Developing Analysis, Modeling, and Simulation Tools for Connected and Automated Vehicle Applications: A Case Study for I–66 in Virginia

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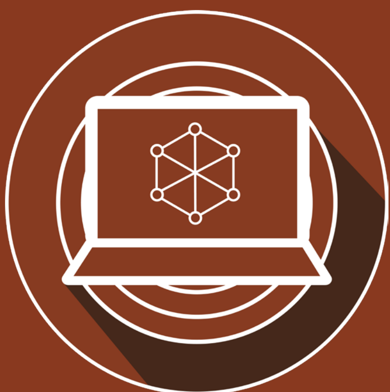

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Federal Highway Administration

Research, Development, and Technology
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FOREWORD

Connected and automated vehicle (CAV) technology is expected to produce significant mobility, safety, and environmental benefits to the traveling public. Real-world case studies are needed to articulate reasonable benefits attributable to the technology. This report details a case study of the impact of vehicle connectivity and automated longitudinal control (i.e., SAE J3016 driving automation Level 1) (SAE International 2016) on I–66) in Virginia to explore the benefits of cooperative adaptive cruise control, cooperative merge, and speed harmonization on mobility performance measures. This final report may be of interest to State and local departments of transportation pursuing a better understanding of possible real-world impacts of CAV technology.

Brian P. Cronin, P.E.
Director of Office of Safety and Operations
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The purpose of this report is to document a simulation-based case study completed by the project team to investigate the effectiveness of SAE J3016 Level 1 automation technology for mitigating or solving existing transportation problems related to congestion, fuel consumption, and emissions (SAE International 2016). The case study conducted simulations on a real-world corridor, I–66 in Northern Virginia. This report discusses simulated infrastructure and connected and automated vehicle (CAV) technological strategies. The study evaluated the effectiveness of three CAV applications: cooperative adaptive cruise control, speed harmonization, and cooperative merge. The case study also evaluated the potential benefits of changes to the physical infrastructure, including dedicated ramps and a realistic managed-lane concept—a connected vehicle (CV)– and CAV–eligible high-occupancy vehicle (HOV) lane—where CVs, CAVs, and HOVs (human-driven or CV and CAV) can access a left-side managed lane. The report identifies the most critical simulation parameters related to CAV algorithms, CV and CAV market penetration, traffic demand, and infrastructure enhancement alternatives and used various combinations of these factors to generate different simulation scenarios. The simulation results provide operational insights that State and local departments of transportation may use in future strategic planning for CAV programs.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS AND ACRONYMS

ACC	adaptive cruise control
API	Application Programmer's Interface
ATM	active traffic management
CACC	cooperative adaptive cruise control
CAMP	Collision Avoidance Metrics Partnership
CAV	connected and automated vehicle
CV	connected vehicle
DLL	Dynamic Link Library
DSRC	dedicated short-range communication
HOV	high-occupancy vehicle
ITS	intelligent transportation system
I2V	infrastructure-to-vehicle
LHD	Latin Hypercube Sampling Design
ML	managed lane
OD	origin–destination
RTMS	remote traffic monitoring system
SOV	single-occupancy vehicle
TMC	traffic management center
VDOT	Virginia Department of Transportation
veh/h	vehicles per hour
veh/h/ln	vehicles per hour per lane
VSL	variable speed limit
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle

EXECUTIVE SUMMARY

The purpose of this report is to document a simulation-based case study completed by the project team to investigate the effectiveness of SAE J3016 Level 1 automation technology for mitigating or solving existing transportation problems related to congestion, fuel consumption, and emissions (SAE International 2016). The case study conducted simulations on a real-world corridor, I–66 in Northern Virginia, and investigated the effectiveness of connected and automated vehicle (CAV) deployment in enhancing existing traffic system performance. This study simulated, evaluated, and discussed strategies incorporating both infrastructure and CAV technologies. It evaluated the effectiveness of three CAV applications: cooperative adaptive cruise control (CACC), speed harmonization, and cooperative merge. It also evaluated the potential benefits of dedicated ramps and a realistic managed-lane (ML) concept—a connected vehicle (CV)– and CAV–eligible high-occupancy vehicle (HOV) lane—where CVs, CAVs, and HOVs (human-driven or CV and CAV) can access a left-side ML.

The case study activities included site selection, model calibration, CAV model development, experimental design, simulation execution, result reporting, and recommendations for future studies, which are summarized as follows:

- Site selection—the project team worked with Federal Highway Administration and the Virginia Department of Transportation (VDOT) to select a 13-mi (20.92-km)-long freeway segment on I–66 outside the I–495 Beltway as the case study location. This site was selected due to its congested traffic patterns and the VDOT strategic initiatives along the corridor, which include active traffic management and CAV programs. During the study period, VDOT contracted a private entity to build and operate infrastructure on I–66. As a result, VDOT had contractual obligations that limited its ability to apply study recommendations to this particular segment of roadway. However, VDOT found the results of this study exceedingly valuable for the purposes of evaluating other roadways.[1]

- Model development—the project team used an existing I–66 simulation network that was calibrated in 2015. This network represents the traffic conditions and road geometry of I–66 in 2015 and does not reflect current construction activities on I–66. The simulation network also included multiple CAV applications that used external driver models from a selected microscopic simulation tool.

- Experimental design—the project team identified the most critical simulation parameters related to CAV algorithms, CV and CAV market penetration rates, traffic demand, and infrastructure enhancement alternatives. The team then used various combinations of these factors to generate different simulation scenarios.

- Simulation execution and result reporting—the project team executed the simulation runs according to the simulation plan, presented simulation results in tabular and graphical forms to demonstrate the potential impacts of the CAV deployments, and shared

[1]Amanda Hamm and Sanhita Lahiri from VDOT provided these comments to authors in January 2020 via phone calls and emails.

interpretations of the results and insights for operational management with CAV technologies.

- Recommendations for future studies—the project team discussed the limitations of the simulation, assessed unanswered questions, and made recommendations for future studies.

The simulation results show that, for all scenarios, individual and bundled CAV applications can significantly improve traffic performance in terms of delay and throughput. Forming the CACC string is the most effective individual strategy because it directly reduces the gaps between vehicles and stabilizes traffic flow using unique string-control algorithms. In the capacity analysis, the effect of CACC continued to increase as the market penetration rate increased (81.2-percent capacity increase for the 100-percent penetration scenario). Speed harmonization naturally smooths mainline traffic, resulting in increased throughput and reduced delay in most cases. Cooperative merge can positively impact traffic performance by reducing force-in merge occurrences and smoothing the merging process. In the I–66 case study, the mainline vehicles slowed down or made lane changes, when appropriate, to create safe gaps for the merging vehicles. However, the cooperative merge process (i.e., algorithm parameters) needs to be tweaked and optimized to reflect local geometric and traffic conditions to ensure that cooperative merging will not negatively impact the overall system performance of the merge areas and the entire corridor.

The I–66 case study shows that the bundled CAV applications with high CAV market penetration rates, if deployed, can handle 130 percent of the traffic demand without incurring congestion, indicating that the resultant highway capacity is greater than 130 percent of the traffic demand. Additionally, even with low CAV market penetration rates, there are still system benefits in early deployment stages. These benefits apply to both vehicle-to-vehicle applications (i.e., CACC) and infrastructure-to-vehicle applications (i.e., speed harmonization and cooperative merge).

The three infrastructure scenarios can be summarized as follows:

- ML 1—dedicated ramps and CV- and CAV-eligible HOV lanes.
- ML 2—CV- and CAV-eligible HOV lanes.
- ML 3—HOV lanes (baseline).

The first scenario, ML 1, performed the best whereas the third scenario, ML 3, performed the worst for low- and medium-market penetration cases, indicating that the dedicated ramps and ML operational strategies were beneficial, even during early deployment stages. Though this conclusion is intuitive because these two infrastructure-side enhancements reduce weaving and increase the chance of forming strings, the results are significant because they prove the effectiveness of a more realistic scenario in which human-driven HOV traffic is still allowed to access the dedicated ramps and ML. For high CAV market penetration cases, these three scenarios had similar performances due to the bundled CAV applications' ability to fully handle 130 percent of the traffic demand.

There are many existing HOV facilities in the country. The results of this case study suggest there are early deployment benefits with no or a limited need for infrastructure adjustment (e.g., adding dedicated ramps for HOV lanes) to those facilities. The results also provide a foundation for State and local departments of transportation making strategic decisions on CAV deployment for existing HOV facilities.

CHAPTER 1. INTRODUCTION

BACKGROUND

For now, the best way to understand the impact of connected and automated vehicle (CAVs) on traffic mobility, energy consumption, and emission is through microscopic simulation with proper modeling of the dynamic interactions between CAVs and manually driven vehicles. This understanding can be achieved by testing CAVs in live, public traffic and using the test data to develop models because CAV high market penetration does not exist in practice and will not exist for about a decade. Therefore, such data cannot be collected for mixed-traffic (i.e., manually driven vehicles and CAVs) modeling. To this end, FHWA has sponsored three case studies (I–66, State Route 99, and Traffic Optimization for Signalized Corridors) under this project to investigate the traffic and energy impacts of CAVs and the bundled applications of CAV and traffic management strategies at various freeway and arterial corridors.

The objective of the I–66 case study was to investigate the effectiveness of CAV applications for mitigating various causes of traffic congestion such as oversaturation, poor weather conditions, 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). Regardless of its original cause, excess congestion leads to unstable traffic flow, which usually leads to breakdowns and bottlenecks. Congestion causes unwanted impacts such as wasted fuel, increased emissions, decreased travel time reliability, emergency vehicle response times, and decreased productivity (e.g., gross domestic product). Constructing new lanes could increase capacity and reduce delays, but construction projects are expensive and often take a long time to complete. Therefore, it is necessary to investigate different strategies for improving operational efficiency of existing lanes.

Because managed lanes (MLs) have evolved into sophisticated roadways, ML operators have a unique opportunity to leverage their facilities as real-world testbeds and preliminary deployment sites for CAVs. ML facilities are frequently equipped with traffic sensors, communication networks, and tolling equipment—all of which can be used to support CAV initiatives. The current equipment can allow further equipment of the facilities with a suite of CAV technologies ranging from preliminary vehicle automation (i.e., automated or autonomous decisionmaking at the vehicle level using onboard sensors) to a connected ecosystem in which vehicles and roadside infrastructure communicate wirelessly.

When combined with current levels of vehicle automation, modern MLs present an incremental opportunity for traffic flow improvements that can produce widespread mobility, safety, and environmental benefits. These CAV technologies could allow maintenance of consistent speeds throughout the facility, thereby increasing the traffic demand levels the roadway can support. The increased throughput and capacity of the MLs could also potentially benefit parallel general-purpose lanes as traffic shifts to the ML. Smoothed, optimized speeds can also reduce fuel consumption, harmful emissions, and highway crashes.

The study network, I–66 in Northern Virginia, is operated and managed by Virginia Department of Transportation (VDOT). VDOT is seeking new ways to improve safety and mobility, including through CAV technologies. The agency expects these technologies to bring transformative change to the safety and efficiency of surface transportation facilities:

> The VDOT CAV program helps guide the department in the deployment and sustainment of related technologies and initiatives. VDOT strives to capitalize on the safety and operational benefits of CAV technologies to meet the program's goals and objectives. (VDOT 2019)

To achieve the set objectives, VDOT will leverage the following key resources unique to the Commonwealth:

- A vast network of urban and rural roadways, most of which VDOT owns and operates.
- Trusted, world-class research, and testing capabilities.
- Mature, robust, and Virginia Connected Corridor–supported networking and cloud-based data services.

VDOT is researching CAV strategies that have the potential to impact roadways in the following ways:

- Reduce the frequency and severity of incidents.
- Reduce congestion.
- Improve situational awareness of the roadway network.
- Reduce traffic management and control infrastructure.

Alongside its role in making imminent advances in vehicle technology, which are primarily led by the private sector, VDOT's role in delivering the infrastructure needed to allow for efficient surface transportation for the Commonwealth will continue. VDOT's vision serves as an environment where CAV applications provide connectivity between vehicles, roadside infrastructure, and wireless devices. This interconnected environment is expected to meet the following objectives:

- Increased safety—CAV safety applications have the potential to reduce crashes through advisories and warnings and, ultimately, remove the driver from the responsibilities associated with vehicle operations at Level 4 or 5 driving automation (SAE International 2016). These applications will help VDOT meet its goal of reducing the frequency and severity of crashes, injuries, and fatalities on roadways within the Commonwealth.

- Improved mobility—mobility applications are intended to provide a connected, data-rich environment to CAVs based on real-time information transmitted anonymously from thousands of vehicles. This information can help transportation managers monitor and improve transportation system performance by adjusting traffic signals, enhancing transit operations, or dispatching maintenance crews and emergency services.

- Reduced infrastructure investments—connected vehicle (CV) environments are expected to reduce the need for new infrastructure investments over time. For example, less signage could be needed as information is sent directly to vehicles, roadway cross sections could be reduced, required guard rails may be reduced as vehicles gain latitudinal control features, and intersection controls could be reduced once vehicles can communicate with each other directly to avoid conflicts.

- Enhanced traveler information—real-time information provided to travelers about traffic congestion and other travel conditions could help them make more informed decisions. Informed travelers may decide to avoid congestion by taking alternate routes, using public transit, or rescheduling their trip. Vehicles' ability to communicate with infrastructure can provide drivers with additional information to help them make better decisions as they travel.

REPORT OBJECTIVE AND OVERVIEW

This report documents a simulation-based case study completed by the project team to investigate the effectiveness of SAE J3016 Level 1 automation technology for mitigating or solving existing transportation problems related to congestion, fuel consumption, and emissions (SAE International 2016). The case study conducted simulations on a real-world corridor (I–66) in Northern Virginia and investigated the effectiveness of CAV deployment in enhancing existing traffic system performance. This study simulated, evaluated, and discussed strategies incorporating both infrastructure and CAV technologies. It evaluated the effectiveness of three CAV applications: cooperative adaptive cruise control (CACC), speed harmonization, and cooperative merge. It also evaluated the potential benefits of dedicated ramps and a realistic ML concept—CV– and CAV–eligible high-occupancy vehicle (HOV) lanes—where CVs, CAVs, and HOVs (human-driven or CV and CAV) can access a left-side ML. The case study activities included site selection, model calibration, CAV model development, experimental design, simulation execution, result reporting, and recommendations for future studies.

The report is structured as follows:

- Chapter 1 defines the scope of the study and describes the background.
- Chapter 2 describes in detail the technologies and operational concepts. The technologies include a bundled CAV freeway application featuring CACC, cooperative merge, and speed harmonization. The operation concepts address how to deploy CAV technologies on the current freeway systems using an ML approach.
- Chapter 3 describes basic information about the case study road network, travel patterns, existing traffic control, and management strategies. The chapter also details key transportation problems that local agencies could potentially mitigate or solve using CAV technologies.
- Chapter 4 describes the CAV modeling and simulation efforts of the case study. First, the chapter introduces the CAV model development and calibration, including the CAV algorithm implemented in the study and efforts conducted to calibrate certain parameters in the algorithm. Second, it documents the base case simulation calibration and validation efforts. Last, the chapter describes the modeling changes made to model selected CAV applications and achieve the modeled CAV operational alternatives.

- Chapter 5 details the simulation execution and results, including the design of simulation results, simulation results for the different scenarios, and discussion of implications.

- Chapter 6 provides the conclusions of the research and discusses recommendations for future studies.

CHAPTER 2. BUNDLED CAV APPLICATIONS

Chapter 2 describes the background and offers a review of the selected CAV applications, including a literature review and an introduction to the infrastructure and vehicles, control algorithms, possible operational strategies, and so forth. The chapter also discusses the potential operational strategies and expected types of transportation system impacts.

TECHNOLOGY REVIEW

Although many CV and CAV applications have been developed, three technologies among these applications show the most promise for early deployment for MLs (Mahmassani et al. 2012, Ma et al. 2017, Zhou et al. 2017, Guo et al. 2019): speed harmonization, CACC, and cooperative merge.

Speed Harmonization

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. This strategy can also be used to reduce vehicle speeds, either delaying or preventing 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 shown positive results by improving traffic flow stability, reducing crashes and injuries, and decreasing emissions (Fudala and Fontaine 2010). Current VSL systems use speed limit signs posted over each lane to regulate freeway speeds by changing the limit based on prevailing traffic conditions. Although successful VSL systems could achieve speed harmonization, driver response to suggested speed limits has not been consistent. Dynamic speed limit adjustments are less efficient than dynamic recommended or actual speed adjustments communicated directly into CAVs, as the speeds are adjusted automatically 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 vehicles on different segments of the roadway and automatically implemented by the vehicles. Such dynamic speed harmonization systems may successfully manage upstream and bottleneck (e.g., merging area) traffic flow through the following actions:

- Detect the location, type, and intensity of downstream congestion (or other relevant) conditions reliably.
- Formulate an appropriate response plan (i.e., vehicle speed and lane selection) for approaching vehicles.
- Disseminate such information to upstream vehicles rapidly and 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 found significant travel-time reductions (e.g., a 10-percent reduction corridor-wide and a 35-percent reduction on localized bottleneck segments) at CAV penetration rates of 10 percent or greater, 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 category of more advanced approaches that control and coordinate an individual vehicle's trajectory. Individual vehicle speeds can be controlled in real time, depending on each vehicle's location on the roadway segment, enabling them to smoothly pass downstream bottlenecks. Recent simulation studies and field experiments suggest such an approach can potentially enhance traffic smoothness, therefore improving efficiency and safety (Ghiasi et al. 2017, 2019; Ma et al. 2016). In particular, a central controller (e.g., traffic management center (TMC)) can facilitate freeway merging using trajectory control by coordinating the trajectories of upstream ML vehicles and merging vehicles so that merging can be smooth and efficient and creates minimum impact on mainline traffic.

CACC

One way to turn an adaptive cruise control (ACC) system into a CACC is by adding vehicle-to-vehicle (V2V) communications. As such, the CAV will leverage its ability to communicate with surrounding vehicles to maintain an optimal following distance. The CAV can slow down when it gets too close, 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 developing CACC is to reduce traffic congestion by improving highway capacity and throughput and attenuating traffic flow disturbances. The class of CACC systems utilizing V2V communication could allow the mean following time gap to decrease from about 1.4 s when driving manually to approximately 0.6 s when using CACC, resulting in increased 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 CAV market penetration rates, had little effect on lane capacity (Vander et al. 2002; Shladover et al. 2012). Additionally, recent on-the-road experiments have shown that a stream of autonomous ACC vehicles is string unstable, resulting in a negative impact on lane capacity and safety (Milanés et al. 2014; Eilbert et al. 2019; Knoop et al. 2019). However, if CAVs reach 100-percent market penetration, the shorter following gaps and greater flow stability that CACC systems enable could increase lane capacity from the typical 2,200 vehicles per hour (veh/h) to almost 4,000 veh/h.

In addition to V2V-based CACC, Shladover et al. (2015) proposed the concept of CACC systems using I2V communication, although it was not investigated in detail. Theoretically, the CACC system would cooperate with the infrastructure to reduce 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 hypothetical is similar to the proposed concept of applying CACC and speed harmonization as a bundle—by controlling the lead vehicle's speed and trajectory (speed harmonization), the vehicle strings will arrive at bottleneck locations at an ideal time, allowing them to pass through the location smoothly. This bundled application can also be coordinated with cooperative merging so that vehicles that attempt to merge into the ML will be integrated without a breakdown in traffic flow.

Cooperative Merge

Cooperative merge leverages V2V and I2V communications to enable CAVs to signal other vehicles (via dedicated short-range communication (DSRC)) of their intention to merge. Using this information, merging vehicles can identify upcoming acceptable gaps on the mainline and make lane changes when possible. This also provides upstream ML vehicles with the opportunity to cooperate by adjusting their speeds to create a gap for the requesting vehicle. This communication optimizes the trajectories of merging vehicles and allows the merge to occur safely and with minimal impact on the string's mobility.

A recent FHWA study described an effort to develop an innovative vehicle control platform that could successfully conduct a proof-of-concept field experiment to validate a simple algorithm-driven cooperative lane-change maneuver (Raboy et al. 2017). This demonstration was executed using automated speed control, V2V communications, and vehicle-based radar systems. Experimental results show the proposed platform's effectiveness and the successful proof of the new cooperative lane change concept. Chou et al. (2016a, 2016b) tested two cooperative automated–merging strategies for highway entry, one using I2V communication and the other using V2V communication in microscopic simulation. The results show that I2V strategy reduced travel time in the merging section when the traffic flow was high, and the V2V strategy supported a significant increase in traffic flow without increasing travel times. The results indicate there are potential advantages of using cooperative automation to relieve the bottleneck in the merging section.

