Evaluating the Effectiveness of Integrated Connected Automated Vehicle Applications Applied to Freeway Managed Lanes

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***Abstract*— The purpose of this study is to define an operational concept involving connected automated vehicle (CAV) operation on freeway managed lanes. Despite the low projected market penetration of CAVs during the next decade, the use of managed lane facilities has the potential to support the realization of increased mobility benefits by their very nature. The proposed CAV operation involves platoons of equipped vehicles governed by integrated CAV applications, including cooperative adaptive cruise control (CACC), cooperative merge, and speed harmonization. This study proposes an algorithm for integrating CAV applications. Through microscopic simulation, the study particularly examines the effectiveness of CACC, CACC plus cooperative merge, and the addition of speed harmonization under different penetration rates. Simulation results show the effectiveness of the bundled application to enhance system throughput and reduce delay, even with low CAV penetration rates. The speed harmonization shows the greatest effects on delay reduction at medium-to-high penetration rates and some benefits even at low penetration rates. The conclusions provide operational insights and guidance for traffic management centers to implement CAV-based traffic control in the future.**

***Index Terms*— Connected automated vehicles (CAV), bundled CAV applications, managed lanes, cooperative adaptive cruise control (CACC), cooperative merge, speed harmonization.**

I. Introduction

A MANAGED lane is a type of highway lane that is operated with a management scheme, such as lane use restrictions or variable tolling, to optimize traffic flow, vehicle throughput, or both. With rapid advancements in connected and automated vehicle (CAV) technology, managed lanes can either benefit directly from associated wireless communication systems and in-vehicle innovations, or aid in their development and deployment, thereby further adding to the original return on investment value of these managed lanes [1], [2]. Combined vehicle connectivity and automation technologies could allow consistent speeds to be maintained throughout the facility [3]. This would increase the throughput and capacity of the managed lanes and could also potentially benefit parallel general-purpose lanes as traffic moves to the managed lane [4], [5]. Smoothed, optimized speeds would also create a reduction in fuel consumption, harmful emissions, and highway crashes [6]–[9].

Managed lanes offer several features that are favorable and, in many respects, critical to the testing and implementation of CAV technologies. Managed lanes are separated from general-purpose lanes, either through barriers or markings, and provide the opportunity for active management of traffic through access control, vehicle eligibility restriction, pricing, or a combination thereof. They also offer operational flexibility such that the operating agency can proactively manage demand and capacity on the facility by applying new strategies or modifying existing strategies. The infrastructure and associated investment required for several vehicle-to-infrastructure (V2I) communication protocols are either already available or more readily installed on several types of managed lane facilities versus general-purpose lanes.

To date, more than three dozen connected and/or automated vehicle applications concepts have been developed, many through prototyping and demonstration [10]–[13]. In this study, we propose the concept of the integrated CAV application, including but not limited to speed harmonization, cooperative adaptive cruise control (CACC), and cooperative merge. These three applications are selected because their effectiveness has been approved in the literature, e.g., [14]–[19]. In our opinion, these selected applications are three of the most promising ones for improving freeway system performance.

There can also be different configurations of applying the integrated application to managed lanes. Generally, such managed lane facilities should be positioned at the left side of the freeways. While sharing on- and off-ramps with the regular traffic are possible, this may create weaving bottlenecks and it is ideal that the CAV managed lane can have dedicated ramps to facilitate CAV cooperative operations [1], [20]–[21]. Note that, in the early deployment stages when the CAV market penetration is low, special-purpose vehicles, such as conventional high-occupancy vehicles, may be allowed to use the facility as well [22], [23] to avoid wasting capacity on the

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managed lanes. As the market penetration increases, the eligibility requirement of the managed lane use can be tightened, and only CAVs can be allowed at some penetration level. This is, to a large extent, site-dependent and we do not address it in this paper. However, it is also possible to require these special-purpose human-driven vehicles to be equipped with vehicle awareness devices (VAD), a device that can broadcast real-time vehicle information at a minimum such that other vehicles and the system managers can have full knowledge of the real-time traffic status [24]. By transmitting real-time data, these vehicles can serve as leaders of CAV platoons, and this can greatly increase the likelihood of platooning and the average length of platoons. This will be considered in our analysis. Additionally, constructing the managed lanes, either creating a new lane or converting existing general-purpose lanes are also of practical significance, but outside the scope of this paper. The focus of the paper is to develop algorithms for the integrated application and evaluate the effectiveness. Readers who are interested in a comprehensive discussion on the Concept of Operations of the CAV managed lane concept can refer to [25] authored by the research team. We also leave discussions of more complex scenarios, such as the existence of pure human-driven vehicles without information communication and how to construct the managed lanes, to future studies.

