiting vehicle disconnect itself from the string to exit via an off-ramp.

2. The TMC aggregates, organizes, and summarizes streaming data received from CVs and infrastructure-based systems. The TMC-operated monitoring and detection systems identify flow breakdown events based on real-time data received.

3. For the current traffic demand and congestion level, the TMC uses existing pricing algorithms to calculate dynamic tolls and, via the infrastructure-based communications systems, sends this updated information to all users to indicate the cost of using the facility is increasing. Some SOVs may be discouraged from using the facility and, therefore, guarantee the service quality for HOVs and CAVs.

4. For bottleneck traffic conditions, the TMC's speed-harmonization algorithm generates recommended speeds for all vehicles. Manually driven OBU-equipped vehicles receive a recommended speed command for each freeway subsegment. CAVs receive recommended speed profiles, which are automatically followed by CAVs and platoon leaders. The TMC disseminates this information via I2V DSRC communication. The TMC also displays recommended speeds on dynamic message signs within each subsegment for informational purposes.

5. At merge areas, RSE receives merging requests from merge vehicles at on-ramps. The TMC speed-harmonization algorithm generates speed commands for CAVs on the managed lane for gap creation and disseminates it via an infrastructure-based communications system. The TMC speed-harmonization algorithm also generates speed commands for merging CAVs or suggests release time of merging CVs from on-ramps to ensure merge vehicles can use the created assigned gaps to merge into the managed lane.

Steps 1 through 5 are continuous throughout the peak period.

SUMMARY

The emergence of CAV technologies offers extensive opportunities to advance safety, mobility, and reliability on the Nation's roadways. The market-penetration rate of these vehicles, however, is expected to be low in the next decade, and as such, potential benefits of CAVs may not be fully realized. The use of managed-lane facilities can facilitate the realization of these benefits at early deployment stages. This chapter focuses on deployment stages with low market-penetration rates and how the proposed bundle of speed-harmonization, CACC, and cooperative-merge applications is operated to improve existing system performance.

For early CAV deployment, single-lane, controlled-access facilities equipped with existing communication devices and RSUs offer the opportunity to begin integrating CAVs into traffic. Because the facilities are single lane, a small number of CAVs can significantly impact traffic operations on the managed lanes and, therefore, improve system performance and travelers' experiences. The ConOps provides detailed discussions of CAV deployment on managed lanes and, for illustrative purposes, gives an example operational scenario: a single-lane managed facility dedicated exclusively for CV and CAV operation while the market-penetration rate of CAVs is low.

The deployment of CAVs on managed lanes poses multiple challenges. Technically, no integrated platforms that combine CACC, speed-harmonization, and cooperative-merge applications currently exist. Additional efforts in algorithm development are needed. These algorithms also need to be tested in microscopic simulations before they can be deployed in the field. Existing managed-lane facilities also need to be equipped with basic communications infrastructure, such as DSRC, readily available for CAV deployment.

CHAPTER 3. SIMULATION

This chapter introduces the algorithms used to develop the simulation. The simulation scenarios are described, and results are discussed.

CACC PLATOONING

A successful CACC-platooning operation strategy can increase the probability of individual CACC vehicles joining strings. Once a string is formed, the strategy can also help maintain the string operation throughout a highway corridor. CACC vehicles exhibit car-following behavior that is significantly different from the behavior of manual drivers; CACC vehicles can form strings that allow them to follow preceding vehicles safely with short gaps.

This study adopts the CACC framework developed by Milanés and Shladover (2014) and Liu et al. (2017). It also incorporates the recent results from the FHWA High-Performance Vehicle Stream project (2015). Note that the proposed framework is for simulation purposes; it can be used to demonstrate a state-of-the-art strategy for CACC operation. A variation of this framework uses CACC logic implemented in real time on vehicles with the addition of different control components. Also, Liu et al. (2017) consider multilane highway operations using CACC and, therefore, different types of operational logic are developed for managing lane changes of CACC vehicles. However, this study focuses on CACC operations on one managed lane at early stages of deployment. It uses a simplified form of the CACC-operation algorithm developed by Liu et al. (2017) and enhances it by combining it with speed-harmonization and cooperative-merge algorithms discussed in chapter 2 and chapter 4.

This combined algorithm will determine whether the target vehicle is a CACC-string leader or follower. The CACC vehicle is the string leader if the preceding vehicle is neither a CACC vehicle nor a vehicle equipped with a VAD, the time gap from the preceding vehicle is larger than 2 s, or the preceding CACC-vehicle string has reached the maximum string length. Otherwise, the CACC vehicle is a string follower. Two recommended general CACC operational strategies considered in this study are as follows:

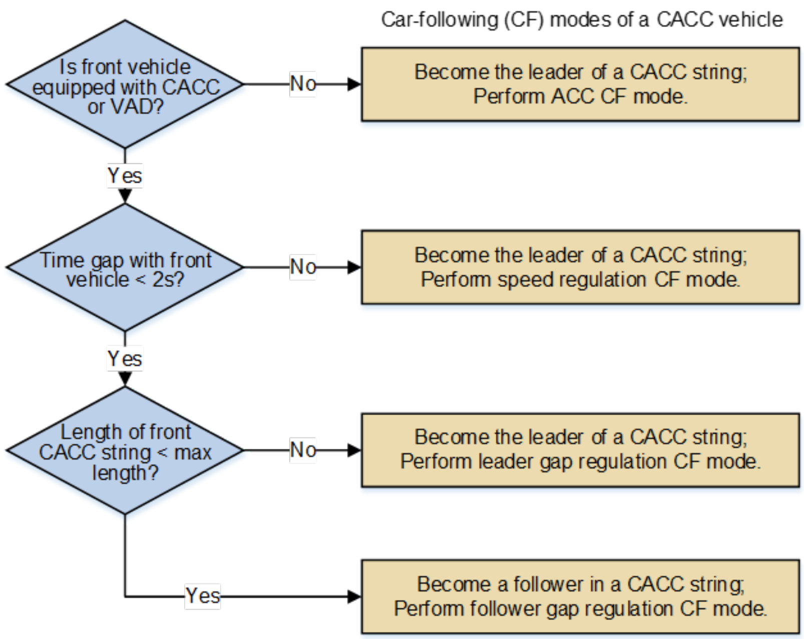
- Implementation of VAD on manually driven vehicles: VAD-equipped vehicles can serve as leaders of CACC-vehicle strings. Under this strategy, the probability of CACC-equipped vehicles traveling in CACC mode greatly increases, thus offering an incentive for users to equip their vehicles with CACC even when CACC market-penetration rates are low.

- Implementation of CACC vehicles on a managed lane: Managed lanes can adopt an operational concept that only allows CACC- and VAD-equipped vehicles to enter. It physically separates the CACC- and VAD-equipped traffic stream from regular traffic. As CACC-equipped vehicles concentrate in the managed lane, they will have a higher probability of traveling in CACC-vehicle strings. The managed lane also reduces the interaction between CACC-equipped and manually driven vehicles. CACC-vehicle strings are less likely to be interrupted in managed lanes.

Algorithm Design

To design the CACC-platooning algorithm, ACC and CACC car-following models developed by Milanés and Shladover were adopted (2014). These models are considered more computationally efficient than other CACC-platooning models in the literature. Such efficiency was desired because of the need to simulate many CACC-equipped vehicles in a complex environment.

CACC vehicles exhibit significantly different car-following behavior than manual drivers and can form strings that allow them to follow a preceding vehicle with a short gap. The modeling framework for CACC vehicles is summarized in figure 2. Drivers of CACC-equipped vehicles can also exit their closely coupled strings and switch off CACC to make lane changes to exit the freeway. The lane-changing behaviors of CACC drivers are depicted in the CACC-vehicle behavior model. Details of the driving behaviors of drivers of CACC-equipped vehicles are discussed in the remainder of this section.

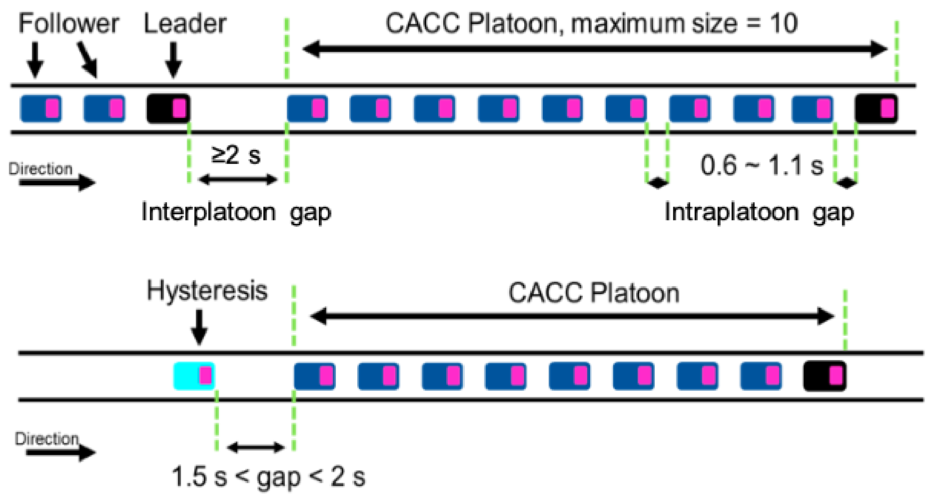


© Liu et al., 2017, adapted by FHWA.

Figure 2. Diagram. Car-following logic for vehicles equipped with CACC.

Although implementation of the CACC system relies on information received from the lead vehicle in the CACC-vehicle string as well as from the immediately preceding vehicle, the empirical models used in the simulation provide a simplified description of the closed-loop vehicle-following dynamics that are achieved relative to the immediately preceding vehicle.

Figure 3 is an illustration of a CACC-vehicle string that was simulated in this study. The detailed following behavior between CAVs and human-driven vehicles (with connectivity) are described in Car-Following Behaviors of Vehicles Equipped with CACC.



Source: FHWA.

Figure 3. Illustration. CACC-platooning logic.

Car-Following Behaviors of Vehicles Equipped With CACC

As shown in figure 2, CACC-equipped vehicles can apply both ACC and CACC car-following modes. The controllers used for automating a CACC vehicle's car-following behavior are represented in the following situations.

If a CACC-equipped vehicle is following a vehicle not equipped with CACC or VAD, the CACC controller can only use the ACC car-following mode. The ACC controller determines the car-following rule according to the clearance distance between the subject vehicle and preceding vehicle. If the distance is larger than a maximum threshold (e.g., 120 m), then the preceding vehicle is beyond the onboard sensors' detection range, so the ACC controller will apply speed-regulation mode as shown in equation 1.

$$a_{sv} = k_1(v_f - v_{sv}) \tag{1}$$

Where:

- a_{sv} = acceleration recommended by the ACC controller to the subject vehicle (m/s^2).
- k_1 = gain in the speed difference between the free-flow speed and the subject vehicle's current speed (k_1 = 0.4 s^{-1} in this study).
- v_f = free-flow speed (m/s).
- v_{sv} = current speed of the subject vehicle (m/s).

If the clearance distance is smaller than the minimum threshold (e.g., 100 m), the ACC controller will turn on gap-regulation mode and help the subject vehicle follow the motions of the preceding vehicle. Gap-regulation mode is described in equation 2.

$$a_{sv} = k_2(D - t_{hw}v_{sv} - L) + k_3(v_l - v_{sv}) \tag{2}$$

Where:

k_2 = gain on position difference between the preceding vehicle and the subject vehicle (k_2 = 0.23 s^{-2} in this study).

D = distance between the subject vehicle's front bumper and the preceding vehicle's front bumper (m).

t_{hw} = desired time gap of the ACC controller (s).

L = length of the preceding vehicle (m).

k_3 = gain on speed difference between the preceding vehicle and the subject vehicle (k_3 = 0.07 s^{-1} in this study).

v_l = current speed of the preceding vehicle (m/s).

t_{hw} was drawn from the distribution of time gaps selected by ACC drivers in the field test described in Nowakowski et al. Their distribution was 31.1 percent of their vehicle-following time gap at 2.2 s, 18.5 percent at 1.6 s, and 50.4 percent at 1.1 s.

If the clearance distance is between the maximum and minimum thresholds, the ACC controller will use the control rule implemented in the previous time step. This condition introduces a hysteresis in the control loop such that the ACC controller can perform a smooth transfer between the speed-regulation and gap-regulation mode.

If a subject vehicle is a CACC-vehicle string leader and the preceding vehicle is a CACC vehicle in another CACC-vehicle string, the subject vehicle may implement one of two modes. When the time gap between the subject vehicle and the preceding vehicle is more than 2 s, the subject vehicle will switch to the speed-regulation mode, which is represented by equation 1. If the time gap is less than 2 s and the preceding CACC-vehicle string is operating at the maximum allowable string length, the subject vehicle will use the string-leader gap-regulation mode, in which speeds and accelerations are regulated by equation 3 and equation 4, respectively.

$$v_{sv}(t) = v_{sv}(t - \Delta t) + k_p e_k(t) + k_d \dot{e}_k(t) \tag{3}$$

Where:

t = time.

Δt = time step for each update (s).

k_p = first gain coefficient for adjusting the time gap between the subject vehicle and preceding vehicle (0.45 s^{-1}).

e_k = time gap error (m).

k_d = second gain coefficient for adjusting the time gap between the subject vehicle and preceding vehicle (0.0125 s^{-1}).

$\dot{e}_k$ = change in time gap error (m).

$$a_{sv}(t) = (v_{sv}(t) - v_{sv}(t - \Delta t))/\Delta t \tag{4}$$

$e_k(t)$ is described by equation 5, and $\dot{e}_k(t)$ is described by equation 6.

$$e_k(t) = D(t - \Delta t) - t_1 v_{sv}(t - \Delta t) - L \tag{5}$$

Where t_1 is the constant time gap between the last vehicle of the preceding CACC-vehicle string and the subject vehicle (t_1 equal to 1.5 s is the time gap that has been chosen for use in this study after evaluations of the effects of alternative values).

$$\dot{e}_k(t) = v_l(t - \Delta t) - v_{sv}(t - \Delta t) - t_1 a_{sv}(t - \Delta t) \tag{6}$$

If the subject vehicle is following a CACC-vehicle string, two car-following modes are possible. The subject vehicle will implement the in-string follower gap-regulation mode if the time gap from the preceding vehicle is less than 1.5 s. This mode uses the algorithms represented by equation 3 through equation 6 with the minor adjustment of replacing t_1 with t_2, which is the intrastring constant time gap. The values for t_2 are selected randomly in the simulation. They are drawn from the distribution of time gaps that were chosen by the CACC drivers in the field test described in Nowakowski et al. (2010). The drivers in that test chose a time gap of 0.6 s 57 percent of the time when they were car following, 0.7 s 24 percent of the time, 0.9 s 7 percent of the time, and 1.1 s 12 percent of the time. For time gaps larger than 2 s, the subject vehicle will turn on the speed-regulation mode (i.e., equation 1). When the time gap is between 1.5 and 2 s, the subject vehicle will use the hysteresis control rule, which applies the car-following mode implemented in the previous time step.

The forward collision–warning algorithm developed by the Crash Avoidance Metrics Partnership (CAMP) is included in the ACC and CACC car-following modes to determine whether the gap between the subject vehicle and the preceding vehicle is sufficient for safe car following. (Kiefer et al. 2003) The CAMP algorithm first determines a required deceleration for the subject vehicle in equation 7 and equation 8.

$$d_{REQ} = -0.165 + 0.685 \cdot d_l + 0.080 \cdot \zeta - 0.00889 \cdot (v_{sv} - v_l) \tag{7}$$

Where:

d_{REQ} = deceleration required to avoid a rear-end collision (g).
d_l = deceleration of the preceding vehicle (g).
ζ = binary coefficient that reflects whether the preceding vehicle has a non-zero speed.

$$\zeta = \begin{cases} 1 & v_l > 0 \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

The required deceleration from equation 7 and equation 8 represents the comfortable deceleration the subject driver may take to avoid a collision with the preceding vehicle, given the current relative speed and deceleration of the preceding vehicle. If d_{REQ} is larger than 0 g, it means the subject vehicle does not need to brake, and the current gap is sufficient. If d_{REQ} is less than 0 g and the preceding vehicle stops prior to the subject vehicle, the required gap is obtained via equation 9.

$$g_{REQ} = \max\left(0, \frac{v_{sv}^2}{-2d_{REQ}} - \frac{v_l^2}{-2d_l}\right) \tag{9}$$

Where g_{REQ} is the required gap to avoid a rear-end collision (m).

If the preceding vehicle does not stop prior to the subject vehicle, the required gap is obtained via equation 10.

$$g_{REQ} = \max\left(0, \frac{(v_{sv} - v_l)^2}{-2(d_{REQ} - d_l)}\right) \tag{10}$$

When the current gap is smaller than g_{REQ}, it implies that a crash will happen if both the subject vehicle and the preceding vehicle keep their current acceleration speeds (i.e., d_{REQ} and d_l, respectively) for the next few seconds. In this case, the subject vehicle will switch to the manual-driving mode to avoid the crash.

CACC Vehicle–String Operations

In this study, as a benchmark, the research team chose a maximum string length of 10 vehicles as recommended in Liu et al. (2017). Shorter string lengths would result in more CACC-vehicle strings, which can lead to lower freeway capacity because interstring gaps are larger than the gaps between consecutive vehicles within the string. On the other hand, long CACC-vehicle strings would lead to less versatility since they make merging more difficult for other vehicles.

Two consecutive CACC-vehicle strings should keep a consistent time gap to maintain stable traffic flow and facilitate lane-change maneuvers. In this study, the research team regulates the time gap between the last vehicle of the preceding string and the first vehicle of the following string. Regulating the time gap allows the dynamic assignment of string leaders to accommodate strings that are shorter than the maximum string length and can prevent a negative impact on freeway capacity. The research team uses a 1.5-s constant time gap between strings based on Liu et al. (2017) as the benchmark.

The joining of two strings is modeled by the following steps:

1. A subject vehicle is selected as the leader of a CACC-vehicle string.

2. The subject vehicle is registered as the last follower of the preceding string if the time gap from the last vehicle of the preceding string is less than 2 s and the length of the preceding string is less than the maximum permitted string length.

3. Vehicles in the following string update their position identities (IDs) (i.e., ID that reflects the location of a vehicle in the CACC-vehicle string). If the new string would be longer than the maximum permitted length, the string-splitting process (described in the following list) will be executed by the vehicles behind the one that reaches the maximum allowable ID.

4. The subject vehicle switches to the speed-regulation mode until the time gap to the preceding vehicle is less than 1.5 s. Afterward, it switches to the CACC-vehicle string follower gap-regulation mode.

5. Other vehicles in the following string continue to update their speeds using the CACC-follower gap-regulation mode.

A string needs to be split if it is longer than the maximum allowed string length. The steps of the string-splitting process are as follows:

1. Each vehicle in a string updates its position ID.

2. If a vehicle is the first vehicle in the string with a position ID larger than the maximum string length, that vehicle becomes the subject vehicle of the string-splitting process.

3. The subject vehicle becomes the leader of a new string and switches from the CACC-follower gap-regulation mode to the CACC leader gap-regulation mode.

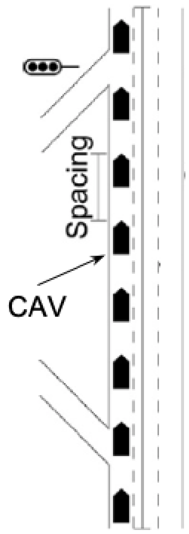
4. Each vehicle in the new string updates the position ID and starts following the new leader using the CACC-follower gap-regulation mode.

This study also models cut-out maneuvers by using a combination of lane-changing and the string-joining and -splitting algorithms when a vehicle exits the string to the off-ramp. In the cut-out process, a subject vehicle first applies lane-changing mode to exit the CACC-vehicle string. Afterward, the string-joining process is implemented for the remaining vehicles in the string. No cut-in process is modeled in the study. Merging only occurs between two existing strings to avoid disturbance to mainline traffic. See chapter 4 for a detailed discussion of the merging process at on-ramps.

COOPERATIVE MERGING

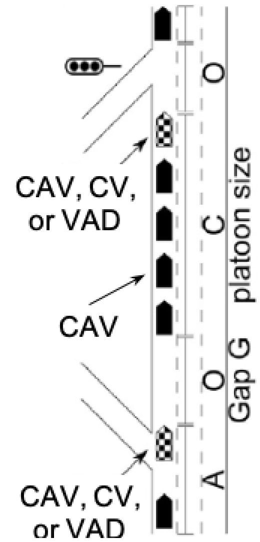
To a large extent, algorithms for cooperative merging combine speed-harmonization and CACC-control algorithms at merge areas because CACC-vehicle strings need to operate differently at merging points to accommodate new merge vehicles, and gaps need to be created, in many cases, by controlling managed-lane vehicles through I2V speed control. Figure 4-B shows a configuration of managed-lane vehicles that is rearranged from figure 4-A because vehicle trajectories are controlled, facilitating the formation of strings and creation of gaps for merge vehicles. When a gap is created, the next merge vehicle can be released ahead of time (similar to ramp metering) and that vehicle's trajectory is automatically controlled such that it can smoothly merge into the managed lane using the assigned gap. The creation of gaps relies on algorithms that can slow upstream vehicles (usually the lead vehicle of CACC-vehicle strings) in the managed lane; therefore, additional logic for gap creation needs to be added to the trajectory-based speed-harmonization algorithm discussed in chapter 2.

After merging is completed, the CACC-vehicle following algorithm engages to let the merge vehicle join a CACC-vehicle string. Figure 5 shows the infrastructure setting and data flow for a cooperative-merge scenario. In addition to two-way communication between CACC vehicles (including vehicles equipped with VADs or automated CACC vehicles) and RSE, data from traffic detectors, which are readily available on existing managed lanes, can be transmitted to RSE and TMCs and then fused with real-time data from CACC vehicles for better decisionmaking.



© Scarinci, R., Hegyi, A., and Heydecker, B., et al., 2017, adapted by FHWA.

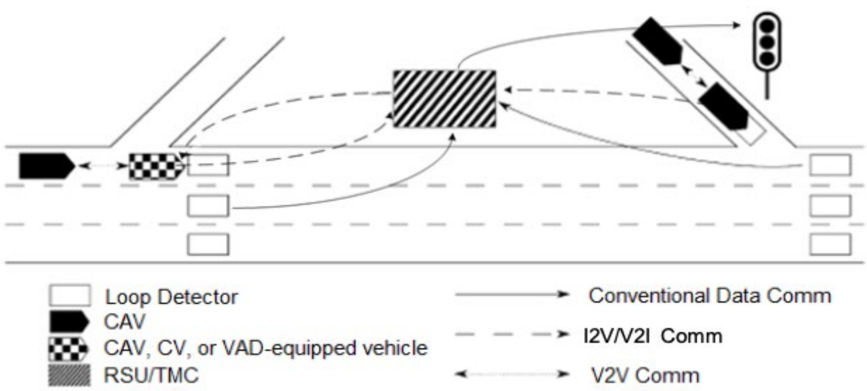
A. Regular merging.



© Scarinci, R., Hegyi, A., and Heydecker, B., et al., 2017, adapted by FHWA.
A = distance from front bumper of lead vehicle to rear bumper of following vehicle.
O = distance from front bumper of lead vehicle in one string to rear bumper in preceding string.
C = distance from rear bumper of last vehicle in preceding string to front bumper of the string's leader.

B. Cooperative merging.

Figure 4. Illustrations. Cooperative merging.



© Scarinci, R., Hegyi, A., and Heydecker, B., et al., 2017, adapted by FHWA.
Comm = communication.

Figure 5. Illustration. Cooperative-merge data flows.

Algorithm Design

Cooperative merging consists of two layers of problems: merge scheduling and individual vehicle control. Merge scheduling determines the sequence of mainline, managed-lane, and on-ramp vehicles moving downstream. After the sequence is determined, the individual vehicles should be controlled to fit the determined schedule. With the availability of real-time vehicle information for all vehicles (CVs and VAD-equipped manually driven vehicles), the trajectory of mainline vehicles of interest and the on-ramp vehicle can be predicted, and arrival times for available or created gaps can be generated. As shown in figure 6, the TMC's RSU releases an on-ramp merge vehicle, and the merge vehicle coordinates with mainline vehicles of interest (upstream and downstream of a gap) using a virtual-platooning concept until it smoothly merges into the mainline, shown in figure 6-C. (Lu et al. 2000, Chou et al. 2016A) The four-step cooperative-merge algorithm follows:

1. Detection: As figure 6-A shows, at a merge area, a local center (e.g., RSU) collects real-time information (i.e., location, speed, acceleration, vehicle operation mode) on all vehicles. If there is a desired or qualified time gap between two CACC- and/or VAD-equipped vehicles, an available gap will be recorded. These two vehicles will start to keep this gap if the following vehicle is a CAV. The research team assumes this gap can be kept at the less congested location upstream of the merge area if the following vehicle is not a CAV.

2. Release: After the gap is recorded, the on-ramp vehicle waiting at a prespecified location will be released when the leader of the recorded gap arrives at the position, which includes two components: the vehicle distance traveled by the identified gap leader when the merge vehicle is accelerating to the speed of the leader and the vehicle distance traveled by the identified gap leader when the merge vehicle is conducting gap regulation with the gap leader. Here, the research team is interested in calculating relative distance to the merge point (p_{merge}) (D_{merge}), the minimum distance between p_{merge} and the release point ($p_{release}$), which could be obtained by calculating D_{merge} (equation 11).

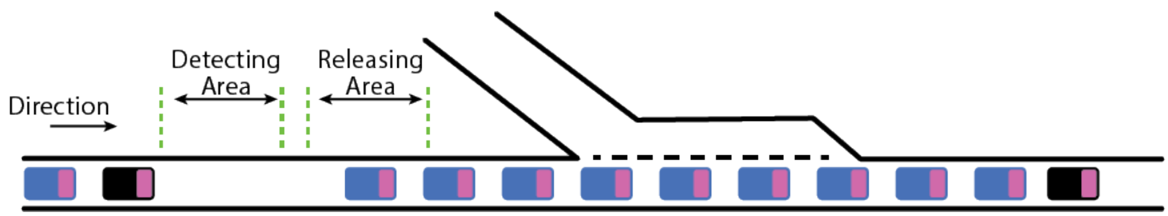
$$D_{merge} = (v_L \cdot t_3) + D_{GR} = \left(v_L \cdot \frac{v_L}{a_{merge}}\right) + D_{GR} = \frac{v_L^2}{a_{merge}} + D_{GR} \tag{11}$$

   Where:
   v_L = speed of the gap leader (m/s).
   t_3 = duration for the merge vehicle to accelerate to the gap leader's speed (m/s).
   D_{GR} = minimum gap-regulation distance (m) (200 m in this study).
   a_{merge} = acceleration of the on-ramp vehicle (m/s^2).