These existing studies, however, only use simple algorithms and target limited merging areas. The effectiveness of cooperative merging cannot be isolated from other CAV operations such as platooning. Additionally, cooperative merging combined with speed harmonization (by controlling and coordinating arrivals of upstream ML vehicles to create gaps for merging) can further improve merging area performance. The bundled application proposed in this study addresses integrating three such applications.

OPERATIONAL STRATEGIES WITH MLS

The role of State and local departments of transportation such as VDOT is to ensure a smooth transition from conventional human-driven traffic to mixed-autonomy traffic as market penetration and the number of CAVs in the traffic stream gradually increases. To address infrastructure development and traffic management, agencies can adapt their infrastructure to make CAV benefits possible during the early deployment stages. One of these strategies is offering CAVs eligibility for using existing MLs so CAVs can concentrate on a certain traffic stream portion, interact and platoon with each other, and therefore have an impact on the traffic stream performance. MLs offer several features that are favorable and, in many respects, critical to testing and implementing CAV technology. Many ML facilities provide the facility design and operational and institutional infrastructure that is necessary to implement vehicle-to-infrastructure (V2I) protocols on existing infrastructure—one of the first steps toward broader CAV technology adoption and penetration.

ML operation goals and CAV application goals overlap. While each ML project is implemented with its own set of goals and performance measures, in general all ML 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, MLs 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 roadway operational efficiency. Federal statutes recommend a minimum average operating speed of 45 mi/h (72 km/h) for 90 percent of the time for HOV+ facilities (i.e., those that combine HOV with single-occupancy vehicles (SOVs) or low emission or energy-efficient vehicles) over a consecutive 180-day period during morning or evening weekday peak hours. While this minimum is considered a de facto test for HOV-only facilities, it is not mandated.

MLs encompass a suite of operational strategies including lane-use restrictions, access limitations, and tolling that are designed to achieve the following goals:

- Enhance lane efficiency and utilization by increasing use of underutilized lanes and efficiently allocating capacity in overutilized lanes.
- Provide travel-time reliability by enabling superior traffic performance by maintaining reliable speeds and unimpeded travel for public transit.
- Yield revenue to offset lifecycle costs (in case of toll lanes) by bringing in enough income from user fees to fund operations and maintenance activities.

Despite the significant potential for customization in ML operational policy at the State and local levels, ML facilities face several challenges in meeting their performance goals. The limitations that agencies face include capacity restrictions, demand increases (due to demographic patterns), time-of-day variations (due to weather and events), and organizational or regulatory restrictions (e.g., policies that limit HOV+ requirements, minimum-occupancy-requirement changes, and toll-rate increases that could effectively respond to changing traffic patterns). MLs also face challenges including issues related to data collection and performance management.

The CAV strategies proposed in this study present a mechanism for increasing the efficiency of available ML capacity and improving traffic performance without significant capital investment. As such, these strategies pose an attractive solution to ML operators struggling to meet Federal, State, and local performance requirements, or those seeking innovative solutions to growing travel demand. CAV technologies may also facilitate synergy gain by allowing more efficient data collection to meet ML facilities' performance management and reporting requirements.

EXPECTED EFFECTS

As MLs have evolved from simple restriping and signage improvements to more sophisticated intelligent transportation systems (ITSs) and toll systems, they present ideal testbeds for V2V and V2I technologies and potential first locations for CAV deployments.

Separate from general-purpose lanes, MLs allow for the partial CAV isolation and segregation during the initial market penetration phase. They also provide a more controlled traffic environment than general-purpose lanes. Besides having a pre-existing physical infrastructure that includes power and communications networks, modern ML elements—including ITS, signage, and toll technologies—also support and facilitate CAV deployment. ML facilities also often have the institutional framework required to implement innovative technologies such as CAV. These frameworks include developers and operators familiar with a system engineering approach as well as the existence of a performance management system that would meet the increased accountability needs of a managed facility. Enhanced V2I technologies can address many of the challenges these facilities face related to meeting performance requirements and managing data. These technologies largely support the ML objectives of providing superior traffic performance through better traffic management and increased utilization.

This section presents the expected effects of deploying the proposed CAV technologies on MLs from the transportation users' and facility operators' perspectives.

Transportation Users' Perspectives

Transportation users' needs include the following:

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

Integrating CAVs into ML facilities will support and enhance the following benefits from transportation users' perspectives:

- Greater traffic 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 unimpaired driver crashes (Harding et al. 2014).

- Smoother, faster travel and lower driver stress levels—merge coordination and CACC can reduce the friction in traffic flow and increase the capacity of highway bottleneck locations by increasing lane capacity and improving vehicle-following stability.

- Greater operational efficiency and travel-time reliability—combined speed harmonization, cooperative merging, and CACC can substantially reduce uncertainty in travel times by smoothing traffic and enabling real-time prediction of travel times.

- More productive travel experience—several results of employing CAV technologies, including speed harmonization, can help improve the travel experience. These include but are not limited to eliminating stop-and-go movements, improving travel-time reliability, proactively managing congestion, and controlling access.

Transportation Operators' Perspectives

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

- Reducing recurring congestion on urban freeways.
- Improving reliability and safety.
- Reducing travel times, fuel consumption, and emissions.
- Maintaining and increasing the use of alternative and emerging transportation modes (e.g., car-sharing options; travelers consider CAVs to be a separate mode, according to a recent survey (Krueger et al. 2016)).

Integrating CAVs into ML facilities will also support and enhance the following benefits from transportation operators' perspectives:

- Faster realization of efficiency goals—adopting CAVs early on in an existing ML increases the facility operator's ability to manage congestion, increase throughput, enhance safety, and improve the overall driver experience. These benefits will result from the relatively higher fraction of CAV-enabled vehicles using the ML facility as compared with the number using the general travel lanes.

- Maximized resource utilization for more efficient solutions—traditional approaches to managing congestion, such as capacity expansion, are increasingly becoming obsolete both due to funding constraints as well as inherent limitations of these approaches in alleviating transportation problems. CAV technologies offer potential innovative solutions to the problems of congestion and travel-time variability that continue to plague facilities.

- Preserved agency influence—by gaining first-mover advantage, outside entities are less likely to take operators' roles and dictate the direction of CAV technology development if operators make the voluntary move to test and advance this technology.

- Agile organizational adaptation—organizations that learn to evolve and respond to rapid technological change will be more likely to thrive in this era of rapid technological enhancement in the transportation field.

Operational Strategies for CAV Operation on MLs

This section discusses operational concepts and policies for speed harmonization, CACC, and cooperative merging on MLs. The concepts are delineated in an evolutionary framework that addresses the operational goals, policies, and constraints of typical ML facilities along with the anticipated technology evolution and CAV market penetration. Though ML operational policies originate from specific project goals and use a variety of performance metrics, this concept assumes that the overarching goal of the target facility is to improve traffic performance, reduce congestion, and enhance safety through active demand management. For a CAV application to be successful, the operational concepts should be synergistically combined with the framework and goals of ML operations.

The operational concept in this section could apply to the SAE Level 1 V2V and V2I communication automation via a suitable communication protocol (e.g., DSRC) at low CAV market penetration rates (SAE International 2016). This concept includes the following CAV applications:

- Speed harmonization—the TMC uses speed harmonization algorithms to determine reasonable speeds by lane section and conveys this information to communications-equipped vehicles on the lane as advice or, in the case of a CAV, a directive. The recommended speeds are based on safety and traffic flow considerations. Equipped vehicles may be adjusted to the recommended speed manually by the driver (at Level 0) or may perform automatic longitudinal speed control (at Level 1). If nonequipped vehicles are allowed on MLs, 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 vehicle-control strategy. These vehicles receive information from lead vehicles at a high frequency and maintain safety and stability at a close following distance, thus forming a string of connected, speed-harmonized vehicles. Using DSRC or other communication methods, V2V-only communication allows data regarding vehicle characteristics, position, speed, acceleration, yaw rate, brake status, throttle position, steering angle, and so forth, to be exchanged.

  Cooperative merge—cooperative merge control requires coordination between ML vehicles and merging vehicles. Ideally, once all vehicles are CAVs, ML vehicles can be automatically controlled to speed up or slow down to create gaps for merging vehicles, the trajectories of which are controlled to accurately merge into the created gaps. If some manually driven CVs (and even nonequipped vehicles) use the lanes, data from onboard units and roadside communication units and sensors can be fused to predict gap arrivals at merging points, and merging CAVs can be controlled accordingly and merged into the ML. For optimal efficiency, only CAVs would be allowed on the dedicated MLs. If manually driven CVs are also allowed at dedicated on-ramps, a virtual ramp-metering system is needed to predict manual driving and merging trajectories prior to releasing merging vehicles into the ML.

CHAPTER 3. DESCRIPTION OF CASE STUDY LOCATION

Chapter 3 describes the basic information for the case study site, including the road network, travel patterns, existing traffic control and management strategies, and the existing transportation problems CAV technologies address. This chapter also introduces the available data for model calibration and the results of calibration and validation.

The selected case study location was I–66 westbound between the I–495 interchange (mile marker 64) and US 29 interchange (mile marker 51), a total of 13 mi (20.9 km). The six interchanges in this section cause traffic congestion along the freeway segments during the afternoon peak hours.

The VDOT active traffic management (ATM) system on I–66 was installed in September 2015 with the goal of improving safety and operations by better managing the existing roadway capacity. The ATM system includes advisory VSLs, queue warning systems, lane-use control signs, and hard shoulder running. This case study aims to evaluate CAV-based operational strategies and their impacts on the corridor's traffic performance.

Researchers at the FHWA Saxton Transportation Operations Lab collected data along the corridor during the week of Nov. 13, 2015. These data were used to quantify corridor conditions and include the following:

- Speed and volume data collected by six remote traffic monitoring system (RTMS) trailers along the major mainline segments.
- On- and off-ramp volume data collected by high-resolution cameras.
- Travel-time data for selected mainline segments (INRIX 2018).

Table 1 shows the westbound remote traffic microwave sensor trailer locations, and table 2 provides a list of westbound INRIX TMC locations. Figure 1 uses a map to indicate each RTMS sensor's location at each of the six interchanges. Cameras are also deployed at each on- and off-ramp to collect corresponding traffic volumes. Figure 2 shows each TMC segment used in this calibration. RTMS data were collected every 15 seconds but were later aggregated to intervals of 15-min intervals for calibrating and validating traffic simulation models. It is worth noting that the study segment of I–66 is now under construction and therefore the actual driving behavior, including lane change and gap acceptance, may have changed since the data collection period.

Table 1. Westbound remote traffic microwave sensor trailer locations.

Interchange ID	Nearest Exit	Nearest Crossing Street	Mile Marker
IC 1	62	VA-243/Nutley Street	61.6
IC 2	60	VA-123	60.0
IC 3	57	US 50	58.0
IC 4	55	VA-286	55.5
IC 5	53	VA-28/Sully Road	53.0
IC 6	52	US 29	51.8

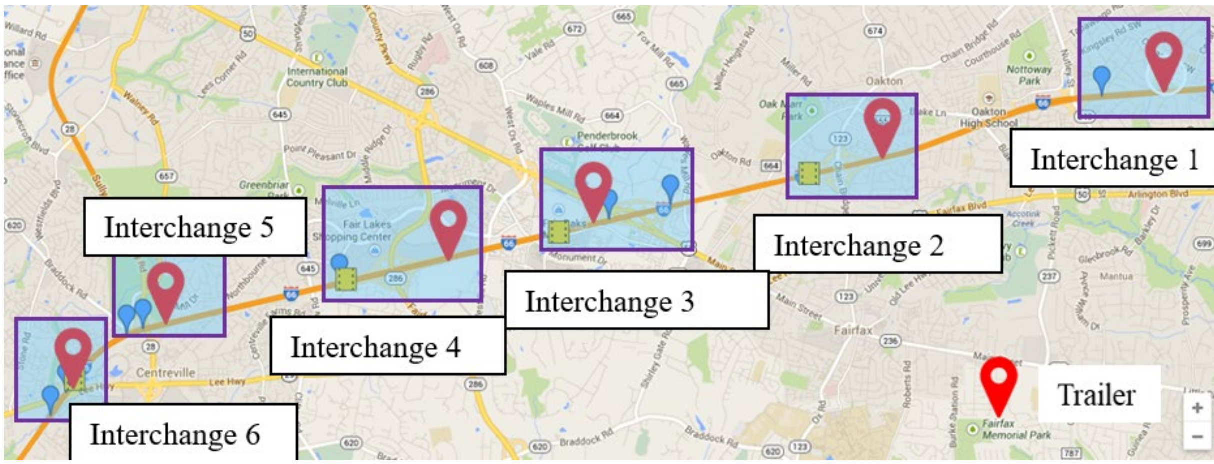
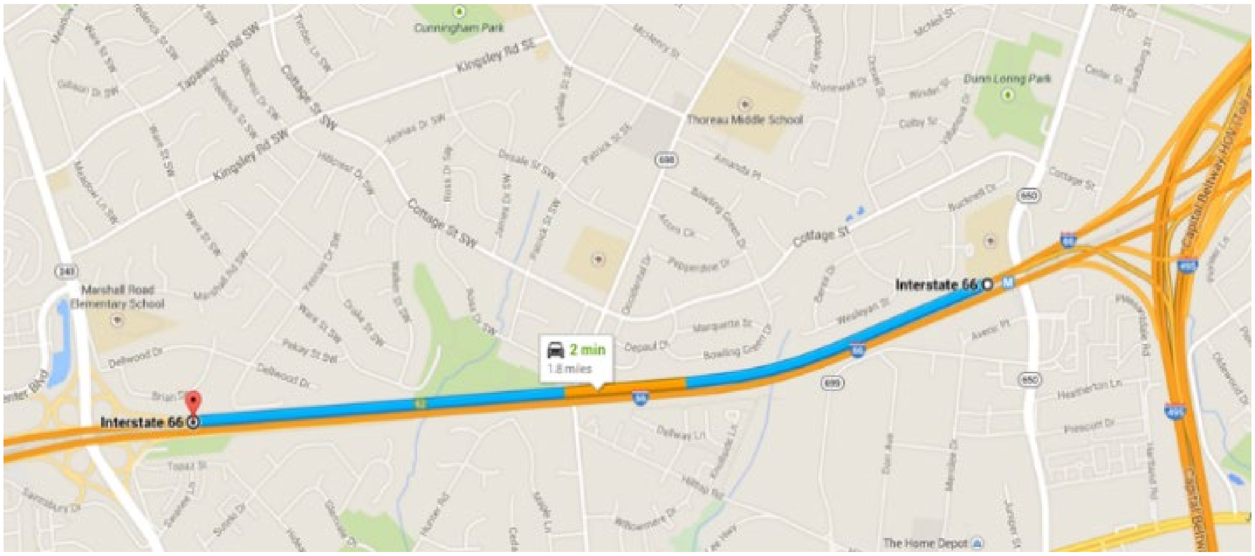


Figure 1. Map. Westbound trailer locations.

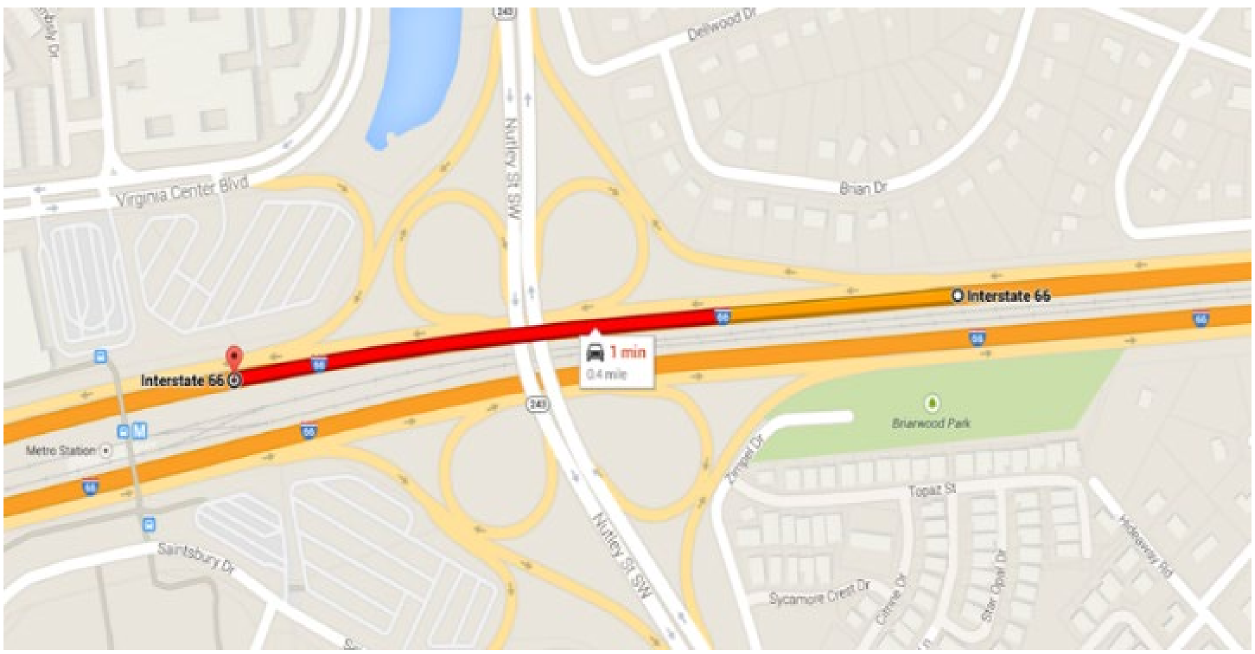
Table 2. Westbound INRIX TMC locations.

TMC Code	From	To	Mileage/Kilometers
110+04176	I–495/exit 64	VA-243/Nutley Street/exit 62	1.8/2.89
110P04176	I–495/exit 64	VA-243/Nutley Street/exit 62	0.4/0.64
110+04177	Vaden Drive/exit 62	VA-123/exit 60	0.3/0.48
110+04178	VA-243/Nutley Street/exit 62	VA-123/exit 60	1.4/2.25
110P04178	VA-123/exit 60	US-50/exit 57	0.9/1.45



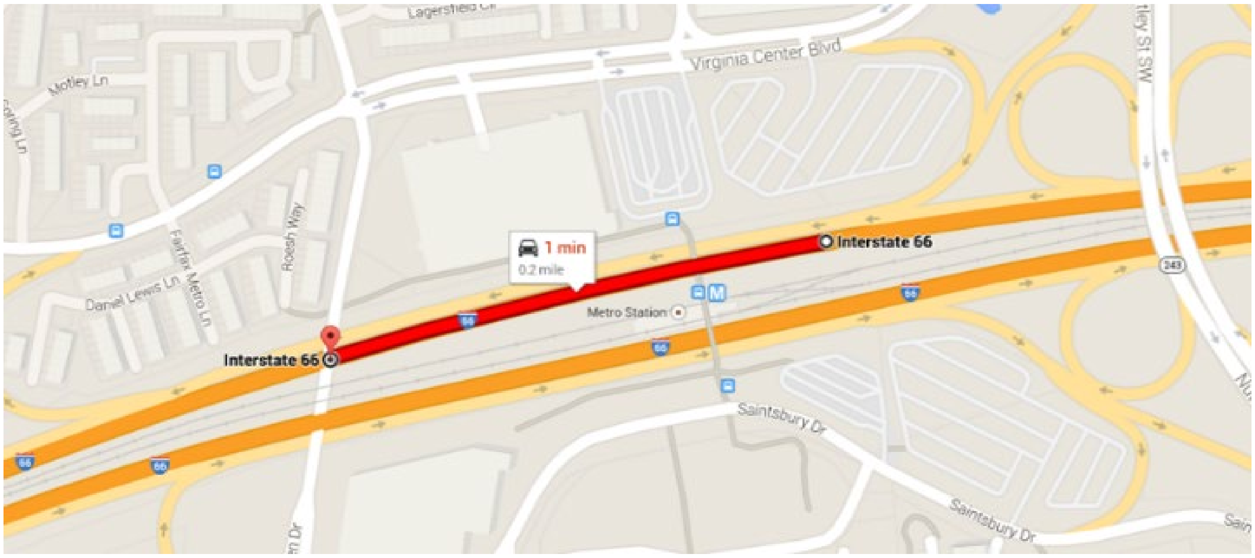
© 2017 Google. Modifications by FHWA to show locations of interchanges. Data from Hale et al. (2020).