In this study, we focus on one representative, preferred scenario of a single-lane managed facility and dedicated ramps on the left side of the freeway exclusively for connected vehicle/connected and automated vehicle (CV/CAV) operations in an environment under various CAV market penetration rates. In the remainder of the paper, we will first review the development of the three key CAV applications in the integration. Then, we detail the algorithms for vehicular control. Last, we use a microscopic traffic simulation tool to evaluate the effectiveness of the proposed integrated application to enhance the operations of the managed lane facility under different scenarios.

II. Technology Review

The primary motivation for the development of CACC is to reduce traffic congestion by improving highway capacity and throughput and attenuating traffic flow disturbances [14]. The class of CACC systems utilizing V2V communication could potentially allow the mean following time gap to be reduced from about 1.4 seconds when driving manually to approximately 0.6 seconds when using CACC, resulting in an increase in highway lane capacity [26]. Several highway traffic simulations [14], [27] showed that autonomous ACC (i.e., sensor-based ACC [28]) alone, even at high market penetration rates, had little effect on lane capacity, and 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. However, with the shorter following gaps enabled by CACC systems, lane capacity could potentially be increased from the typical 2,200 vehicles per hour to almost 4,000 vehicles per hour at 100 percent market penetration [3]. In addition to V2V-based CACC, reference [29] proposed the concept of CACC systems utilizing I2V communication, although it was not investigated in detail. Theoretically, the CACC system cooperates with the infrastructure to reduce the potential for congestion at bottleneck locations by automatically reducing the speeds of upstream vehicle platoons using I2V communication to set speed values, thus reducing speed differentials and allowing the traffic flow to be maintained at peak throughput. This is similar to the proposed concept of the integrated application of CACC and speed harmonization.

The concept of cooperative merge leverages V2V and V2I communications to enable CAVs to signal other vehicles (e.g., via dedicated short-range communication, or DSRC) of their intention to merge into traffic streams. Using this information, merging vehicles may identify upcoming acceptable gaps in the mainline and make lane changes when possible [16]. Also, upstream managed lane vehicles may cooperate by adjusting their speeds to create a gap for the requesting vehicle. The trajectories of merging vehicles are then optimized. The merging movement can then occur safely and with minimal impact on the string's stability [30]. Reference [31] 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 reduced travel time in the merging section when the traffic flow was high, and the V2V case supports a significant increase in traffic flow without increasing travel times. The results indicate the potential advantages of using cooperative automation to relieve the bottleneck in the merging section.

Generally speaking, speed harmonization involves gradually lowering speeds upstream of a heavily congested area in order to reduce the stop-and-go traffic that contributes to frustration and crashes. To date, a related strategy known as variable speed limits (VSL) has been applied at several locations in Europe and a few locations in America [32], but the driver response to suggested speed targets has not been consistent. Dynamic speed limit adjustments are less efficient than dynamic adjustments of recommended and/or actual speeds communicated directly into connected and automated vehicles as the speeds are adjusted automatically unless drivers intervene. Compared to the segment-based speed harmonization (similar to VSL) [33], trajectory-based speed harmonization can control and coordinate an individual vehicle's trajectories depending on each vehicle's location. Recent simulation studies (e.g., [34]) and field experiments [35] suggest the potential of such an approach in enhancing traffic smoothness and therefore improving efficiency and safety. In particular, trajectory control can facilitate freeway merge. In this scenario, a central controller (e.g., traffic management center) coordinates the trajectories of upstream managed lane vehicles and merging vehicles such that smooth and efficient merging and minimum impact on mainline traffic can be guaranteed.

Reference [2] summarized previous studies that involve CACC and cooperative merge. Those positive results show the potential of integrated CAV applications and cooperative merge cannot be isolated from other CAV operations (e.g., such as platooning), to realize the full benefits. Additionally, the combination of cooperative merge and speed harmonization (by controlling and coordinating arrivals of upstream managed lane vehicles to create gaps for merging) can further improve merging area performance because the upstream traffic flow can be smoothed to reduce the congestion at merge area. However, those CAV applications should be integrated to collaboratively fulfill CAV cooperative control and avoid the potential conflicts and improve the traffic system performance. Therefore, the integrated CAV application proposed in this study tries to address such integration of three different applications in the next section.