3. Speed Regulation: Once the on-ramp vehicle is released, a virtual leader (VL) and virtual follower (VF) will be assigned to the on-ramp vehicle, as shown in figure 6-B. The VL and VF are the two vehicles immediately before and after the identified gap on the mainline, respectively. The VL, VF, and merge vehicle aim to form a virtual platoon. Therefore, the on-ramp vehicle starts to regulate its speed with v_f set as the current speed of the VL when equation 11 is applied. When the speed of the on-ramp vehicle approximately equals the speed of the VL (±2 m/s in this study), the on-ramp vehicle will

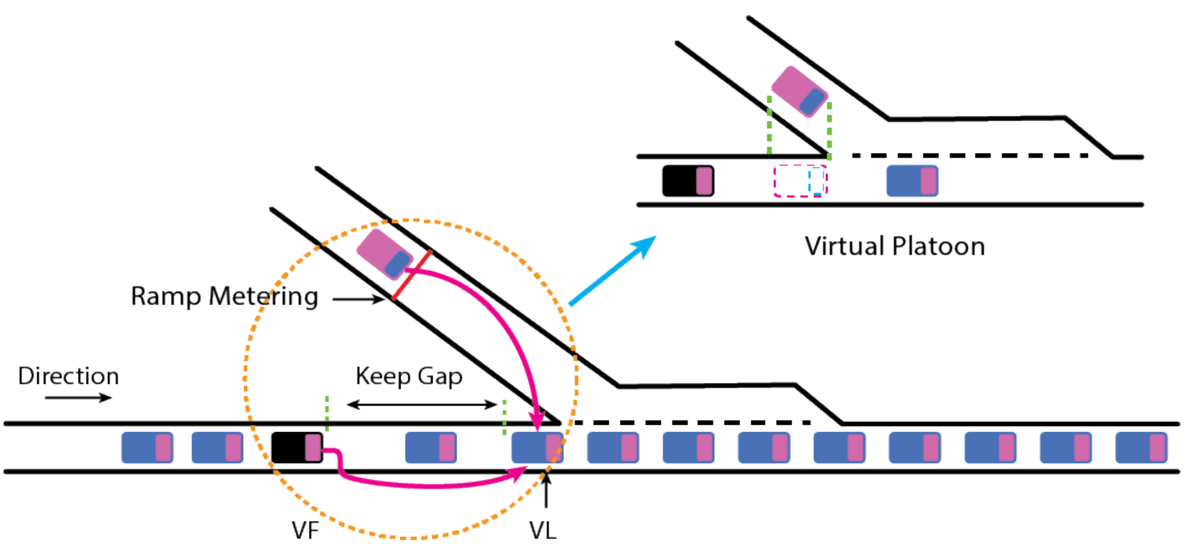
change to gap-regulation mode with the VL, and the VF will change to gap-regulation mode with the merge vehicle on the ramp. If the distance to the merge point becomes less than the minimum gap-regulation distance before the speed of the on-ramp vehicle approximately equals the speed of the VL, the on-ramp vehicle will change to the gap-regulation mode with the VL while the VF is still following the VL in gap-regulation mode (keeping the identified gap).

4. Gap Regulation and Merge: The on-ramp vehicle will keep the relative intraplatoon gap with the VL, and equation 14 through equation 17 are applied with t_2 equal to 0.7 s. The VF begins following the on-ramp vehicle as shown in figure 6-C, and equation 14 through equation 17 are applied. The gap for VF in the gap regulation is dependent on the vehicle type of the VF and which vehicle the VF is following. When the vehicle reaches the specified merge point at the acceleration lane, the vehicle can change lanes and merge into the right lane. After this point, the cooperative-merge process is complete, and the CACC-platooning logic kicks in to control how the new vehicle will join existing strings. Note that, because of the existence of on-ramps and off-ramps, vehicles may join and leave platoons. Therefore, the strings in the system do not always comprise 10 vehicles, the preset maximum string length. Instead, the merge vehicles are usually able to join the string before or behind it and then continue the operation as a part of the CACC-vehicle string.



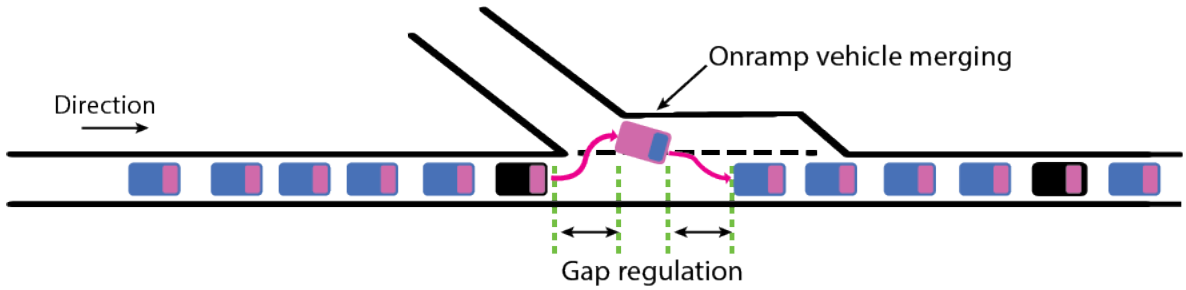
Source: FHWA.

A. Detecting and releasing areas.



Source: FHWA.

B. Virtual platoon in cooperative merge.



Source: FHWA.

C. Gap regulation in cooperative merge.

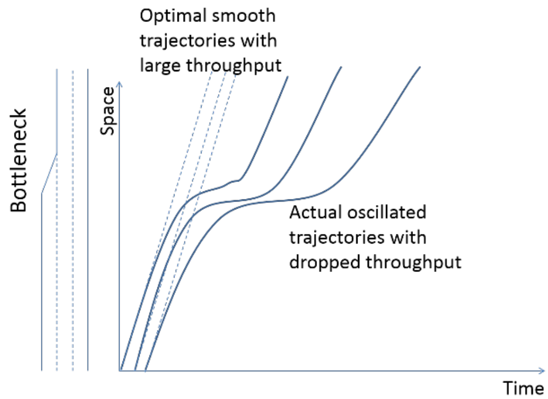
Figure 6. Illustrations. Cooperative-merge algorithm.

SPEED HARMONIZATION

Speed-harmonization strategies can be categorized into two types: segment-based traffic-speed harmonization and trajectory-based I2V speed control. Segment-based traffic-speed harmonization refers to a control strategy that generates the same speed commands or recommendations for all traffic across each subsegment of a roadway. The goal is to ensure all vehicles travel at similar speeds, thereby minimizing conflicts between vehicles and improving efficiency and safety of the system. Some advanced segment-based strategies also respond to potential or existing downstream traffic congestion at roadway bottlenecks and slow upstream traffic aggregately to avoid the onset of traffic-flow deterioration based on downstream bottleneck congestion.

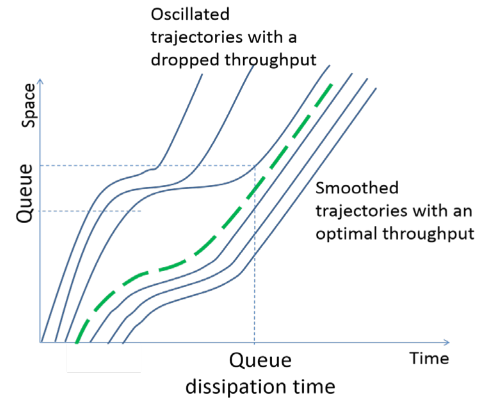
Trajectory-based I2V speed control aims to control each individual vehicle's trajectory at both basic freeway segments and merge areas to coordinate trajectories of vehicles and, thus, smooth traffic, particularly at bottleneck locations. This method can be used in conjunction with cooperative merging to effectively create gaps for merge vehicles. However, it results in more computational burden due to the need to control and coordinate all individual vehicles in real time. The combination of a segment-based (or a simplified, efficient trajectory-based) algorithm at basic segments and a trajectory-based algorithm at merge areas is also considered a feasible compromise between the two.

This study adopts the trajectory-based I2V speed-control algorithm, as proposed in FHWA's *Saxton Transportation Operations Laboratory STOL I Task Order 22: Speed Harmonization Fundamental Research I*. (FHWA 2016) As shown in figure 7, when detecting an imminent downstream speed drop at a bottleneck, to avoid hitting the downstream queue at a sudden full stop, a CAV (the dashed curve) should slow down moderately and pass the bottleneck smoothly at a reasonable speed just as the downstream queue dissipates. This trajectory-control strategy not only smooths the CAV's trajectory, but also helps any type of following vehicles (if not CAVs) on the managed lane to move in a similar smooth manner. As a result, the platoon of vehicles following this CAV will pass the bottleneck with a larger throughput rate due to reduced headway at a high speed, less fuel consumption due to smoothed trajectories, and less collision risk due to harmonized speeds.



Source: Amir Ghiasi.

A. Benchmark without trajectory smoothing.



Source: Amir Ghiasi.

B. CAV-based trajectory smoothing.

Figure 7. Graph. Projected trajectories with and without smoothing.

To achieve this ideal trajectory-smoothing paradigm, the research team needs to be capable of detecting the speed drop and predicting the corresponding shock-wave propagation and queue dissipation. Then, the research team needs to control the CAV so that it follows a smooth trajectory to properly lead the vehicle queue and enter the bottleneck right after the queue clears.

In the case of a downstream speed drop, if the congestion is moderate, the algorithm will seek to smooth the traffic, let the queue dissipate, and allow the following CAVs 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 period of time, the CAVs will guide the upstream traffic to avoid hitting the downstream queue at a sudden full stop by slowing down and smoothly joining the downstream queue.

Algorithm Design

The traffic and queue status can be captured either by traffic sensors located downstream of the traffic or data collected by RSUs sent from vehicles equipped with OBUs. The algorithm records all sensor information such that traffic and queue status can be predicted. Then, recommended trajectories are generated by assuming homogeneous traffic conditions between each sensor or probe vehicle. Note that this trajectory-based harmonization strategy is a real-time action that is updated frequently for each vehicle (e.g., every 2 s). Therefore, at the beginning of each time increment, queue characteristics are updated based on newly detected traffic conditions, so the actions taken by CAVs may be modified based on the updated data. Note that, in this study, the research team assumes 100 percent of vehicles in the managed lane are CVs (or at least equipped with VADs), and therefore, real-time traffic conditions at any location can be estimated using the data of all probe vehicles that pass the location during a specified duration. With probe data available for 100 percent of vehicles, the research team can use data from those vehicles to define virtual detectors anywhere in the network and collect corresponding traffic information. This study does not focus on how to use these data to best estimate traffic status. In this simulation, the research team has full information of the system and, therefore, extracts the information directly to generate I2V speed-control commands. For detailed information on the estimation and more advanced trajectory construction, interested readers can refer to an earlier publication. (Ghiasi et al. 2017)

This study adopts a heuristic approach for speed-command generation, building on Ma et al. (2017). The research team set many virtual loop detectors along the speed-harmonization segment (e.g., 3.2 km before the merge area). The traffic speed is monitored at these points and the values are calculated as the arithmetic mean of speed of the past 5 min. Two components are considered in the process: global and local commands. First, the speed-harmonization algorithm gradually slows the vehicle down based on the difference in traffic conditions at the vehicle's current location and the bottleneck location. The research team applies a simple linear speed-transition algorithm to obtain the global harmonization commands as shown in equation 12.

$$v_{des} = v_{cur} + \left(v_{pre} - v_{cur}\right) \times \left(1 - \frac{D_{cur}}{L_{seg}}\right) \tag{12}$$

Where:

v_{des} = desired speed (m/s).
v_{cur} = current speed of the subject vehicle (m/s).
v_{pre} = prevailing speed in the merge area (m/s).
D_{cur} = distance between the current position and boundary of speed-harmonization area.
L_{seg} = total length of the speed-harmonization area.

Second, the algorithm also has CAVs following local harmonization commands subject to the differences in the front vehicle's distance and speed.

The algorithm uses data from densely deployed virtual detectors to predict the trajectory of the front vehicle (CAV or human driven) and the trajectories of all preceding vehicles before the merge area. When the front vehicle is predicted to be slower at a certain speed threshold (i.e., slow front vehicle), then local harmonization is triggered to issue a spatiotemporal linear speed command using a method similar to that shown in equation 12 except the distance and speed are measured for the front vehicle at the predicted slow moment. This process ensures the CAV does not tightly follow the front vehicle to join the congestion.

When the CAV is too close to the front vehicle (i.e., less than a threshold, such as a 50-m in-distance gap) and the speed difference is less than a specified value (e.g., 5 m/s), the CAV will be asked to slow down in a linear fashion using a method similar to that in equation 12 except the distance and speed are measured for the front vehicle at current moment. For a CAV approaching the front vehicle at a high speed, this local harmonization ensures operational safety and lets CAVs more smoothly join the queue.

BUNDLED-APPLICATION PROCESS

The three CAV applications are bundled during real-time operations, referred to as "bundled CAV operations." The pseudo code for the bundled application process is shown in figure 8. The CACC module first determines the CACC status and corresponding operational mode and calculates the desired speed (v_{CACC}) for the specific CACC mode. If the vehicle is within the speed-harmonization zone or I2V speed control is activated, the speed-harmonization module calculates the desired speed (v_{SH}). When the vehicle approaches the merge area, the cooperative-merge module is activated. This module then releases an on-ramp vehicle when a qualified gap is identified on the mainline upstream of the merge area. For mainline vehicles, if the subject vehicle is a VL, the module sends speed and corresponding acceleration commands. If the subject vehicle is a VF, the VF follows the VL and keeps the recorded gap when the on-ramp vehicle is controlled by speed-regulation mode. The VF follows the on-ramp vehicle and is controlled by gap-regulation mode when the on-ramp vehicle is controlled by gap-regulation mode. For released on-ramp vehicles, if the on-ramp vehicle reaches the target speed or the boundary of the gap-regulation segment, it will commence the gap-regulation mode; otherwise, it is controlled by the speed-regulation mode.

Bundled Application Algorithm

```
vehMode ← get_CACC_Status // get the CACC status and operation mode
vCACC ← cal_CACC_speed(vehMode) // calculate the desired speed in CACC platoon
If Speed Harmonization is applied
        vSH ← cal_SH_speed
End
If Cooperative Merge is applied
        If on-ramp vehicle released
                If not the VL
                        If Gap Regulation
                                vCoop ← cal_Gap Regulation_speed
                        Else
                                vCoop ← cal_Speed Regulation_speed
                        End
                        If not the VF
                                If merge conditions met
                                        Prepare to merge into the gap
                                End
                        End
                End
        End
End
vdes = Min(vCACC, vSH, vCoop)
ades = cal_Acc(vdes)
Send_Command(vdes, ades)
```

Source: Jiaqi Ma.

vehMode = operation mode; v_{Coop} = desired speed calculated by the cooperative-merge module; a_{des} = desired acceleration (calculated by the bundled application algorithm in this case).

Figure 8. Diagram. Pseudocode for the bundled CAV application.

SIMULATION SCENARIOS

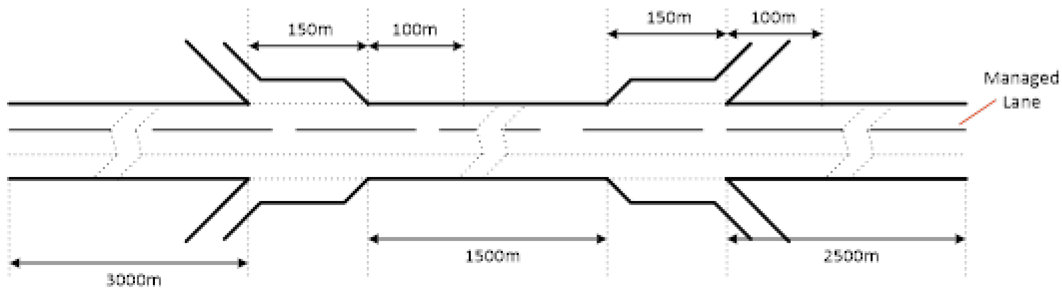
The goal of the simulation is to investigate the effectiveness of different CAV applications under the same simulation environment. Understanding the performance bundled CAV technologies is also of interest. The following three analysis scenarios are identified and investigated in this study:

- CACC traffic streams: CACC is one of the most popular CAV applications that can enhance freeway operating capacity as proven by many studies in the literature. (Shladover et al. 2009, Wang et al. 2018) This study explored implementing the latest CACC algorithm proposed in FHWA's High-Performance Traffic Streams project (2015), re-evaluating the effectiveness of the algorithm using a microscopic traffic simulation tool, and confirming those results using a second microsimulation tool. (Liu et al. 2017) Also, the research team is interested in understanding the CACC-pipeline capacity, which is the best performance of the managed lane, and setting it as a benchmark when incorporating other technologies, such as cooperative-merge applications and speed-harmonization algorithms. Further, CACC traffic-stream performance varies under different CAV market-penetration rates, which also impact the effectiveness of other technologies.

- CACC combined with cooperative merge: Freeway merges are always bottlenecks that cause excessive delay. When considering merging traffic, CACC enhancement to freeway capacity can be significantly compromised because of the disturbance to otherwise stable, but tightly coupled, CACC-vehicle strings. The research team is interested in understanding the impact of this disturbance and how cooperative-merge applications can reduce such impacts to a possible minimum. In particular, the research team hopes to understand what the possible on-ramp volume is under different CACC mainline volumes to achieve optimal performance. This consideration is of particular importance when the managed-lane operator hopes to create high-performance traffic streams while accommodating necessary on-ramp demand.

- Effects of speed harmonization: The effects of speed-harmonization algorithms, when bundled with other CAV technologies, are also of interest in this study. Speed harmonization can have two possible effects to improve traffic efficiency: to delay or reduce slow-down or stop-and-go occurrences at the merge area and to help create larger gaps by slowing upstream vehicles before the merge area and letting merge vehicles more smoothly join the mainline traffic.

The assumed simulation network is a simple three-lane freeway segment with an on-ramp and an off-ramp (figure 9). The freeway mainline is 7 km long. There is a 2-km warm-up mainline segment in the beginning. The simulated vehicles will use this segment to reach a stable car-following state after entering the network. This segment also allows CACC vehicles to form stable CACC-vehicle strings in the CACC analysis cases. There is an on-ramp 3 km downstream from the beginning of the network. An off-ramp is located 4.65 km from the network beginning. Both the on-ramp acceleration lane and off-ramp auxiliary lane are 150 m long. The first data-collection point locations 500 m downstream from the end of the on-ramp. Since this study is interested in the performance of managed lanes, this simulation only examines the left-most managed lane and the corresponding dedicated ramps. The bottom part of the network is for general-purpose traffic and provided for illustration purpose.



Source: Jiaqi Ma.

Figure 9. Illustration. Sketch plot of a simple network.

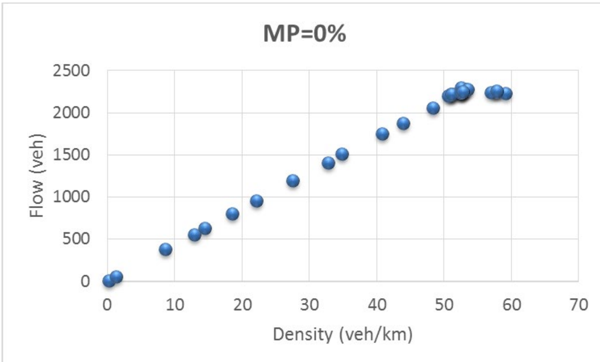
SIMULATION RESULTS

This subsection presents simulation results for the three scenarios described in Simulation Scenarios.

Analysis 1—CACC-Pipeline Capacity

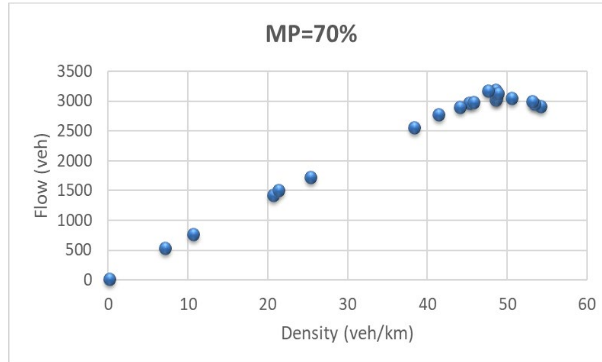
This study estimates the CACC-pipeline capacity under different CV and CAV market-penetration rates. In the CACC simulation, the maximum platoon size is set to 10 vehicles. The interplatoon gap is 1.5 s. The intraplatoon gap is based on a distribution derived from a survey, as explained in chapter 2. When data are collected to draw fundamental diagrams under each market-penetration rate, traffic input demand varies from 2,000 vehicles/h/lane to 4,000 vehicles/h/lane to generate different conditions. The simulation output data were collected and archived at 15-min intervals. Output 15-min flow rates were converted to equivalent hourly flow rates by multiplying by four, as shown in figure 10.

The density flow-rate diagrams under each market-penetration rate are presented in figure 10. The maximum flow is considered to be maximum capacity. The results shown in figure 11 demonstrated a significant increase in capacity with the increase in the market-penetration rate of CACC vehicles. The maximum CACC-pipeline capacity is around 3,288 vehicles/h/lane. At market-penetration rates of 30, 50, 70, and 100 percent, capacity increased by 5.5, 25.0, 37.8, and 42.7 percent, respectively.



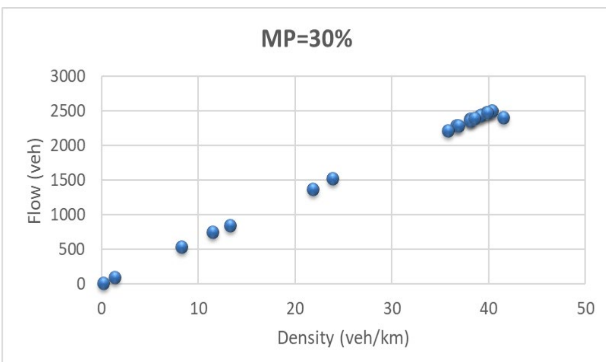
Source: FHWA.
MP = market penetration; veh = vehicles.

A. Market penetration = 0 percent.



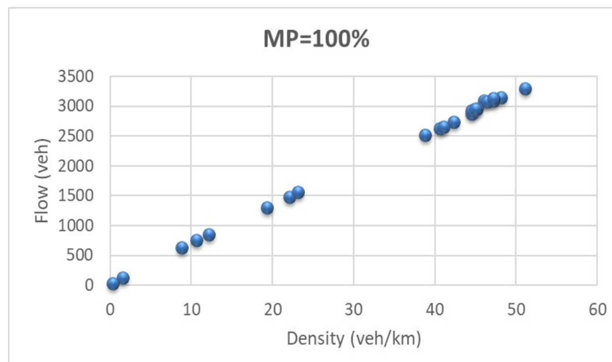
Source: FHWA.
MP = market penetration; veh = vehicles.

C. Market penetration = 70 percent.



Source: FHWA.
MP = market penetration; veh = vehicles.

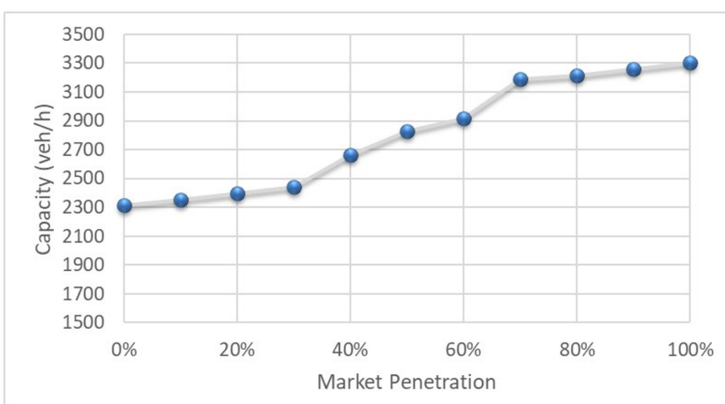
B. Market penetration = 30 percent.



Source: FHWA.
MP = market penetration; veh = vehicles.

D. Market penetration = 100 percent.

Figure 10. Graphs. Fundamental diagrams for CACC-pipeline capacity based on market-penetration rate.



Source: FHWA.
veh = vehicles.

Figure 11. Graph. CACC-pipeline capacity under different market-penetration rates.

Analysis 2—CACC and Cooperative Merge

Vehicles entering via on-ramps bring disturbance to the mainline managed lane. Their impacts mainly depend on the volume of traffic on the mainline managed lane. Lighter traffic volumes make more and longer gaps into which vehicles from the on-ramp can merge possible. This analysis compares managed-lane performance with and without cooperative-merge applications. The gap threshold is an important element of the platooning algorithm. If the gap threshold is too large, the roadway is not fully utilized. If the threshold is too small, the leader of a following CACC-vehicle string will frequently slow down during congestion to create gaps for merge vehicles due to the virtual-platooning process of the cooperative merge and therefore cause disruptions to the local traffic. The actual gap threshold is ideally dependent on the real-time local traffic conditions to optimize the throughput and delay. In this study, this value has been selected through many trial simulation runs under different scenarios (e.g., congestion levels) to ensure the merge maneuver does not cause too much disturbance to local traffic in terms of throughputs and delays.

Table 2 shows selected simulation results with combined CACC and cooperative-merge algorithms under different CAV market-penetrations rates. The managed-lane volume is around 85 percent of the pipeline capacity such that additional vehicles are allowed to enter the segment through on-ramps. The merge volume is generated by actual simulation runs with cooperative-merge scenarios and is dependent on the available merging gaps. The same merge volume is used in the scenarios of noncooperative merge to compare results with the cooperative merge.

Table 2. Selected results with combined CACC and cooperative merge.

MP (%)	ML Volume (vphpl)	Merge Volume (vphpl)	Throughput (Coop/ Noncoop, vphpl)	Average Delay (Coop/ Noncoop, s)	Pipeline Capacity (vphpl)	Improvement of Throughput (%)	Reduction of Average Delay (%)	Reduction From Pipeline Capacity (%)
*100	2800	248	3,064	37.33	3,288	7.51	77.21	–6.81
100	2800	248	2,850	163.82	3,288	7.51	77.21	–13.32
*70	2700	289	3,012	36.74	3,192	19.61	67.15	–5.64
70	2700	289	2,518	111.87	3,192	19.61	67.15	–21.11
*30	2050	428	2,401	34.27	2,412	1.57	62.91	–0.46
30	2050	428	2,364	92.40	2,412	1.57	62.91	–1.99
*0	1970	382	—	—	2,316	—	—	–10.49
0	1970	382	2,073	132.23	2,316	—	—	–10.49

—No data.
MP = market-penetration rate; ML = managed lane; vphpl = vehicles per hour per lane.
Note: Shaded rows (asterisked) indicate cooperative (Coop) cases; nonshaded rows indicate noncooperative (Noncoop) cases.

The improvement caused by the cooperative merge is dramatic when the market-penetration rate is at 100 percent. The throughput improvement is 7.51 percent (from 2,850 to 3,064 vehicles/h/lane), and the delay reduction is 77.21 percent (from 163.82 to 37.33 s). The throughput improvement at a market-penetration rate of 70 percent is larger than other cases. Because 85 percent of the pipeline capacity was consistently used as the mainline managed lane traffic input and more gaps were potentially available, more vehicles merged smoothly into the managed lane. With lower market-penetration rates, the benefits of cooperative-merge applications become relatively small. This occurrence is mainly because low market-penetration rates lead to additional gaps that vehicles can use to merge into traffic since the desired gaps between manually driven vehicles are usually larger than the critical gap (i.e., 1.4 s) used in this study. Small benefits partially result because, at a CAV market-penetration rate of 100 percent, the identified gaps can be maintained by controlling the virtual platoon with the merge vehicle in the middle as described in the cooperative-merge algorithm. For other cases involving manually driven vehicles, it is likely the identified gap no longer exists when the merge vehicle arrives at the merge area, and the merge vehicle needs to find a gap just like noncooperative-merge scenarios. In the extreme case of a market-penetration rate of 0 percent, the performance of cooperative-merge applications is even worse than the noncooperative-merge applications.

The reduction in mainline capacity compared with the CACC-pipeline capacity is most significant when the market-penetration rate of CAVs is 100 percent. This significant reduction occurs because many more vehicles are on the roadway due to the small gaps between vehicles, and disturbances from the on-ramps can quickly impact many CAVs in strings. This disturbance further emphasizes the importance of cooperative-merge applications. In the extreme case of 0-percent market-penetration rate, the noncooperative-merge throughput is larger than the pipeline capacity of 0 percent. This situation occurs because all the on-ramp vehicles are CAVs, and the traffic after the merge area is actually mixed traffic with CACC-vehicle strings and, thus, have higher throughput.

Analysis 3—Effects of Speed Harmonization

This section evaluates the scenarios in analysis 2 again with the addition of speed harmonization. The capability of speed harmonization to relieve congestion at the merge area and create more and larger gaps for merge vehicles is of interest. Speed-harmonization effects are also analyzed with and without a cooperative-merge application.

Table 3 and table 4 show the simulation results with bundled CACC, cooperative-merge applications, and speed-harmonization algorithms under different CAV market-penetration rates. The research team uses the same method for generating managed-lane and on-ramp traffic volumes. Speed harmonization is effective from 1,500 m upstream of the merge area. The length of the speed-harmonization zone is obtained through multiple trial runs, which show 1,500-m zone facilitates the best performance. The speed-harmonization algorithm is implemented as automatic speed control of CAVs, and therefore, manually driven vehicles, including VADs, are not directly affected by speed harmonization. They may, however, be harmonized by nearby CAVs.