A. TMC 110+04176.



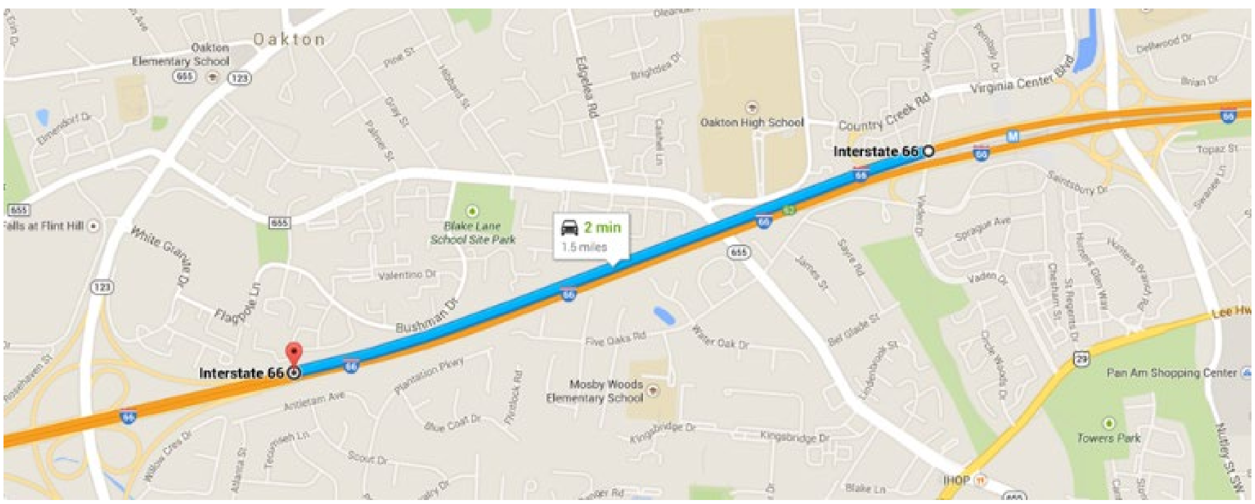
© 2017 Google. Modifications by FHWA to show locations of interchanges. Data from Hale et al. (2020).

B. TMC 110P04176.



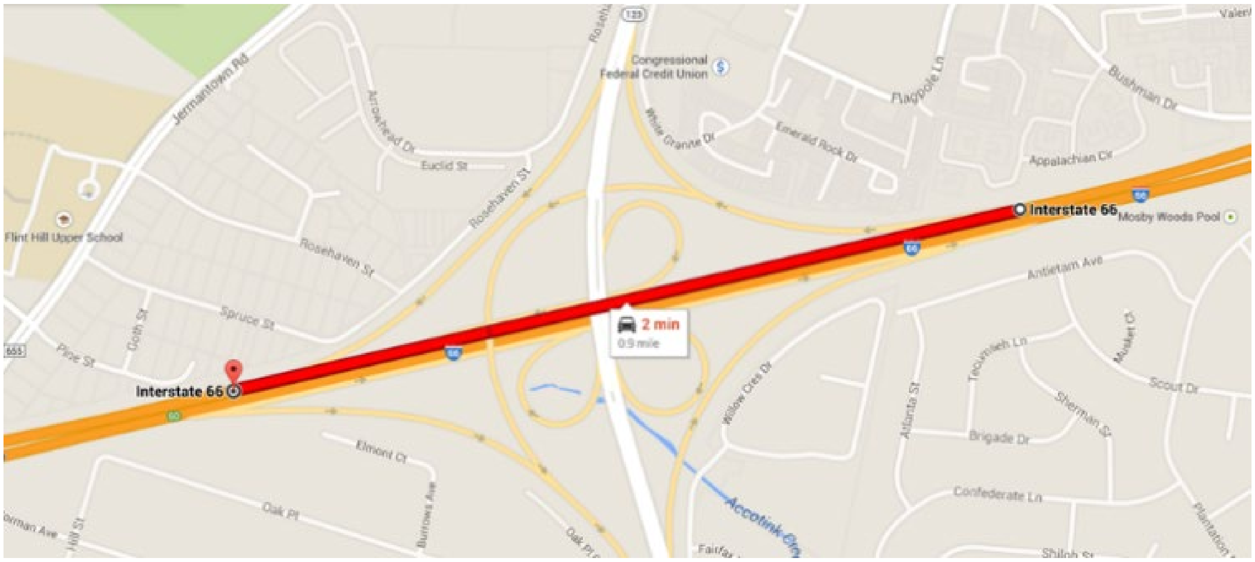
© 2017 Google. Modifications by FHWA to show locations of interchanges. Data from Hale et al. (2020).

C. TMC 110P04177.



© 2017 Google. Modifications by FHWA to show locations of interchanges. Data from Hale et al. (2020).

D. TMC 110+04178.



E. TMC 11P04178.

Figure 2. Map. TMC segments used in the calibration.

CHAPTER 4. MODELING AND SIMULATION

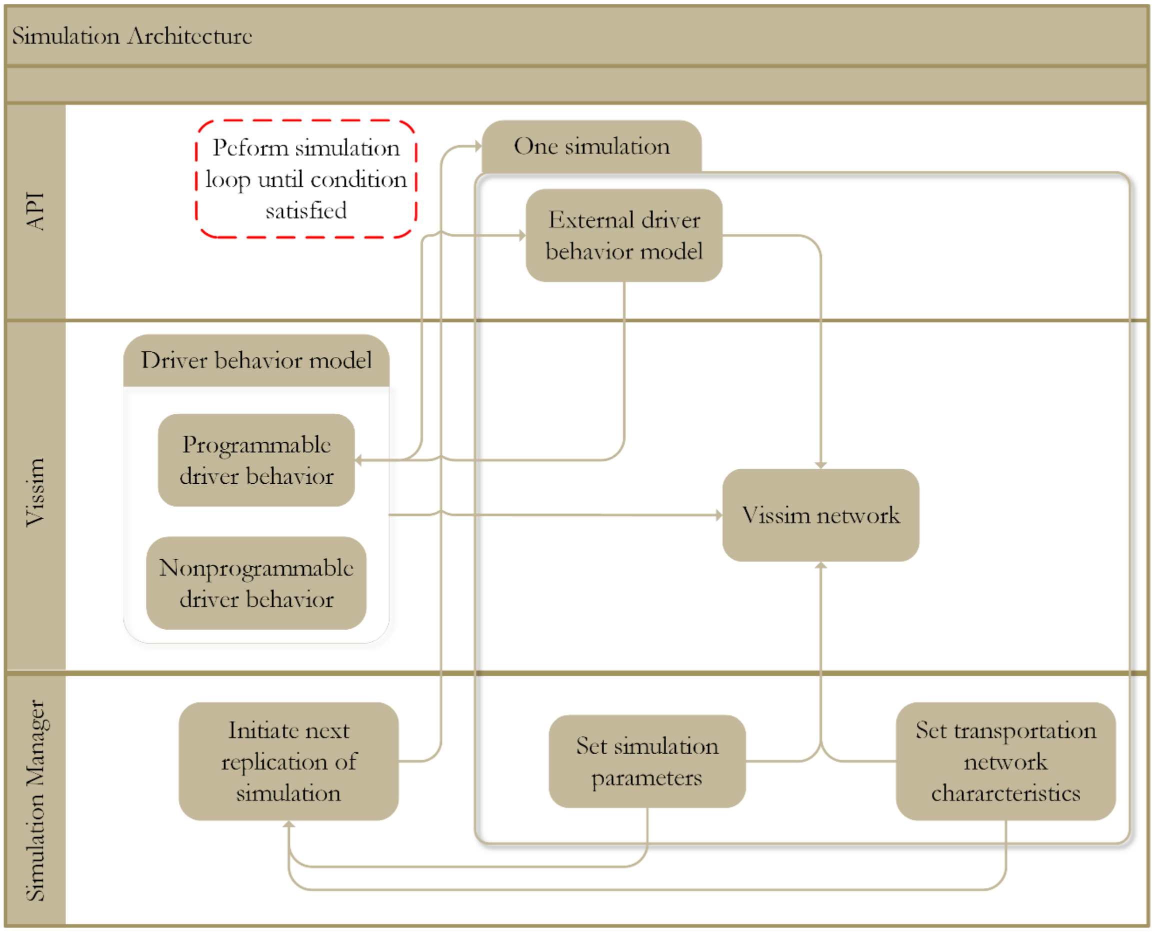
Chapter 4 describes the CAV modeling and simulation efforts of this case study. First, the chapter introduces the proposed modeling framework for the case study. Second, it documents the base case simulation calibration and validation efforts. Then, the chapter describes the CAV model development and calibration, including the CAV algorithm implemented in the study and calibration efforts conducted to calibrate certain parameters in the algorithm. Last, this chapter presents the changes made to model selected CAV applications and the CAV operational alternatives that were modeled as a result.

MODELING FRAMEWORK DEVELOPMENT

PTV Vissim® is a multimodal traffic flow–simulation software (PTV Group 2019). It can conduct microscopic simulations in which each entity (e.g., vehicle, train, pedestrian) is simulated individually with certain car-following and lane-changing rules (in the case of vehicular traffic). Such capability is one of the most crucial elements for CAV concept implementation and evaluation, as these car-following and lane-changing rules can be adjusted to reflect the effects of CAV technology.

To implement various CAV applications, three major modules are required: the Vissim network module, the simulation manager module, and the Application Programmer's Interface (API) module. The overall framework is as follows (and is illustrated in figure 3):

- The Vissim module is the underlying transportation network that tests a large variety of CAV algorithms.
- The simulation manager supports easy scenario building and system-level control and is enabled through a component object model.
- The API module is a program that determines driving behavior by programming corresponding parameters for different CAV applications.



Source: FHWA.

Figure 3. Diagram. Simulation architecture.

Vissim Network

Vissim can conduct a simulation network with geometry and driving-behavior design. The calibrated traffic volume and desired speed and routes can be easily performed with Vissim internal models and functions. Vissim also provides built-in performance evaluation.

Simulation Manager

The simulation manager allows users to easily adjust control parameter values crucial to implementing CAV applications in Vissim without directly accessing the Vissim driver model API source codes. It also provides users with an interface that can modify simulation scenario parameters, such as market penetration rates, traffic volumes, and simulation times.

Driver Model API

Vissim is capable of not only conducting a conventional transportation behavior simulation in a network but also implementing its external driver model through the Dynamic Link Library (DLL) interface, which substitutes the driving behavior built in Vissim by a fully user-defined behavior for vehicles. In a properly set up framework, Vissim passes the current state of a vehicle and its surrounding traffic to the DLL. The DLL computes and determines the succeeding behavior of the vehicle as an algorithm specifies and then passes the updated state of the vehicle back to Vissim for the next simulation period. This feature allows the user to model (and test) various CAV applications.

BASE CASE NETWORK CALIBRATION AND VALIDATION

The research team utilized Vissim microscopic traffic simulation software in this study. This section provides a detailed introduction of calibration and validation results. Vissim uses origin–destination (OD) matrices to specify travel demand. The I–66 network has 10 zones as shown in figure 4. The information of these 10 zones is listed in table 3. Zones 2 through 9 contain the intermediate interchanges, and zones 5 and 7 are only applicable to HOV vehicles. Hale et al. (2020) provide a detailed calibration analysis discussion.

Table 3. Zone definitions.

Zone ID	Zone Description
1	I–66 East at I–495
2	Exit 62 on-ramp and off-ramp
3	Exit 60 off-ramp to north and on-ramp from north
4	Exit 57 off-ramp to north and on-ramp from north
5	Exit to Monument Drive, destination only
6	Exit 55 on-ramp and off-ramp
7	Exit to Stringfellow Road, destination only
8	Exit 53 off-ramp to north and on-ramp from north
9	Exit 52 off-ramp to north and on-ramp from north
10	I–66 West

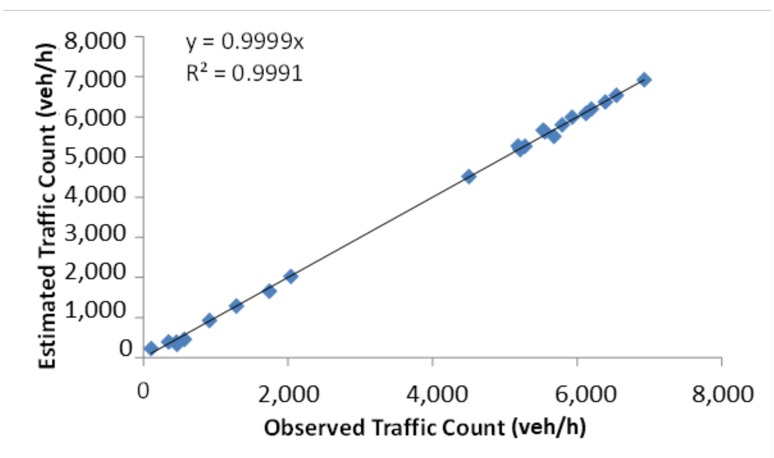
Figure 4. Map. Zone locations.

The field-collected data were used to identify how many vehicles traveled between some, but not all, OD pairs. The research team used QueensOD software (Aerde and Rakha 2010) to estimate OD matrices. Table 4 shows an example and lists an estimated OD matrix for the 3:00 p.m. to 3:15 p.m. period. Figure 5 shows estimated and field-measured OD trips in the same period have a good match. This good match indicates the estimated OD trips serve as good inputs for simulation network correlation (Hale et al. 2020).

Table 4. OD example for the 3:00 p.m. to 3:15 p.m. period (veh/h).

Zone ID*	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10
1	457.0	97.2	375.8	149.0	1.4	228.1	756.1	417.9	3,599.7
2	—	287.2	414.8	—	14.2	—	31.3	—	—
3	—	—	861.4	—	72.2	—	0.1	—	—
4	—	—	—	—	242	—	71.7	39.1	41.7
6	—	—	—	—	—	—	1,164.5	8.9	401.8
8	—	—	—	—	—	—	—	64.2	1,223.8
9	—	—	—	—	—	—	—	—	925.6

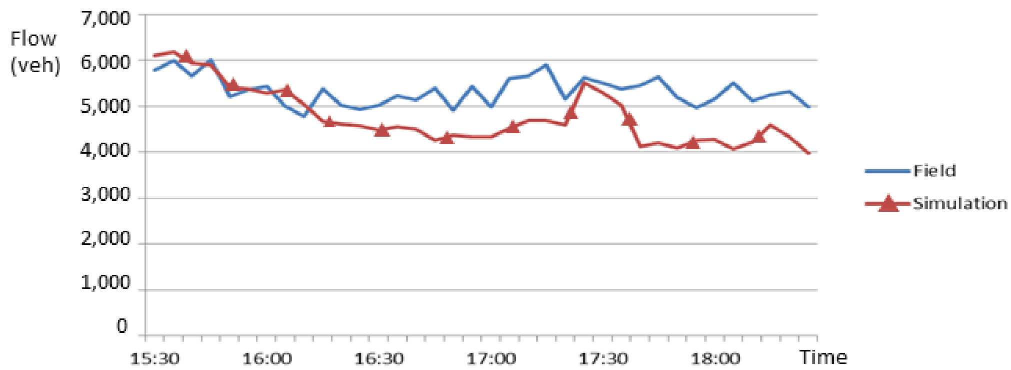
— No data.
* Zone ID: Zone 1, I–66 East at I–495; Zone 2, Exit 62 on-ramp and off-ramp; Zone 3, Exit 60 off-ramp to north and on-ramp from north; Zone 4, Exit 57 off-ramp to north and on-ramp from north; Zone 5, Exit to Monument Drive, destination only; Zone 6, Exit 55 on-ramp and off-ramp; Zone 7, Exit to Stringfellow Road, destination only; Zone 8, Exit 53 off-ramp to north and on-ramp from north; Zone 9, Exit 52 off-ramp to north and on-ramp from north; and Zone 10, I–66 West.



Source: FHWA. Data from Hale et al. (2020).

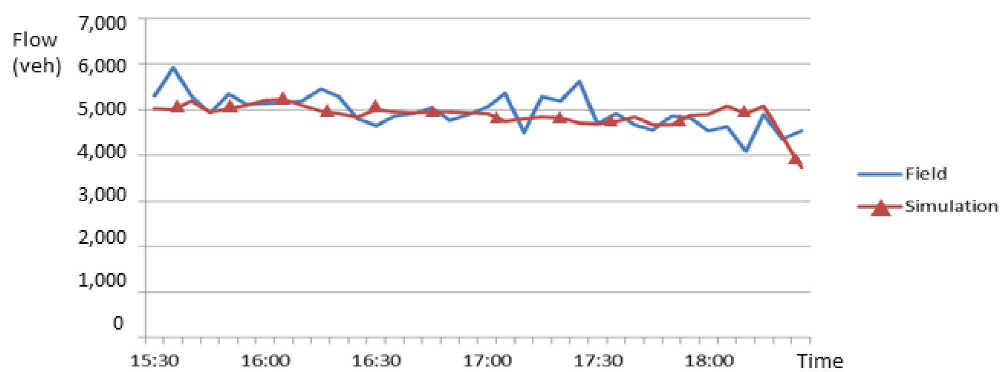
Figure 5. Graph. Comparison of estimated flow and observed flow from 3:00 p.m. to 3:15 p.m.

Figure 6 shows the comparison of simulated and field values at three interchanges. The charts indicate the simulated traffic volumes satisfactorily match the actual field RTMS data with an average absolute percent error less than 10 percent.



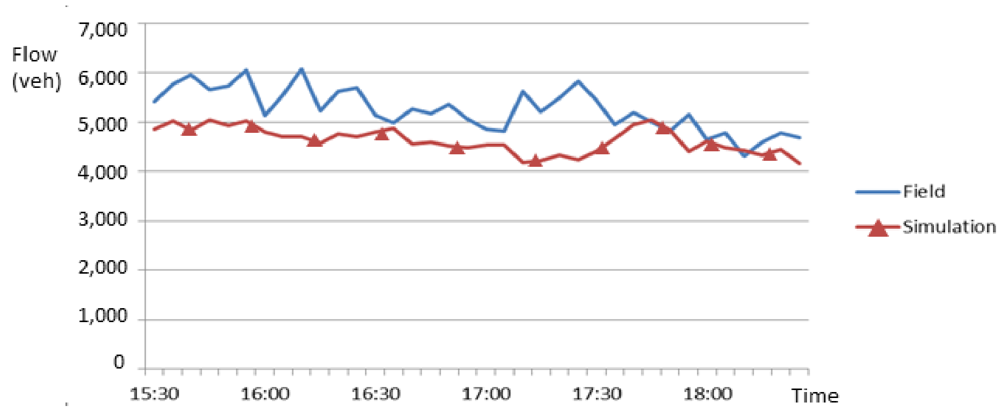
Source: FHWA. Data from Hale et al. (2020).
veh = vehicles.

A. Calibration results for interchange 1 traffic counts.



Source: FHWA. Data from Hale et al. (2020).
veh = vehicles.

B. Calibration results for interchange 3 traffic counts.

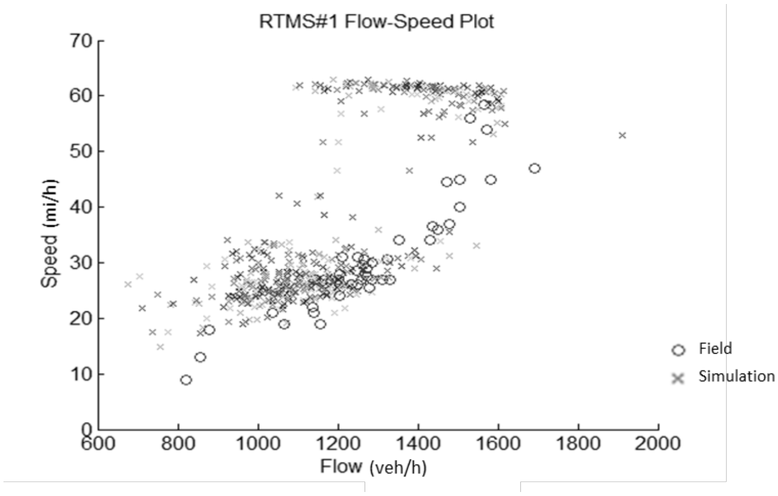


Source: FHWA. Data from Hale et al. (2020).
veh = vehicles.