III. Integrated CAV Application

A. Cooperative Adaptive Cruise Control (Platooning)

The concepts of Cooperative Adaptive Cruise Control have been widely discussed, and several CACC implementation methods are proposed. Among those designs, one of the major differences is the topology of communication, which includes decentralized communication [36], centralized communication [37], communication with nearest vehicles [38], [39], and communication with platoon leader and nearest vehicles [40]. Since this study focuses on CACC operations on one managed lane at early stages of deployment, it adopts the single-lane operation of the CACC operation algorithm developed by [41], which applies the communication with nearest vehicles, and enhances it with components that enable the speed harmonization and cooperative merging algorithms. The implementation also assumes the implementation of vehicle awareness devices (VAD) on manually driven vehicles. VAD-equipped vehicles broadcast their real-time status to surrounding vehicles and can serve as the leader of CACC vehicle platoons. Under this strategy, the probability of CACC-equipped vehicles traveling in the CACC mode greatly increases, thus offering an incentive for users to equip their vehicles with CACC, even when the CACC market penetration is low. Note that there may be safety risks when VAD vehicles are platoon leaders due to the stochasticity of human-driven behavior. This risk is partially reduced through the real-time communication and exchanges of messages between the VAD leader and the following CAV. While this is outside the scope of this paper, future research may need to investigate algorithms that particularly address the safety concerns.

We choose a maximum platoon length of 10 vehicles, as recommended in [41]. Shorter platoon lengths would result in more CACC platoons, which can lead to lower freeway capacity because inter-platoon gaps are larger than the gaps between consecutive vehicles within the platoon. On the other hand, longer CACC platoons would lead to less versatility since they make merging more difficult for other vehicles.

Fig. 1 provides an illustration of CACC platoons simulated in this study. If the preceding vehicle is a conventional vehicle and the clearance distance exceeds the detecting range of the onboard sensors, or there is no vehicle in front of the subject vehicle, the subject CAV will switch to the ACC speed regulation mode to regulate the following behavior. This mode keeps the subject vehicle cruising with target speed to reduce unnecessary oscillations and detecting the clearance distance to avoid the collision. The ACC controller will apply the

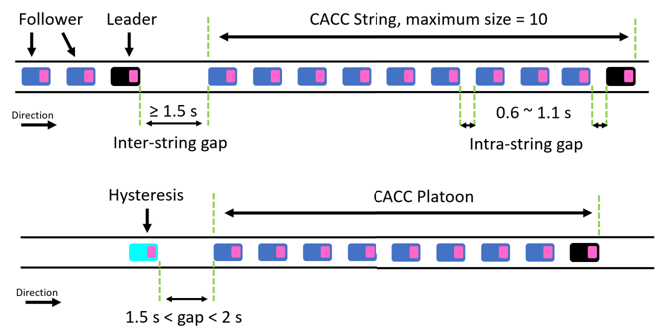


Fig. 1. Illustration for CACC platooning logic.

Equation (1) proposed by [41] in this mode.

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

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 ($k_1 = 0.4s^{-1}$ in this study)

v_f : free-flow speed (m/s) or reference speed commands when speed harmonization is applied.

v_{sv} : current speed of the subject vehicle (m/s).

Different from [41], since we assume all vehicles in the managed lane is at least equipped with vehicle awareness devices, the ACC gap regulation mode will not be implemented in this study. The subject CAV may encounter two other possible scenarios and can be either a platoon leader or follower.

If the length of the previous CACC platoon exceeds the maximum allowable platoon length, the subject vehicle will be a leader of a CACC platoon and keep a constant time gap from the preceding vehicle (1.5 seconds in this study), referred to as an inter-platoon gap. If the time gap between the subject vehicle and the preceding vehicle is more than 2 seconds, the subject vehicle will switch to the speed regulation mode, which is represented by Equation (1). Otherwise, a CACC platoon leader gap regulation mode will be implemented [41] by using Equation (2) and Equation (3).

$$v_{sv}(t) = v_{sv}(t - \Delta t) + k_p e_k(t) + k_d \dot{e}_k(t) \tag{2}$$

$$a_{sv}(t) = \left(v_{sv}(t) - v_{sv}(t - \Delta t)\right) / \Delta t \tag{3}$$

where,

Δt : time step for each update (s)

k_p and k_d: gains for adjusting the time gap between the subject vehicle and preceding vehicle ($k_p = 0.45s^{-1}$ and $k_d = 0.0125$) [42]

e_k : time gap error, which is described by the following: $e_k(t) = d(t-\Delta t) - t_1 v_{sv}(t-\Delta t) - L$, and $\dot{e}_k(t) = v_l(t-\Delta t) - v_{sv}(t-\Delta t) - t_1 a_{sv}(t-\Delta t)$

t_1 : is the constant time gap between the last vehicle of the preceding CACC platoon and the subject vehicle ($t_1 = 1.5s$ for inter-platoon gaps in this study)

d : headway between the subject vehicle and immediately preceding vehicle

L : length of the immediately preceding vehicle.

v_l : speed of the leading vehicle.