Table 3. Volume, throughput, and delay results with bundled CACC, cooperative-merge, and speed-harmonization algorithms by market-penetration rate.

MP (%)	ML Volume (vphpl)	Merge Volume (vphpl)	Throughput (Coop/Noncoop, vphpl)	Average Delay (Coop/Noncoop, Seconds)	Pipeline Capacity (vphpl)
*100	2,800	376	3,190	32.53	3,288
100	2,800	376	2,934	153.46	3,288
*70	2,700	440	2,942	32.38	3,192
70	2,700	440	2,484	65.10	3,192
*30	2,050	520	2,428	27.68	2,412
30	2,050	520	2,244	75.85	2,412
*0	1,970	382	—	—	2,316
0	1,970	382	2,073	132.23	2,316

—No data.
MP = market-penetration rate; ML = managed lane; vphpl = vehicles per hour per lane.
Note: Shaded rows (asterisked) indicate cooperative (Coop) cases; nonshaded rows indicate noncooperative (Noncoop) cases.

Table 4. Percentage of throughput, delay, and pipeline-capacity improvements with bundled CACC, cooperative-merge, and speed-harmonization applications by market-penetration rate.

MP (%)	Improvement of Throughput (%)	Reduction of Average Delay (%)	Reduction From Pipeline Capacity (Coop/Noncoop, %)	Throughput Compared With Analysis 2 (Coop/Noncoop, %)	Average Delay Compared With Analysis 2 (Coop/Noncoop, %)
*100	8.73	–78.8	–2.98	+4.11	–12.86
100	8.73	–78.8	–10.77	+2.95	–6.32
*70	21.16	–50.26	–7.83	–2.32	–11.87
70	21.16	–50.26	–22.18	–1.35	–41.81
*30	8.19	–63.51	+0.66	+1.12	–19.23
30	8.19	–63.51	–6.97	–5.08	–17.91
*0	—	—	—	—	—
0	—	—	—	—	—

—No data.
MP = market-penetration rate; ML = managed lane; vphpl = vehicles per hour per lane.
Note: Shaded rows (asterisked) indicate cooperative (Coop) cases; nonshaded rows indicate noncooperative (Noncoop) cases.

Similar to the results in table 2, the improvements caused by cooperative-merge applications is dramatic when the market-penetration rate is 100 percent. The throughput improvement is 8.73 percent (from 2,934 to 3,190 vehicles/h/lane), and the delay reduction is 78.8 percent (153.46 to 32.53 s). Other trends are also similar to those in table 2, including higher throughput at a 70-percent market-penetration rate. In the extreme case of a 0-percent market-penetration rate, the performance is exactly the same as in table 2 because speed harmonization does not affect non-CAVs. Similarly, the reduction in capacity compared with the CACC-pipeline capacity is also most significant when the CAV market-penetration rate is 100 percent, but cooperative-merge scenarios are much better than noncooperative-merge scenarios, implying the importance of cooperative-merge applications.

The effect of speed harmonization can be seen in multiple aspects. Compared with analysis 2 in table 2, the throughout increases under different market-penetration rates with cooperative merge. Under 100-percent market-penetration rate in particular, the merge volume increased from 248 to 376 vehicles/h/lane, implying an increase of gaps that are greater than the threshold value by 51.61 percent. This positive effect should be attributed to the combination of smoothed traffic flow and lower vehicle arrival rate because of upstream slowdown. The last two columns of table 4 show the comparison of overall system performance.

In summary, the simulation results show the bundled application has great potential to significantly reduce system delay and increase throughput as compared to the baseline case. Higher CAV market-penetration rates result in larger system benefits, around 15 and 65 percent improvements, on average, in throughput and delay, respectively, when the market-penetration rate is above 70 percent. The results also show the importance of bundling the three applications. For example, table 2 implies huge differences between the cases with and without cooperative merge. In fact, most of the benefit of the bundled application comes when the cooperative-merge application is added because the cooperation through I2V communication significantly reduces the conflicts between the merge and mainline vehicles. The incorporation of speed-harmonization algorithms generates additional benefits due to more and larger gaps being made available, and thus, ramp vehicles have more opportunities to merge into the mainline managed lane. These huge benefits result from the integration of the three separately developed CAV applications, and the simulation results emphasize the importance and necessity of bundling the three applications to lead to greater system benefits that cannot be possibly achieved by each individually.

CHAPTER 4. FIELD EXPERIMENT

This chapter describes the base functionality of the bundled applications that were demonstrated during the field experiment and establishes the characteristics that were evaluated and the characteristics that were compared with a baseline scenario. The evaluation covered the performance of the vehicles and infrastructure.

The bundled applications (speed harmonization, CACC, and cooperative merge) were developed under past Saxton Lab projects[1] and were implemented under a parallel project.[2] (Raboy et al. 2017) Vehicles equipped with these applications feature longitudinal control, which falls under SAE International's level-1 automation. In addition, they use DSRC to communicate with surrounding vehicles and DSRC and cellular to communicate with infrastructure.

OBJECTIVE

The goal of the field experiment was to quantify the performance of the implementation of the bundled applications with regard to a baseline case, specifically the performance of manually driven vehicles.

TEST ENVIRONMENT

The tests were conducted at the I-95 express lanes facility, owned by the Virginia Department of Transportation (VDOT) and managed by Transurban. Use of the express lanes for the purposes of this test is governed by the Memorandum of Understanding between FHWA, VDOT, and Transurban. (Commonwealth Transportation Board 2017)

Requirements

Multiple candidate sites were considered along I-395, I-495, and I-95. The requirements, shown in table 5, were generated based on how the field experiment was expected to play out and used to select the test sites.

---

[1]FHWA STOL I TO 4 Simulation of Evolutionary Introduction of Cooperative Adaptive Cruise Control Equipped (contract number DTFH61-12-D-00020/212006); FHWA STOL I TO 22 Speed Harmonization Fundamental Research (contract number DTFH61-12-D-00020/310294).

[2]FHWA STOL II TO 0022 Develop AMS Model Algorithms/Logic for CAV Apps (contract number DTFH61-16-D-00030/323321); FHWA STOL II TO 18-225 Development of Cooperative Automation Capabilities, Integrated Prototype II (contract number DTFH61-16-D-00030/327152).

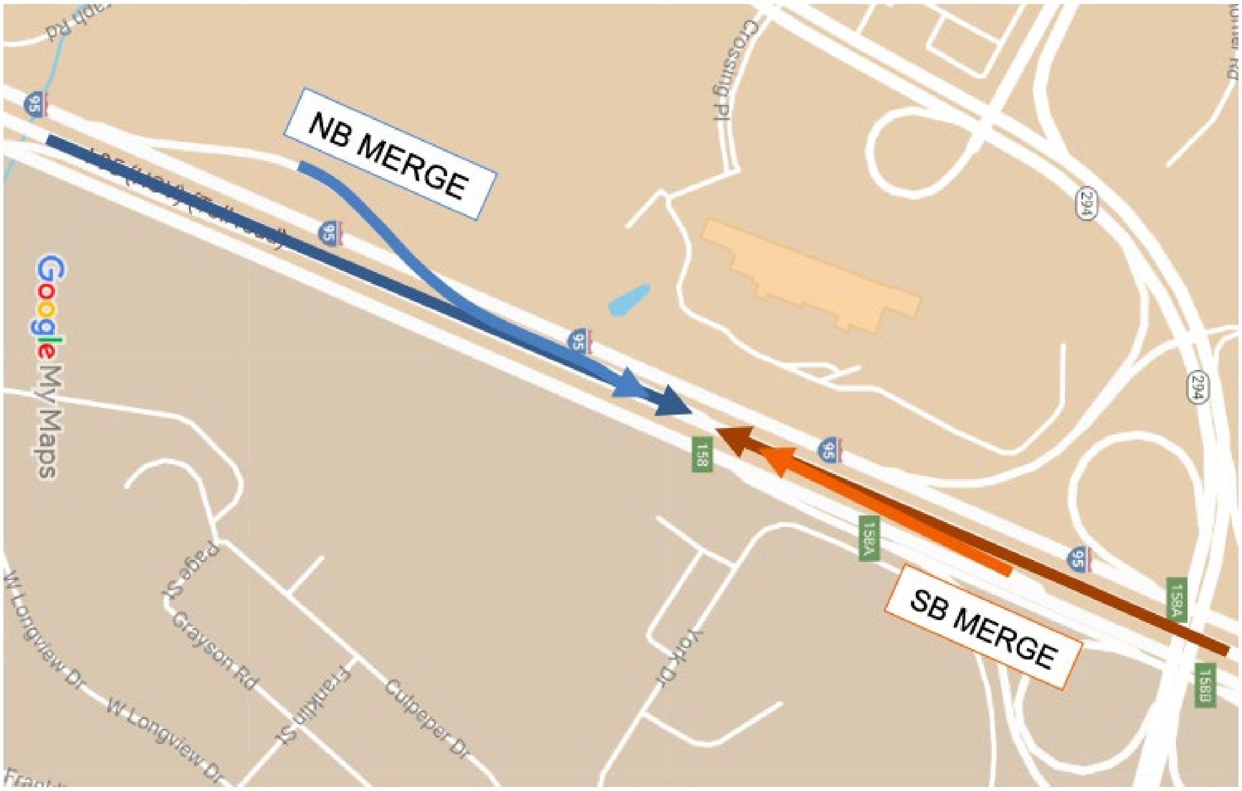
Table 5. Test-site requirements.

Requirement	Reason
Dedicated entrance to HOT lanes (exclusive use if possible)	Minimize disruption from regular traffic
Minimum 150-m acceleration lane	Provide time for the merge vehicle to accelerate to highway speed
Minimum 150-m merge lane	Provide time for the vehicles to negotiate lane change
Safe waiting area for a vehicle on the ramp (e.g., shoulder)	Minimize disruption to regular traffic
Area to deploy mobile roadside-unit trailer within 100 m of merge area	Provide infrastructure communication component
Minimum 3.2 km of mainline road upstream of merge area	Allow time for platoon to form and stabilize
Minimum 4.8 km of mainline road downstream of merge area	Allow time for merge vehicle to enter platoon and stabilize
Northbound and southbound entrance close by (desirable)	Maximize test time by running in both directions
Close proximity to the Turner-Fairbank Highway Research Center (desirable)	Increase efficiency by minimizing travel time
Staging area nearby (e.g., parking lot)	Provide an area for the team to prepare and regroup
Smooth pavement surface	Minimize disturbances to drivers and sensors
Absence of work zone or construction on the on-ramp or on the test portion of the facility April–June	Minimize disruption from other activities
Helicopters allowed to fly overhead	Provide the ability to film the field experiment from the air

In general, the I-95 reversible lanes were preferred over I-495 because initial testing could be done during the reversal times when no other traffic was present. After adjusting for the roadway with no traffic, testing could continue in mixed traffic along the same route. I-395 was eliminated because it would have been difficult to get approval to fly (for purposes of video documentation) within 13 km of Reagan National Airport and because of ongoing construction along that road.

Location

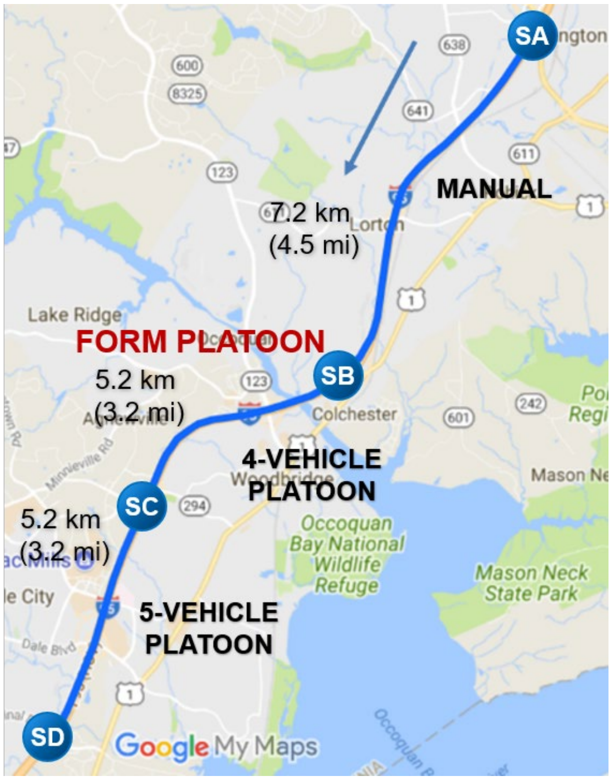
The selected location for the merge area is just south of exit 158 on the I-95 express lanes, near Potomac Mills, a large shopping mall in Woodbridge, VA. This location satisfies all requirements, including 2 ramps that can be used exclusively, depending on the direction of traffic flow. These ramps are normally off-ramps for the express lanes, and when they are not in use, they are facing opposite the flow of traffic, so entry barriers, which would block the merge vehicle, are not necessary. More specifically, when the reversible lanes are moving northbound, the southbound off-ramp can be used as a northbound on-ramp and vice versa. Figure 12 is a map of the test site.



NB = northbound; SB = southbound.
Note: The map overlays were developed for this project to illustrate vehicle movements in the merge area. The darker lines show the direction of through traffic and the lighter lines show the direction of the merge vehicle.

Figure 12. Map. Test-site map.

Since the lanes are reversible, the time at which each ramp can be used is constrained. Specifically, when testing in light traffic, the direction of the vehicles must follow the direction of the traffic. The typical schedule during the work week at the time of this experiment was northbound flow in the morning (3 to 10 a.m.) and southbound flow in the evenings (12 p.m. to 12 a.m.). Initial testing was performed during reversal times when there was no traffic. There are two reversals each day, from approximately 10 a.m. to 12 p.m. and 12 to 3 a.m. The test routes and key points are given in figure 13.



© 2018 Google®; overlay by authors.
SA = southbound at point A; SB = southbound at point B; SC = southbound at point C; SD = southbound at point D.
Note: The map overlays were developed for this project to illustrate the southbound and northbound test routes and points of interest.

A. Southbound route.

© 2018 Google®; overlay by authors.
ND = northbound at point D; NC = northbound at point C; NB = northbound at point B; NA = northbound at point A.
Note: The map overlays were developed for this project to illustrate the southbound and northbound test routes and points of interest.

B. Northbound route.

Figure 13. Maps. Southbound and northbound test routes.

SCHEDULE, PERSONNEL, AND DOCUMENTATION

This section contains a high-level test schedule, lists the personnel required to execute the tests, and lists the resources used to record test activities and results.

TEST SCHEDULE

Table 6 lists the activities done for the evaluation process once the vehicles and infrastructure were prepared.

Table 6. Test activities.

ID	Activity	Estimated Duration
1	Preliminary testing	4 d
2	Initial tests	3 d
3	Data collection (base case)	2 d
4	Data collection (bundled applications)	4 d
5	Document results and submission of final report	1 mo

The test activities took place in several phases that were coordinated with the development of the applications. The following is a summary of these activities:

- Preliminary testing was performed at Aberdeen Test Center over the course of 1 week to verify the functionality of the bundled applications. Prior to that, each application went through a separate testing process.

- Initial testing was performed on the managed-lane facility during the midnight reversal, when the longest time was available for testing. Three test sessions were used for initial testing.

- Data were collected for the base case starting during the morning reversal. Since the command speed around the merge area was lower and following distances were larger, this was not tested in light traffic.

- Data were collected for the bundled applications starting during the morning reversal and continued in light traffic in the southbound direction. Three test sessions were planned for the bundled applications.

Figure 14 shows the days and nights spent testing on the I-95 managed lane. The numbers below the dates are test session numbers.

JUNE 2018						
SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
27 MAY	28	29	30	31	1 JUNE	2
3	4	5 MIDNIGHT (#1)	6	7	8	9
10	11	12 MIDNIGHT (#2)	13 MIDNIGHT (#3)	14 MIDDAY (#4) (reversal only)	15	16
17	18	19 MIDDAY (#5) (reversal only)	20 MIDDAY (#6) (reversal only)	21 MIDDAY (#7)	22	23
24	25 MIDDAY (#8)	26 MIDDAY (#9)	27 MIDDAY FILMING (#10)	28 MIDDAY FILMING (#11)	29	30

Source: FHWA.

Figure 14. Illustration. Days and nights spent testing on the I-95 managed lane.

A typical test event making use of the I-95 express lanes alternated between northbound and southbound runs for efficiency. The itineraries in table 7 through table 14 describe general test activities to execute northbound and southbound tests. The various activities are broken up into blocks that were repeated as needed. Setup, which was conducted before and after the tests, has been documented and may be performed irrespective of vehicle orientation. These blocks form the bases of test session plans in table 7 through table 14.

Table 7. Initial setup (33 min).

Minutes Elapsed	Activity
0	Test conductor arrives at HOT lanes staging area (*x*A).
5	Test conductor begins vehicle preparation.
25	Test conductor completes vehicle preparation.
26	Test conductor sends merge vehicle to merge point.
33	Merge vehicle arrives at merge point (*x*C).

*x*A = northbound or southbound at point A (i.e., the staging area); *x*C = northbound or southbound at point C (i.e., the merge point).

Table 8. Return setup—next test in opposite direction (22 min).

Minutes Elapsed	Activity
0	Test conductor completes data verification. Test conductor notifies Transurban of completion. Transurban verifies lanes clearance and sends an OK signal to test conductor to proceed for next run.
1	Four vehicles continue to the opposite starting point via HOT lanes. Merge vehicle turns around and heads toward merge point (*x*C).
6	Merge vehicle stops at merge point (*x*C).
14	Four vehicles arrive at staging area (*x*A), stop, and turn around.
15	Test conductor begins vehicle preparation.
20	Test conductor completes prior run review with observers.
22	Test conductor completes vehicle preparation.

*x*A = northbound or southbound at point A (i.e., the staging area); *x*C = northbound or southbound at point C (i.e., the merge point).

Table 9. Southbound test, vehicle start to stop (11 min).

Minutes Elapsed	Activity
0	Transurban verifies lanes are clear and sends an OK signal to test conductor to proceed.
1	Four vehicles enter HOT lanes in manual mode (SA).
5	Four vehicles form platoon (SB).
8	Fifth vehicle merges into platoon at merge point (SC).
10	Five vehicles arrive at end point (SD).
11	Vehicles stop on HOT lanes (SD) to return if exclusive access to HOT lanes, else make first exit.

SA = southbound at point A (i.e., the staging area); SB = southbound at point B; SC = southbound at point C (i.e., the merge point); SD = southbound at point D (i.e., the end point).

Table 10. Northbound test, vehicle start to stop (12 min).

Minutes Elapsed	Activity
0	Transurban verifies lanes are clear and sends an OK signal to test conductor to proceed.
1	Four vehicles enter HOT lanes in manual mode (NA).
5	Four vehicles form platoon (NB).
8	Fifth vehicle merges into platoon at merge point (NC).
11	Five vehicles arrive at end point (ND).
12	Vehicles stop on HOT lanes (ND) if exclusive access to HOT lanes, else make first exit.

NA = northbound at point A (i.e., the staging area); NB = northbound at point B; NC = northbound at point C (i.e., the merge point); ND = northbound at point D (i.e., the end point).

Table 11. Southbound setup for light traffic scenario (27 min).

Minutes Elapsed	Activity
0	Vehicle operators take manual control of the vehicles.
2	Vehicles exit the freeway from the nearest exit after SD.
3	Vehicles move toward SA using general-purpose lanes.
19	Vehicles arrive at southbound staging area (SA).
20	Test conductor begins vehicle preparation.
25	Test conductor completes prior run review with observers.
27	Test conductor completes vehicle preparation.

SA = southbound at point A (i.e., the staging area); SD = southbound at point D (i.e., the end point).

Table 12. Midnight test (no traffic—4 h).

Series No.	Activity	Staging Area	Merge Point	End Point
1	Initial setup	SA—Fairfax County Parkway	—	—
2	Southbound test	SA	SC	SD
3	Return setup	NA (Manual travel from SD to NA)	—	—
4	Northbound test	NA—Joplin Road	NC	ND
5	Return setup	SA (Manual travel from ND to SA)	—	—
6	Southbound test	SA	SC	SD
7	Return setup	NA (Manual travel from SD to NA)	—	—
8	Northbound test	NA	NC	ND
9	Return setup	SA (Manual travel from ND to SA)	—	—
10	Southbound test	SA	SC	SD
11	Return setup	NA (Manual travel from SD to NA)	—	-
12	Northbound test	NA	NC	ND
13	End of test	Manual travel using general-purpose lanes to TFHRC for Review	—	—

—Not applicable.
NA = northbound at point A; NC = northbound at point C; ND = northbound at point D; SA = southbound at point A; SC = southbound at point C; SD = southbound at point D; TFHRC = Turner-Fairbank Highway Research Center.

Table 13. Midday test (no traffic—1 h).

Series No.	Activity	Staging Area	Merge Point	End Point
1	Initial setup	NA—Joplin Road	—	—
2	Northbound test	NA—Joplin Road	NC	ND
3	Return setup	SA (Manual travel from ND to SA)	—	—
4	Southbound test	SA—Fairfax County Parkway	SC	SD
5	Return setup	NA (Manual travel from SD to NA)	—	—
6	Northbound test	NA	NC	ND
7	End of test	Manual travel using general-purpose lanes to TFHRC for Review	—	—

—Not applicable.
NA = northbound at point A; NC = northbound at point C; ND = northbound at point D; SA = southbound at point A; SC = southbound at point C; SD = southbound at point D; TFHRC = Turner-Fairbank Highway Research Center.

Table 14. Midday test (light traffic—3 h).

Series No.	Activity	Staging Area	Merge Point	End Point
1	Initial setup	SA—Fairfax County Parkway	—	—
2	Southbound test	SA	SC	SD
3	Return setup	NA (Manual travel from SD to NA)	—	—
4	Northbound test	NA—Joplin Road	NC	ND
5	Return setup	SA (Manual travel from ND to SA)	—	—
6	Southbound test	SA	SC	SD
*7	Southbound setup	SA (Manual travel from SD to SA)	—	—
*8	Southbound test	SA	SC	SD
*9	Southbound setup	SA (Manual travel from SD to SA)	—	—
*10	Southbound test	SA	SC	SD
*11	End of test	Manual travel using general-purpose lanes to TFHRC for Review	—	—

—Not applicable.
NA = northbound at point A; NC = northbound at point C; ND = northbound at point D; SA = southbound at point A; SC = southbound at point C; SD = southbound at point D; TFHRC = Turner-Fairbank Highway Research Center.
Note: Shaded rows (asterisked) indicate lanes are open to public traffic; unshaded rows indicate lanes are closed to public traffic.

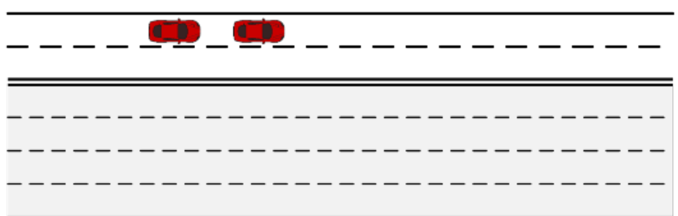
Cancellations

One consideration in using a live road for testing is that its main purpose is for transportation of the general public. So, at all times, the traffic conditions on the general-purpose lanes were monitored for incidents and congestion. In one case, testing ended early due to an incident on the general-purpose lanes. No tests were canceled due to adverse weather.

EXPERIMENT OVERVIEW

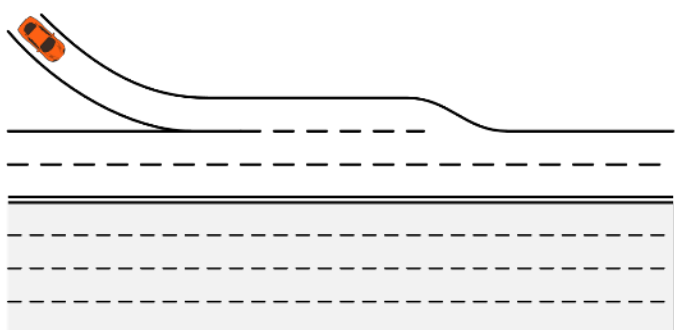
The experiment was designed to be carried out with five vehicles: four vehicles traveling down the managed lane and one vehicle merging into the managed lane. The experiment was performed with multiple scenarios to evaluate the effectiveness of the CAV applications on traffic flow. In the baseline case, the platooning vehicles were driven manually, and the merge vehicle was released in a fashion similar to a metering light and manually driven to the merge point. In the experimental case, the vehicles executed the platooning maneuver cooperatively, and the merge vehicle was released automatically. Data, such as vehicle speed, following distance, and time to merge, were recorded and compared between the two cases.

A step-by-step illustration of the experiment is given in figure 15. The roadway configuration shows six lanes, two of which are managed and four of which are general purpose. In accordance with the simulation, the experiment was carried out in a single managed lane. The general-purpose lanes are physically separated from the managed lanes and are shown for the reader's information. The circumstances of each step are given alongside the illustration. The illustrations are intended to be general enough to apply to either a cooperative scenario or a manual scenario. For clarity, only three vehicles are illustrated.



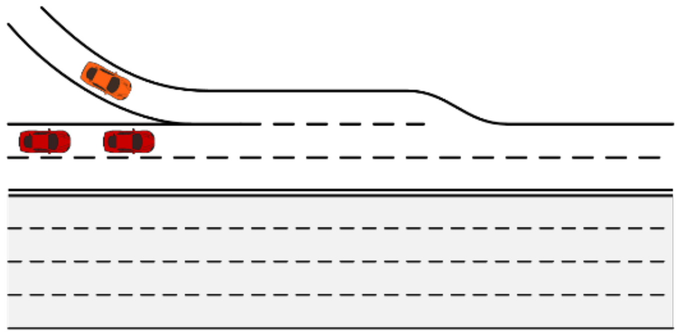
Source: FHWA.

A. Step 1: Cooperative control—two vehicles travel in the left managed lane in a platoon; manual control—two vehicles travel in the left managed lane.



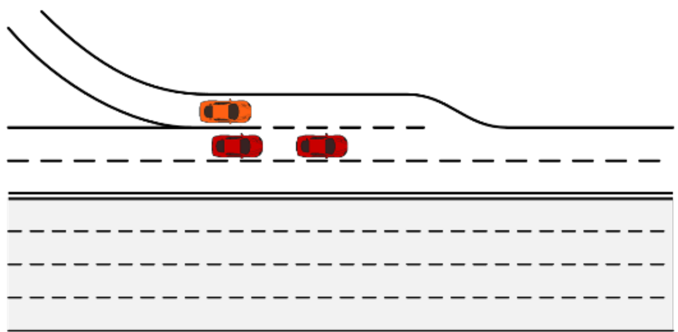
Source: FHWA.

B. Step 2: A third vehicle waits to be released from an entry ramp.



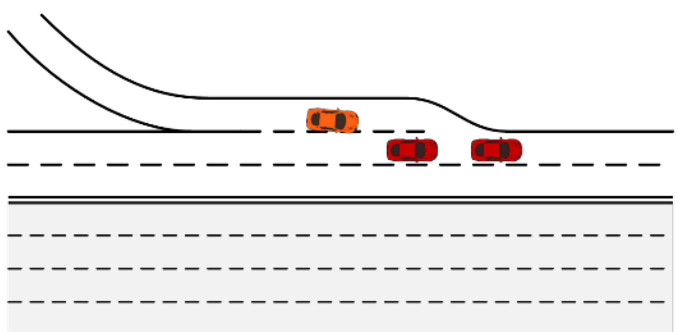
Source: FHWA.

C. Step 3: Cooperative control—as the two-vehicle platoon approaches the entry ramp, the third vehicle is released and accelerates along the ramp; manual control—as the vehicles on the mainline approach the entry ramp, the third vehicle is released and accelerates along the ramp.