C. Calibration results for interchange 5 traffic counts.

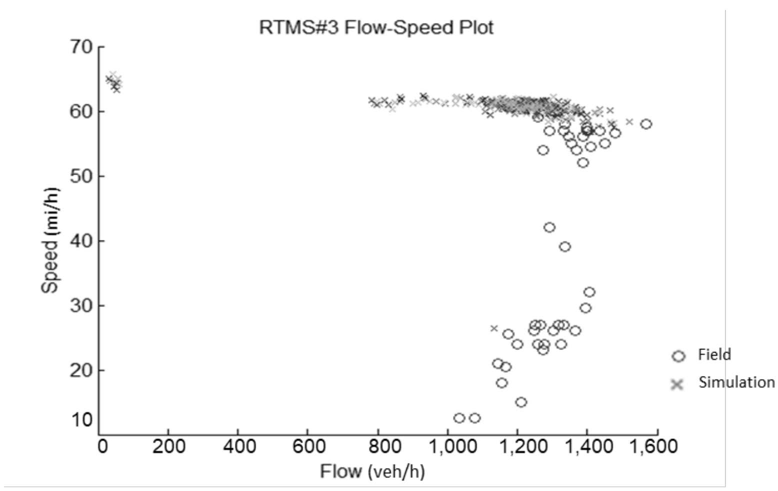
Figure 6. Graph. Calibration results for traffic counts.

Figure 7 shows the comparison of the speed-flow fundamental diagrams constructed using the field RTMS data and simulation data, indicating a good match at these interchanges. The free-flow, or desired speed, of this roadway segment is between 55 mi/h (88.55 km/h) and 75 mi/h (120.75 km/h), even though the speed limit of this segment is 55 mi/h (88.55 km/h).



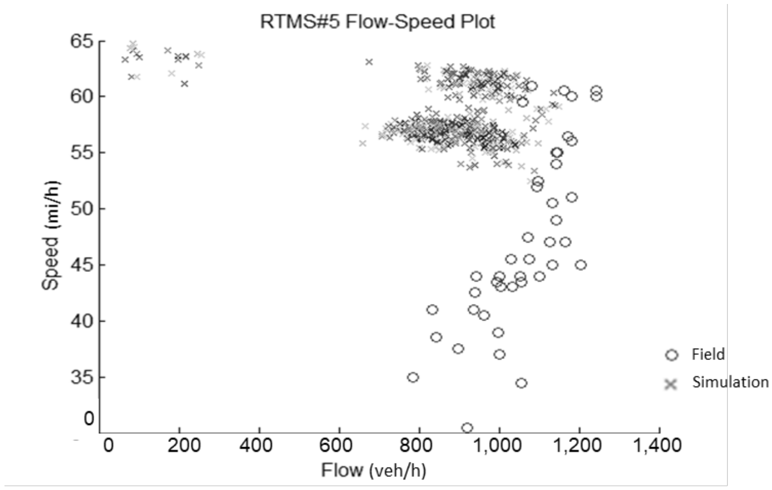
Source: FHWA. Data from Hale et al. (2020).

A. Calibration results for interchange 1 speed-flow curves.



Source: FHWA. Data from Hale et al. (2020).

B. Calibration results for interchange 3 speed-flow curves.

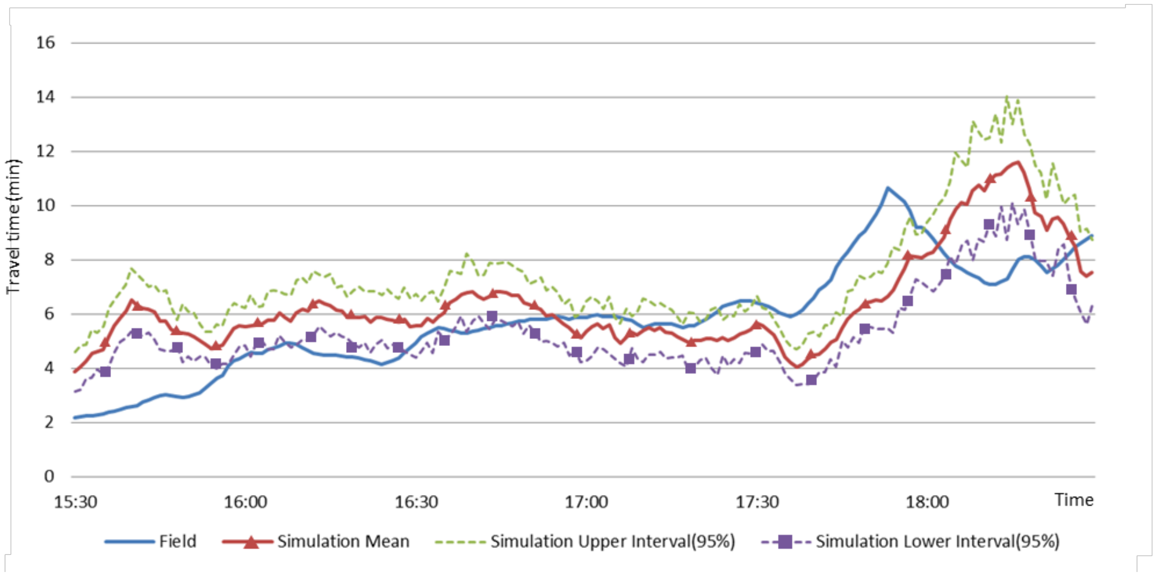


Source: FHWA. Data from Hale et al. (2020).

C. Calibration results for interchange 5 speed-flow curves.

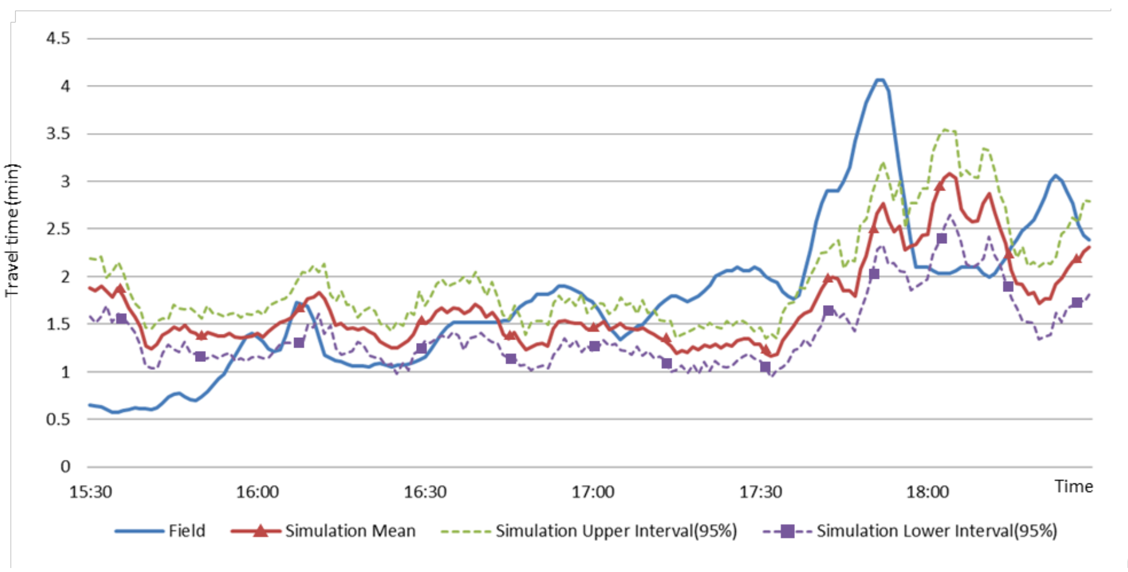
Figure 7. Graph. Calibration results for speed-flow curves.

Figure 8 provides two examples of simulation model validation using INRIX travel-time data. The travel-time ranges used in the simulation were generated from different simulation runs using different random seeds to account for the stochasticity of demand and driving behavior. The data indicate that the simulated travel times match the field data well with an average absolute percent error less than 15 percent.



Source: FHWA. Data from Hale et al. (2020).

A. Calibration results for TMC 110+01476 speed and travel times.



Source: FHWA. Data from Hale et al. (2020).

B. Calibration results for TMC 110P01476 speed and travel times.

Figure 8. Graph. Calibration results for speed and travel time.

MODELING CHANGES TO REPRESENT CAV APPLICATIONS

This section introduces the three CAV applications' algorithm design and implementation. The section also refers to the literature or sensitivity analysis through simulation runs to discuss how the key algorithm parameters were selected.

CACC/Platooning

A successful CACC operation can help individual CACC-equipped vehicles form stable strings and maintain the string throughout a highway corridor. The car-following behavior of CACC-equipped vehicles is significantly different from the behavior of humans in that the CACC-equipped vehicle is able to follow the preceding vehicle safely with a much smaller gap than a human-driven vehicle can safely keep, while reducing fuel consumption, emissions, and increasing efficiency.

This study adopted the CACC framework concept developed by Milanés and Shladover (2014) and Liu et al. (2018). It also incorporated the most recent results from the FHWA Exploratory Advanced Research Program project (FHWA 2015). The proposed framework is for simulation purposes; it can be used to demonstrate a state-of-the-art strategy for CACC operation. The CACC logic implemented on vehicles in real time can be a variation of this framework with different control components added. Liu et al. (2018) also considered multilane highway operations using CACC. However, this study focused on the car-following behavior of CACC operations at early stages of deployment, and therefore the lateral behaviors are considered the same as human-driven behaviors.

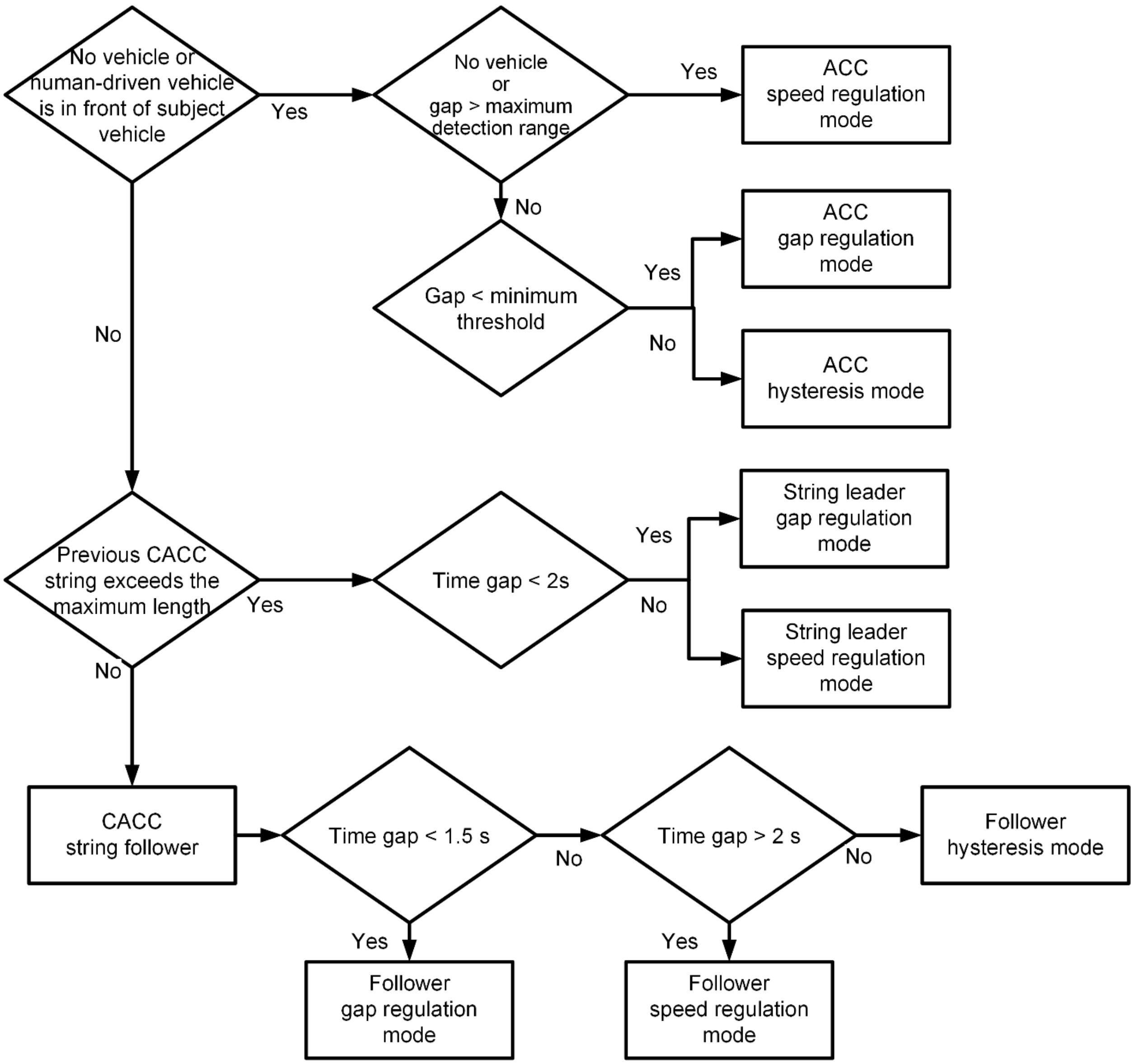
For this study, as figure 9 shows, the algorithm will determine whether the target vehicle is a CACC string leader or follower, then it will decide the target vehicle's desired speed and acceleration. The target CACC vehicle will be the string leader if the preceding vehicle is neither a CACC vehicle nor a CV, if the time gap from the preceding vehicle is greater than 2 s, or if the preceding CACC string has reached the maximum string length. Otherwise, it will be a string follower.

Note that this study uses the term CACC string in most cases to indicate that the vehicles rely on V2V communication to follow each other closely and stably. In some cases, the word platoon is used when a more sophisticated, hierarchical control of the string, in addition to close following, exists. For example, the platoon leader (and/or members) will negotiate with the merge vehicle to create gaps to facilitate the merge.

CACC Algorithm Design

To design the algorithm, this study adopted the ACC and CACC car-following models developed in Milanés and Shladover (2014). These simplified models were implemented because of the need for computational efficiency when simulating many CACC-equipped vehicles in a complex environment.

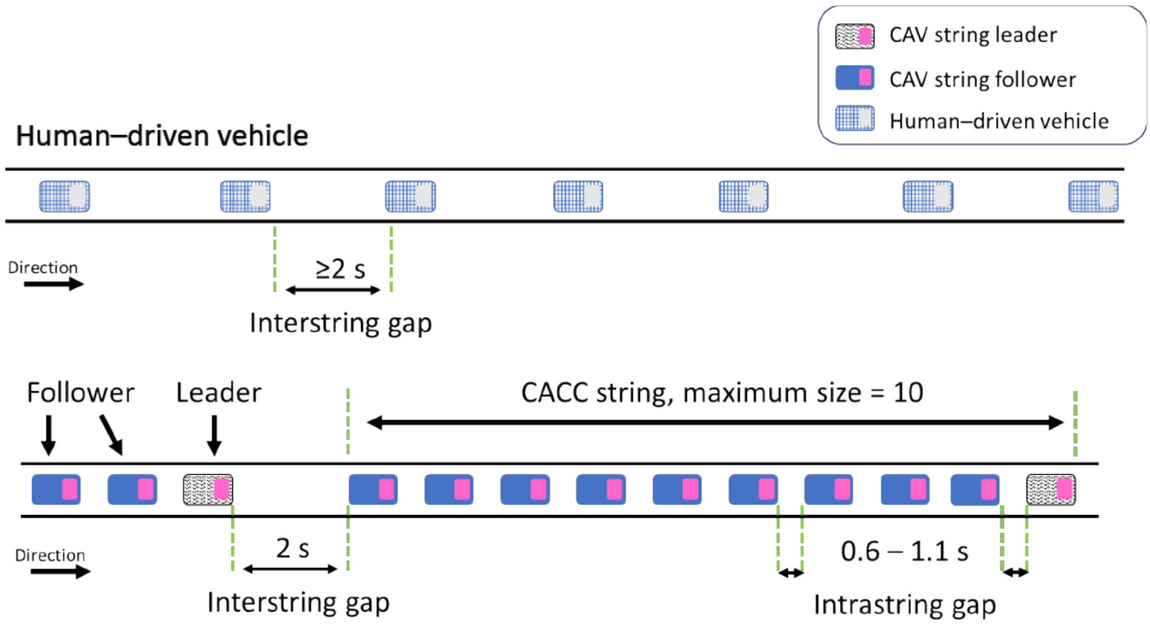
As noted in the last section, the car-following behavior of CACC-equipped vehicles is significantly different from that of human-driven vehicles because CACC-equipped vehicles can follow the preceding vehicle with a much smaller gap. CACC-equipped vehicles can switch off CACC either to leave the current CACC string or to execute a lane change. Although CACC system implementation relies on information received from the leading vehicle in the CACC string and 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. The modeling framework for CACC vehicles is highlighted in figure 9.



Source: FHWA.

Figure 9. Diagram. Car-following logic for CACC-equipped vehicles.

Figure 10 provides an illustration of the CACC string simulated in this study. The detailed following behavior between CAVs and human-driven CVs is described in the rest of this section.



Source: FHWA.

Figure 10. Illustration. CACC platooning logic.

As shown in figure 9, if the preceding vehicle is not a CACC-equipped vehicle or a CV, the target vehicle becomes the CACC string leader and enters the ACC car-following mode. The ACC controller determines the car-following rule according to the clearance distance between the target vehicle and the preceding vehicle. If the distance is larger than the maximum threshold (e.g., 393.7 ft (120 m)), then the preceding vehicle is beyond the onboard sensors' detection range, so the ACC controller will apply the speed regulation mode, which is obtained by 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., 328.08 ft (100 m)), the ACC controller will turn on the gap regulation mode and help the subject vehicle follow the motions of the preceding vehicle. The gap regulation mode is obtained by equation 2:

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

Where:

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

k_3 = gain in the speed difference between the preceding vehicle and the subject vehicle (k_3 = 0.07 s^{-1} 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 controllers, which is drawn from the time gap distribution selected by the ACC drivers in the field test described in Nowakowski et al. (2010): 31.1 percent of the vehicle following time at 2.2 s; 18.5 percent at 1.6 s; and 50.4 percent at 1.1 s.
L = length of the preceding vehicle (m).
v_l = current speed of the preceding vehicle (m/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. In doing so, a hysteresis in the control loop will be introduced such that the ACC controller can perform a smooth transfer between the speed regulation mode and gap regulation mode.

If a subject vehicle is a CACC string leader and the preceding vehicle is a CACC vehicle in another CACC string, the subject vehicle may implement either of the following 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 speed regulation mode, which is represented by equation 1. If the time gap is less than 2 s and the preceding CACC string is operating at the maximum allowable string length, the subject vehicle will use one of the following two string leader gap regulation modes as shown in equation 3 and equation 4:

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

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

Where:
t = current time (s).
Δt = time step for each update (s).
k_p and k_d = gain in adjusting the time gap between the subject vehicle and preceding vehicle (k_p = 0.45 s^{-1} and k_d = 0.0125).
e_k = time gap error, which is obtained by equation 5.
$\dot{e}_k$ = derivative of time gap error, which is obtained by equation 6.

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

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

Where t_1 is the constant time gap between the last vehicle of the preceding CACC string and the subject vehicle (t_1 = 1.5 s, this is the time gap that has been chosen for use in this study after evaluating alternative value effects).

If the subject vehicle is a CACC string follower, the vehicle may engage two possible car-following modes. The controller will implement the in-string follower gap–regulation mode if the time gap from the preceding vehicle is less than 1.5 s. The in-string follower gap–regulation mode uses the algorithm represented by equations 3 through 6, with a minor adjustment of replacing t_1 with the intrastring constant time gap (t_2). In this study, t_2 = 0.6 s was chosen to generate homogeneous intrastring-following behavior. 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 s and 2 s, the subject vehicle will use the hysteresis control rule, which applies the car-following mode implemented in the previous time step. In this study, for the purpose of forming a CACC string with the desired following gap, CACC-equipped vehicles were allowed to temporarily exceed the desired speed by up to 10 percent to catch up to preceding vehicles.

The forward collision warning algorithm developed by the Collision Avoidance Metrics Partnership (CAMP) is included in the 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 and is obtained by 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 ζ is a binary variable.

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

Where:

d_{REQ} = deceleration required to avoid a rear-end collision (g).
d_l = deceleration of the preceding vehicle (g).

The required deceleration from this empirical function represents the comfortable deceleration speed the subject driver may choose to avoid a collision with the preceding vehicle given the vehicle's relative speed and d_l. If d_{REQ} is larger than zero, the subject vehicle does not need to brake and the gap is sufficient. If d_{REQ} is less than zero and the preceding vehicle stops prior to the subject vehicle, the required following gap to avoid a rear-end collision (g_{REQ}) is obtained by equation 9:

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

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

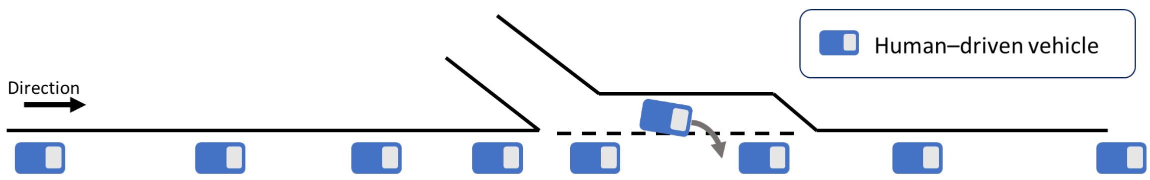
$$g_{REQ} = max\left(0, \frac{(v_{sv} - v_l)^2}{-2 \cdot (d_{REQ} - d_l)}\right) \tag{10}$$

When the current gap is smaller than g_{REQ}, the calculation 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 calculate a desired deceleration speed using the human driving model to avoid the crash.