If the subject vehicle can join the preceding CACC platoon, it will be a CACC platoon follower and apply a smaller time gap, referred to as an intra-platoon gap, to tightly follow its preceding vehicle. A survey conducted by [27] proposed a distribution of desired intra-platoon gaps, and we choose 0.7 seconds in this study to keep the homogeneous driving behavior among CACC followers. If the time gap is no more than 2 seconds, this CACC platoon follower gap regulation mode uses the same method using Equation (2) and Equation (3) except that the following desired constant time gap $t_1 = 1.5$ seconds will be replaced with $t_2 = 0.7$ seconds [41]. For time gaps larger than 2 seconds, the subject vehicle will turn on the speed regulation mode (i.e., Equation (1)). When the time gap is between 1.5 seconds and 2 seconds, the subject vehicle will use the hysteresis control rule [41], which applies the car-following mode implemented in the previous time step.

The forward collision warning algorithm [43] 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. The CAMP algorithm determines a required deceleration for the subject vehicle:

$$des_{REQ} = -0.165 + 0.685 \cdot des_l + 0.080 \cdot \zeta - 0.00889 \cdot (v_{sv} - v_l) \quad (4)$$

where,

des_{REQ} : deceleration required to avoid a rear-end collision (in g)

des_l : deceleration of the preceding vehicle (in g)

$$\zeta : \zeta = \begin{cases} 1 & v_l > 0 \\ 0 & otherwise \end{cases} \quad (\text{in } g)$$

Therefore a required deceleration is obtained to avoid a collision with the preceding vehicle. If des_{REQ} is less than zero, the brake action is needed to avoid a potential collision.

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

Fig. 2 summarizes the steps mentioned above and demonstrates the logic of the CACC platooning process, which introduces many details of the algorithm implementation. For each pre-defined step, the subject CAV will detect the surrounding environment and communicate with the immediately preceding and following vehicles. If there is no vehicle in front of the subject vehicle, i.e., the gap exceeding the pre-defined maximum range, the subject CAV will switch to the ACC speed regulation mode. If immediately preceding vehicle is within the pre-defined range and is a VAD vehicle, the subject CAV will switch to CACC control logic. Because the VAD-equipped vehicle can be a CACC platoon leader only, the subject CAV will be the CACC platoon follower. The specific regulation mode depends on the detected gap. If the immediately preceding vehicle is a CAV, the subject CAV will switch to CACC control logic and request the length of the previous CACC platoon. If the platoon length has reached the preset maximum value, the subject vehicle will become the leader of a CACC platoon and maintain a constant inter-platoon gap from the preceding vehicle (i.e., the last vehicle in the previous platoon). Otherwise, the subject CAV will become a CACC platoon follower and try to catch up with the front CACC platoon using the intra-platoon gap for regulation. There are three regulation modes, as discussed above, the determination of which depends on the detected time gap in real-time.

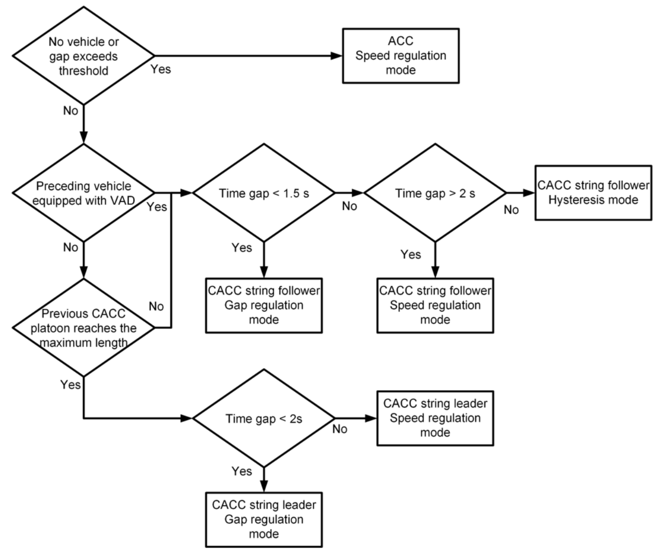
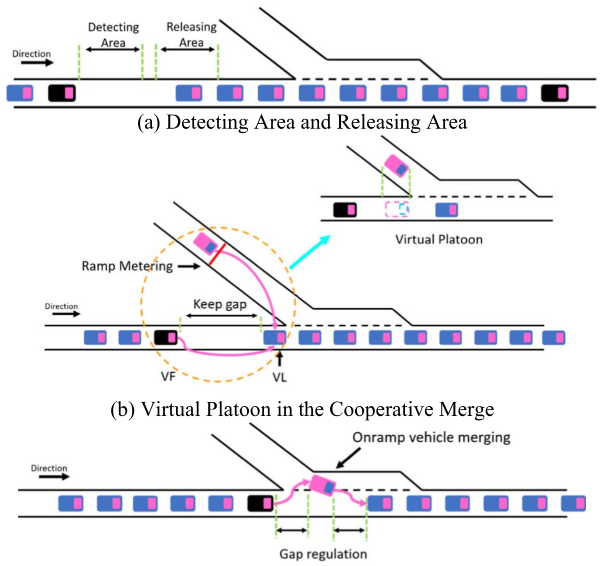