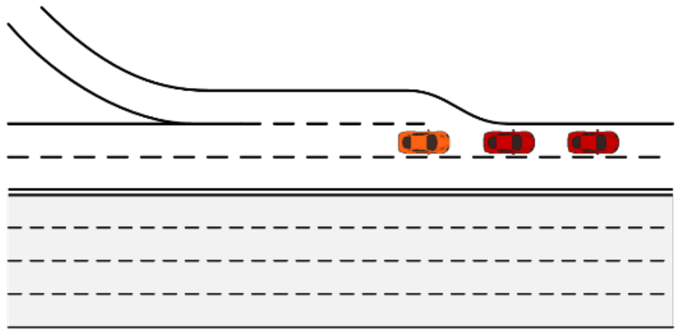
Source: FHWA.

D. Step 4: Cooperative control—the third vehicle approaches the merge point and aligns itself with the platoon; manual control—the third vehicle approaches the merge point and aligns itself with the string of manually driven vehicles.



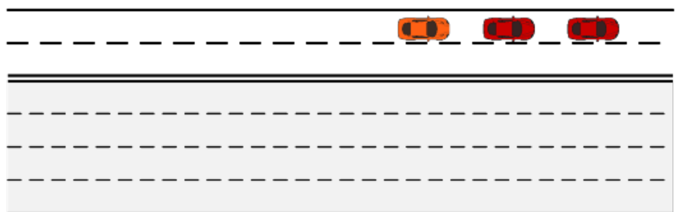
Source: FHWA.

E. Step 5: The third vehicle is in position and begins to merge.



Source: FHWA.

F. Step 6: Cooperative control—the third vehicle has joined the platoon; manual control—the third vehicle has entered the string of manually driven vehicles.



Source: FHWA.

G. Step 7: Cooperative control—the new three-vehicle platoon responds to speed-harmonization commands given by the TMC over cellular; manual control—the three vehicles proceed in the left lane.

Figure 15. Illustrations. Step-by-step experiment.

VEHICLE PLATFORM

To facilitate the execution of the experimental tests using the algorithms developed for this task order (TO), the team used the FHWA Saxton Lab's fleet of Cooperative Automation Research for Mobility Applications (CARMA℠) vehicles. This fleet of 2013 crossover vehicles, using software developed by the FHWA Saxton Lab, provides a robot-operating-system framework for testing and evaluating CAV applications. This framework includes a hardware abstraction layer consisting of drivers and an interface manager, environment data processing through a sensor fusion component, route information processing, and an upper-level guidance component responsible for consuming the available data and producing motion plans for the vehicle.

The platform provides for the implementation and execution of custom algorithms in the form of plugins to the vehicle software's guidance module. These plugins are loaded onto the Linux PC installed in the vehicle and then selected by the user at software startup. Once selected by the user, the plugins are allowed to participate in a cooperative-motion planning process for the vehicle, working in conjunction with all other enabled plugins to generate a speed profile for the vehicle to execute. These speed profiles consist of discrete maneuvers including "speed up," "slow down," "steady speed," and "change lane" and are planned over a span of distance rather than time. Once a plan has been generated by the plugins and accepted by the vehicle's validation system (to ensure that the trajectory passes basic sanity checks, obeys the local speed limits, does not conflict with known current or future locations of other vehicles, etc.), these maneuvers are executed as the vehicle passes its start location in the planned motion profile. This system also allows for more sophisticated complex maneuvers that enable the vehicle's commanded speed to be planned on a moment-to-moment basis. This planning enables the fine-grained and responsive gap control needed for the vehicle's included platooning plugin to function and enables similar control functionality needed for the operation of the speed-harmonization functionality.

The vehicle's general path along the road and other details, such as speed limits, lane information, enabled or disabled plugins, and so forth, are configured via the usage of route files and routes. Routes, as defined by route files, are a series of points and connecting line segments that contain the various information and metadata needed by the vehicle platform to accomplish its mission. These routes define the path of travel and provide a consistent reference frame used by all motion planning in terms of down-track distance traveled and cross-track distance relative to the route centerline. These route files also allow for the selected plugins to be enabled or disabled for specific regions of the roadway. This functionality was used in the experimental design to enable platoon formation at a designated location by disabling platooning for all vehicles prior to that location.

The hardware platform from a CARMA vehicle is built on top of the test vehicles' ACC applications. The vehicles are outfitted with a drive-by-wire system that is capable of overriding the stock ACC system to directly command throttle and brakes over the vehicle Controller Area Network (CAN) bus. Speed commands are generated by the CARMA Platform on the in-vehicle Linux PC and are sent to a real-time control module with a proportional-integral-derivative (PID)-based speed-control loop. (FHWA 2018)

For localization, the CARMA Platform relies on a pinpoint device which uses a global positioning system (GPS) and an inertial measurement unit to produce an accurate reading on the vehicle location and altitude which remains available in the face of momentary GPS satellite drop out due to occlusion or other issues. The CARMA Platform uses the stock forward-facing radar sensor via a tap into the vehicle's forward object CAN bus, and the data are provided to the Linux PC and its objects driver and sensor fusion system. Other data elements, such as vehicle speed and ACC status, are also available from the high-speed CAN bus. The CARMA system includes networking hardware that provides a cellular access point to enable communication with the standard internet while the vehicle is in motion. The vehicle's DSRC communications are powered by an OBU forwarding messages to and from the PC for processing.

Platooning

The platooning plugin, which is included in the vehicle, uses an algorithm for platooning that was derived from an algorithm originally designed by California Partners for Advanced Transit and Highways (PATH). The algorithm was significantly enhanced by a graduate research fellow working with FHWA, with flexibility and extensibility in mind. The software to execute the algorithm was developed and tested by the evaluation team at FHWA's Saxton Transportation Operations Lab at the Turner-Fairbank Highway Research Center in McLean, VA. This algorithm provides means for leader selection when two or more vehicles begin to communicate with each other. This communication takes place using the set of mobility messages called MobilityRequest, MobilityResponse, MobilityPath, and MobilityOperations.

Once a leader is selected, the following vehicle plans a motion profile that will bring it in close proximity to the lead vehicle or the rear-most vehicle in the lead vehicle's platoon (if one already exists). Joining a platoon is only possible from the rear, and no allowances are made for lane changes to join a platoon. Once the following vehicle is in position, it switches to controlling its target gap to the lead vehicle (based on position reported via DSRC) or its gap to the preceding vehicle (as measured by radar), depending on circumstances (such as immediate proximity to the preceding vehicle), by means of a standard PID controller and smoothing filters. At all points in time during this platooning operation, the CARMA Platform's basic radar-based ACC system is enabled with a significantly reduced headway setting to act as a safety measure should platooning fail for any reason.

Speed Harmonization

The speed-harmonization plugin included with the CARMA Platform enables remote server control of the vehicle's speed. The speed-harmonization server itself is deployed remotely in the cloud and communicates with the plugin running in the vehicle via hypertext transfer protocol/representation state transfer (HTTP/REST) through a cellular modem installed on the vehicle's network. The plugin on the vehicle is responsible for sending the remote server periodic status updates with regard to the vehicle's automation status, location, and speed, which will be used by the algorithms configured to run on the server itself. Once enabled by the user and after it has established communications with the remote server, the speed-harmonization plugin will insert a complex maneuver into the vehicle's motion profile that will allow it to execute the speed commands the server sends it. As the server is able to send speed commands at a variable rate the vehicle will maintain the last received speed command if one was sent or it will simply maintain the current speed of the vehicle until the first speed command is received.

Cooperative Merge

A cooperative-merge plugin for the vehicle was developed under Saxton Lab TO 26. This plugin enabled the vehicle to coordinate with an RSU deployed at the experimental merge area and with the experimental platoon vehicles. The cooperative-merge plugin listens for the periodic broadcasts from the RSU that announce its presence and availability, and upon approaching the ramp-metering point (where a traffic signal would normally be) it places itself under direct control of the RSU. This direct RSU control is accomplished via 10-hz messages from the RSU containing speed commands, which are used by the cooperative-merge complex maneuver to immediately control the vehicle. The RSU will command the vehicle to a stop at the merge point and hold it there until it determines that the rearmost vehicle of the approaching platoon is in such a position that the merge would be acceptable. At this point, the RSU commands the vehicle to accelerate to the speed of the platoon. Due to the way the vehicle's original equipment manufacturer ACC system functions when coming to a stop, it is necessary for the driver to apply a minimal amount of throttle and re-engage the ACC system to reauthorize automated control. When the merge is complete, the vehicle is released from RSU control and begins execution of the platooning plugin logic to join the platoon.

Cruising

The CARMA Platform uses a cruising plugin to fill any space in a motion profile that is not handled by another plugin. This process primarily occurs at the beginning of test runs in the experimental case, while the vehicles are traveling under automated control but have not passed the platoon-formation point yet. This cruising plugin attempts to smooth out any speed transitions between maneuvers planned by other plugins. Otherwise, if no maneuvers are planned, it defaults to travelling at the road's assigned speed limit (as defined by the route file currently in use). A configurable multiplier between 0 and 1 may be applied to this target-speed value if it is desirable to leave headroom above the vehicle's travel speed to allow the following vehicle to catch up or shorten their headway.

Speed-Harmonization Server

The speed-harmonization server is a cloud-based application responsible for communicating with the CARMA Platform vehicle(s) and providing speed commands for them to follow. The speed-harmonization server communicates with the vehicle through a shared set of messages exchanged in a HTTP/REST interface over cellular. To receive speed commands, vehicles first register their presence with the server via a request and then begin sending periodic data on their speed, location, and automation status back to the server. A user (or an automated script) may then create an experiment and mark any number of registered vehicles as participating in the experiment. This experiment assignment allows for simple collection and correlation of data to experimental runs when performing data analysis. A user (or an automated script) may then create and assign an algorithm to control each vehicle. This assignment causes the server to create an instance of the appropriate logical class in the server and to allow that code to control the remote vehicle, sending speed commands at whatever rate the algorithm deems necessary.

In the experimental testing, the speed-harmonization server was deployed with a new algorithm purposely built for this testing that would control the speed of all test vehicles other than those following a leader in a platoon. This algorithm used trajectory data output from the simulation task (either for the baseline or experimental case, as appropriate) and commanded the vehicle to replay the same trajectory. Upon receiving a status update from the vehicle, the algorithm compared it against the locations in the simulated trajectory and selected the point that most closely matched. This speed command is then sent back to the vehicle where it is executed.

RSU-Metering Application

The RSU-metering application was purpose-built under this TO to enable the merge vehicle to closely synchronize its merge with the passing platoon. This RSU-metering application runs on a stripped-down version of the CARMA Platform (containing only the DSRC driver, message processor, and a new RSU-metering component) on a Linux PC deployed alongside the RSU on a trailer in the field. This application continuously broadcasts requests (in the form of mobility messages) to begin metering while waiting for a response from the merge vehicle. Upon the merge vehicle's response (acknowledging intent to allow RSU control), the RSU-metering application sends (via mobility messages) commands to the merge vehicle to stop and hold at the configured metering point, a digital analogue for where the traffic light might be in a more traditional ramp-metering scenario. Once the vehicle is brought to a stop, the RSU-metering application begins listening for status mobility messages from an approaching platoon. Once the platoon is discovered, the RSU-metering application computes the location of the rearmost vehicle of that platoon and begins to continuously calculate how long it would take the merge vehicle to reach the end of the merge area compared to how long it would take the rearmost vehicle of the platoon to reach that location. When the timing for both vehicles would allow the merge vehicle to join at a safe distance behind the rearmost platoon vehicle, the RSU-metering application commands the merge vehicle to accelerate to the platoon speed. The command is continuously updated until the merge vehicle reaches a predefined merge point. Once the merge vehicle completes its acceleration and reaches the merge point, it is released from RSU metering control and allowed to engage in platooning operations.

DATA AND RESULTS

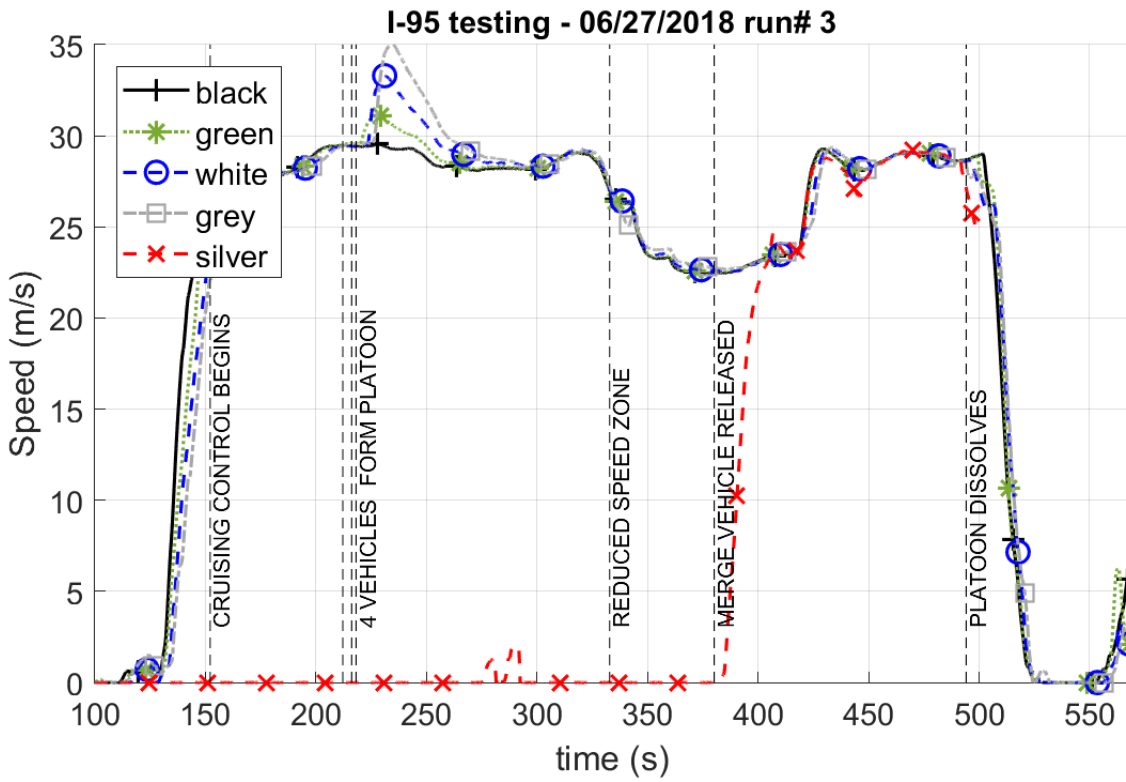
Data were recorded from the vehicles and infrastructure for analysis. Key parameters include the vehicle's location, speed, speed command, acceleration, and distance to preceding vehicle as well as a common time base.

Automated Case

In the automated case, vehicles respond automatically to attributes of the route, such as speed limit and applicable control algorithms. The route dictates the effective entry point into the managed-lane section, at which point the four vehicles form a platoon. The lead vehicle uses commands issued by the speed-harmonization server and slows around the merge area. The merge vehicle is released automatically and joins the platoon.

Data from two key runs are plotted in figure 16 through figure 21, one from a run on the closed road and one from a run in light traffic. The vehicles are tracked according to their color as shown in the legend of each plot.

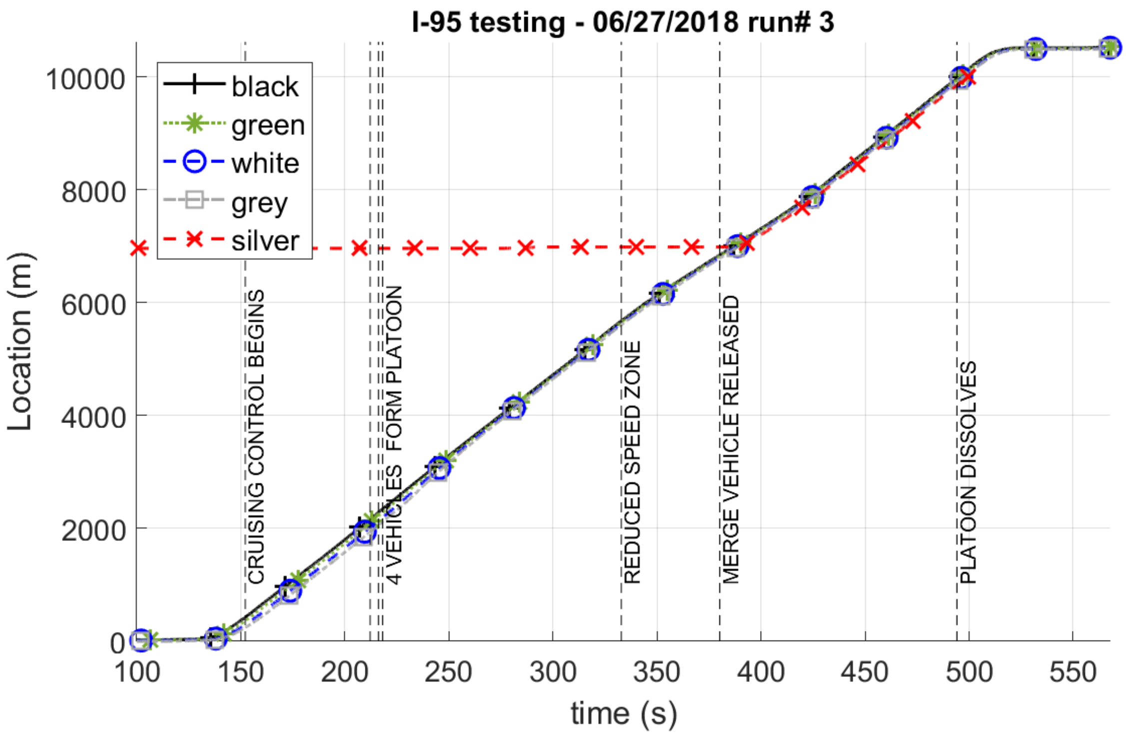
Figure 16 shows vehicle speed during a typical automated run in closed conditions. The vehicles are listed in the legend according to their order in the platoon and the color of the vehicle. The vehicles leave the staging area together under manual control. The line labeled, "Cruising Control Begins," indicates the point at which the automated system took over (about 150 s). During that time, the vehicles followed the speed limit associated with that point on the route. As the vehicles crossed the virtual entrance to the managed lane (about 215 s), the platoon began to form. The four lines labeled, "4 VEHICLES FORM PLATOON," indicate the time at which each vehicle crossed this virtual entrance and began the search for a platoon to join. At this point, vehicle speeds spiked as the following vehicles closed the gaps in the platoon. Vehicle speeds eventually stabilized as the vehicles within the platoon approached the programmed headway, though some variations in speed occurred primarily due to the terrain. Prior to the merge point (about 275 s), the merge vehicle activated and approached the holding point under RSU control. As the four-vehicle platoon approached the merge area, speed-harmonization algorithms slowed the speed of the platoon. The line labeled, "REDUCED SPEED ZONE," indicates the time at which the reduced speeds went into effect. The RSU detected the approaching platoon and sent a command to the merge vehicle to release it from its holding point. The line labeled, "MERGE VEHICLE RELEASED," indicates the time at which the merge vehicle began to accelerate toward the mainline. In this case, the speed overshot slightly as the merge vehicle aligned itself with the rear of the platoon. With the merge vehicle in place and at speed, a five-vehicle platoon formed. The platoon traveled an additional distance until it dissolved, beginning with the rear vehicle, and the experiment ended.



Source: FHWA.

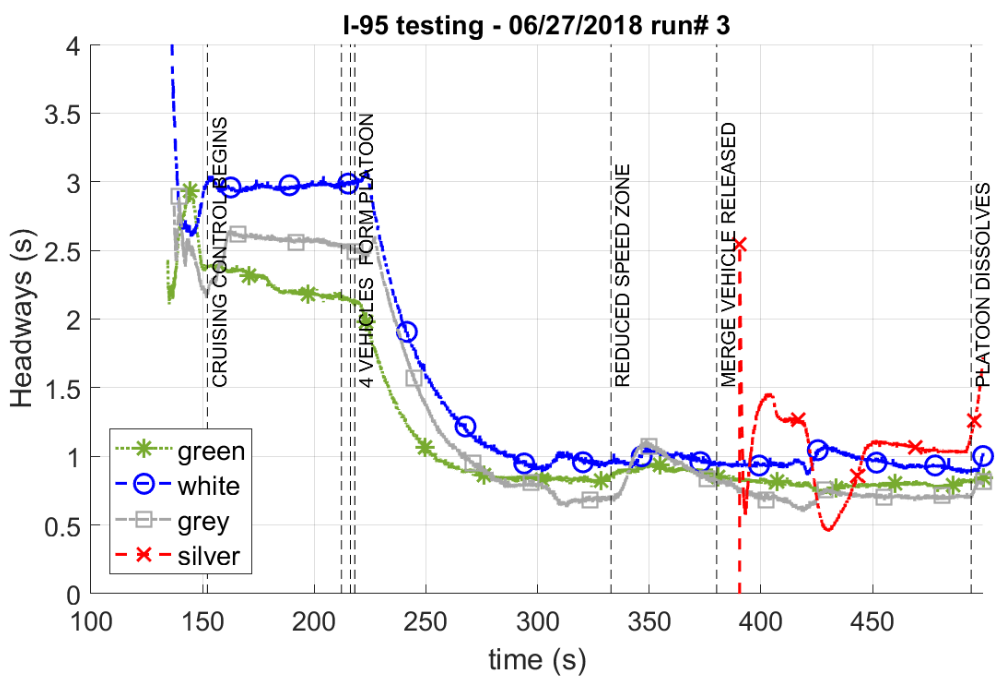
Figure 16. Graph. Vehicle speeds during a typical automated experiment in closed conditions.

Figure 17 shows the trajectories of the five vehicles involved in the experiment. The spread in vehicle positions narrows following the four lines labeled, “4 VEHICLES FORM PLATOON.” The merge-vehicle position is constant at about 7 km downstream from the staging area. When the four-vehicle platoon reached that point, the merge-vehicle position changed such that it followed and joined the platoon. Figure 18 shows each vehicle’s headway and spacing relative to its preceding vehicle for the same run. The platoon formation and merge event are analyzed further in the upcoming sections, Platooning Analysis and Merging Analysis.



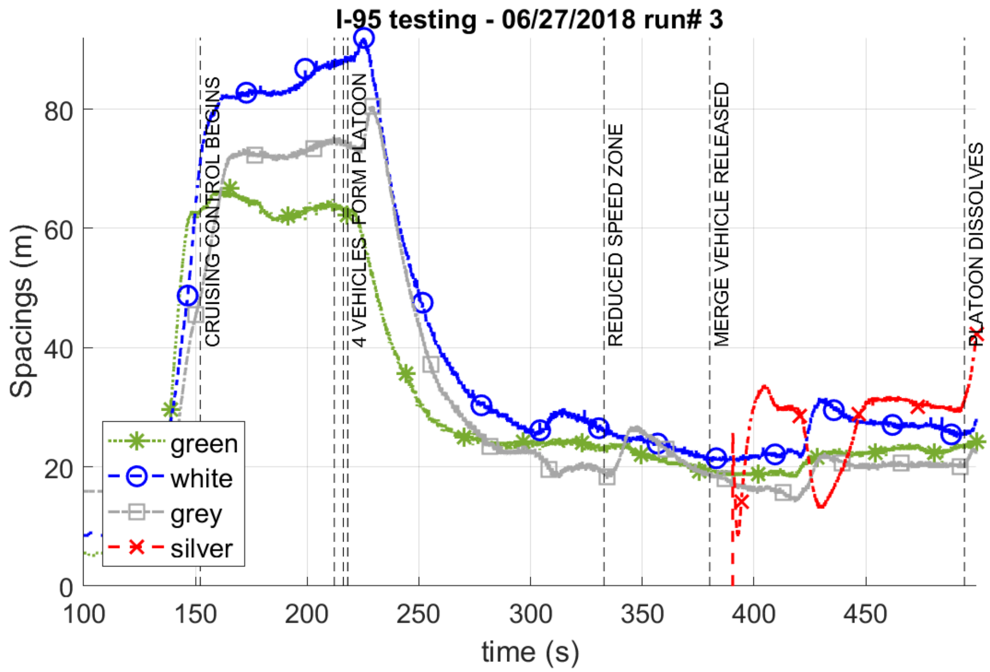
Source: FHWA.

Figure 17. Graph. Vehicle trajectories during a typical automated experiment in closed conditions.



Source: FHWA.

A. Vehicle headway.

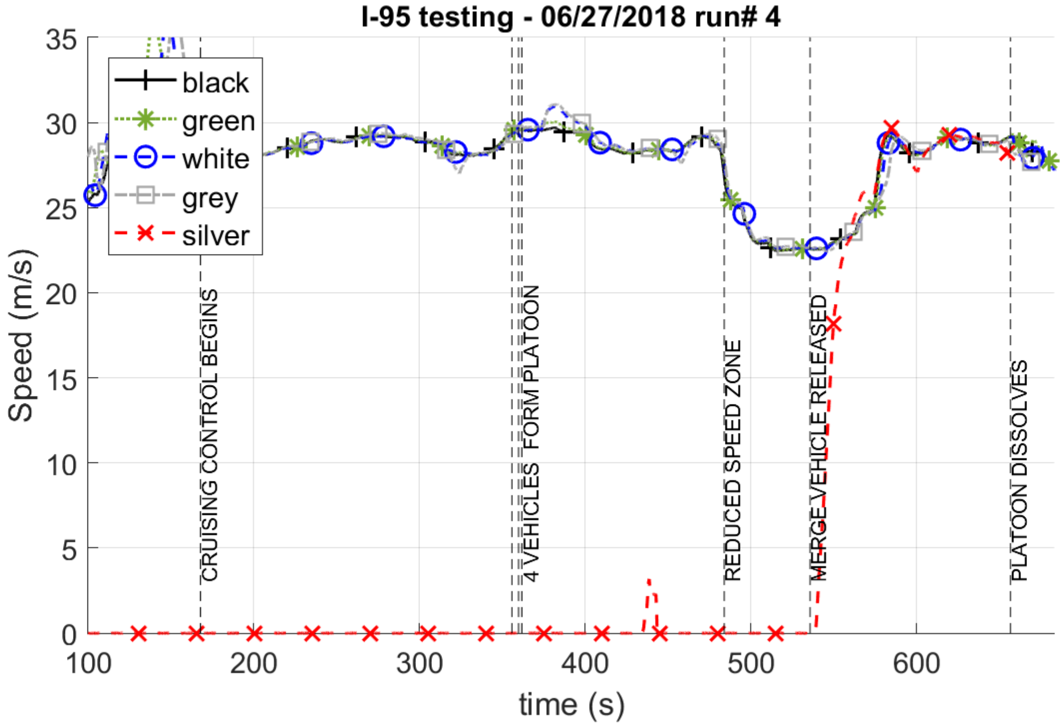


Source: FHWA.

B. Vehicle spacing.

Figure 18. Graphs. Vehicle headway and spacing during the initial platoon formation.

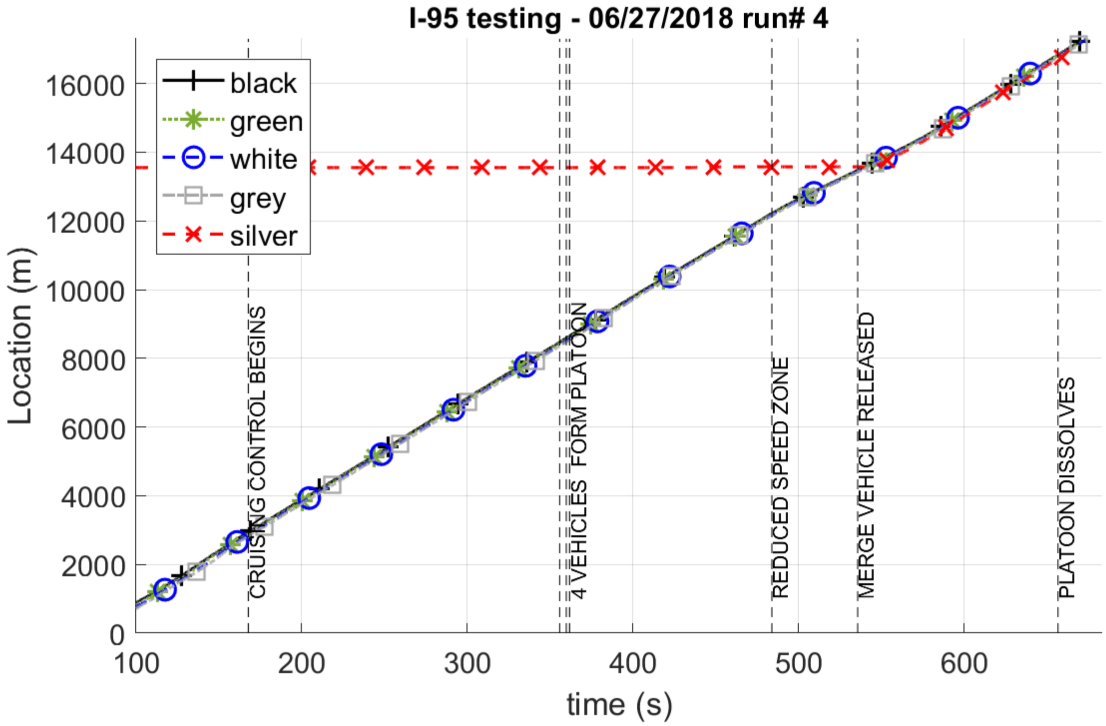
Figure 19 shows the vehicle speeds during a typical light-traffic run. In terms of the experiment itself, the run in light traffic is very similar to the run in closed conditions. The major differences occur before and after the experiment. In the case of the light-traffic runs, the four vehicles departed from the staging area and merged into live traffic, positioning themselves in the left lane and then engaging the system. The light-traffic run proceeded just as the run in closed conditions. At the end, the vehicles disengaged quicker and maintained their speed until exiting the test site.