In this study, the project team chose a maximum string length of 10 vehicles as a benchmark, as recommended in Liu et al. (2018). Shorter string lengths result in more CACC 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 strings lead to less versatility since they make merging more difficult for other vehicles.

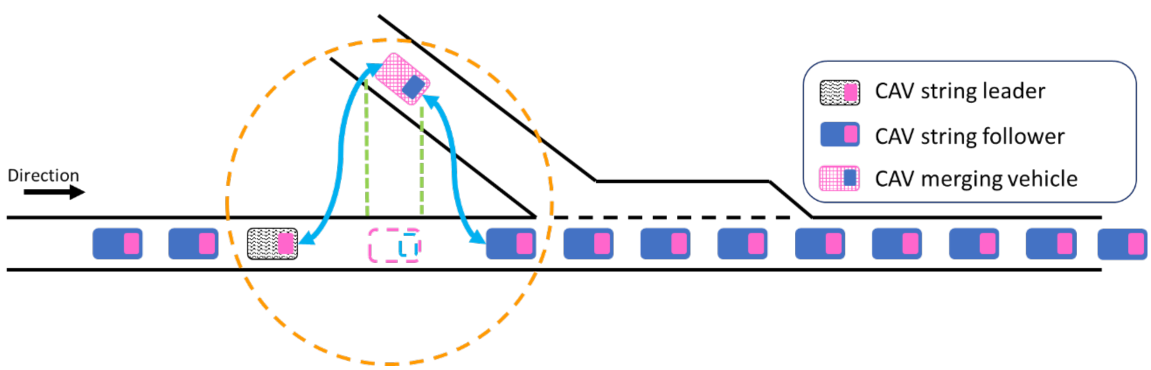
Cooperative Merge

Cooperative merge aims to cooperatively operate both mainline vehicles and merging vehicles to create qualified gaps at merging areas through V2V or V2I communications. Figure 11 illustrates a conceptual cooperative merge representation. Figure 11-A shows a base merging scenario in which mainline vehicles travel in a certain traffic state dependent on demand level and the gaps among them follow a random distribution. Figure 11-B shows the mainline vehicle configuration that changes when cooperative merge is activated and the system is trying to create gaps for merging vehicles. When a vehicle requests to merge or is detected, the mainline vehicles will create a gap to allow the merging vehicle into the mainline. Gap creation relies on the situations described in the following sections, such as mainline vehicles cooperatively changing lanes or slowing down to create qualified gaps.



Source: FHWA.

A. Regular merge.



Source: FHWA.

B. Cooperative merge.

Figure 11. Illustration. Cooperative merge versus regular merge.

Cooperative Merge Algorithm Design

The algorithm process uses many parameters, and their values have been determined by selecting those that generated the best system performance during initial simulation runs on both a simplified network and an actual network (I–66). Additionally, the algorithm detailed in the rest of this section can be applied in a V2V or I2V environment. However, since the communication range of DSRC is short (i.e., 984.3 ft (300 m)), an I2V approach through which roadside infrastructure can facilitate the cooperative merge process by allowing the cooperation process to start earlier is recommended to reach a higher level of benefit (Harding et al. 2014; Bettisworth et al. 2015). When a merging vehicle intends to merge into the mainline, there are four scenarios that will activate the cooperative merge, as described in the next four sections.

Case 1

As shown in figure 12-A, vehicle B is on the target lane in front of the merging vehicle (vehicle A). If vehicles A and B have a similar speed (i.e., small speed difference (Δv)), vehicle A will slightly slow down and merge into the mainline. In this study, the range of speed difference is −1.0 m/s (−3.3 ft/s) < Δv < 0.1 m/s (0.3 ft/s) and in this case the deceleration rate of vehicle A is a constant value of −0.5 m/s^2 (−0.16 ft/s^2).

Case 2

As shown in figure 12-B, if vehicle A intends to merge into the mainline and vehicle B in the target lane is behind vehicle A, then the system will advise vehicle B to cooperatively move over to the adjacent lane to create a safe and acceptable gap into which vehicle A can merge. This cooperative merge will activate if the following conditions are met:

- The new lane will not affect vehicle B's ability to complete its original route.
- The difference between vehicle A's speed (v_A) and vehicle B's speed (v_B) (Δv_{AB}) is less than the maximum speed difference (Δv_{max}), where $\Delta v_{AB} = v_A - v_B$. In this study, Δv_{max} = 10.8 km/h (6.7 mph) (i.e., 3 m/s (9.8 ft/s)).
- The collision time does not exceed the maximum collision time (t_σ), and v_B has increased less than Δv_{max}. In this study, t_σ = 10 s, per Vissim's recommendations (PTV Group 2019).

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

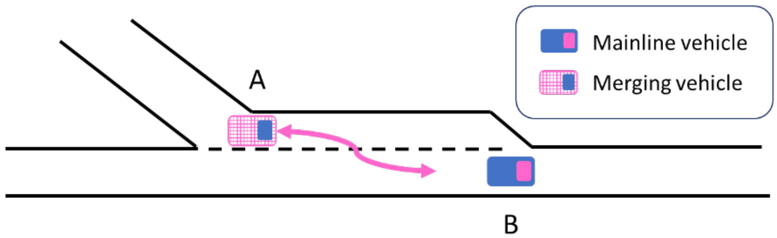
Case 3

As shown in figure 12-C, vehicle A on the on-ramp intends to merge into the mainline, and vehicle B in the mainline is behind vehicle A. In this case, vehicle B will slow down to create an acceptable gap to let vehicle A merge into the mainline from the on-ramp. Meanwhile, the following vehicle C will also cooperatively slow down to keep a safe following distance from vehicle B. Vehicles B and C can either be independent vehicles or part of a CACC platoon.

Case 4

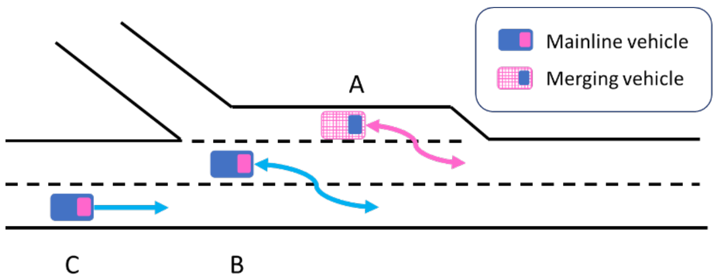
Figure 12-D shows another situation in which vehicle A requests to merge into traffic from the on-ramp, but vehicle B in the mainline is too close to slow down. In this case, vehicle B will

keep its speed. The following vehicle C will slow down and let vehicle A merge into the mainline.



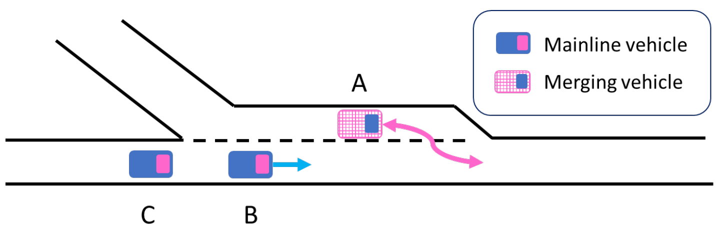
Source: FHWA.

A. Cooperative merging case 1.



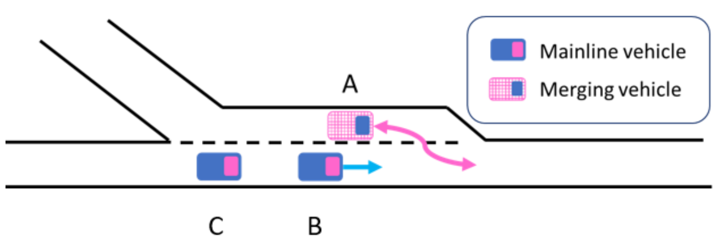
Source: FHWA.

B. Cooperative merging case 2.



Source: FHWA.

C. Cooperative merging case 3.



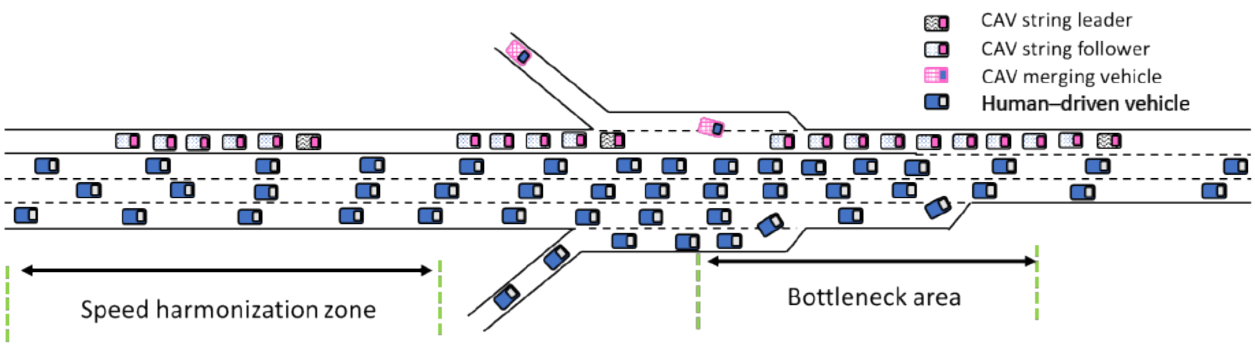
Source: FHWA.

D. Cooperative merging case 4.

Figure 12. Illustration. Different cooperative merging cases.

Speed Harmonization

This study adopts the segment-based I2V speed harmonization as proposed by Hale et al. (2016). As shown in figure 13, when imminent or existing congestion at a bottleneck is detected, the upstream CAV should slow down moderately and pass the bottleneck smoothly at a reasonable speed just as the downstream queue dissipates, thus avoiding hitting the downstream queue at a sudden full stop. This speed harmonization strategy not only smooths the CAV's trajectory but also helps any type of following vehicles on the mainline to move in a similarly smooth manner. As a result, the platoon of vehicles following the lead CAV will pass the bottleneck with a larger throughput rate due to the reduced time headway at high speeds—with less fuel consumption due to smoothed trajectories and less collision risk due to harmonized vehicle speeds (Guo et al. 2019).



Source: FHWA.

Figure 13. Illustration. Speed harmonization.

In the case of a downstream speed drop, if congestion is moderate, the algorithm will seek to smooth the traffic, let the queue dissipate, and then allow the following CAVs to pass the bottleneck smoothly at a reasonable speed. Otherwise, if traffic is too congested and the queue does not show the ability to dissipate in a short period of time, the CAVs will guide the upstream traffic to slow down and smoothly join the downstream queue to avoid hitting the queue at a sudden full stop.

Speed Harmonization Algorithm Design

Traffic and queue status can be captured either by traffic sensors located downstream of the traffic or by data collected by roadside units sent from vehicles equipped with onboard units. The algorithm records all sensor information to obtain traffic conditions and generates and distributes recommended speeds to CVs and CAVs through V2I communication.

This study adopts a speed-based approach for segment-based speed–command generation (Hale et al. 2016). The speed-based algorithm determines advisory speeds for freeway segments upstream and downstream of a known bottleneck location based on measured speeds within the bottleneck area. The speed-based algorithm is intended to increase throughput and prevent bottleneck formation. Traffic detectors are assumed to be available at bottleneck locations to monitor the real-time traffic condition to calculate the arithmetic mean of speed and occupancy of the past 3 min at these locations. Within a bottleneck area, the speed-based algorithm tends to generate advisory speeds 10 to 50 percent greater than measured bottleneck speeds. This approach does not claim system optimization yet emphasizes simplicity and practical field implementation. The approach applies a simple linear algorithm to generate the recommended speed, as shown in equation 11:

$$u_m(k) = \alpha_m \times \bar{v}_m(k) \tag{11}$$

Where:

$u_m(k)$ = recommended speed at time step k (usually different from time step t in platooning operations since each uses a different time interval) in bottleneck area m, $u_m(k)$ is no greater than the speed limit in bottleneck area m.

α_m = proportional control gain in bottleneck area m for bottleneck traffic, where $\alpha_m \in [1.1, 1.5]$; in this study $\alpha_m = 1.3$.

$\bar{v}_m(k)$ = measured arithmetic mean of speed at time step k in bottleneck area m.

Additionally, when an imminent or existing congestion is detected, this algorithm generates a lower recommended speed than $\bar{v}_m(k)$ to smooth the upstream traffic. This algorithm is triggered by the measured occupancy of the bottleneck area ($o_m(k)$), as shown in equation 12:

$$u_{m+1}(k) = \begin{Bmatrix} v_f & if\ o_m(k) < \sigma_{sw} \\ \beta_m \times \bar{v}_m(k) & if\ o_m(k) \geq \sigma_{sw} \end{Bmatrix} \tag{12}$$

Where:

$u_{m+1}(k)$ = the recommended speed at time step k in section $m + 1$ (the upstream segment), $u_{m+1}(k)$ is no less than 80 percent of the speed limit in section $m + 1$.

β_m = proportional control gain in bottleneck area m for upstream traffic, where $\beta_m \in [0.7, 0.9]$; the default value is 0.8.

σ_{sw} = switch threshold of occupancy close to the critical occupancy (o_{cri}) (i.e., $\sigma_{sw} = 1 - o_m(k) / o_{cri}$) in bottleneck area m, where $\sigma_{sw} \in [0.1, 0.125]$; in this study $\sigma_{sw} = 0.125$.

In a legacy algorithm of speed harmonization for human-driven traffic, the value of o_{cri} in the bottleneck area m stays constant as a basic attribute of the traffic stream (Hale et al. 2016). With CAV traffic, however, o_{cri} varies depending on the CAV market penetration rate because the fundamental diagrams shift with different market penetration rates. In this study, initial simulation runs were conducted to obtain the capacity and critical density values under different CAV market penetration rates.

OPERATIONAL ALTERNATIVES

Infrastructure Scenarios

Prior to the study, the project team worked with representatives from VDOT and identified three scenarios that model and analyze infrastructure. These three scenarios attempted to illustrate the benefits VDOT anticipates from early CAV deployments. The main idea is to convert the existing HOV-2 lane on I–66 into the ML that also allows CVs and CAVs to access the lane. Different from the CAV-dedicated ML in Liu et al. (2018), this case study investigated a CV- and CAV-eligible HOV lane, meaning that CVs and CAVs can access the existing HOV lane, even if the vehicles are SOVs. Any HOVs—human-driven or CVs and CAVs—can still access the MLs. Therefore, this case study investigated the mixed-traffic scenario where human-driven vehicles, CVs, and CAVs may coexist on any part of the network. Although the existence of human-driven traffic on MLs may negatively impact the CAV traffic performance, the mixed-traffic condition in this case study is considered more realistic in the short run. The mixed traffic will allow early deployment of CAVs to be directly incorporated into the DOT's network without sacrificing the benefits for important network users, particularly HOVs.

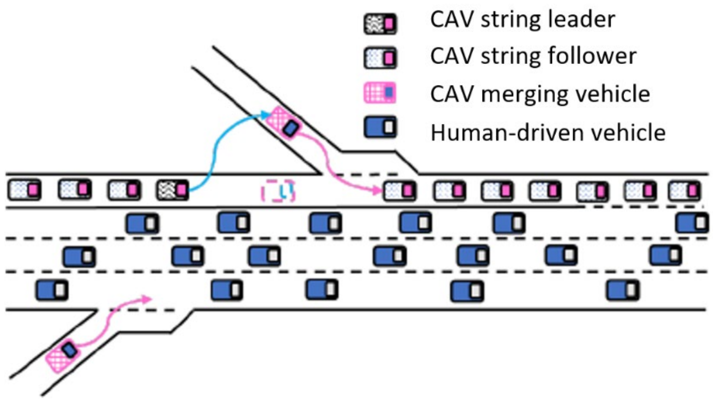
Another infrastructure component of interest is the left side–dedicated ramps connected to the ML. Because more vehicles will have access to the left-side ML, vehicles may make multiple lane-change maneuvers to access the ML, thereby creating a man-made weaving section that can reduce highway capacity and increase safety risks. Dedicated ramp construction can reduce such negative effects and is considered part of the CAV infrastructure strategy.

The following three scenarios are illustrated in figure 14:

- ML 1 has the following key features:
    - Dedicated ramp for HOVs, CVs, and CAVs.
    - Existing one-lane ML for HOVs, CVs, and CAVs.
    - Ramp access on both sides for HOVs, CVs, and CAVs.

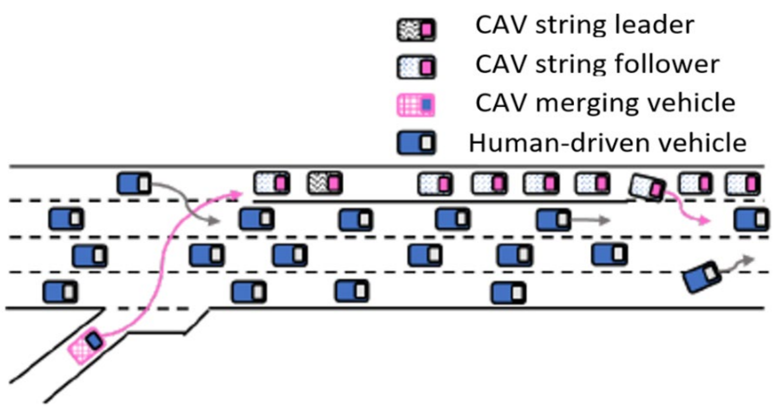
- ML 2 has the following key features:
    - Existing ramp for all vehicles.
    - Existing one-lane ML for HOVs, CVs, and CAVs.

- ML 3 has the following key features:
    - Existing ramp for all vehicles.
    - Existing one-lane ML for HOVs only.



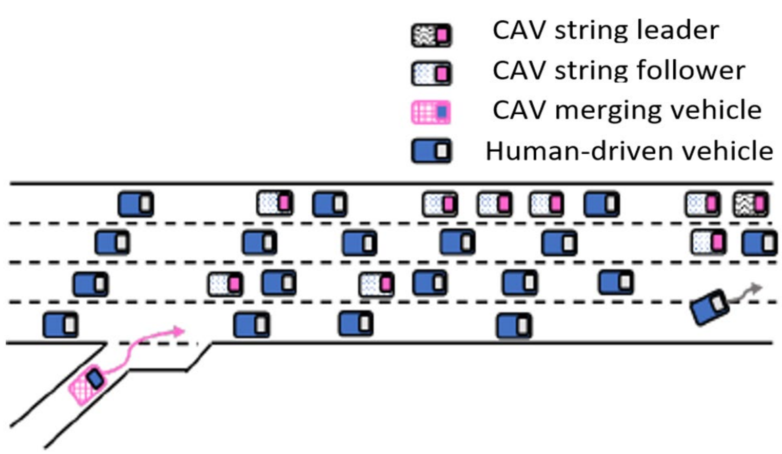
Source: FHWA.

A. ML 1.



Source: FHWA.

B. ML 2.



Source: FHWA.

C. ML 3.

Figure 14. Illustration. Three ML operational scenarios.

CAV Technology Scenarios

As indicated previously, the project team evaluated three CAV technologies: CACC/platooning, speed harmonization, and cooperative merge. The three applications were applied independently and bundled together to evaluate potential extra system benefits. The technology scenarios include the following combinations:

- CACC only.
- Speed harmonization only.
- Cooperative merge only.
- CACC and speed harmonization.
- CACC, speed harmonization, and cooperative merge.

System Parameters

In this case study, multiple system parameters were varied to evaluate the effectiveness of CAV technological and infrastructure scenarios under different background settings. First, to evaluate future congested traffic conditions, two demand scenarios were considered: the 100 percent–demand level and the 130 percent–demand level.

Different market penetration rates for CVs and CAVs were also factored into the scenarios. The CV market penetration rates included 0, 33, 67, and 100 percent. The CAV market penetration rates included 0, 25, 50, and 100 percent. In this study, CAVs were considered a subset of CVs, and therefore the percentage of CAVs is always smaller than or equal to CVs under any given scenario.

There are a total of 220 scenarios with the proposed CAV technological and infrastructure scenarios and different system parameters. Also, five random seeds in the simulation were used for each of the scenarios to account for stochastic factors such as traffic demand arrival patterns and driving behavior. Therefore, a total of 1,100 simulation runs were conducted.

PERFORMANCE MEASURES

CAV technology and enhanced infrastructure deployment can systemically impact efficiency, safety, and the environment. This study focused on systemic performance and used three performance measures to quantify the enhanced traffic system performance.

Capacity and Fundamental Diagrams

Technically, capacity is an attribute of the highway rather than a performance measure. However, the capacity of the highway, as well as the fundamental diagrams, may change dynamically in the new traffic and roadway environment with different CAV technologies and CV and CAV market penetration rates. Therefore, it is critical to quantify the updated capacity and critical density values (before traffic breakdown) to better understand system attributes and thus enable better decisionmaking.

Total Network Throughput

Throughput has been traditionally used to quantify transportation corridor or network performance. Considering the nature of the analysis, this study adopted total network throughput during the entire simulation period. This performance quantifies the network's capability to meet traffic demand.

Total Network Delay

Delay has also been widely used to quantify transportation corridor or network performance. Considering the nature of the analysis, this study considered the total network delay during the entire simulation period. This performance quantifies the extent of congestion throughout the network. Total network delay can also be used to quantify the cost of delay using selected time values among travelers for future cost–benefit analysis.

CHAPTER 5. SIMULATION AND RESULTS

Chapter 5 describes the simulation results for the different scenarios, including statistical analysis of the simulation data and visualization of the simulation results. It also discusses the implications for CAV deployment at this site.

DESIGN OF SIMULATION EXPERIMENTS

Chapter 4 illustrated different infrastructure and CAV technology scenarios in this case study. These scenarios were identified in consultation with representatives from VDOT to ensure that the evaluated deployment scenarios realize the benefits VDOT anticipates from early CAV deployments.

The research team evaluated single CAV applications and selected combinations of CAV applications under different infrastructure scenarios. For the purpose of simulating stochastic factors, the team used five random seeds for each of the scenarios. Therefore, a total of 1,100 simulation runs were conducted. The Simulation Results section documents and analyzes these results.

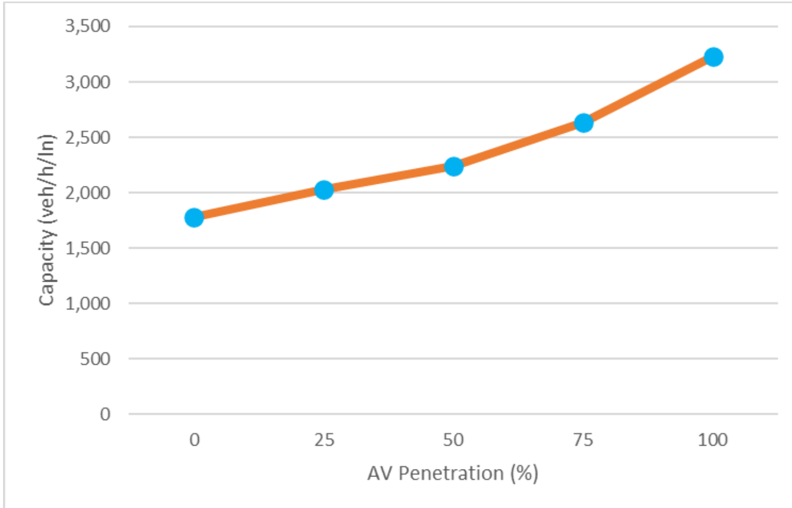
SIMULATION RESULTS

Analysis 1: CACC Pipeline Capacity

Since this study assessed five different CAV market penetration levels of 0, 25, 50, 75, and 100 percent, it estimated the CACC pipeline capacity under each of those different market penetration percentages. The capacity values are particularly useful for the speed harmonization algorithm, for which the system's critical density values need to be specified under different scenarios.

Capacity was tested on a 7-mi (11.26-km)-long simplified freeway segment with four lanes. In the capacity test simulation, the maximum platoon size was 10 vehicles. The interstring gap was 1.5 s, and the intrastring gap was 0.6 s (Liu et al. 2018). To generate different conditions, the traffic input demand varied from 1,400 vehicles per hour per lane (veh/h/ln) to 4,000 veh/h/ln. The data were collected every 15 min after a simulation warmup period of 15 min. Capacity was represented as four times the maximum 15-min volume collected from all simulation runs for one market penetration scenario.

As shown in figure 15, the results demonstrate a significant increase in capacity corresponding to the increase in CAV market penetration. The benchmark capacity is 1,780 veh/h/ln, and the maximum CACC pipeline capacity is around 3,227 veh/h/ln, an increase of 81.2 percent. At CAV market penetration rates of 25, 50, and 75 percent, capacity increased by 14.0, 25.9, and 48.0 percent, respectively.



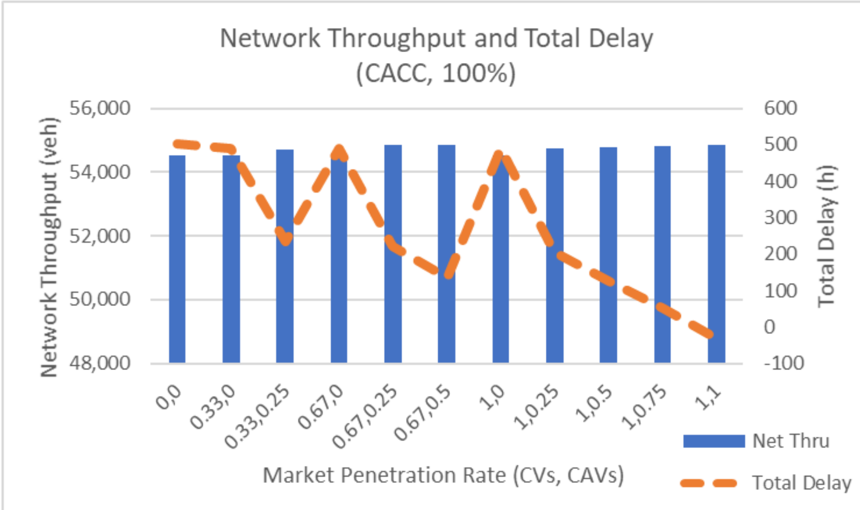
Source: FHWA.

Figure 15. Chart. CACC pipeline capacity under different market penetration rates.

Analysis 2: CACC, Speed Harmonization, and Cooperative Merge

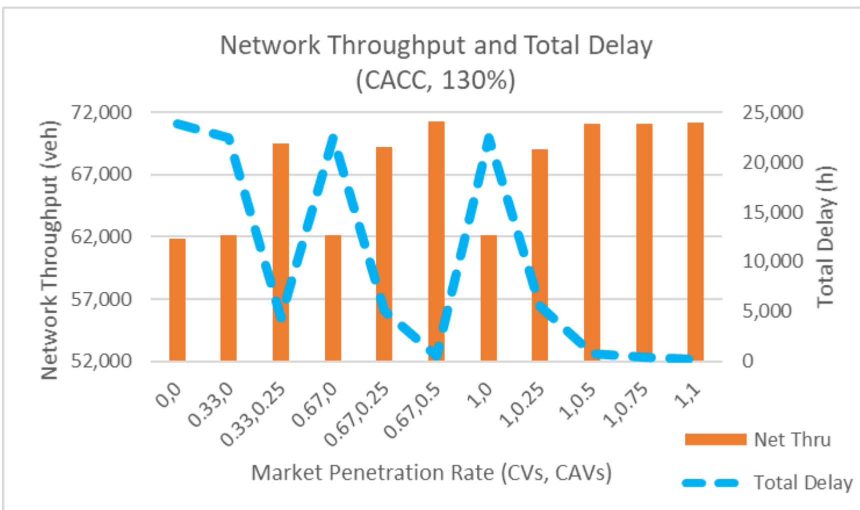
The analysis in this and the subsequent chapter 5 sections were all conducted on the I–66 calibrated network. as shown in figure 16, CACC implementation can significantly improve traffic performance in terms of both throughput and delay. At a 100 percent–demand level, the increasing trend of throughput was not obvious, but the reduction in delay was significant. At a 130 percent–demand level, the increasing trend of throughput was obvious when the CAV market penetration increased from 0 percent to 50 percent. From 50 percent to 100 percent, the throughputs did not change significantly as CAV market penetration increased because the input volume was less than the corresponding mixed traffic's capacity. The descending trend in delay is significant for both demand levels mainly because CACC can form CAV strings with small gaps, maximizing the use of the existing facility and reducing disturbances or oscillations in traffic flow. CACC platoons are also capable of stabilizing traffic flow due to their unique control algorithms and faster, smoother responses to the lead vehicle's speed changes.

In all the graphs in this chapter, the horizontal axis represents the CV and CAV market penetration rates. For example, (0.33, 0.25) indicates that CVs make up 33 percent of all traffic and CAVs make up 25 percent. This means if there are 100 vehicles in the traffic stream, there are 33 CVs and 67 human-driven vehicles, and among the 33 CVs 25 vehicles are CAVs.



Source: FHWA.
Net Thru = network throughput; veh = vehicles.

A. CACC application performance at the 100 percent–demand level.



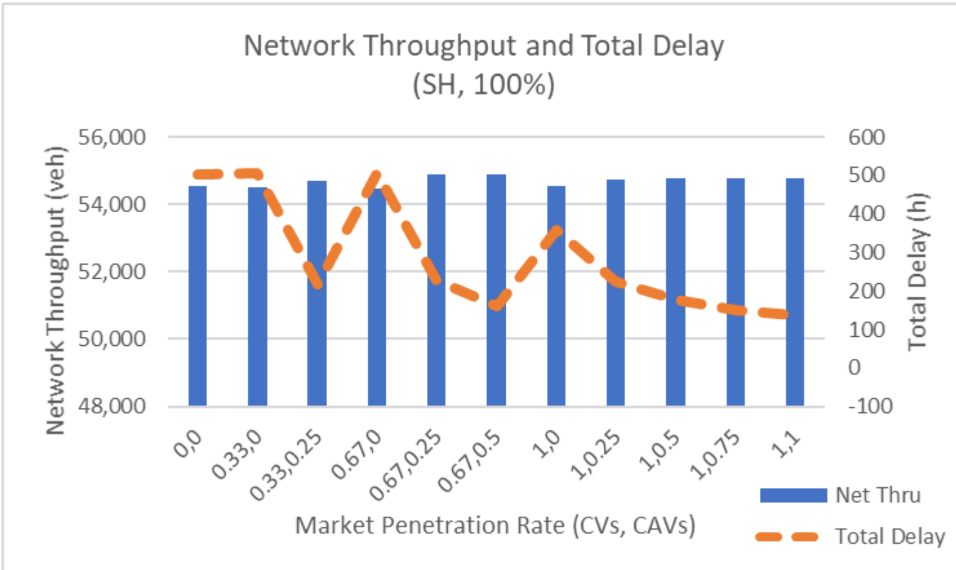
Source: FHWA.
Net Thru = network throughput; veh = vehicles.

B. CACC application performance at the 130 percent–demand level.

Figure 16. Chart. CACC application performance at different demand levels.

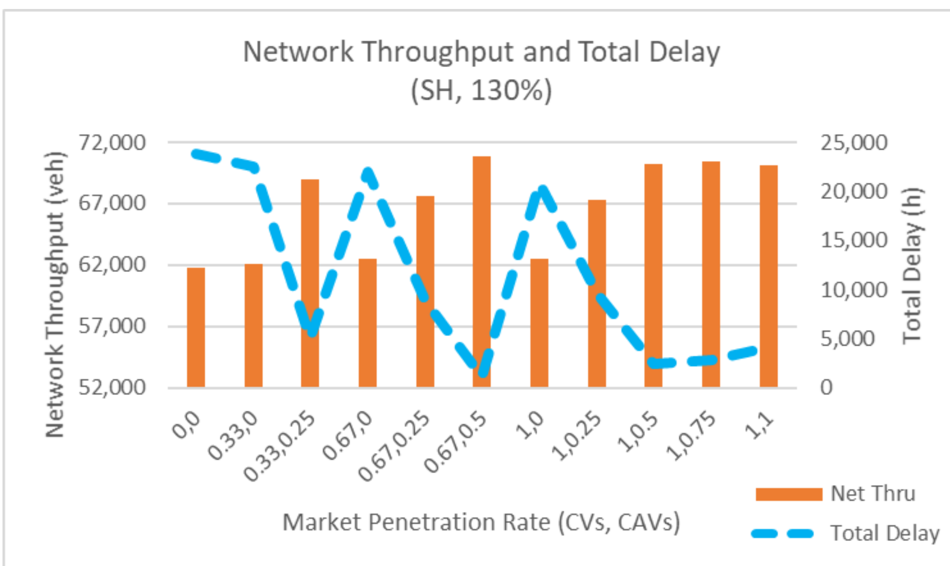
As shown in figure 17, speed harmonization can help reduce delay and increase throughput by smoothing upstream traffic and discharging existing queues at the bottleneck areas. Comparing the (0, 0), (0.33, 0), (0.67, 0), and (1, 0) cases, delay decreases as CV market penetration increases, but the throughput does not significantly change. As discussed previously, if the speed harmonization algorithms are not designed carefully, speed harmonization's slowdown effect may cause negative impacts in throughput and delay (FHWA 2016). When the CV market penetration rate is fixed and the CAV penetration rate increases, such as in (0.67, 0), (0.67, 0.25), and (0.67, 0.5), both throughput and delay decrease significantly, particularly in the 130 percent–demand case. This trend occurs mainly because CAVs assume the deterministic behavior of the

ACC/CACC mode and maintain relatively stable following distances with preset, deterministic inter- and intrastring gaps. As shown in figure 17, this stabilizing effect directly impacts traffic system performance.



Source: FHWA.
Net Thru = network throughput; SH = speed harmonization; veh = vehicles.

A. Speed harmonization application performance at the 100 percent–demand level.



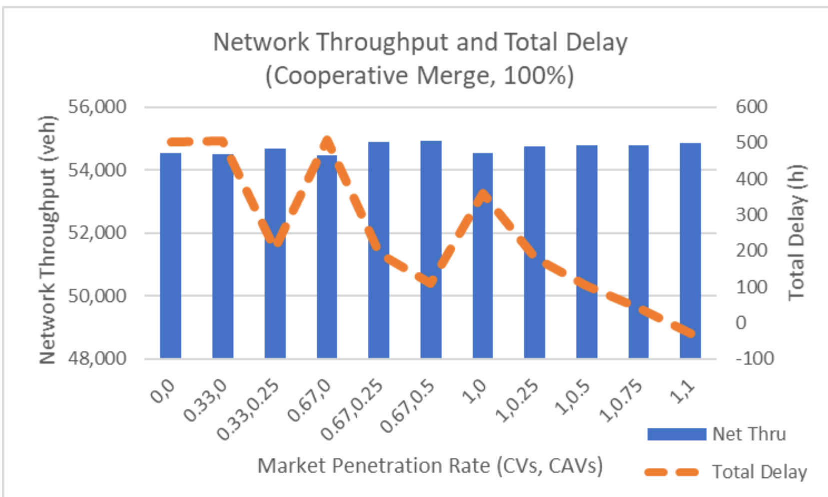
Source: FHWA.
Net Thru = network throughput; SH = speed harmonization; veh = vehicles.

B. Speed harmonization application performance at the 130 percent–demand level.

Figure 17. Chart. Speed harmonization application performance at different demand levels.

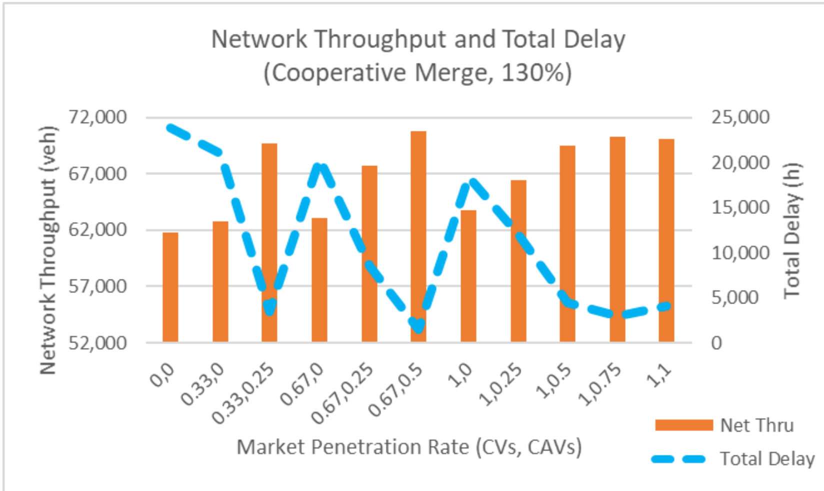
Cooperative merge facilitates traffic operations by creating gaps for merging vehicles. As shown in figure 18, cooperative merge also improves traffic performance in terms of delay and throughput. These results prove the effectiveness of the cooperative merge algorithm and the corresponding parameters in this study. However, if the parameters selected in the algorithm are not optimized, initial simulation runs show that gap creation may become too frequent, negatively impacting overall traffic performance.

There is an interesting phenomenon between cases (0.33, 0.25), (0.67, 0.25), and (1, 0.25). As was the case in figure 18-B, traffic performance worsens at the low AV market penetration rate (0.25) when CV market penetration increases. This phenomenon is a result of the study's cooperative merge application. As CV market penetration increases, more vehicles are eligible to cooperatively merge, and they then create gaps for on-ramp vehicles. Since CV driver behavior (i.e., manual driving behavior) is stochastic and incurs errors, the lane change, acceleration, and deceleration processes impact mainline traffic performance. However, this phenomenon disappears when the stabilizing effect of automated vehicle traffic flow—resulting from deterministic machine driving behavior coded in the ACC/CACC vehicle algorithms—causes high CAV market penetration.



Source: FHWA.
Net Thru = network throughput; veh = vehicles.

A. Cooperative merge application performance at the 100 percent–demand level.



Source: FHWA.
Net Thru = network throughput; veh = vehicles.

B. Cooperative merge application performance at the 130 percent–demand level.

Figure 18. Chart. Cooperative merge application performance at different demand levels.

Table 5 shows the results of CACC, speed harmonization, and cooperative merge application separately for ML 1 with 130 percent–demand level. CACC application performed better overall than the other two applications because CACC efficiently utilizes existing facility capacity and reduces mainline disturbances. There is no automation when AV penetration is 0 percent; in other words, the (0, 0), (0.33, 0), (0.67, 0), and (1,0) cases, and thus CACC was not applied. The results of these cases are regarded as base cases. There is a slight difference in traffic performance between (0, 0) and other 0-percent automated vehicle penetration cases. This difference is because, in the (0, 0) case, only HOVs—about 30 percent of total traffic volume—can use the ML and dedicated ramps. In other 0-percent automated vehicle penetration cases, about 50 percent of total traffic volume (including both HOVs and CVs) can use the ML and dedicated ramps. This rebalanced volume slightly relieves congestion in the merge area, resulting in a 0.5-percent throughput increase and 5.52-percent reduction in delay.