Source: FHWA.

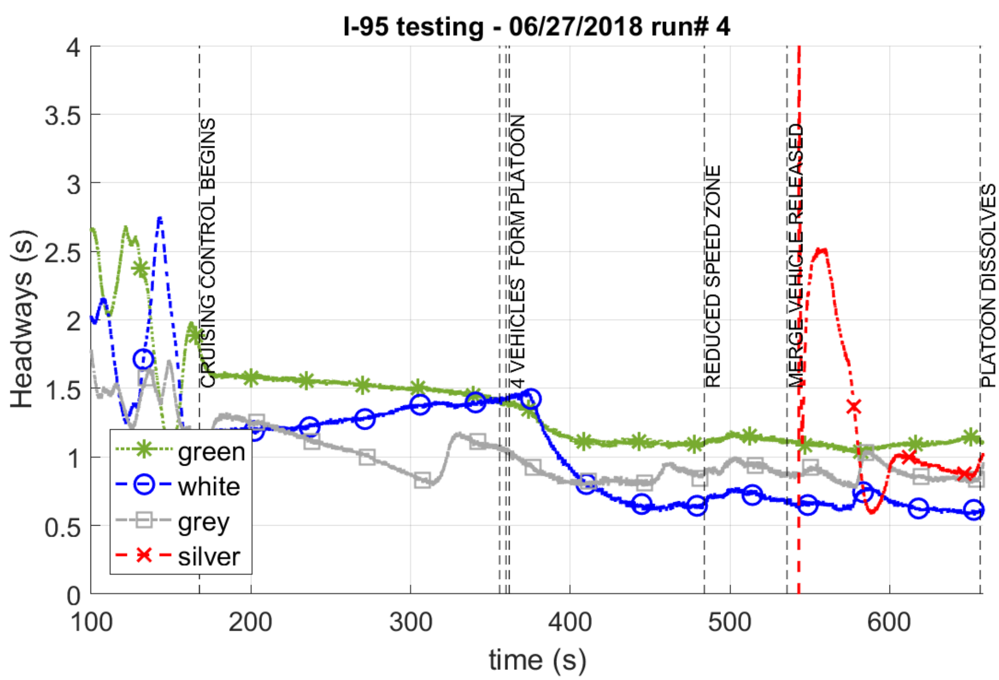
Figure 19. Graph. Vehicle speeds during a typical automated experiment in light traffic.

Figure 20 shows the trajectories of the five vehicles involved in a typical run in light traffic. The plot is similar to the run in closed conditions but covers a longer distance. Figure 21 illustrates vehicle headway and spacing during the initial platoon formation.



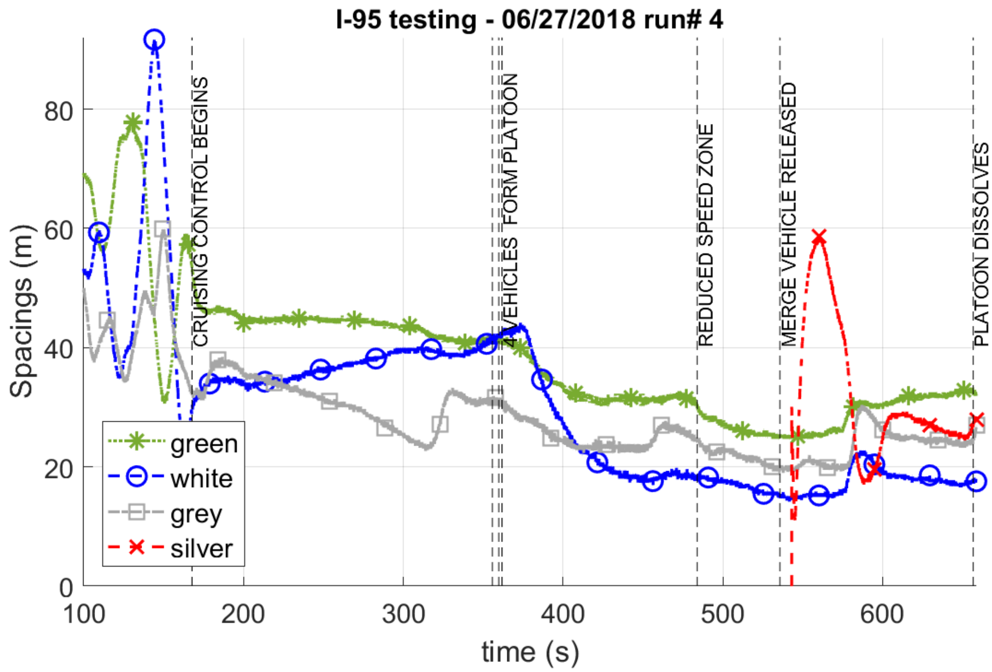
Source: FHWA.

Figure 20. Graph. Vehicle trajectories during a typical automated experiment in light traffic.



Source: FHWA.

A. Vehicle headway.



Source: FHWA.

B. Vehicle spacing.

Figure 21. Graphs. Vehicle headway and spacing during the initial platoon formation.

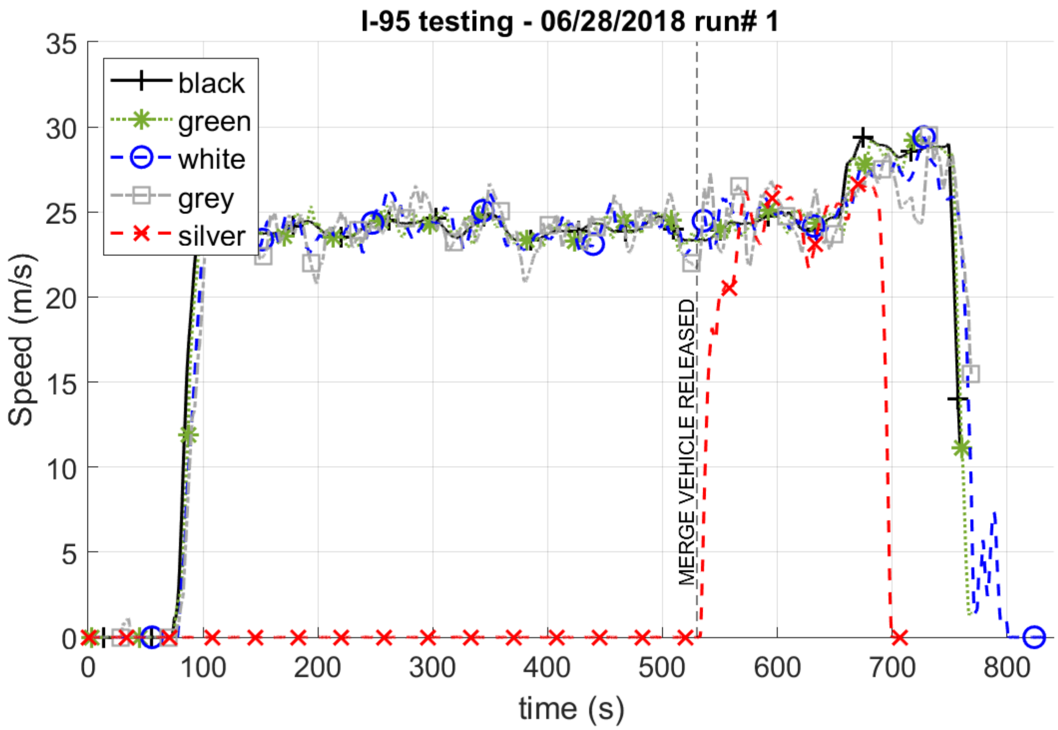
Manual (Base) Case

In the manual case, the lead vehicle follows a predetermined trajectory, and following-vehicle drivers regulate their own speeds to maintain a specified gap. The target gap for each following-vehicle driver was selected to represent a range of following distances used by most drivers. The time gap was based on data from a previous study by California PATH, which gave preferred following distances for 16 drivers. (Liu et al. 2017) These distances were condensed to four values for this experiment: 0.8, 1.4, 1.4, and 1.8 s. It is difficult for a driver to maintain an exact time gap without overapplying brake and throttle, which can lead to unnatural driving behavior. To make driving behavior more natural, drivers were instructed to be “aggressive,” “normal,” or “conservative.”

The merge vehicle was released manually based on the position of the platoon. When the platoon passed a predetermined point ahead of the merge area, the driver of the lead vehicle informed the merge vehicle by radio, and the merge vehicle started accelerating down the on-ramp. This method of merging is meant to approximate a more traditional ramp meter. Just as in a normal nonautomated driving environment, acceleration is not constant, and the alignment of the vehicles is not perfect.

Data from two key runs are plotted in figure 22 through figure 27; in one run, the vehicles maintained the speed limit, and in the other, the vehicles followed slower speed-harmonization commands in the merge area.

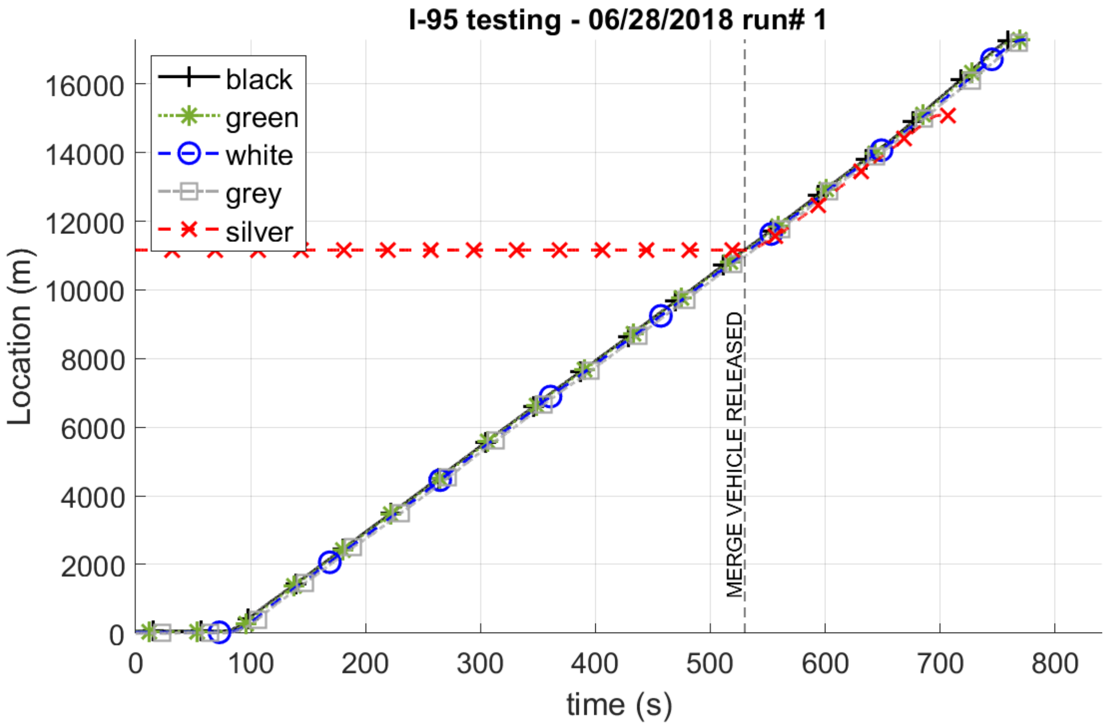
Figure 22 shows the speed profiles of the five vehicles during a constant-speed manual run. The vehicles are listed in the legend according to their order in the platoon and the color of the vehicle. In this case, four vehicles left the staging area together under manual control. The automated system took control of the lead vehicle, and the following vehicles remained under manual control. The four vehicles continued in this configuration to the end of the experiment. When the merge vehicle was released, the driver manually accelerated and merged into the mainline to join the four-vehicle platoon as it passed. Speed variations of plus or minus 4 m/s can be seen in all vehicles throughout the experiment.



Source: FHWA.

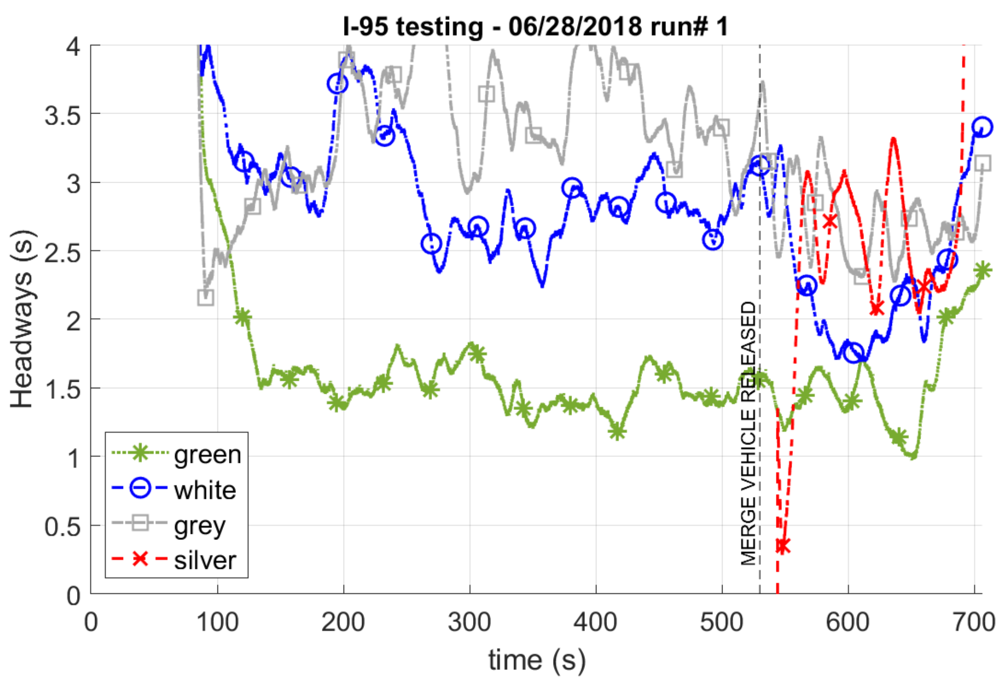
Figure 22. Graph. Vehicle speeds during a constant-speed manual experiment in closed conditions.

Figure 23 shows the trajectories of the five vehicles involved in the experiment. Since the vehicles were manually driven, no platoon formed, and the spacing remained relatively large and varied throughout the experiment. This difference can be seen more clearly in figure 24, which shows each vehicle's headway and spacing relative to its preceding vehicle.



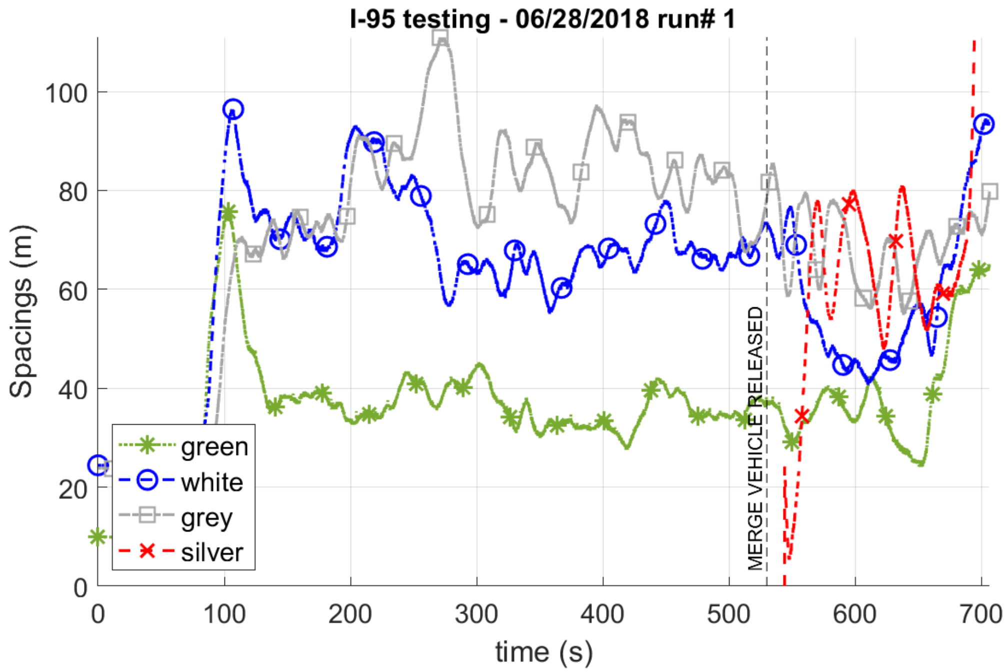
Source: FHWA.

Figure 23. Graph. Vehicle trajectories during a constant-speed manual experiment in closed conditions.



Source: FHWA.

A. Vehicle headway.

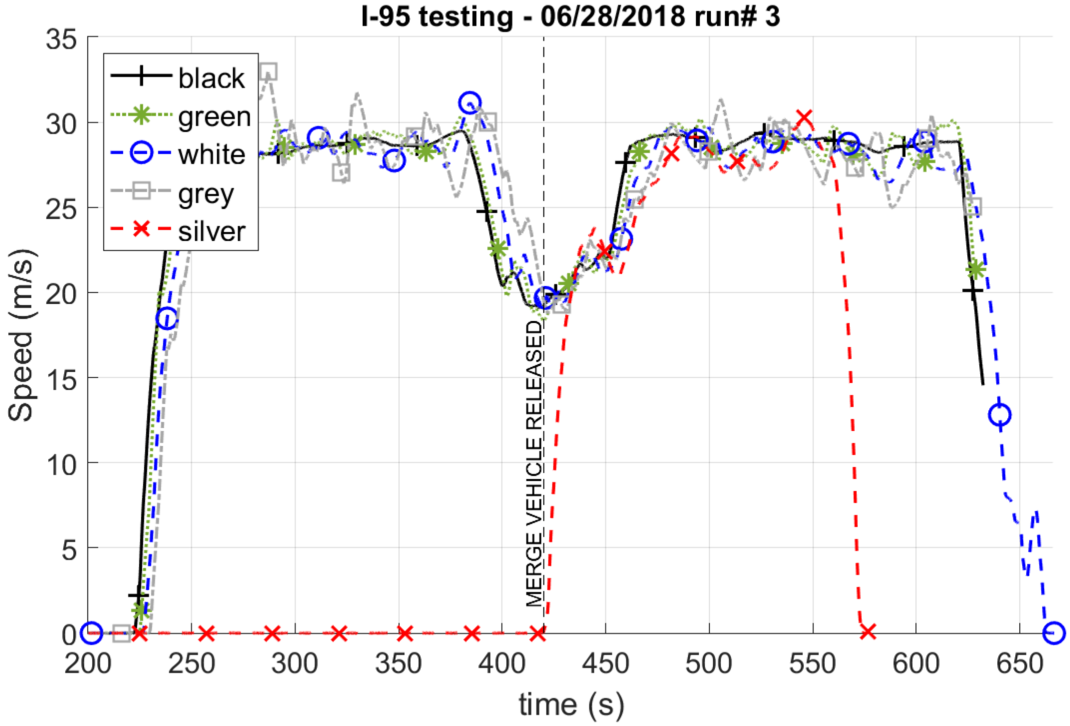


Source: FHWA.

B. Vehicle spacing.

Figure 24. Graphs. Vehicle headway and spacing during a constant-speed manual run.

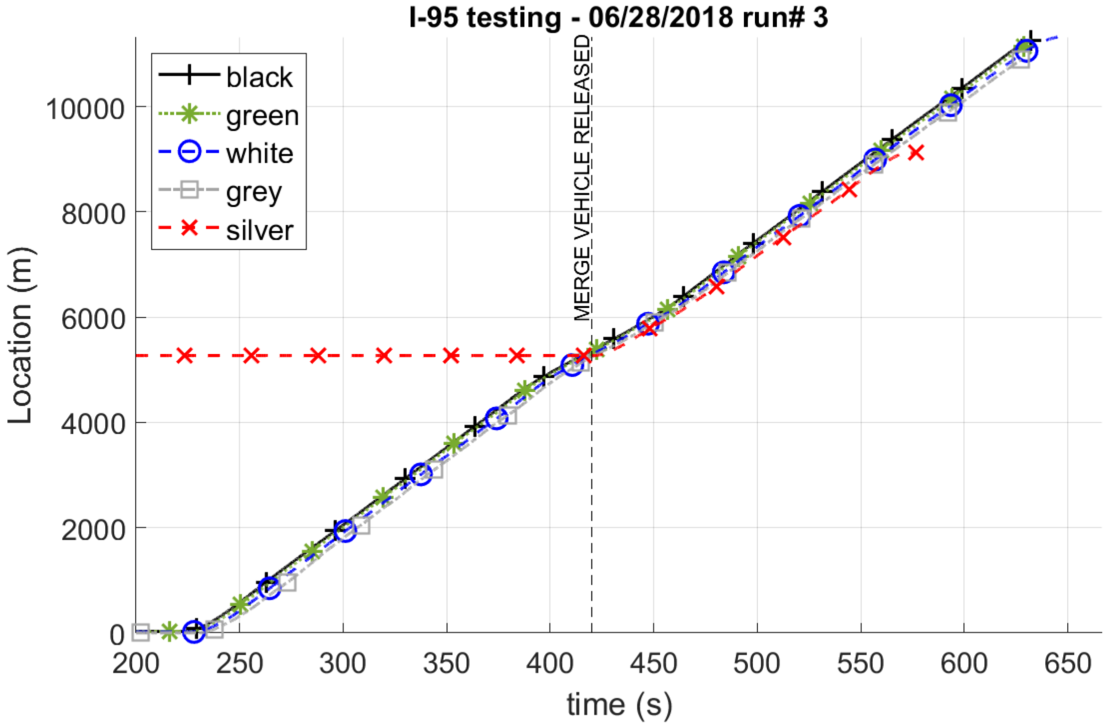
Figure 25 shows the vehicle speeds during a manual run in which the lead vehicle slowed in the merge area. In this case, the lead vehicle followed a pregenerated set of speed commands based on the output of the traffic simulation discussed in chapter 3. As in the constant-speed case, the manually driven vehicles had rather large fluctuations in speed throughout the experiment.



Source: FHWA.

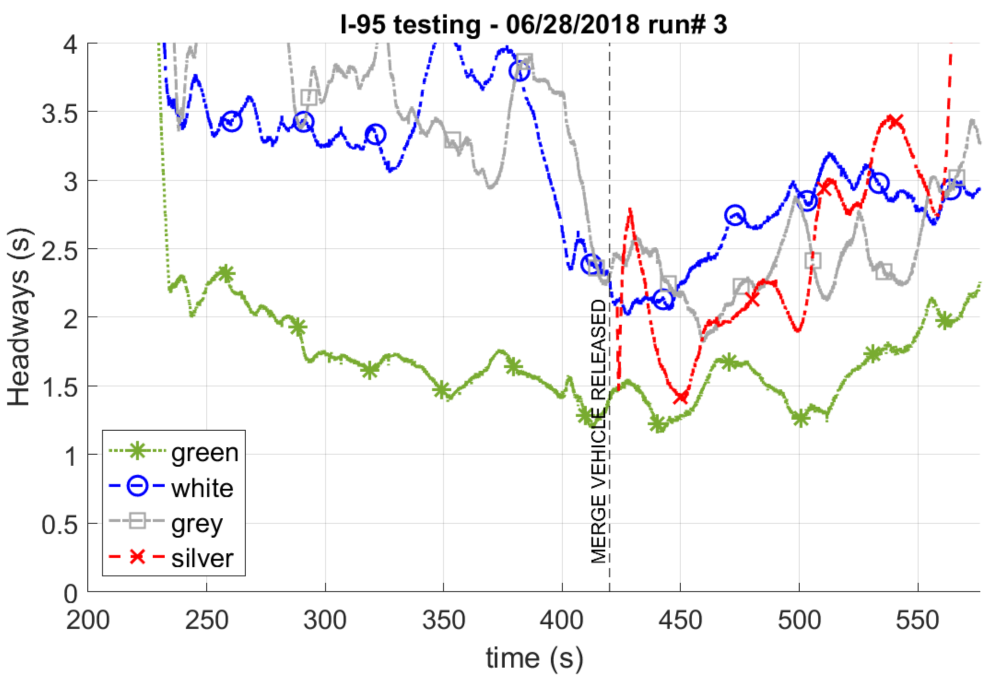
Figure 25. Graph. Vehicle speeds during a typical manual experiment in closed conditions.

Figure 26 shows the vehicle trajectories for the manual run. It can be seen around the merge point (about 420 s), as the vehicles slowed down, that the vehicle spacing slightly reduced. But as speeds increased, the spacing also increased. This phenomenon is more clearly shown in figure 27.



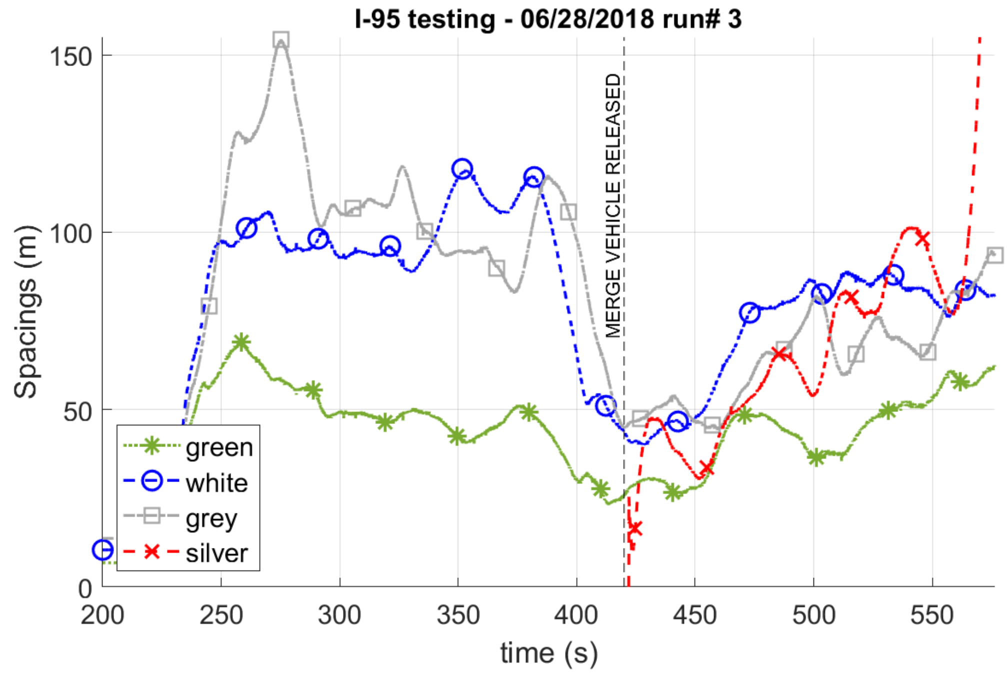
Source: FHWA.

Figure 26. Graph. Vehicle trajectories during a typical manual experiment in closed conditions.



Source: FHWA.

A. Vehicle headway.



Source: FHWA.

B. Vehicle spacing.

Figure 27. Graphs. Vehicle headway and spacing during a typical manual run.

Comparison and Analysis

Platooning Analysis

According to the experiment observations, when a group of vehicles attempts to form a platoon, a safe level of space to the preceding vehicles must be reached, and thus, each vehicle needs to adjust its speed and spacing in coordination with other vehicles in the group. These adjustments impose some fluctuations in vehicle speed, headway, and spacing profiles target spacing, or headway is reached with relatively small fluctuations. In this section, the period required for the vehicles to adjust their spacings and headways, denoted by T^P, is analyzed. A set of criteria is defined to quantify the stable platoon and measure the adjustment period.

These criteria basically investigate two factors:

- Analyzing vehicle gaps to see if the vehicles are sufficiently close to each other.
- Investigating the stability of vehicle maneuvers.

These analyses were conducted on the vehicles' spacing and headway profiles. Since the spacing and headway profiles obtained from the field measurements were quite noisy, these profiles were smoothed using a moving-average method before applying the criteria. Let M denote the moving-average parameter such that each spacing (or headway) value in the smooth profiles is an average of the current value and the spacings (or headways) from the previous $M – 1$ time points.

Two criteria are considered in defining a stable platoon. First, in for vehicles to be considered a platoon, the vehicles need to be sufficiently close to each other. Per this criterion, the maximum absolute difference between the spacing and headway values should be less than the corresponding predetermined threshold parameters, denoted by Φ^s and Φ^h, respectively.

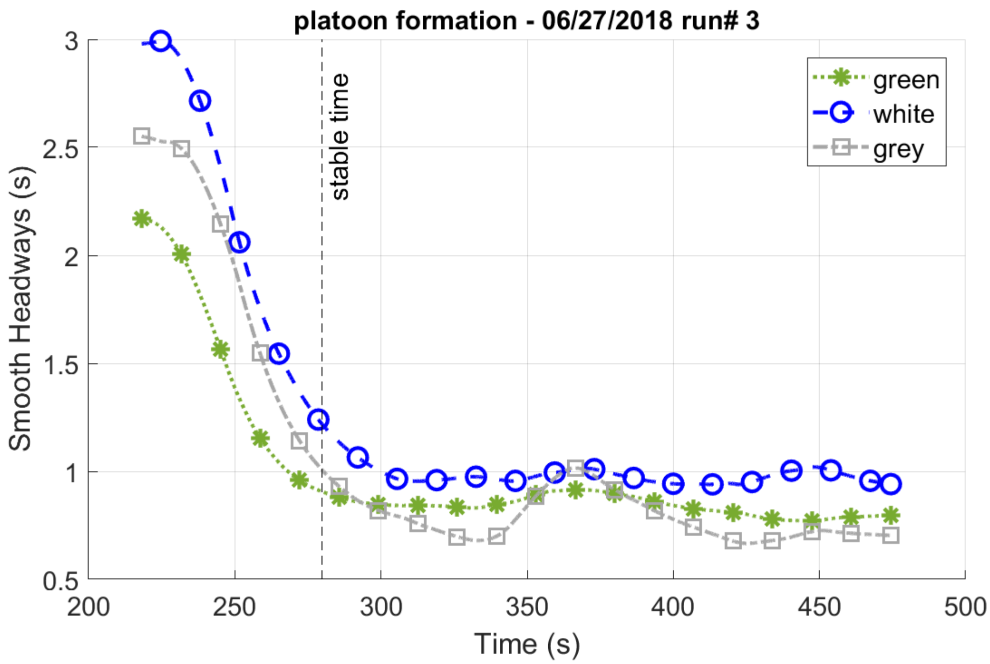
The second criterion requires the oscillations in spacing and headway profiles to be dampened. This criterion focuses on the rates of change of spacing and headway values and states the maximum absolute-spacing and headway-rate values should be less than the corresponding predetermined threshold parameters, denoted by φ^s and φ^h, respectively.

A stable platoon status should meet four requirements (i.e., the first criterion on spacing, the first criterion on headway, the second criterion on spacing, and the second criterion on headway). With that, "stable time" is defined as the time at which all these requirements are met. Then, T^P is determined by calculating the difference between stable time and the start time of platoon formation (that is obtained from the vehicles' log files). The parameters for this analysis are defined in table 15.

Table 15. Platooning analysis parameters.

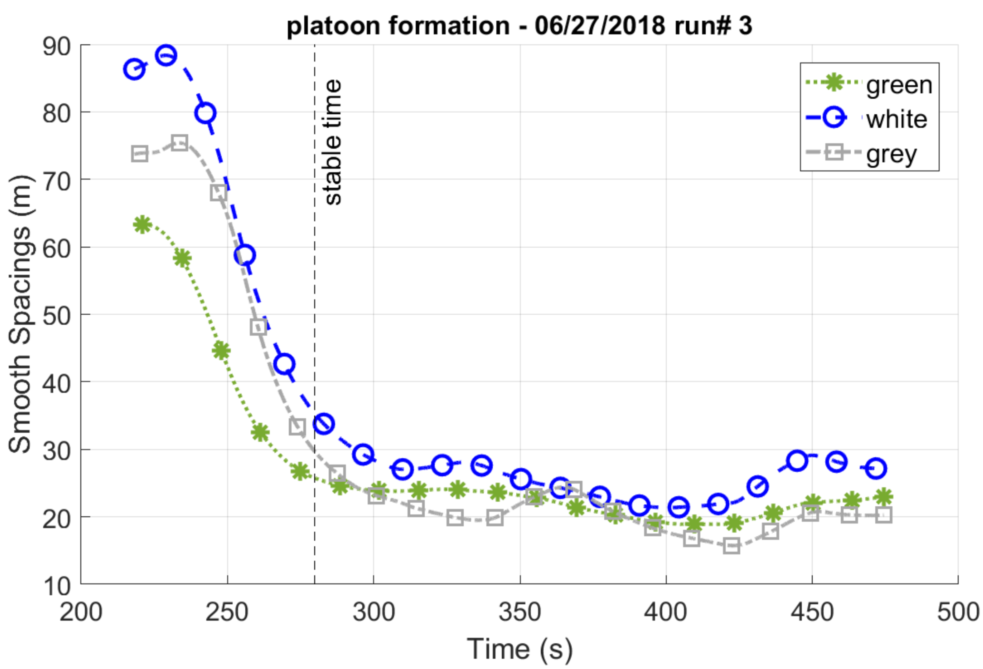
Parameter	Value	Unit
M	500	samples
Φ^s	10	meters
Φ^h	0.4	seconds
φ^s	0.5	meters per second
φ^h	0.015	seconds per second

For this analysis, four experiment runs containing reliable data were identified. With the assumed parameters, the results show an average value of 64 s for T^P. Note that this outcome is sensitive to the assumed parameters. In other words, there is not a universal set of characteristics that can be used to define stable time, which depends on the Φ^s, Φ^h, φ^s, and φ^h parameters. However, the general concepts of the defined criteria are extensible to any other experimental settings. Figure 28 and figure 29 show the platooning-analysis results for two experiment runs with obtained stable-time values. In these plots, the vehicle orders are shown in the legends.



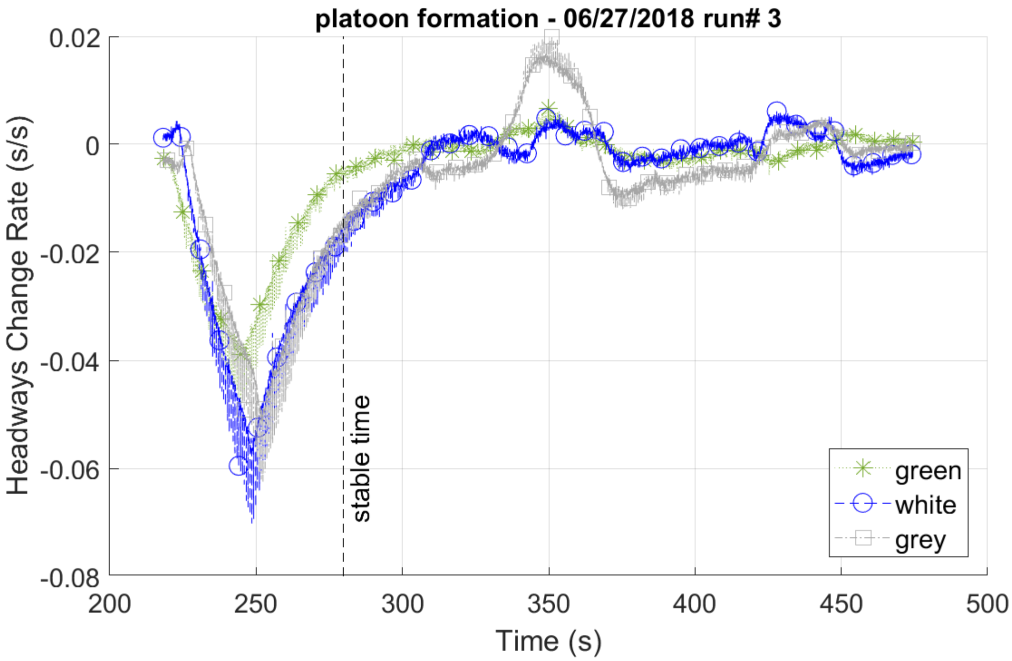
Source: FHWA.

A. Smooth headways.



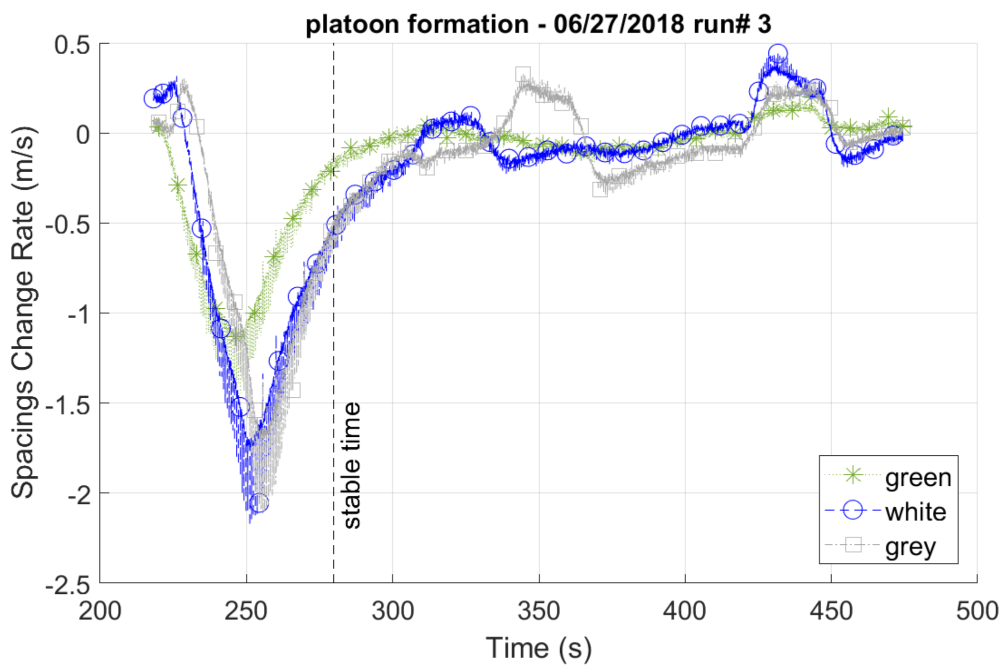
Source: FHWA.

B. Smooth spacings.



Source: FHWA.

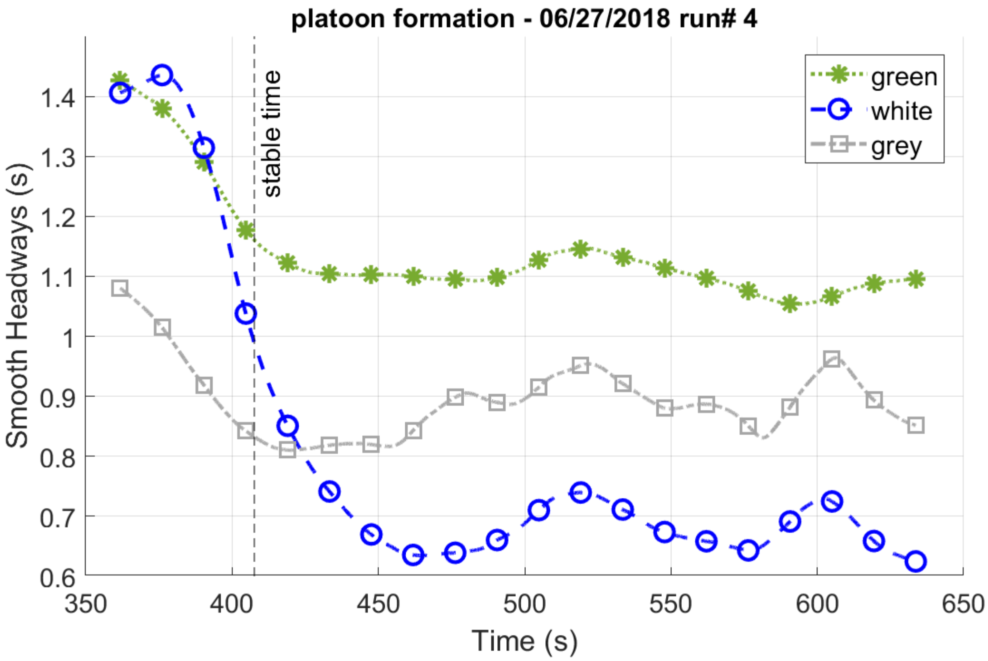
C. Headway rate of change.



Source: FHWA.

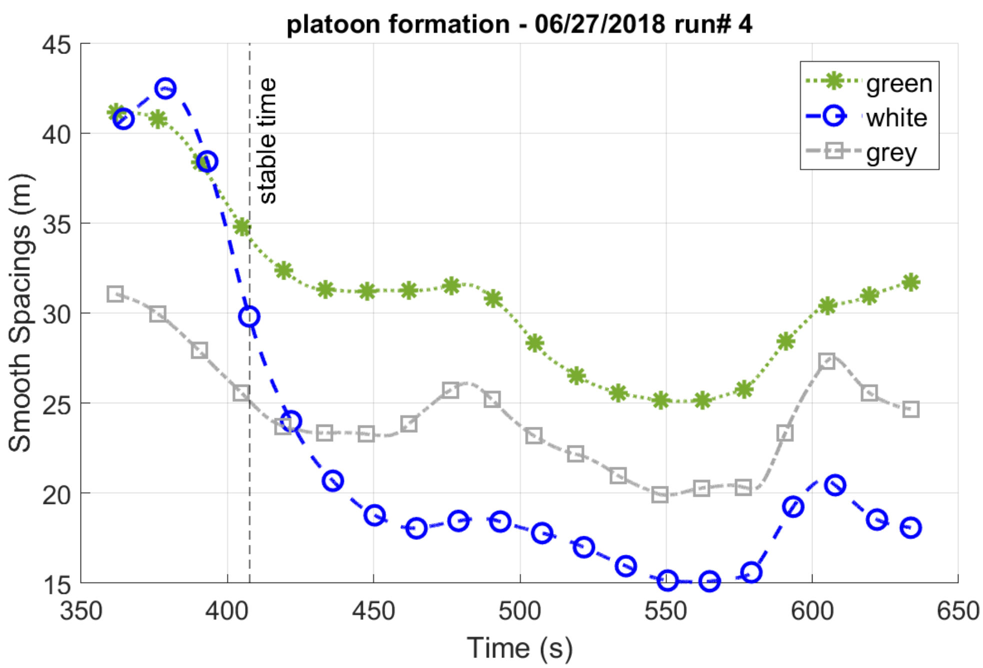
D. Spacing rate of change.

Figure 28. Graphs. Headway and spacing characteristics during the initial platoon formation.



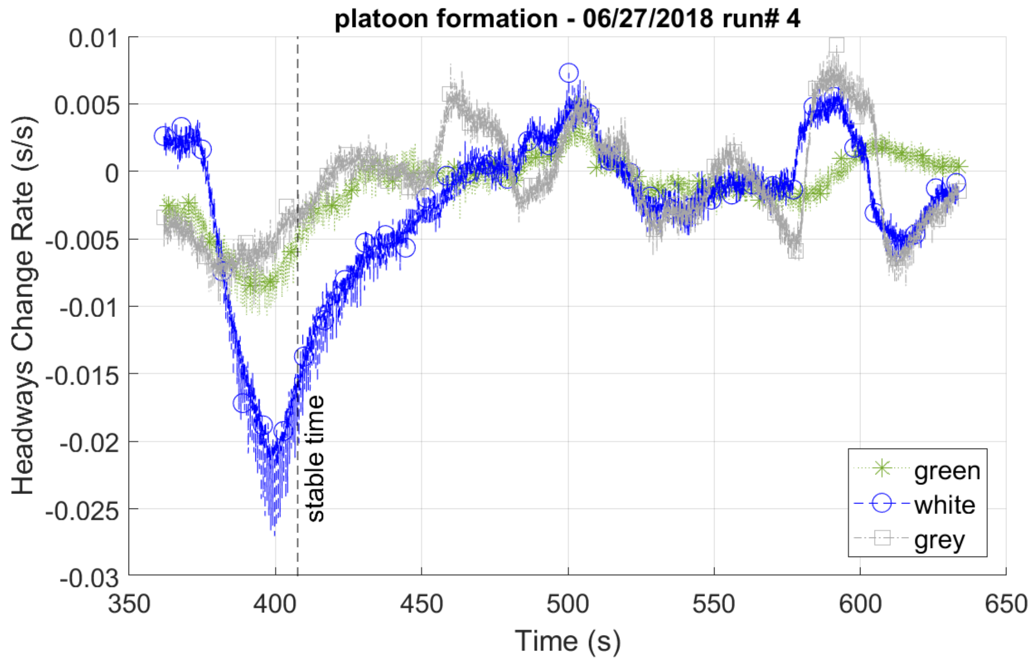
Source: FHWA.

A. Smooth headways.



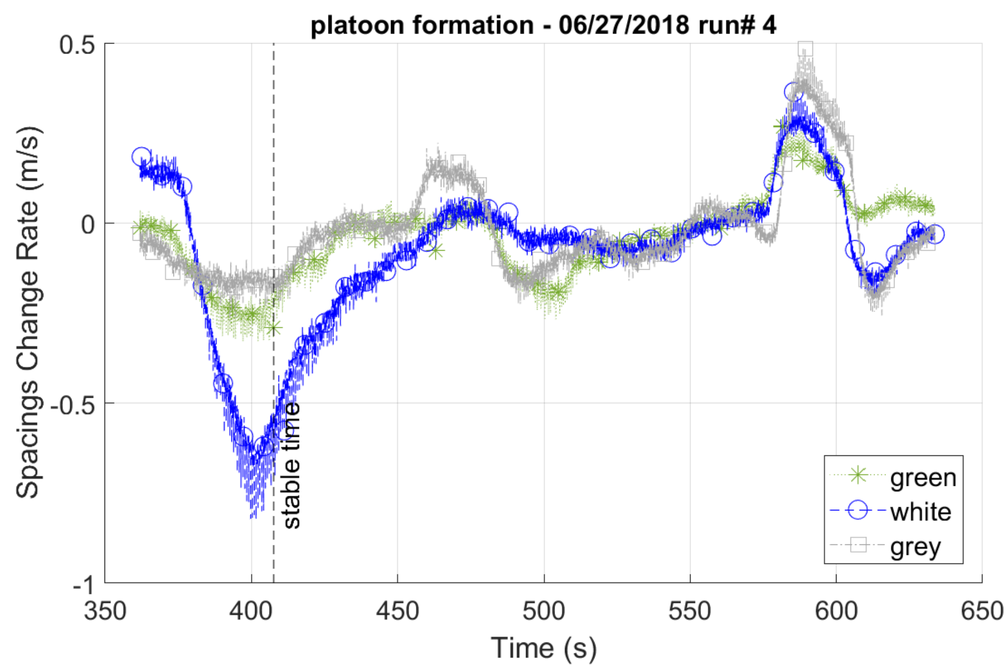
Source: FHWA.

B. Smooth spacings.



Source: FHWA.

C. Headway rate of change.



Source: FHWA.

D. Spacing rate of change.

Figure 29. Graphs. Headway and spacing characteristics during the initial platoon formation.

Merging Analysis

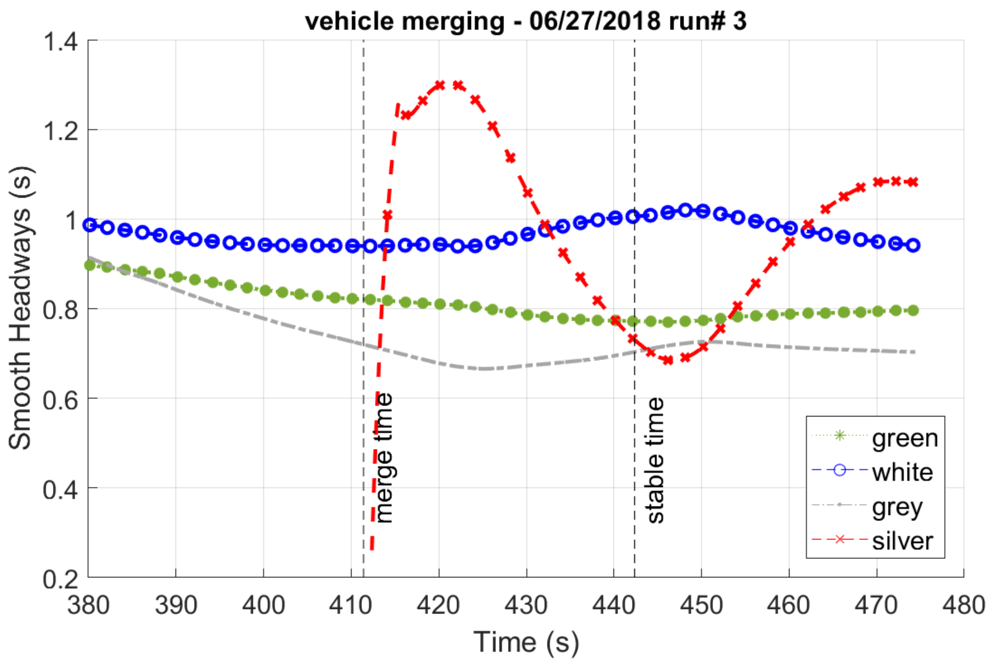
Merging maneuvers are another important component of the experiments conducted in this study. Such maneuvers consist of three periods. In the first period, the merge vehicle accelerates to catch up to the tail of platoon. When the merge vehicle reaches the end of the platoon (the beginning of the second period), the platoon size increases by one, and the last vehicle in the platoon starts adjusting its speed and spacing to balance the following distances according to the target values. In this period, the spacing and headway of the last vehicle may fluctuate until they reach the stable levels. Finally, in the last period, the platoon proceeds in a stable state until the end of the experiment. In this analysis, the start time of the second and the third periods are estimated using the following analysis procedures.

The analyses in this section have also been conducted on spacing and headway profiles. Again, since the profiles obtained from the field measurements are noisy, these profiles are smoothed using a moving-average method with parameter M.

To estimate the arrival time of the merge vehicle to the tail of the platoon, it is assumed the merge vehicle reaches a speed equal to or greater than that of the platoon. With this assumption, the spacing and headway of the merge vehicle decrease during the first defined step. When the merge vehicle becomes sufficiently close to the platoon tail, the spacing and headway adjustments (the second step) begin, and as a result, these values start fluctuating rather than strictly decreasing. With that being said, "merge time" is defined as the maximum time corresponding to first local minima of the smooth spacing and headway profiles of the merge vehicle (or when their rates of change reach positive values). Then, the time needed for the vehicle to merge into the platoon, denoted by T^m, is determined by calculating the difference between merge time and release time of the vehicle, which is obtained from the vehicle's log file.

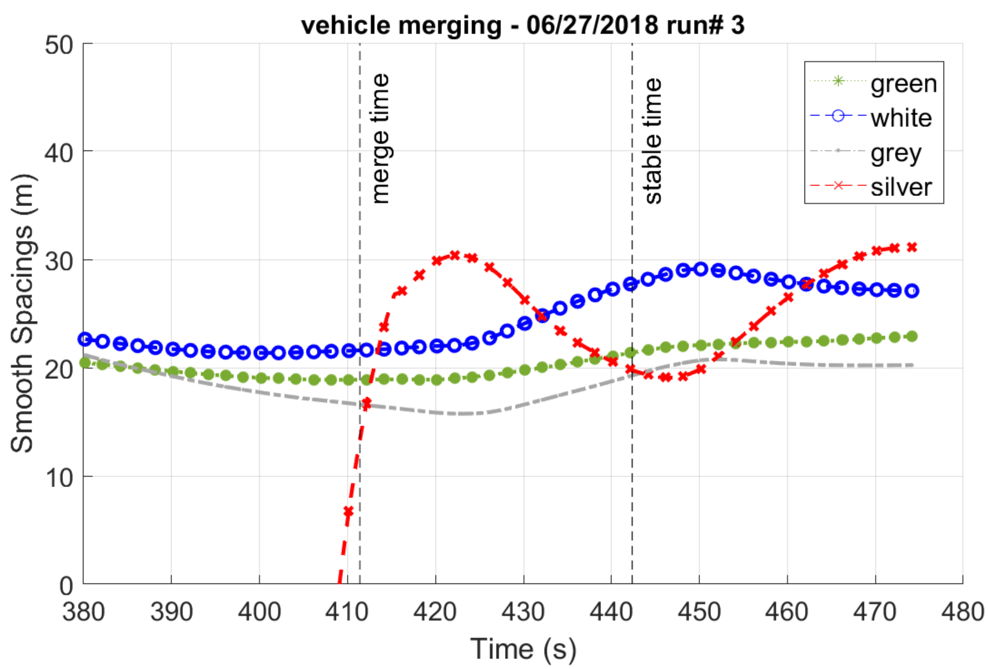
To estimate the start of the third step, a process similar to that described in the platooning analysis section is implemented to identify the time when the merge-vehicle headway becomes stable. In this analysis, the same criteria defined in the platooning-analysis section is used with the same parameter set (i.e., Φ^s, Φ^h, φ^s, and φ^h). Again, all four requirements (i.e., the first criterion on spacing, the first criterion on headway, the second criterion on spacing, and the second criterion on headway) should be met. The parameters are also set to the same values shown in table 7.

The same four experiment runs used in the platooning-analysis section are used for this analysis. With the assumed parameters, the results show average values of 35 and 64 s for T^m and T^P, respectively. The average T^P value obtained in this analysis is perfectly consistent with the platooning analysis results. Again, note that these outcomes are sensitive to the experimental settings. More specifically, T^m depends on the on-ramp length, location of the merge-vehicle staging area, and speed of platoon at the merge area. Further, T^P depends on the definition of the stable platoon (i.e., the Φ^s, Φ^h, φ^s, and φ^h). Despite this dependence, the general concepts of the defined requirements may be valid and extensible to any other experimental settings. Figure 30 and figure 31 show the merging-analysis results for two experiment runs with the obtained values for merge time and stable time. In these plots, the vehicle orders are shown in the legends.