Table 5. Results of CACC, speed harmonization, and cooperative merge cases.*

Case (CV, CAV)	CACC Network TH (veh)	CACC Delay (h)	SH Network TH (veh)	SH Delay (h)	CM Network TH (veh)	CM Delay (h)
0, 0	61,828.00 (0.00%)	23,808.20 (0.00%)	61,828.00 (0.00%)	23,808.20 (0.00%)	61,828.00 (0.00%)	23,808.20 (0.00%)
0.33, 0	62,136.00 (0.50%)	22,495.15 (−5.52%)	62,133.00 (0.49%)	22,493.52 (−5.52%)	62,804.00 (1.58%)	20,963.30 (−11.95%)
0.33, 0.25	69,516.00 (12.43%)	4,367.58 (−81.66%)	69,020.00 (11.63%)	5,032.74 (−78.86%)	69,695.00 (12.72%)	3,412.22 (−85.67%)
0.67, 0	62,136.00 (0.50%)	22,495.15 (−5.52%)	62,491.00 (1.07%)	22,015.76 (−7.53%)	63,119.00 (2.09%)	20,395.98 (−14.33%)

Case (CV, CAV)	CACC Network TH (veh)	CACC Delay (h)	SH Network TH (veh)	SH Delay (h)	CM Network TH (veh)	CM Delay (h)
0.67, 0.25	69,248.00 (12.00%)	5,110.94 (−78.53%)	67,655.00 (9.42%)	8,828.23 (−62.92%)	67,774.00 (9.62%)	8,542.69 (−64.12%)
0.67, 0.5	71,237.00 (15.22%)	572.71 (−97.59%)	70,822.00 (14.55%)	1,172.15 (−95.08%)	70,758.00 (14.44%)	1,427.67 (−94.00%)
1, 0	62,136.00 (0.50%)	22,495.15 (−5.52%)	62,545.00 (1.16%)	20,864.48 (−12.36%)	63,743.00 (3.10%)	18,389.62 (−22.76%)
1, 0.25	68,988.00 (11.58%)	5,511.25 (−76.85%)	67,318.00 (8.88%)	9,558.41 (−59.85%)	66,416.00 (7.42%)	12,019.20 (−49.52%)
1, 0.5	71,047.00 (14.91%)	737.72 (−96.90%)	70,233.00 (13.59%)	2,475.64 (−89.60%)	69,556.00 (12.50%)	4,498.56 (−81.11%)
1, 0.75	71,093.00 (14.99%)	470.25 (−98.02%)	70,424.00 (13.90%)	2,793.13 (−88.27%)	70,273.00 (13.66%)	2,964.61 (−87.55%)
1, 1	71,166.00 (15.10%)	238.41 (−99.00%)	70,098.00 (13.38%)	4,116.97 (−82.71%)	70,064.00 (13.32%)	4,100.12 (−82.78%)

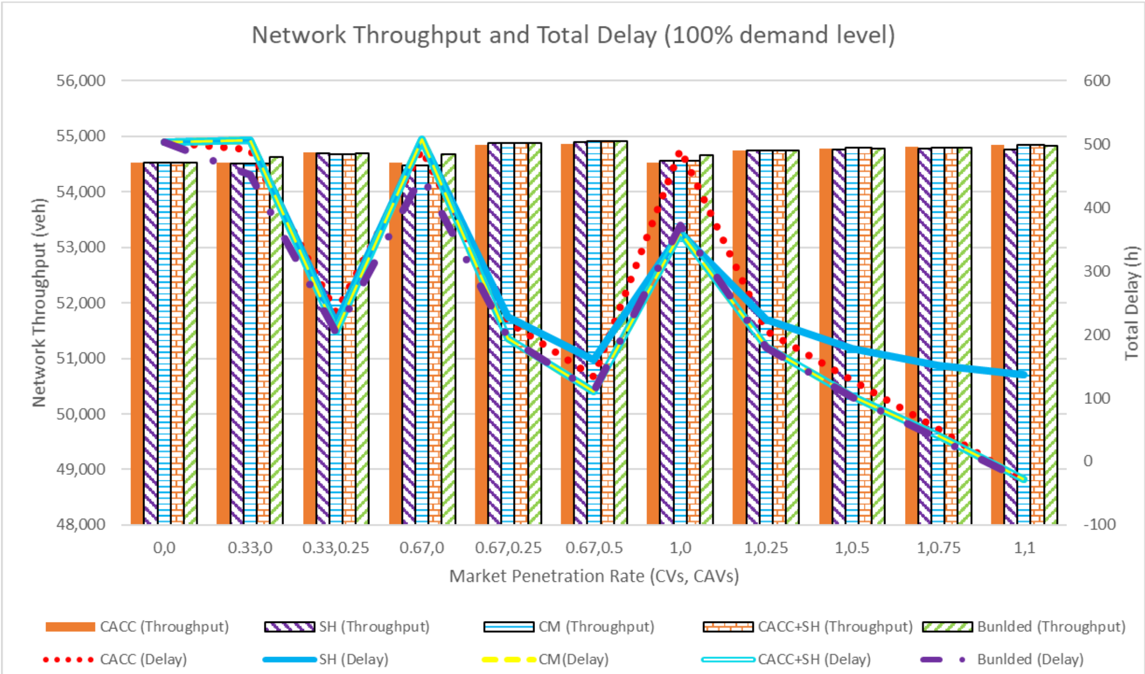
*All percentages (which appear in parentheticals) were calculated by comparing that cell's value with the (0, 0) case value of the same column,
CM = cooperative merge; Network TH = network throughput; SH = speed harmonization; veh = vehicles.

Analysis 3: Bundled CAV Application Performance

Figure 19 shows the comparison of traffic performance between the bundled and single CAV applications in ML 1. Unless otherwise specified, the term bundled is used to indicate the bundled application of all three CAV applications.

The additional benefits of combining multiple applications (i.e., bundling CACC with speed harmonization and cooperative merge) are not obvious in the 100 percent–demand level because the input traffic volume does not create as much congestion as it does in the 130 percent–demand level. As shown in figure 19-B, bundling CACC and speed harmonization can improve traffic performance further than by applying only CACC or speed harmonization. As table 6 and table 7 show, bundling CACC and speed harmonization can help increase throughput by 0.49 to 15.38 percent and reduce delay by 5.52 to 100.18 percent. The bundled application can improve throughput by 1.37 to 15.73 percent and reduce delay by 10.53 to 100.17 percent. The performance of the bundled application is better than CACC and speed harmonization combined only when CAV market penetration is less than 50 percent. When CAV market penetration is greater than 50 percent, longer CACC strings can be formed than are possible in the low CAV market penetration scenario, efficiently increasing the level of capacity the facility can support. Under low CAV market penetration conditions, the mainline is not congested and there are more qualified gaps for on-ramp vehicles to use, whereas there are fewer qualified gaps when the CAV market penetration is high.

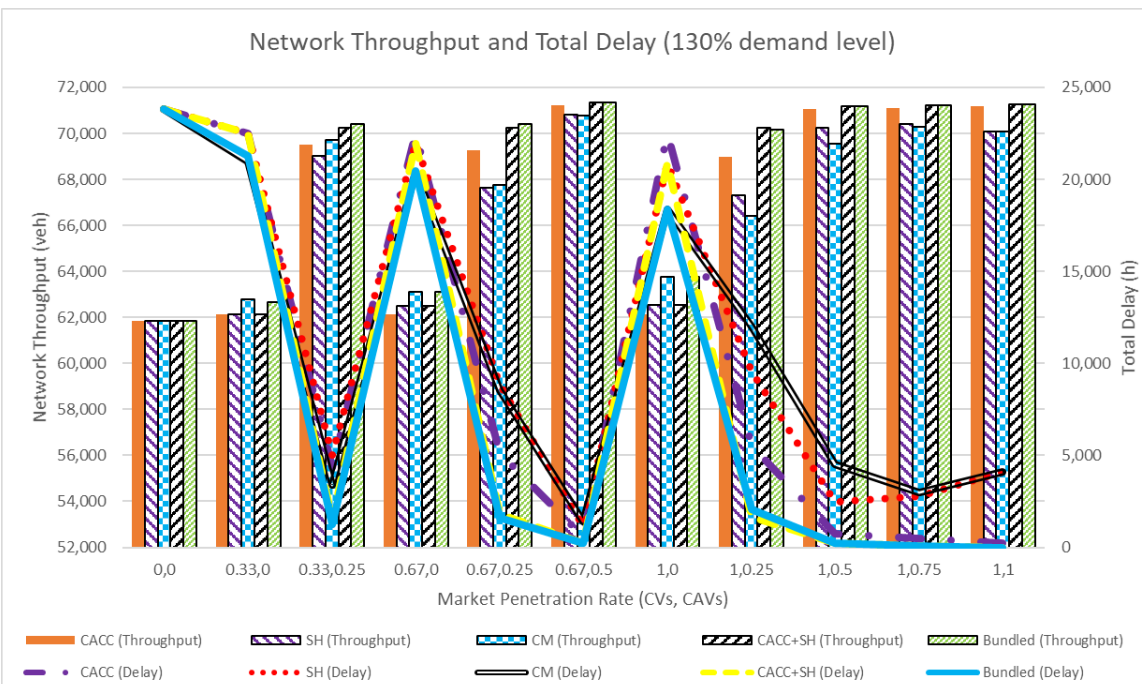
As shown in figure 20 and figure 21, MLs 2 and 3 have shown the same trends for both the 100 percent–demand and 130 percent–demand levels when the applications are compared with ML 1, and therefore their results are not discussed separately.



Source: FHWA.

CM = cooperative merge; SH = speed harmonization; veh = vehicles.

A. Performance comparison for ML 1 at the 100 percent–demand level.



Source: FHWA.

CM = cooperative merge; SH = speed harmonization; veh = vehicles.

B. Performance comparison for ML 1 at the 130 percent–demand level.

Figure 19. Chart. Performance comparison between single application and bundled applications, ML 1.

Table 6. Performance results of ML 1 at the 100 percent–demand level.*

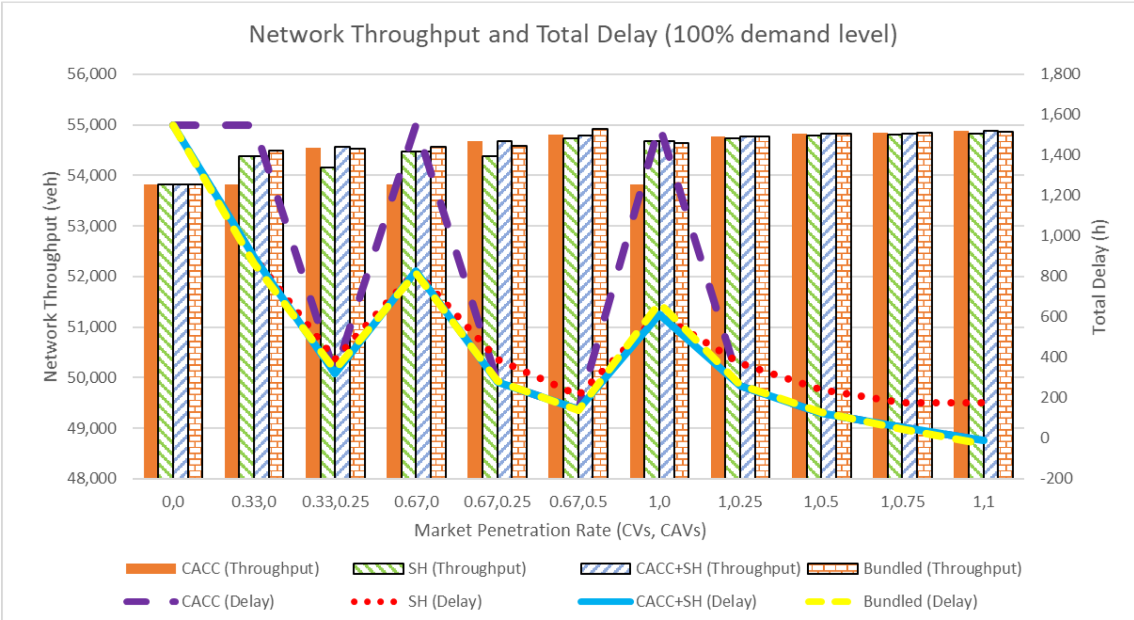
Case (CV, CAV)	CACC Network TH (veh)	CACC Delay (h)	SH Network TH (veh)	SH Delay (h)	CM Network TH (veh)	CM Delay (h)	Bundled** Network TH (veh)	Bundled** Delay (h)
0, 0	54,531.00 (0.00%)	503.52 (0.00%)	54,531.00 (0.00%)	503.52 (0.00%)	54,531.00 (0.00%)	503.52 (0.00%)	54,531.00 (0.00%)	503.52 (0.00%)
0.33, 0	54,530.00 (0.00%)	491.36 (−2.41%)	54,508.00 (−0.04%)	505.94 (0.48%)	54,508.00 (−0.04%)	505.94 (0.48%)	54,625.00 (0.17%)	452.03 (−10.23%)
0.33, 0.25	54,707.00 (0.32%)	234.94 (−53.34%)	54,690.00 (0.29%)	217.76 (−56.75%)	54,684.00 (0.28%)	204.78 (−59.33%)	54,685.00 (0.28%)	203.48 (−59.59%)
0.67, 0	54,530.00 (0.00%)	491.36 (−2.41%)	54,473.00 (−0.11%)	507.93 (0.88%)	54,473.00 (−0.11%)	507.93 (0.88%)	54,668.00 (0.25%)	450.51 (−10.53%)
0.67, 0.25	54,838.00 (0.56%)	220.40 (−56.23%)	54,883.00 (0.65%)	227.67 (−54.78%)	54,885 (0.65%).00	193.55 (−61.56%)	54,884.00 (0.65%)	195.76 (−61.12%)
0.67, 0.5	54,856.00 (0.60%)	134.34 (−73.32%)	54,895.00 (0.67%)	160.39 (−68.15%)	54,913.00 (0.70%)	110.67 (−78.02%)	54,910.00 (0.70%)	110.92 (−77.97%)
1, 0	54,530.00 (0.00%)	491.36 (−2.41%)	54,552.00 (0.04%)	360.15 (−28.47%)	54,552.00 (0.04%)	360.15 (−28.47%)	54,655.00 (0.23%)	371.98 (−26.12%)
1, 0.25	54,750.00 (0.40%)	206.10 (−59.07%)	54,749.00 (0.40%)	223.56 (−55.60%)	54,749.00 (0.40%)	180.71 (−64.11%)	54,750.00 (0.40%)	178.82 (−64.49%)
1 ,0.5	54,770.00 (0.44%)	127.44 (−74.69%)	54,764.00 (0.43%)	177.84 (−64.68%)	54,789.00 (0.47%)	102.75 (−79.59%)	54,783.00 (0.46%)	101.79 (−79.79%)
1, 0.75	54,810.00 (0.51%)	51.84 (−89.70%)	54,770.00 (0.44%)	151.92 (−69.83%)	54,795.00 (0.48%)	41.26 (−91.81%)	54,796.00 (0.49%)	37.05 (−92.64%)
1, 1	54,841.00 (0.57%)	−31.47 (−106.25%)	54,757.00 (0.41%)	137.02 (−72.79%)	54,844.00 (0.57%)	−27.92 (−105.55%)	54,827.00 (0.54%)	-29.51 (−105.86%)

*All percentages (which appear in parentheticals) were calculated by comparing that cell's value with the (0, 0) case value of the same column.
**Combined speed harmonization, CACC, and cooperative merge applications.
CM = cooperative merge; Network TH = network throughput; SH = speed harmonization; veh = vehicles.

Table 7. Performance results of ML 1 at the 130 percent–demand level.*

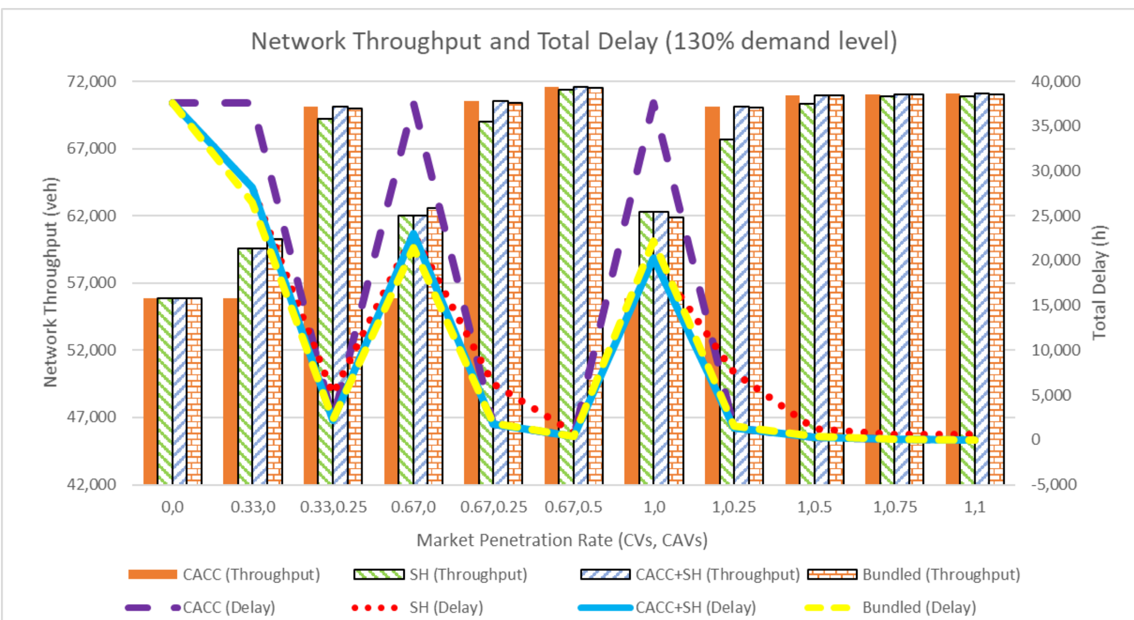
Case (CV, CAV)	CACC Network TH (veh)	CACC Delay (h)	SH Network TH (veh)	SH Delay (h)	CM Network TH (veh)	CM Delay (h)	CACC+SH Network TH (veh)	CACC+SH Delay (h)	Bundled** Network TH (veh)	Bundled** Delay (h)
0, 0	61,828.00 (0.00%)	23,808.20 (0.00%)	61,828.00 (0.00%)	23,808.20 (0.00%)	61,828.00 (0.00%)	23,808.20 (0.00%)	61,828.00 (0.00%)	23,808.20 (0.00%)	61,828.00 (0.00%)	23,808.20 (0.00%)
0.33, 0	62,136.00 (0.50%)	22,495.15 (5.52%)	62,133.00 (0.49%)	22,493.52 (−5.52%)	62,804.00 (1.58%)	20,963.30 (−11.95%)	62,133.00 (0.49%)	22,493.52 (−5.52%)	62,675.00 (1.37%)	21,301.99 (−10.53%)
0.33, 0.25	69,516.00 (12.43%)	4,367.58 (−81.66%)	69,020.00 (11.63%)	5,032.74 (−78.86%)	69,695.00 (12.72%)	3,412.22 (−85.67%)	70,234.00 (13.60%)	1,482.48 (−93.77%)	70,406.00 (13.87%)	1,251.18 (−94.74%)
0.67, 0	62,136.00 (0.50%)	22,495.15 (−5.52%)	62,491.00 (1.07%)	22,015.76 (−7.53%)	63,119.00 (2.09%)	20,395.98 (−14.33%)	62,491.00 (1.07%)	22,015.76 (−7.53%)	63,090.00 (2.04%)	20,445.62 (−14.12%)
0.67, 0.25	69,248.00 (12.00%)	5,110.94 (−78.53%)	67,655.00 (9.42%)	8,828.23 (−62.92%)	67,774.00 (9.62%)	8,542.69 (−64.12%)	70,250.00 (13.62%)	1,802.01 (−92.43%)	70,414.00 (13.89%)	1,595.93 (−93.30%)
0.67, 0.5	71,237.00 (15.22%)	572.71 (−97.59%)	70,822.00 (14.55%)	1,172.15 (−95.08%)	70,758.00 (14.44%)	1,427.67 (−94.00%)	71,340.00 (15.38%)	240.08 (−98.99%)	71,329.00 (15.37%)	240.20 (−98.99%)
1, 0	62,136.00 (0.50%)	22,495.15 (−5.52%)	62,545.00 (1.16%)	20,864.48 (−12.36%)	63,743.00 (3.10%)	18,389.62 (−22.76%)	62,545.00 (1.16%)	20,864.48 (−12.36%)	63,781.00 (3.16%)	18,387.38 (−22.77%)
1, 0.25	68,988.00 (11.58%)	5,511.25 (−76.85%)	67,318.00 (8.88%)	9,558.41 (−59.85%)	66,416.00 (7.42%)	12,019.20 (−49.52%)	70,241.00 (13.61%)	1,637.05 (−93.12%)	70,150.00 (13.46%)	2,064.93 (−91.33%)
1, 0.5	71,047.00 (14.91%)	737.72 (−96.90%)	70,233.00 (13.59%)	2,475.64 (−89.60%)	69,556.00 (12.50%)	4,498.56 (−81.11%)	71,194.00 (15.15%)	226.84 (−99.05%)	71,186.00 (15.14%)	243.37 (−98.98%)
1, 0.75	71,093.00 (14.99%)	470.25 (−98.02%)	70,424.00 (13.90%)	2,793.13 (−88.27%)	70,273.00 (13.66%)	2,964.61 (−87.55%)	71,228.00 (15.20%)	85.93 (−99.64%)	71,227.00 (15.20%)	89.51 (−99.62%)
1, 1	71,166.00 (15.10%)	238.41 (−99.00%)	70,098.00 (13.38%)	4,116.97 (−82.71%)	70,064.00 (13.32%)	4,100.12 (−82.78%)	71,255.00 (15.25%)	−43.68 (−100.18%)	71,268.00 (15.27%)	42.22 (−100.18%)

*All percentages (which appear in parentheticals) were calculated by comparing that cell's value with the (0, 0) case value of the same column.
**Combined speed harmonization, CACC, and cooperative merge applications.
CM = cooperative merge; Network TH = network throughput; SH = speed harmonization; veh = vehicles.