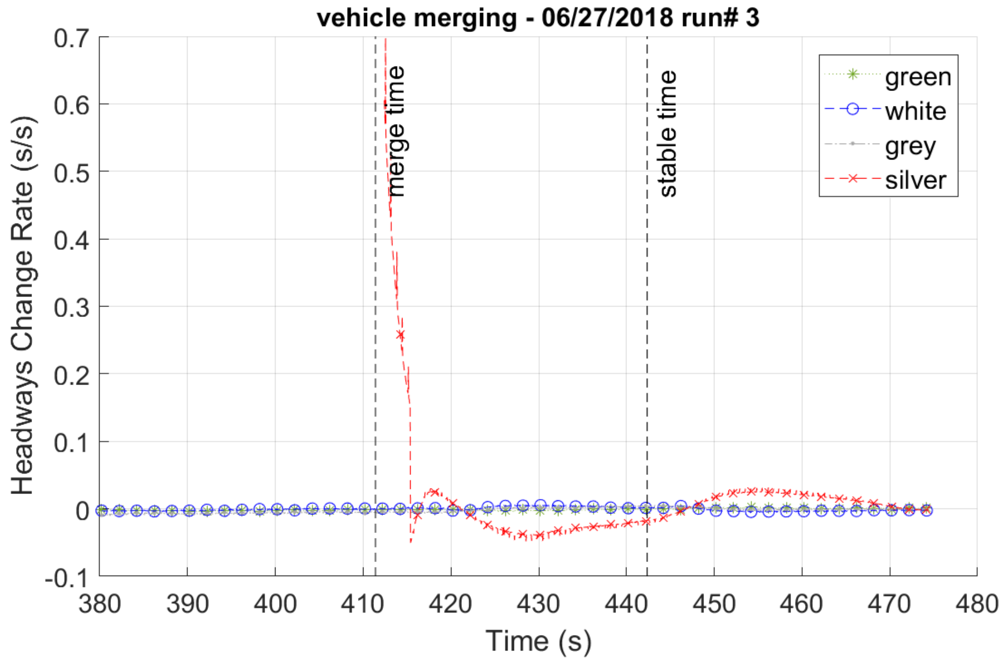
Source: FHWA.

A. Smooth headways.



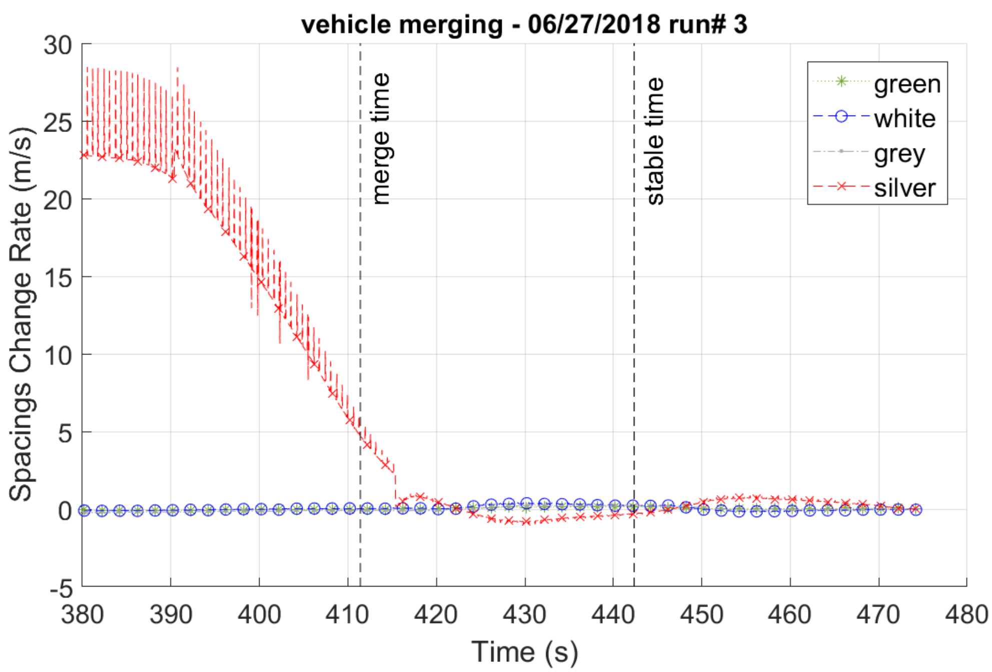
Source: FHWA.

B. Smooth spacings.



Source: FHWA.

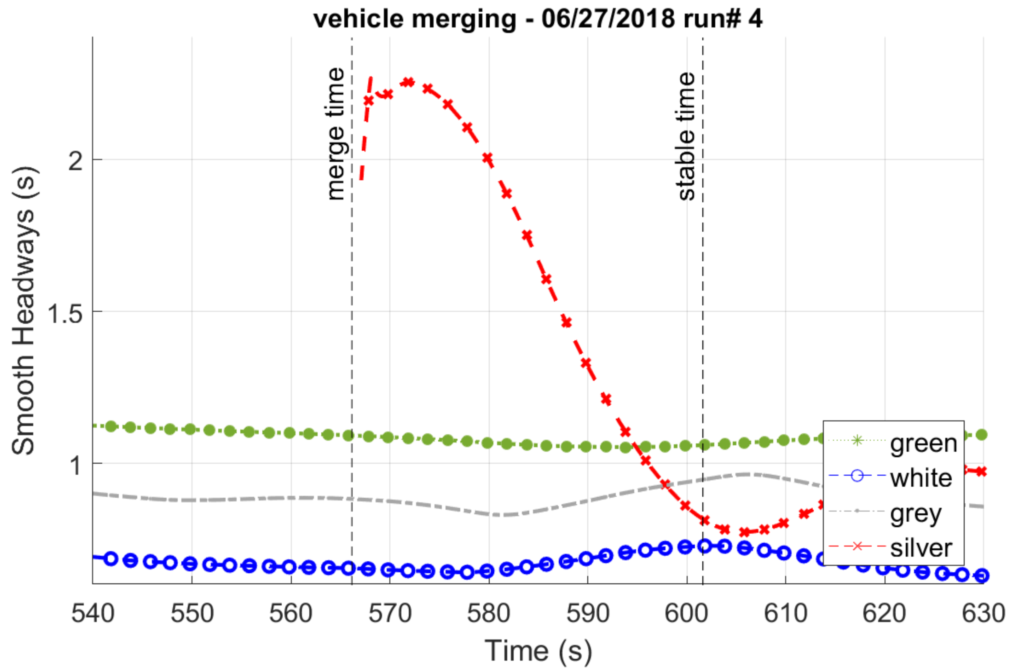
C. Headway rate of change.



Source: FHWA.

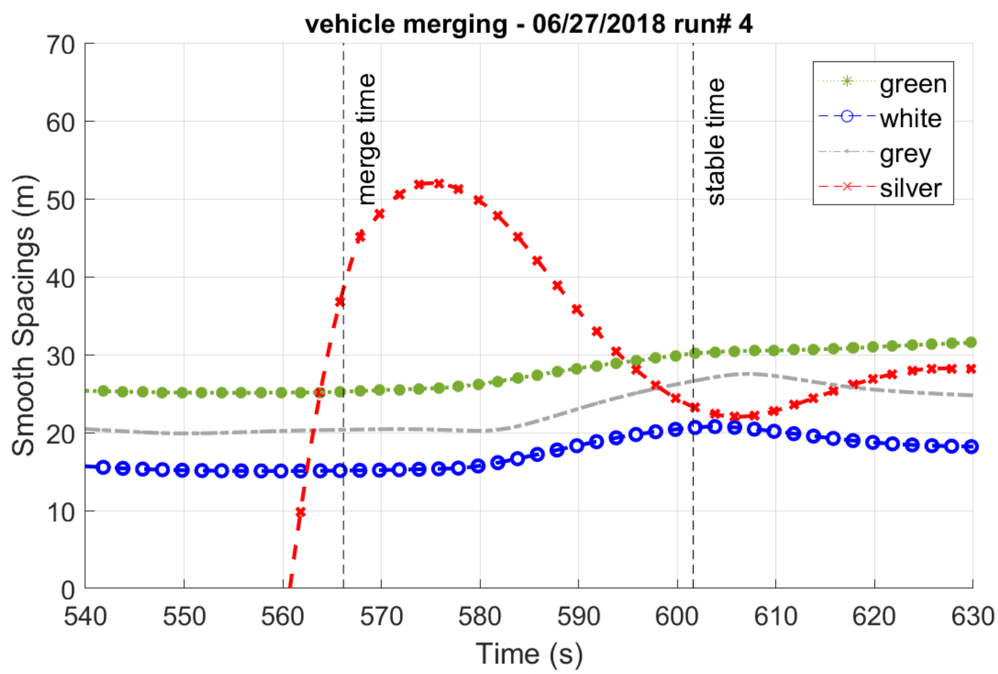
D. Spacing rate of change.

Figure 30. Graphs. Headway and spacing characteristics during a typical cooperative-merge event.



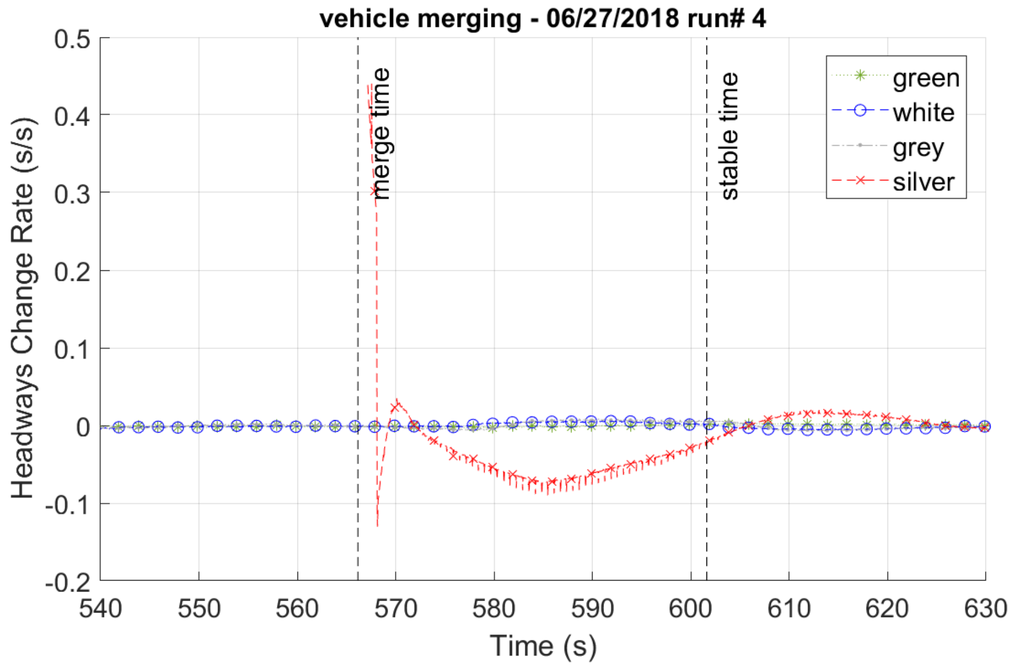
Source: FHWA.

A. Smooth headways.



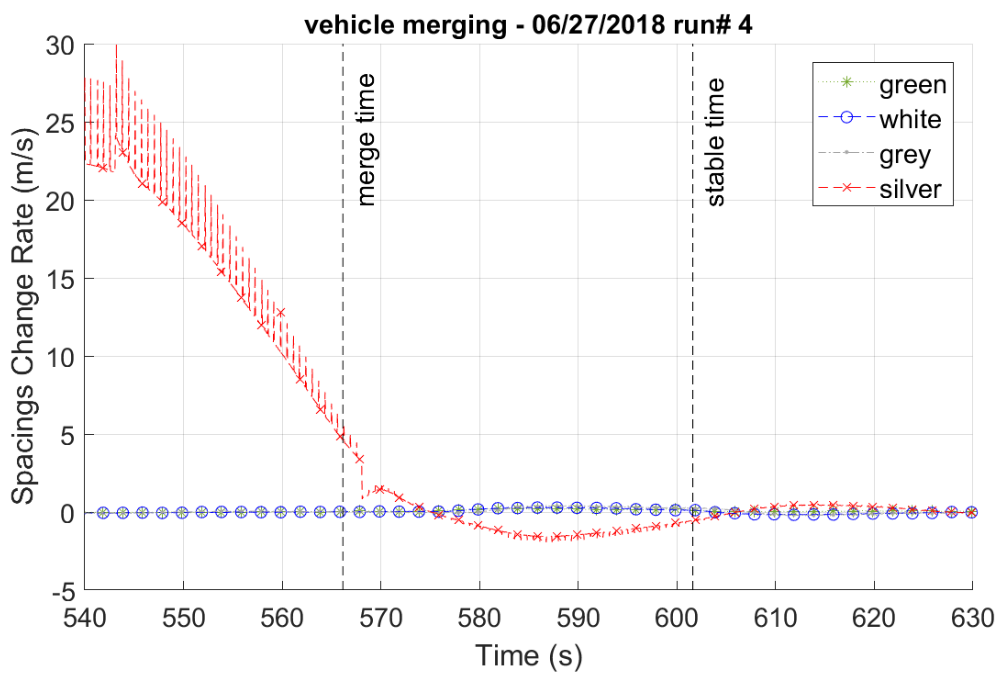
Source: FHWA.

B. Smooth spacings.



Source: FHWA.

C. Headway rate of change.

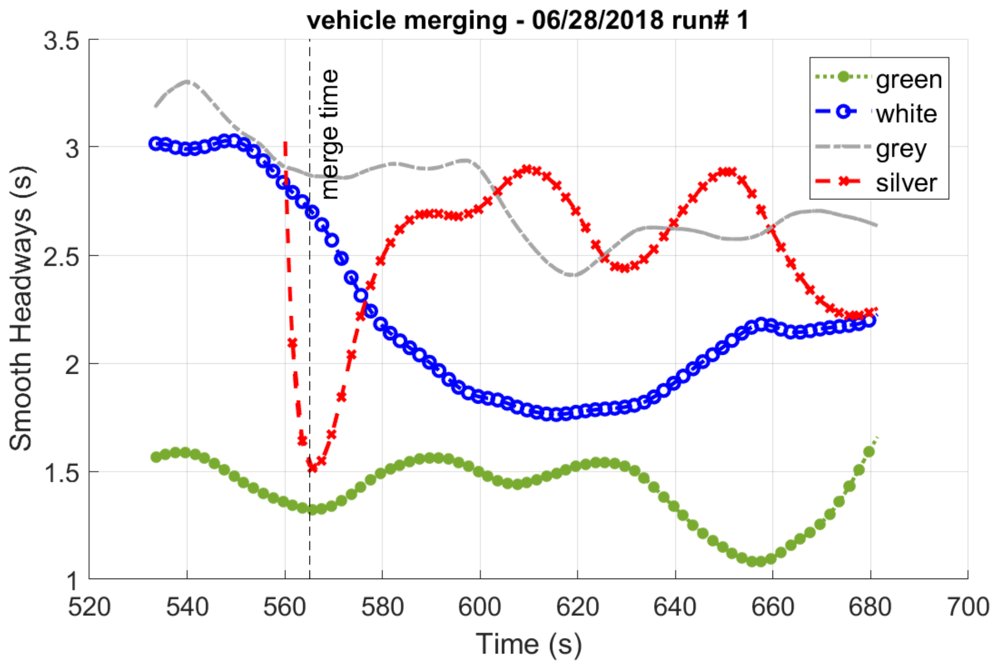


Source: FHWA.

D. Spacing rate of change.

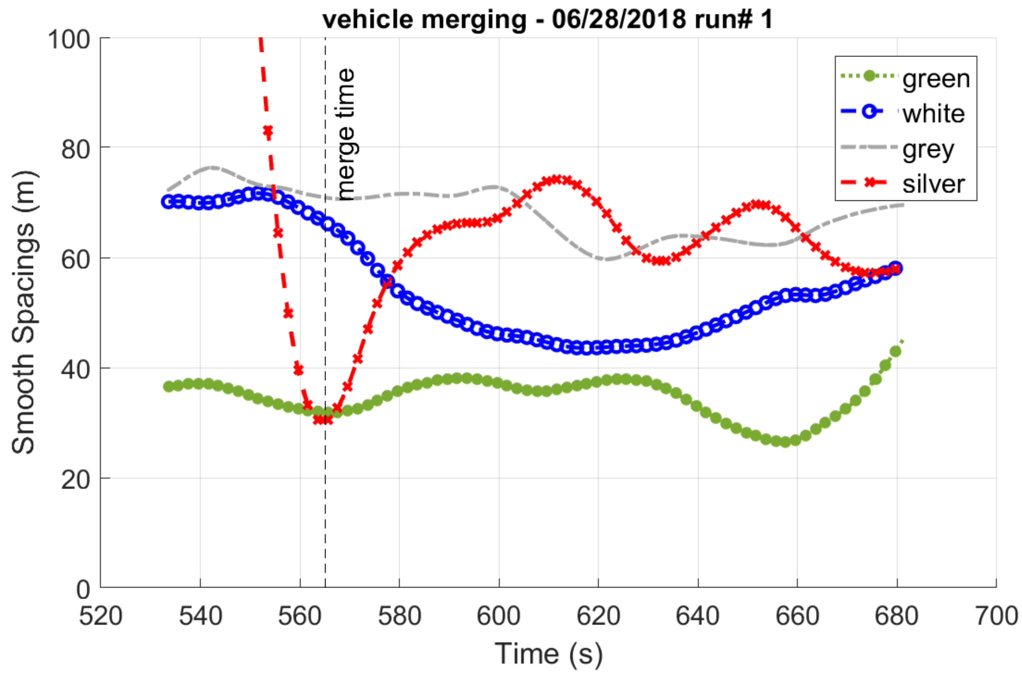
Figure 31. Graphs. Headway and spacing characteristics during a typical cooperative-merge event.

The same merging analysis is also performed on two manual experiment runs. In the manual runs, neither of the two defined criteria are met during the experiments, and thus, stable time is not reported. That lack of reporting results because the spacing and headway oscillations in these runs are significantly greater than in the automated runs, and thus, the manual runs cannot satisfy the criteria according to the defined parameter set shown in table 15. With the assumed parameters, the results show an average value of 36 s for T^m. This result shows no significant difference between the T^m values of the automated and manual runs. That similarity is probably because this time depends so heavily on the geometrical features of the experiment (e.g., the on-ramp length and location of the merge-vehicle staging area) and the speed of platoon at the merge area, which are common in both automated and manual experiment runs. The acceleration of the merge vehicle is also similar in both cases since, in the automated case, it was selected for driver comfort, and in the manual case, the driver accelerated at a comfortable rate. Figure 32 shows the merging analysis results for a typical manual run with the obtained merge-time values.



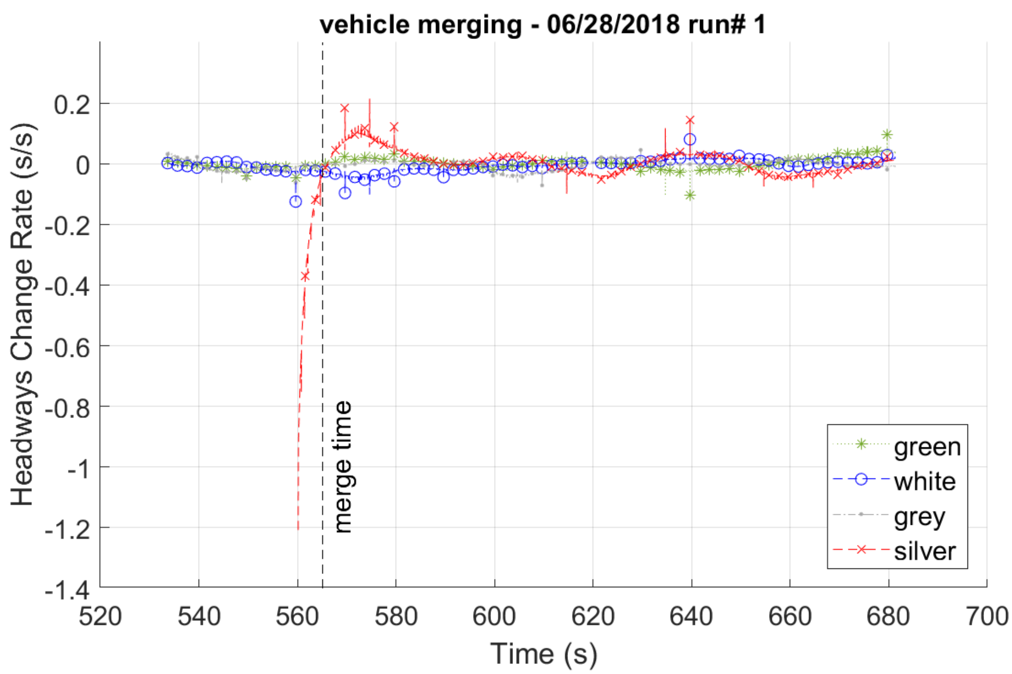
Source: FHWA.

A. Smooth headways.



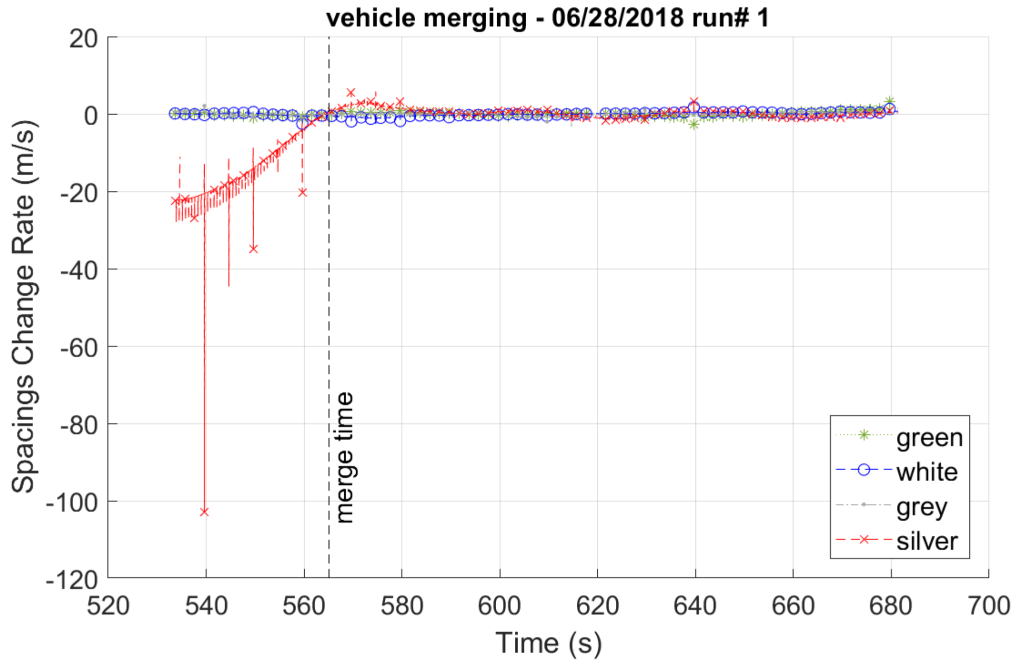
Source: FHWA.

B. Smooth spacings.



Source: FHWA.

C. Headway rate of change.



Source: FHWA.

D. Spacing rate of change.

Figure 32. Graphs. Headway and spacing characteristics during a typical manual merge event.

SIMULATION MODELING AND TESTING

The CAV application has great potential to enhance traffic-system performance, particularly when applied to managed-lane facilities during the early stages of deployment. (Liu et al. 2017) The research team is particularly interested in how string performance will be translated into traffic improvement. Therefore, in this section, CAV car-following behavior is analyzed using the experimental data. A simplified vehicle-controller model is used to represent CAV behavior, similar to Milanés and Shladover, 2014 and Ma et al., 2018.

The CACC simulation model forms are discussed in chapter 3, where equation 13 through equation 17 are discussed in detail. Basically, these models consider two modes of CAV operations: gap and speed regulation. If a CAV is following a vehicle, the ACC controller is used to determine the car-following rule according to the clearance distance between the subject vehicle and the preceding vehicle. If the distance is larger than a maximum threshold (e.g., 300 m), then the preceding vehicle is beyond the range of V2V communication and the onboard sensors' detection, so the ACC controller will apply the speed-regulation mode shown in equation 13.

$$a_{sv} = k_1(v_f - v_{sv}) \tag{13}$$

Where k_1 is 0.457 s^{-1} based on data collected in this study.

Two consecutive CACC-vehicle strings or vehicles within a CACC-vehicle string should keep a consistent time gap to maintain stable traffic flow and facilitate lane-change maneuvers when necessary (e.g., at off-ramps). When the time gap between the subject vehicle and preceding vehicle is more than 2 s, the subject vehicle will switch to the speed-regulation mode, which is represented by equation 13. If the time gap is less than 2 s and the subject vehicle wants to join the preceding CACC-vehicle string (dependent on factors, such as whether the preceding CACC-vehicle string is operating at the maximum allowable string length), the subject vehicle will use the string-leader gap-regulation mode. This mode is expressed by equation 14 and equation 15. Equation 14 is dependent on equation 16 and equation 17.

$$v_{sv}(t) = v_{sv}(t - \Delta t) + k_p e_k(t) + k_d \dot{e}_k(t) \tag{14}$$

$$a_{sv}(t) = (v_{sv}(t) - v_{sv}(t - \Delta t))/\Delta t \tag{15}$$

Where k_p is 0.00756 s^{-1} and k_d is 0.278 based on data collected in this study.

$$e_k(t) = D(t - \Delta t) - t_1 v_{sv}(t - \Delta t) - L \tag{16}$$

$$\dot{e}_k(t) = v_l(t - \Delta t) - v_{sv}(t - \Delta t) - t_1 a_{sv}(t - \Delta t) \tag{17}$$

Where t_1 is the constant time gap between the subject vehicle and the preceding CACC vehicle (0.84 s is the desired headway in this study).

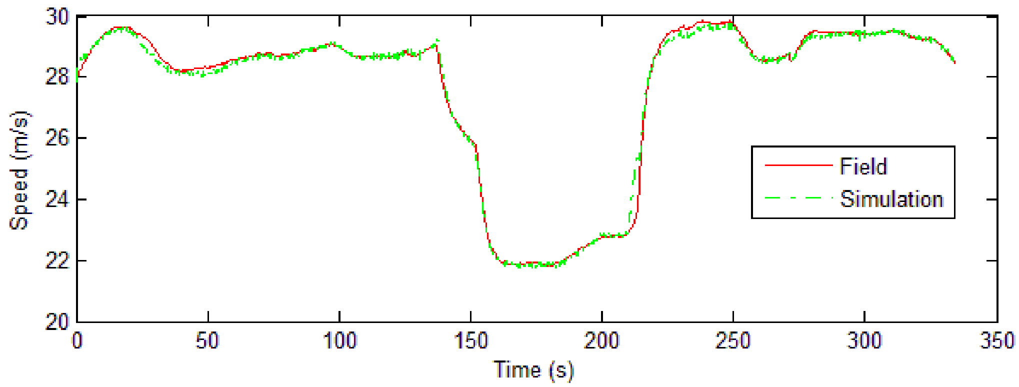
Although one study has calibrated equation 13 through equation 15, the results only apply to specific vehicle models and control platforms. (Milanés and Shladover 2014) Therefore, this dataset collected in the experiment is used to recalibrate the simulation models to reflect a newer vehicle model and control platform. The new vehicle model contains the latest communication and sensing technologies as of 2018 and will serve as the foundation for other simulation studies. The model calibration is to select the gains that can minimize the squared speed differences between the real and simulated vehicles, as shown in equation 18. The optimization covers the uses of the data for all vehicles from different runs of the experiments. The optimization problem is highly nonlinear and has an embedded simulation process. Therefore, the research team uses a genetic algorithm and run a large number of generations to obtain the optimum. The solution is k_1 is 0.457 s^{-1}, k_p is 0.00756 s^{-1}, and k_d is 0.278. The result of these gains is interesting as compared with k_p equal to 0.45 s^{-1} and k_d equal to 0.25. (Milanés and Shladover 2014) The small gain in k_p implies that the research team's controller is less sensitive to e_k, and the slightly larger gain in k_d means that the research team's controller is more responsive to the speed error. This responsiveness is partly due to the fact that the CACC algorithm implemented in this study purposely buffers the headway change when there is a small oscillation (to avoid additional oscillations) before the subject vehicle in the string. While it is impossible to use a large number of vehicles in a field experiment, the research team will use this car-following model later to see the performance of strings with more vehicles with more speed oscillations.

$$[k_1, k_p, k_d] = \text{argmin} \sum_{n_{test}} \sum_{n_{veh}} \sum_{t} (v_{field} - v_{simulation})^2 \tag{18}$$

Where:

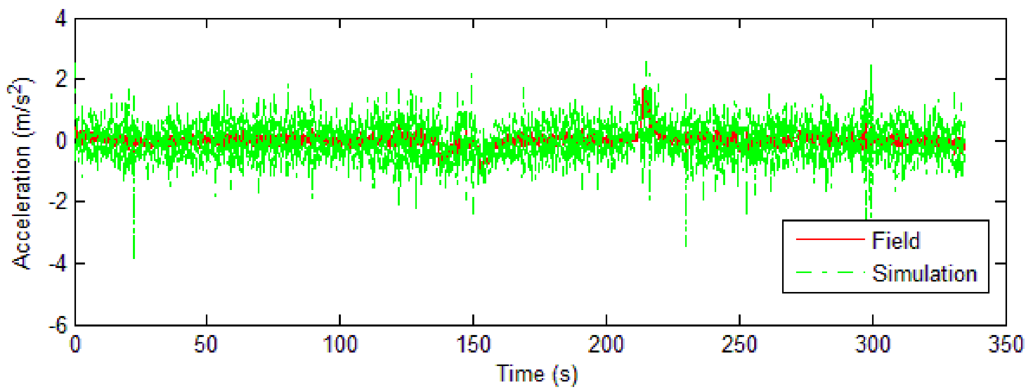
n_{test} = number of experimental runs.
n_{veh} = number of paired vehicles.
v_{field} = speed of the field-observed vehicle.
$v_{simulation}$ = speed of the simulated vehicle.

Figure 33 shows the comparison of the field and simulated data for the vehicle positioned second in the string in this experimental run. The simulated speed and acceleration match the field experiment well. There are discrepancies between the simulated and field headways because they are not directly optimized, but the differences are relatively small and considered acceptable. Although a constant-time-headway policy (for the convenience of implementation) was used, other complex underlying logic of the controller considers other parameters that may cause additional gap or headway changes.



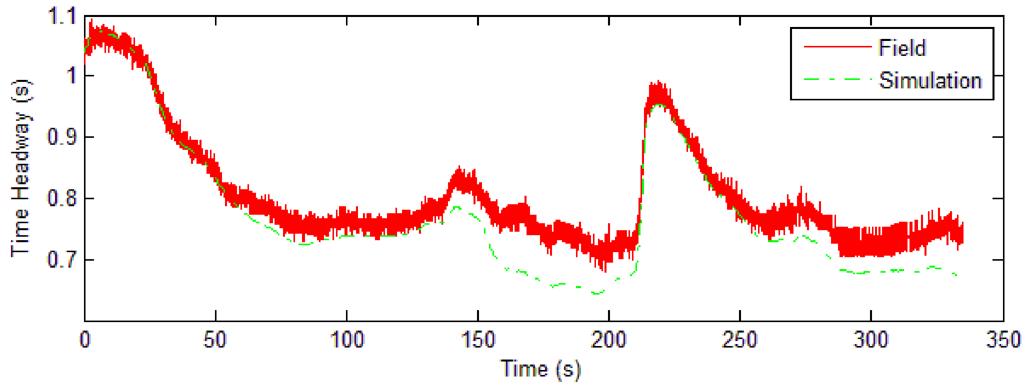
Source: FHWA.

A. Speed data.



Source: FHWA.

B. Acceleration data.



Source: FHWA.

C. Headway data.

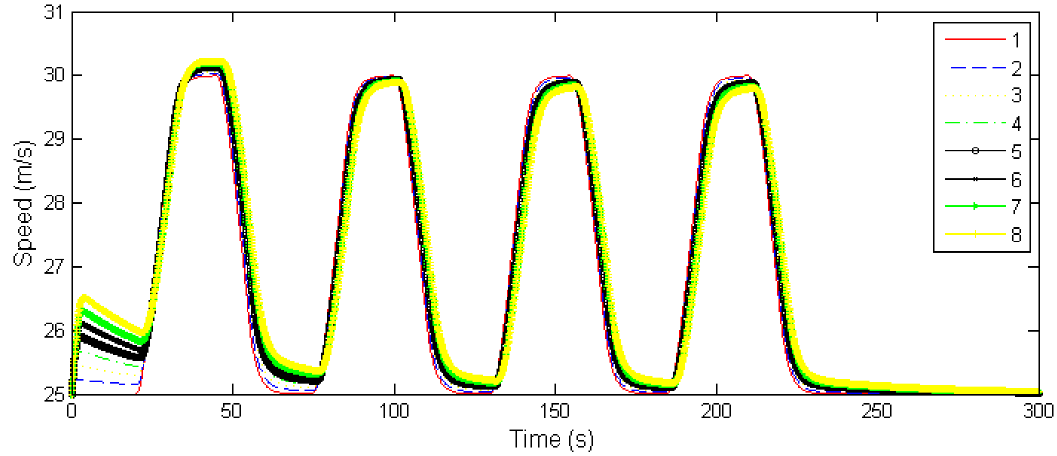
Figure 33. Graphs. Comparison of field and simulated data.

Figure 34 shows the simulation of an eight-vehicle string (the legend indicates the vehicle position in the string). The first vehicle is designed to conduct speed regulation with the following speed commands:

1. The vehicle drives at 25 m/s for 20 s.
2. The vehicle accelerates at a constant acceleration of 0.5 m/s^2 to reach 30 m/s speed.
3. The speed remains constant for 15 s before the vehicle starts to decelerate at a constant rate of 0.5 m/s^2 to come back to a constant speed of 25 m/s for 20 s.

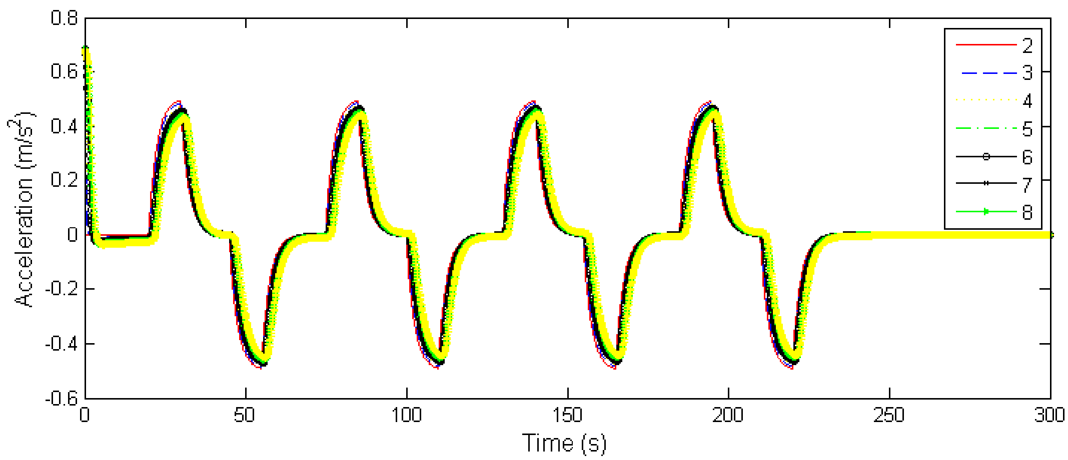
All the vehicles start by cruising at 25 m/s with a 1.2-s headway. This timing simulates the process from manual driving to platooning, such as when vehicles are entering a managed lane for CACC vehicles. Since the entry headway is 1.2 s greater than the desired headway (0.84 s, the same as the field experiment), the research team is interested in if this platoon-forming process will cause additional oscillations.

Figure 34-A presents the vehicle responses to the speed changes of the front vehicle. It can be seen that all the vehicles follow perfectly with the leading vehicle speed changes without amplifying the oscillation. The acceleration figure (figure 34-B) shows no excessive accelerations, and the values reach 0.5 m/s^2 (the speed-command acceleration) at few time stamps. Figure 34-C and figure 34-D show the distance and time headway performance. It can be seen that the headways are gradually closed to be near 0.84 s with no oscilations, even with the effect of the front vehicle speed oscillation. This consistency implies the string stability of the CACC controller or car-following behavior and, therefore, suggests this CACC can potentially improve traffic performance and highway capacity.



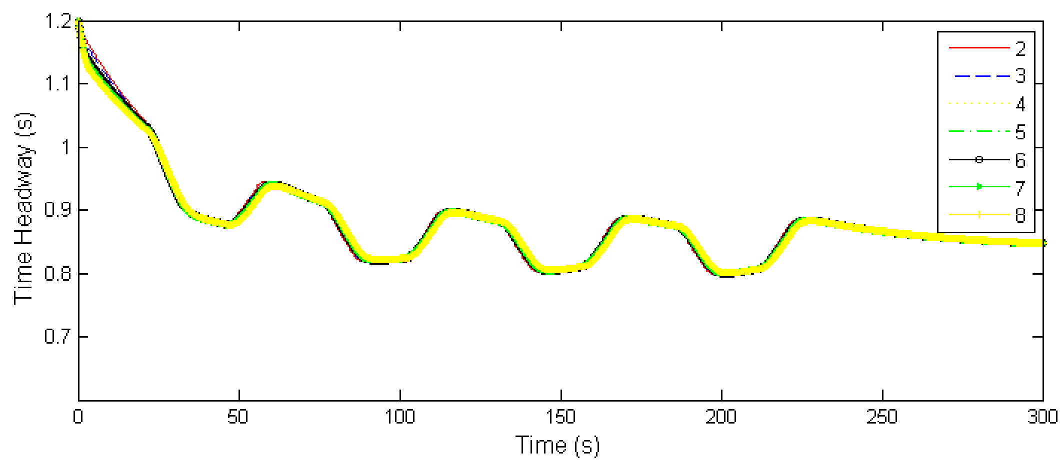
Source: FHWA.

A. Speed data.



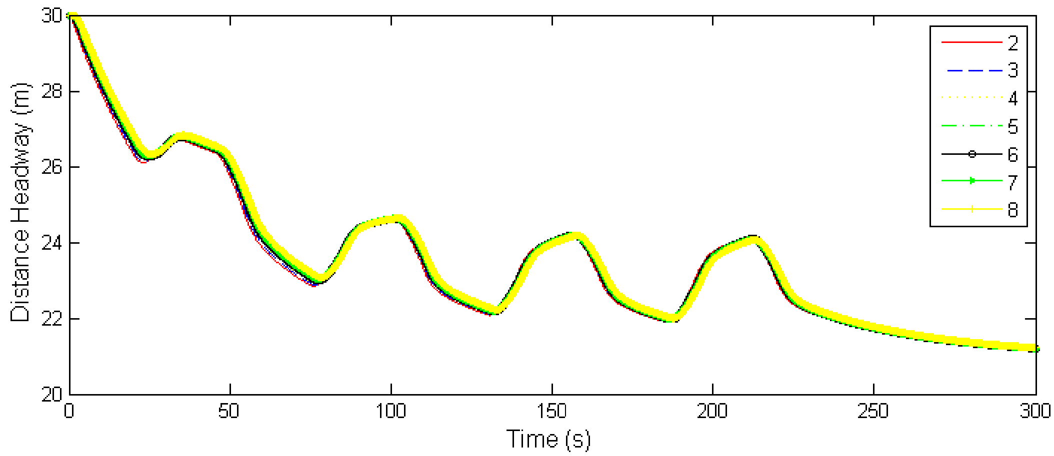
Source: FHWA.

B. Acceleration data.



Source: FHWA.

C. Headway data.



Source: FHWA.

D. Distance data.

Figure 34. Graphs. Simulation results of an eight-vehicle string.

Through the use of the experimental dataset, it is possible to do an extrapolation to calculate the capacity enhancement due to the bundled application. First, the CACC-pipeline capacity can be calculated. The average headway or gap between adjacent vehicles during experimental runs can also be calculated. Other system variables for the analysis, such as platoon size of 10 vehicles and interplatoon gaps of 1.5 s, can be assumed. This scenario is built upon the assumption that this large number of vehicles can be input at the beginning of the freeway segment. Second, some calculation can potentially be done for the merge-area capacity (measured downstream of the merge area). Similar to the pipeline capacity, the experimental data can be used to obtain the required gap for the merge vehicle from its front vehicle (across experimental runs). As reflected in the table 16 example results, the actual headway between the merge vehicle and the fourth vehicle (the merge vehicle is fifth) actually varies from 0.5 to 1.5 s (mostly at the higher end). So, it can be assumed the merge vehicle will need 1.5 s of headway for the merge maneuver at the merge area. While the platoon may become stable and operate with small gaps after the merge, the capacity can be assumed to be limited by the merge area. In a 10-vehicle platoon, the lead vehicle follows the interplatoon headway of 1.5 s and the following 8 vehicles use the intraplatoon headway of 0.84 s (measured from the experimental data), and the last (merging) vehicle uses 1.5 s for the intraplatoon gap. Then, the capacity reduces from 3,973 to 3,703 vehicles/h/lane, a 7-percent decrease. This reduction is attributed to cooperative merging with back-join (i.e., vehicles are allowed to join the back of the platoon), during which merge vehicles look for interplatoon gaps that are large enough for merging. With the assumption of 0.84 and 1.5 s for the intra- and interplatoon headways, respectively, the results in table 16 are calculated. Note that, although platoon size of 15 seems to be better than the size of 10, the allowed merge volume (on-ramp volume) actually decreases.

Table 16. Capacity analysis based on field experimental data.

Platoon Size	Human Capacity (vphpl)	Pipeline Capacity (vphpl)	Improvement of Throughput (%)	Capacity With Merge (vphpl)	Reduction From Capacity With Merge (%)	Improvement of Throughput With Merge (%)
5	2,350	3,704	57.6	3,261	12.0	38.8
10	2,350	3,973	69.1	3,703	6.8	57.6
15	2,350	4,072	73.3	3,879	4.7	65.0
*5	2,350	3,422	45.6	3,092	9.6	31.6
*10	2,350	3,614	53.8	3,422	5.3	45.6
*15	2,350	3,683	56.7	3,548	4.7	51.0

vphpl = vehicles/h/lane.
Note: Shaded rows (asterisked) indicate an average gap of 0.7 s; unshaded rows indicate an average gap of 0.6 s.

In the simulation in chapter 3, the intraplatoon gap follows the following distribution: 0.6 s for 57 percent of the time they were car following, 0.7 s for 24 percent of the time, 0.9 s for 7 percent of the time, and 1.1 s for 12 percent. The weighted average of the gap is 0.7 s. The results in table 8, when the intraplatoon gap is 0.7 s, can be compared to the simulation case with 100-percent penetration rate. As shown in figure 11, the pipeline capacity is about 3,300 vehicles/h/lane in simulation. Data from the field experiment indicate a range of 3,422 to 3,683 vehicles/h/lane depending on the length of the platoon. The theoretical results based on experimental data are a little higher than the simulation values considering that not all platoons will be 10 vehicles (due to the distribution of desired gaps), and there may be some traffic oscillations that can reduce the throughput to some extent. The same is also true for the theoretical estimation of capacity with cooperative merge, and the difference can also be attributed to the disturbance and oscillation of traffic at the merge area. With that in mind, along with the error introduced by a small number of vehicles involved in the field experiment versus the simulation, the pipeline capacity and capacity with cooperative merge in the two cases compare favorably.

CHAPTER 5. CONCLUSION

CAVs could potentially improve traffic safety, travel-time reliability, driver comfort, roadway capacity, environmental impacts, and overall user travel experience substantially. However, an extensive number of significant technical, legal, and logistical challenges must be addressed before CAVs can be widely deployed.

As managed-lane infrastructure advancement has evolved from simple restriping and signage improvements to more sophisticated ITS and toll-system deployments, they are ideal testbeds for V2V, V2I, and vehicle-automation technologies as well as potential first locations for their deployment. Separated from general-purpose lanes, managed lanes allow for the isolation and segregation of CAVs during the initial market-penetration phase. They provide a more controlled traffic environment than general-purpose lanes. Besides having a pre-existing physical infrastructure of power and communications networks, other managed-lane elements, including ITS, signage, and toll technologies also facilitate CAV deployment. Managed-lane developers and operators often have the required institutional frameworks to implement innovative technologies, such as CAV. These frameworks include familiarity with a systems-engineering approach and existence of a performance-management system to meet the increased accountability needs of a managed-lane facility. Further, many of the challenges related to meeting performance requirements and data management can be addressed through enhanced V2I technologies. These technologies largely support the managed-lane objectives of providing superior traffic performance through better traffic management and increased use.

The emergence of CAV technologies offers extensive opportunities to advance safety, mobility, and reliability on the Nation's roadways. The market-penetration rate of these vehicles is, however, expected to be low in the next decade, and as such, the potential benefits of CAVs may not be fully realized. The use of managed-lane facilities can support the realization of these benefits at early deployment stages. The ConOps outlined in this document focuses on deployment stages with low market-penetration rates and how the proposed bundled application of speed-harmonization, CACC, and cooperative-merge applications is operated to improve existing system performance.

For early CAV deployment, single-lane controlled-access facilities, equipped with existing communication devices and RSUs, offer the opportunity to begin integrating CAVs into traffic. Because the facilities that were considered are single lane, the presence of a small number of CAVs can still significantly impact traffic operations on the managed lanes and, therefore, improve system performance and individual travelers' experiences.

The implementation of CAVs on managed lanes also faces multiple challenges. Technically, this experiment showed the first integrated algorithm that combines CACC, speed harmonization, and cooperative merging. These algorithms were tested in a microscopic simulation and then deployed in a field experiment. The simulation showed the potential to significantly increase the capacity of an existing roadway if the three applications are deployed and the CAV market-penetration rate approaches 100 percent. The field experiment showed that the use of the three applications can smooth the vehicle speeds and reduce the footprint of a string of five vehicles in comparison to manual driving, yielding increased capacity, reduced delays, and more consistent travel times.

In the simulation for the cooperative case, the pipeline capacity at a market-penetration rate of 100 percent was about 3,600 vehicles/h/lane and, in the field experiment, was shown to be in the range of 3,704 to 4,072 vehicles/h/lane. Furthermore, throughput in the simulation showed 3,190 vehicles/h/lane compared to 3,261 vehicles/h/lane in the field experiment. Some error is introduced by extrapolating the field-experiment data from such a small number of vehicles, and variations in speed and disturbances to traffic are not taken into account in those numbers. With that, the simulation and field experiments do compare favorably.

Additional algorithm-development efforts are needed before CAVs are considered for widespread deployment. In addition, existing managed-lane facilities will also need to be equipped with basic communication infrastructure, such as DSRC, readily available for CAV deployment. Future work may expand upon this study in a number of ways, including by using more vehicles—either mainline vehicles or merge vehicles, merging into the middle of a platoon, merging from successive on-ramps, and testing with other technologies, including different means of V2V and V2I communication and vehicles outfitted to different levels of automation. Further study may also be done to evaluate the logistics of a real-world implementation, specifically how to direct enough vehicles into the managed lane to best take advantage of the increased capacity.

ACKNOWLEDGMENTS

This work was done in close coordination with and support of VDOT and Transurban, who, respectively, own and operate the I-95 express lanes.

The original maps in figure 12 and figure 13 are the copyright property of Google® Earth™ and can be accessed from https://www.google.com/earth.

REFERENCES

Chou, F.C., Shladover, S.E., and Bansal, G. (2016A). *Using Communications to Improve the Performance of Road Vehicle Automation Systems: Automated Merging*, ITS World Congress, Melbourne, Australia.

Chou, F.C., Shladover, S.E., and Bansal, G. (2016B). "Coordinated merge control based on V2V communication," *In Vehicular Networking Conference (VNC)*, pp. 1–8, IEEE, Piscataway, NJ.

Commonwealth Transportation Board. (2017). *Resolution of the Commonwealth Transportation Board*, Commonwealth Transportation Board, Richmond, VA. Available online: http://www.ctb.virginia.gov/resources/2017/july/reso/resolution_1_mou_testing_connected_vehicles.pdf, last accessed October 22, 2018.

Federal Highway Administration. (2018). *FHWA National Dialogue on Highway Automation*, Washington, DC. Available online: https://ops.fhwa.dot.gov/automationdialogue/presentations/azwksp102418/index.htm, last accessed February 7, 2020.

Federal Highway Administration. (2012). *Priced Managed Lane Guide*, Report No. FHWA-HOP-13-007, FHWA, Washington, DC. Available online: https://ops.fhwa.dot.gov/publications/fhwahop13007/index.htm#toc, last accessed February 12, 2020.

Federal Highway Administration. (2018). "CARMA2 Platform." (website) FHWA, Washington, DC. Available online: https://cms7.fhwa.dot.gov/research/research-programs/operations/carma-platform, last accessed February 12, 2020.

Federal Highway Administration. (2009). *Manual on Uniform Traffic Control Devices*, FHWA, Washington, DC. Available online: https://mutcd.fhwa.dot.gov/kno_2009r1r2.htm, last accessed August 6, 2020.

Federal Highway Administration. (2016). TO-14022: *Speed Harmonization Fundamental Research I*, Report No. FHWA-PROJ-13-0100, FHWA, Washington, DC.

Federal Highway Administration. (2010). *Synthesis of Active Traffic Management Experiences in Europe and the United States*, Report No. FHWA-HOP-10-031, 2010, FHWA, Washington, DC.

Ghiasi, A., Ma, J., Zhou, F., and Li, X. (2017). *Speed harmonization algorithm using connected autonomous vehicles*. Presented at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

Google®. 2016. Google® Earth™, Mountain View, CA, obtained from: https://www.google.com/earth, last accessed February 12, 2020.

Harding, J., Powell, G., Yoon, R., Fikentscher, J., Doyle, C., Sade, D., Lukuc, M., Simons, J., and Wang, J. (2014). *Vehicle-to-vehicle communications: readiness of V2V technology for application*, Report No. DOT HS 812 014, National Highway Traffic Safety Administration, Washington, DC.

Kiefer, R.J., Cassar, M.T., Flannagan, C.A., LeBlanc, D.J., Palmer, M.D., Deering, R.K., and Shulman, M.A. (2003). *Forward collision warning requirements project: refining the CAMP crash alert timing approach by examining "last-second" braking and lane change maneuvers under various kinematic conditions*, Report No. HS-809 574, National Highway Traffic Safety Administration, Washington, DC.

Krueger, R., Rashidi, T.H., and Rose, J.M. (2016). "Preferences for shared autonomous vehicles." *Transportation Research Part C: Emerging Technologies*, *69*, pp. 343–355, Elsevier, Amsterdam, Netherlands.

Liu, H., Xiao, L., Kan, X.D., Shladover, S.E., Lu, X., Wang, M., Schakel, W., and van Arem, B. (2018). *Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams.* University of California, Berkeley, Berkeley, CA. Available online: https://escholarship.org/uc/item/081599dn#main, last accessed August 6, 2020.

Lu X.Y., Tan, H.S., Shladover, S.E., and Hedrick, J.K. (2000). *Implementation of longitudinal control algorithm for automated vehicle merging. Proceedings of AVEC 2000*, 5th International Symposium on Advanced Vehicle Control, August 22–24, 2000, Ann Arbor, MI.

Ma, J., Li, X., Shladover, S., Rakha, H.A., Lu, X.Y., Jagannathan, R., and Dailey, D.J. (2016). "Freeway speed harmonization." *IEEE Transactions on Intelligent Vehicles*, *1*(1), pp. 78–89, IEEE, Piscataway, NJ.

Ma, J., Li, X., and Zhou, F. (2017). "A parsimonious two-way shooting algorithm for connected automated traffic smoothing part II: computational issues and optimization." *Transportation Research Part B*, Elsevier, Amsterdam, Netherlands.

Milanés, V., Shladover, S.E., Spring, J., Nowakowski, C., Kawazoe, H., and Nakamura, M. (2014). "Cooperative Adaptive Cruise Control in Real Traffic Situations." *IEEE Transactions on Intelligent Transportation Systems*, *15*(1), pp. 296–305, IEEE, Piscataway, NJ.

Milanés, V. and Shladover, S.E. (2014). "Modeling cooperative and autonomous adaptive cruise control dynamic responses using experimental data." *Transportation Research Part C: Emerging Technologies*, *48*, pp. 285–300, Elsevier, Amsterdam Netherlands.

National Cooperative Highway Research Program (2016). *Guidelines for Implementing Managed Lanes*, Report No. 835, Transportation Research Board, Washington, DC.

NHTSA. "Automated Vehicles for Safety." (website) USDOT, Washington, DC. Available online: https://www.nhtsa.gov/technology-innovation/automated-vehicles, last accessed August 6, 2020

Nowakowski, C., O'Connell, J., Shladover, S., and Cody, D. (2010). "Cooperative Adaptive Cruise Control: Driver Acceptance of Following Gap Settings Less Than One Second." *Proceedings of the Human Factors and Ergonomics Society 54th Annual Meeting*, *54*(23), pp. 2033–2037, San Francisco, CA.

Perez, B.G., Fuhs, C., Gants, C., Giordano, R., and Ungemah, D.H. (2012). *Priced Managed Lanes Guide 2012*, Report No. FHWA-HOP-13-007, Federal Highway Administration, Washington, DC.

Raboy, K., Ma, J., Stark, J., Zhou, F., Rush, K., and Leslie, E. (2017). *Cooperative Control for Lane Change Maneuvers with Connected Automated Vehicles: A Field Experiment*, Report No. 17-05142, Transportation Research Board 2017 Annual Meeting, Washington, DC.

Research and Innovative Technology Administration, ITS Joint Program Office. (2012). *Concept Development and Needs Identification for Intelligent Network Flow Optimization (INFLO)*, Report No. FHWA-JPO-13-012, FHWA, Washington, DC.

SAE International. (2014). *Automated Driving – Levels of Driving Automation are Defined in New SAE International Standard L3016*, SAE International, Warrendale, PA.

Scarinci, R., Hegyi, A., and Heydecker, B. (2017). "Definition of a merging assistant strategy using intelligent vehicles." *Transportation Research Part C: Emerging Technologies*, *82*, pp 161–179, Elsevier, Amsterdam, Netherlands.

Shladover, S., Nowakowski, C., Lu, X., and Ferlis, R. (2015). "Cooperative Adaptive Cruise Control (CACC) Definitions and Operating Concepts." *Transportation Research Record: Journal of the Transportation Research Board*, *2489*, pp. 145–162, TRB, National Research Council, Washington, DC. Available online: http://dx.doi.org/10.3141/2489-17, last accessed February 12, 2020.

Shladover, S., Nowakowski, C.V., Cody, D., Bu, F., O'Connell, J., Spring, J., Dickey, S., and Nelson, D. (2009). *Effects of cooperative adaptive cruise control on traffic flow: testing drivers' choices of following distances*, California PATH Program, Institute of Transportation Studies, University of California at Berkeley, Berkeley, CA.

Shladover, S.E., Su, D., and Lu, X.-Y. (2012). "Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow." *Transportation Research Record*, *2324*, pp. 63–70, Transportation Research Board, Washington, DC.

Talebpour, A., Mahmassani, H.S., and Hamdar, S.H. (2013). "Speed Harmonization: Evaluation of Effectiveness Under Congested Conditions." *Transportation Research Record*, *2391*, pp. 69–79, Transportation Research Board, Washington, DC.

U.S. Department of Transportation, National Highway Traffic Safety Administration. (2010). *Frequency of Target Crashes for IntelliDrive Safety Systems*, USDOT, Washington, DC. Available online: https://www.nhtsa.gov/DOT/NHTSA/NVS/Crash%20Avoidance/Technical%20Publications/2010/811381.pdf, last accessed February 12, 2020.

U.S. Department of Transportation (2016). "Federal Automated Vehicles Policy: Accelerating the Next Revolution in Roadway Safety." (website) USDOT, Washington, DC. Available online: https://www.transportation.gov/AV, last accessed February 12, 2020.

VanderWerf, J., Shladover S., Miller, M., and Kourjanskaia, N. (2002). "Effects of Adaptive Cruise Control Systems on Highway Traffic Flow Capacity." *Transportation Research Record*, *1800*, pp. 78–84, TRB, Washington, DC.

Wang, Z., Wu, G., and Barth, M.J. (2018). "A review on cooperative adaptive cruise control (CACC) systems: Architectures, controls, and applications." *In 2018 21st International Conference on Intelligent Transportation Systems (ITSC),* pp. 2884–2891. IEEE, Piscataway, NJ.

Zhou, F., Li, X., and Ma, J. (2015). "A parsimonious two-way shooting algorithm for connected automated traffic smoothing part I: Theoretical analysis with generalized time geography," *Transportation Research Part B*, Elsevier, Amsterdam, Netherlands.

Recycled
Recyclable

HRDO-20/03-21(WEB)E