Source: FHWA.
SH = speed harmonization; veh = vehicles.

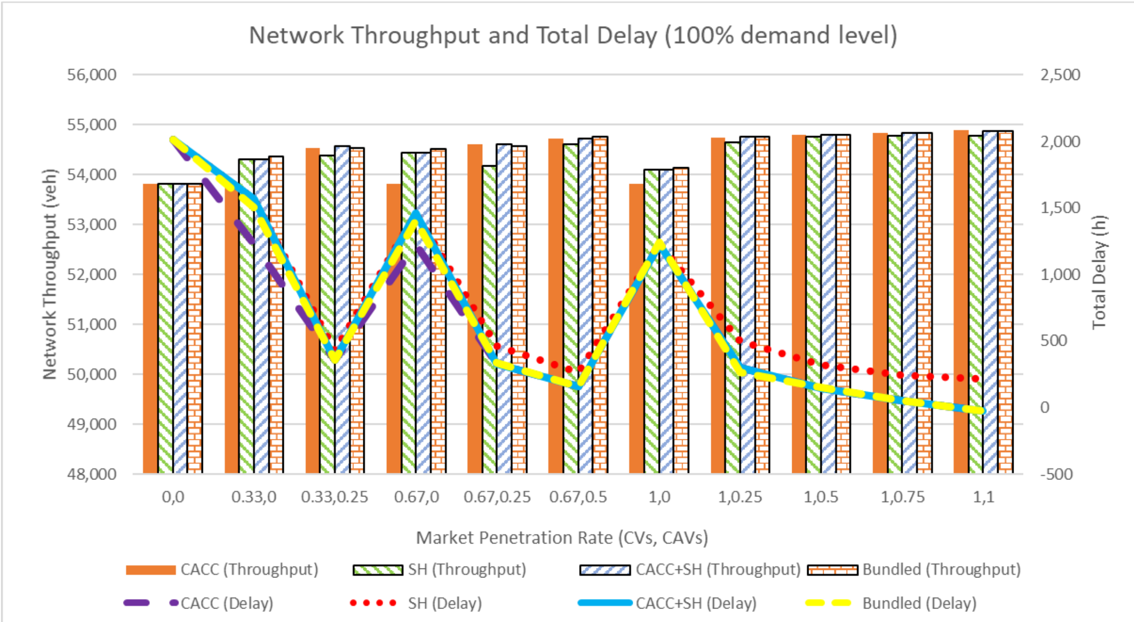
A. Performance comparison for ML 2 at the 100 percent–demand level.



Source: FHWA.
SH = speed harmonization; veh = vehicles.

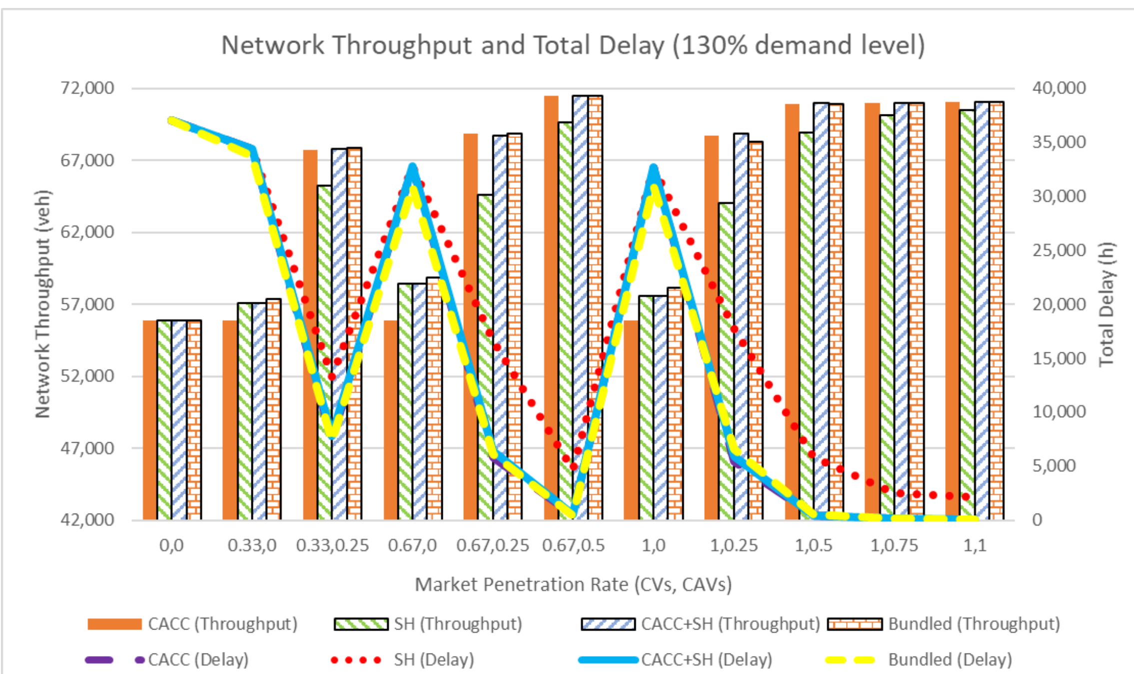
B. Performance comparison for ML 2 at the 130 percent–demand level.

Figure 20. Chart. Performance comparison between single application and bundled applications, ML 2.



Source: FHWA.
SH = speed harmonization; veh = vehicles.

A. Performance comparison for ML 3 at the 100 percent–demand level.



Source: FHWA.
SH = speed harmonization; veh = vehicles.

B. Performance comparison for ML 3 at the 130 percent–demand level.

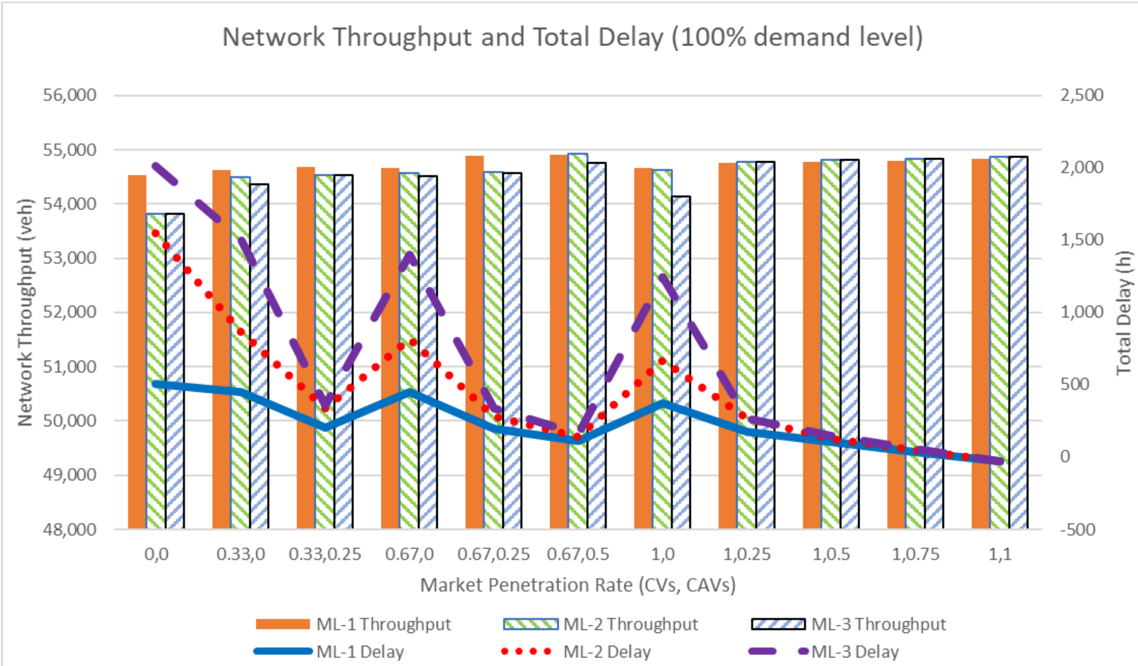
Figure 21. Chart. Performance comparison between single application and bundled applications, ML 3.

Analysis 4: Comparison of Different ML Scenarios

This section compares the results from the three ML scenarios to understand if there are significant differences between the infrastructure scenarios. As shown in figure 21 and figure 22, ML 1's performance is significantly better than that of MLs 2 and 3, which indicates the benefits of constructing dedicated ramps for CVs, CAVs, and HOVs. Dedicated ramps reduce weaving traffic formations in on- and off-ramp areas. Therefore, they are beneficial since they minimize delay and maximize throughput.

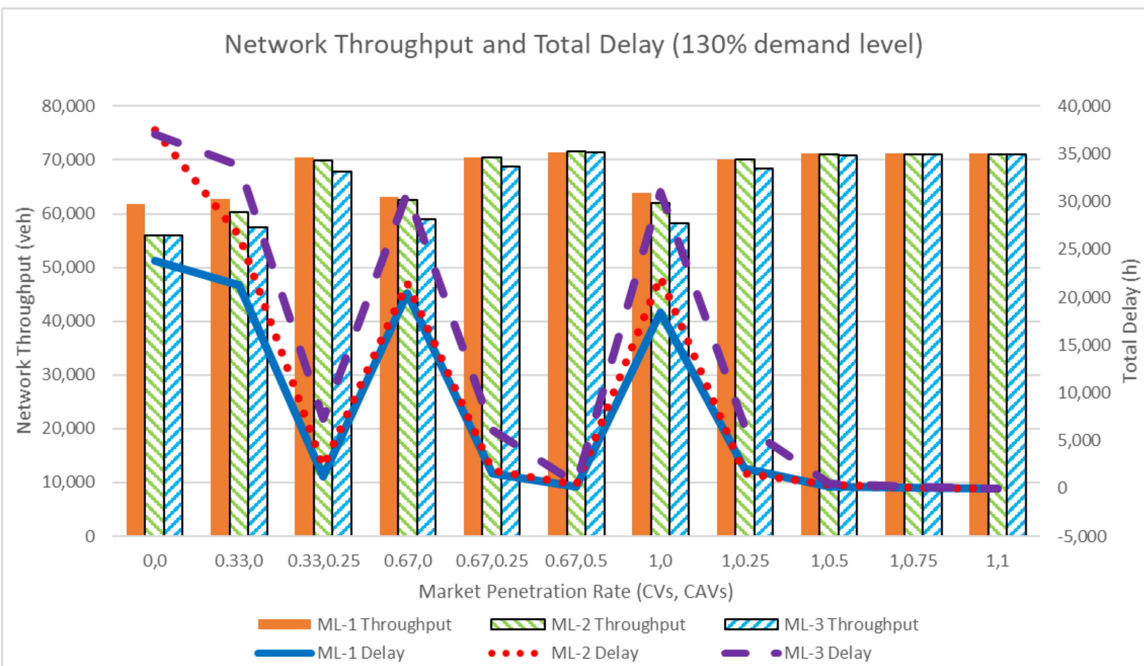
ML 2 and ML 3 result comparisons indicate that allowing CVs and CAVs to access the existing HOV lane improves performance for both system delay and throughput, even when CV and CAV market penetration rates are low. This benefit, however, is relatively minor compared to the additional benefit of constructing dedicated ramps (ML 1). In other words, the weaving effects in ML 2 are quite dramatic and cancel out a large portion of the CAV benefits.

The fact that both MLs 1 and 2 outperform ML 3 in terms of both throughput and delay implies the benefit of the CAV ML strategy. Concentrating CAVs in a single lane can also help realize early deployment opportunities. Additionally, this simulation suggests dedicated CAV lanes are not necessary for realizing early deployment benefits. CAV deployment benefits can still be achieved if CAVs are influenced by human-driven traffic (e.g., making it impossible for certain application operations such as cooperative merge when human-driven vehicles will not create gaps).



Source: FHWA.
veh = vehicles.

A. Performance comparison for all scenarios at the 100 percent–demand level.



Source: FHWA.
veh = vehicles.

B. Performance comparison for all scenarios at the 130 percent–demand level.

Figure 22. Chart. Performance comparison among different ML scenarios.

DISCUSSION OF IMPLICATIONS

Based on the simulation results, the following key observations and implications are summarized:

- Individual and bundled CAV applications can significantly improve traffic performance for all scenarios in terms of delay and throughput in most of the cases examined.

- CACC platooning is the most effective individual strategy because it directly reduces the gaps between vehicles and stabilizes the traffic flow with unique platoon control algorithms. The results of a capacity analysis show the effect of CACC continues to increase as market penetration rates increase (81.2-percent increase for the 100-percent penetration scenario).

- Speed harmonization, by nature, can help smooth mainline traffic, increase throughput, and reduce delay in most of the cases studied. Because speed harmonization relies on monitoring the real-time traffic state to avoid breakdown, it is critical that the existing speed harmonization algorithm be updated to reflect mixed-autonomy traffic conditions. Legacy algorithms may deteriorate traffic performance.

- Cooperative merge can positively impact traffic performance by reducing force-in merge occurrences and smoothing the merge process. In the I–66 case study, mainline vehicles slowed down or made lane changes, when appropriate, to create safe gaps for merging vehicles. However, it is important to note that this process (i.e., algorithm parameters) needs to be tweaked and optimized to reflect local geometric and traffic conditions to ensure that the cooperative merge will not negatively impact overall system performance in merge areas and the entire corridor.

- The I–66 case study shows that deployed bundled CAV applications with high market penetration rates can handle the 130 percent–demand scenario. These results indicate that the resultant highway capacity at high CAV market penetration rates is greater than 130 percent of the current demand. Even at low CAV market penetration rates there are still system benefits in early deployment stages, which applies to both V2V applications (i.e., CACC) and I2V applications (i.e., speed harmonization and cooperative merge).

- System performance still improves, in many cases, when automated vehicle and CAV market penetration increase, even when CACC is not implemented. This trend is a result of the traffic-stabilizing effect resulting from the deterministic behavior of automated vehicles as compared to the stochastic behavior of human drivers. For example, cooperative merge with CVs is implementable, but it deteriorates system performance because human driver slowdown and lane change processes disturb the system too much. In contrast, the deterministic behavior of automated vehicles makes these processes more stable.

- Scenario ML 1 performs better than MLs 2 and 3, and ML 2 outperforms ML 3 in low- and medium-market penetration cases, which indicates the dedicated ramps and ML operation strategies are beneficial. Though this conclusion is intuitive because these two infrastructure-side enhancements reduce weaving and increase the chance of platooning, the result is significant because it illustrates the effectiveness of a more realistic scenario (at least for the I–66 case study) in which human HOV traffic is still allowed to access the dedicated ramps and ML. Previously, this conclusion was only drawn for CAV-dedicated MLs (Liu et al. 2018). There are many such existing HOV facilities in the country, and the results of this case study suggest early deployment benefits with limited infrastructure adjustment.

- All three applications in this case study, when applied individually or bundled together, benefit system performance. Though—for the reasons mentioned in the second bullet point—CACC platooning (V2V CAV operations) generates the most benefits, this study also found speed harmonization and cooperative merge (two I2V traffic control strategies) further improve system performance at low-to-medium CAV market penetration. Even if CACC is not implemented, speed harmonization and cooperative merge, when applied individually, have significantly positive impacts. These impacts indicate the feasibility of incorporating these two applications as elements of the next generation of ATM systems.

CHAPTER 6. CONCLUSIONS

Chapter 6 provides a summary of the case study efforts, simulation results, and operational implications for transportation systems management. This chapter also discusses recommendations for future research.

SUMMARY OF EFFORT AND RESULTS

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

As MLs have evolved from simple physical differentiators such as restriping and signage modifications to the sites of more sophisticated ITS and toll system deployments, they have become ideal testbeds for V2V, V2I, and vehicle automation technologies as well as potential first locations for their deployment. Separated from general-purpose lanes, MLs allow CAV isolation and segregation during the initial market penetration phase. 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 ML's objective to provide superior traffic performance through better traffic management and increased utilization.

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 their potential benefits may not be fully realized. These benefits can be realized at early deployment stages by using ML facilities. This case study focused on different deployment stages for various levels of market penetration and how the proposed bundled application of speed harmonization, CACC, and cooperative merge operates to improve existing system performance.

This case study conducted simulations on a real-world corridor, I–66 in Northern Virginia, and investigated the effectiveness of SAE J3016 Level 1 automation technology in enhancing existing traffic system performance (SAE International 2016). Both infrastructure and CAV technological strategies were simulated and discussed. The case study evaluated the potential benefits of dedicated ramps and a realistic ML concept—a CV- and CAV-eligible HOV lane where CVs, CAVs, and HOVs (human-driven or CV and CAV) can access a left-side ML.

The simulation results show that all three CAV applications, when applied individually or bundled together, benefit system performance. While CACC platooning (V2V CAV operations) generates most of the benefits, this study also found speed harmonization and cooperative merge (two I2V traffic control strategies) further improve this benefit at low-to-medium CAV market penetration rates. This information helps State and local departments of transportation make decisions about deploying suitable CAV technologies. In addition, even if CACC is not implemented, speed harmonization and cooperative merge, when applied individually, have significantly positive impacts, indicating the feasibility of incorporating them into the next generation of ATM systems.

Though this study is a simulation-based analysis with assumed or partially calibrated CV and CAV behavior models, some of the simulation results and insights have been validated by previous experiments conducted at FHWA. The 2015 speed harmonization experiment on I–66 and the 2018 bundled CACC and cooperative merge experiment validated the stabilizing effect of automated vehicles (Ma et al. 2016).[2] Platooning (with 0.6 s of intraplatoon headway) and cooperative merge (through a back-join process) efficiency were also tested and confirmed in the 2018 experiment, which is in line with this study's simulation assumption and shows the potential to generate system-level benefits.[2]

LIMITATIONS AND SUGGESTIONS FOR ADDITIONAL RESEARCH

The simulation case study presents one of the first large-scale, corridor-level simulation-based analyses that evaluate both infrastructure and CAV technological alternatives and strategies. Although this study led to many insights, the following sections detail recommended future areas of research to improve modeling and simulation and address unanswered questions.

Modeling and Simulation

Enhancements in the validity of CAV application models and simulations have always been an area of focused research by FHWA. Only a limited amount of field experiment data are available since CAV technology field tests are still expensive. Therefore, the models used in this case study can only be considered "partially" calibrated and validated. As CAV data becomes increasingly available and field tests become more cost-effective, these models should be constantly enhanced to increase their validity. For the purpose of reducing scenarios and model complexity, the multimodality of the roadway system was not considered in this study. However, this decision will impact driver behavior, including lane changes and gap acceptance.

Algorithms

This case study selected algorithms for the three CAV applications based on the understanding that all algorithms (or their preliminary forms) have been proven effective when applied independently in previous simulation studies, and the algorithms are scalable so they can be applied in large-scale simulation studies. Algorithms that require too many computational resources and have been traditionally applied to control a limited number of vehicles and local traffic will not be applicable for large-scale simulation studies and therefore should be avoided.

Other Operational Strategies

This case study only simulated and evaluated the selected infrastructure and CAV technological strategies as a first-step analysis. FHWA, VDOT, and other agencies may be interested in other scenarios. Additional scenarios that could build on the efforts of this study include the comparing a CAV-dedicated ML and a CAV-eligible HOV lane from the technological and policy perspectives and an examining governmental policy toward MLs as CAV market penetration

[2]Forthcoming FHWA publication: Ma, J., Leslie, E., Ghiasi, A., Guo, Y., Sonika S., Hale, D., Shladover, S.E., Lu, X.Y., and Huang, Z.T. *Applying Bundled Speed Harmonization, Cooperative Adaptive Cruise Control, and Cooperative Merging Applications to Managed Lane Facilities, Final Report*.

increases. Further simulation studies can help an agency understand or determine whether a second ML is needed, or tightened ML access rules should be enacted.

Other System Performance Areas

This case study focused on two performance measures related to system efficiency: throughput and delay. Future analyses should also account for system performance in terms of safety and environmental impacts.

Safety is an essential factor in evaluating the CAV technology impact. As the majority of crashes are due to human errors, automated vehicles have the potential to significantly decrease the number of crashes, specifically at high CAV market penetration rates. One way to quantify safety improvements is by quantifying safety risks though trajectory analysis using surrogate safety measures.

By contrast, calculating emissions and energy consumption is usually an offline process that either uses observed data or data previously obtained by simulation (Treiber et al. 2000, Treiber et al. 2011). For this purpose, several methods are available at different data aggregation levels in the literature. This can be calculated using vehicle trajectories and empirical models, such as EPA MOVES and the VT emission model (Barth et al. 2000, Chamberlin et al. 2011). However, the applicability of traditional safety and energy models to the new mixed-autonomy traffic is a research question. The project team recommends that any future project team uses the latest performance models for system performance evaluation.

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