Fig. 2. Logic of CACC platoon.

The implemented CACC control logic is different from the literature [41] in multiple aspects. First, in this study, since we assume all vehicles in the managed lane is at least equipped with VAD, the ACC gap regulation mode does not exist in this study, which is used to regulate the gap when following a conventional vehicle within the detection range of the onboard sensors, and is replaced by CACC gap regulation. Second, we allow the CACC platoon follower to exceed the speed limit but no more than 1.1 times of the limit when it catches up with the preceding CACC platoon to join the platoon. We allow the maximum length to exceed the regular platoon size threshold at the merge area. Then, we use a different forward-collision warning algorithm. Last but not least, due to the integration with cooperative merge and speed harmonization, the CACC logic uses the output from other applications as the vehicle operation input. For example, the lead vehicle of a platoon follows the speed harmonization, while all platoon followers strictly implement the CACC logic. The CACC logic is also used in this study to guarantee safety (through strict gap regulations and collision avoidance) when three applications interact.



(a) Detecting Area and Releasing Area

(b) Virtual Platoon in the Cooperative Merge

(c) Gap Regulation in Cooperative Merge

Fig. 3. Illustration for cooperative merge process.

B. Cooperative Merge

To a large extent, algorithms for cooperative merge combine speed harmonization and CACC control algorithms at merging areas because CACC platoons need to operate differently at merge points to accommodate new merging vehicles, and gaps can be potentially created in many cases by controlling managed lane vehicles through I2V speed control. The cooperative merge algorithm consists of four main steps: detection, release, speed regulation, and gap regulation.

1) Cooperative Merge-1: Detection: As Fig. 3 (a) shows, at a merge area, a local center (e.g., roadside units, or RSU) collects real-time information (location, speed, acceleration, vehicle operation mode, etc.) of all vehicles. If there is a desired/qualified time gap between two CACC and/or VAD vehicles, an available gap will be recorded. These two vehicles will start to keep this gap if the following vehicle is a CAV. If the following vehicle is VAD vehicle, the gap may or may not be kept, and this is not controllable. Generally, when the traffic is in the uncongested traffic regime (i.e., the actual density is below the critical density of the local traffic, which is also dependent on the CAV market penetration), the qualified gap can be more likely kept. Otherwise, the gap may be closed by human followers due to the decelerations of the front vehicles, which run into the slow- moving traffic at the merge area first. Prediction of human-driver behavior may be a solution to this problem and we leave it for future explorations.

2) Cooperative Merge-2: Release: After the gap is recorded, the on-ramp vehicle waiting at a pre-specified "metered" location will be released when the leader of the recorded gap arrives at the position p_{release}, which includes two components: 1) the vehicle distance traveled by the identified gap leader when the merge vehicle is accelerating to the speed of the leader and 2) the vehicle distance traveled by the identified gap leader when the merge vehicle is "platooning" (or conducting gap regulation) with the gap leader. This virtual platooning concept will be discussed later. Here, we are interested in calculating d_{merge}, the minimum distance between the merge point p_{merge} and the release point $p_{release}$, which could be obtained by calculating the relative distance d_{merge} to the merge point p_{merge} by using Equation (5).

$$\begin{aligned} d_{merge} &= (v_L \cdot t_1) + d_{GR} = \left(v_L \cdot v_L / a_{merge}\right) + d_{GR} \\ &= v_L^2 / a_{merge} + d_{GR} \end{aligned} \tag{5}$$

where,

v_L : speed of the gap leader (m/s)

t_1 : time duration for the merging vehicle to accelerate to the gap leader's speed (m/s)

a_{merge} : acceleration of the on-ramp vehicle (m/s^2)

d_{GR} : minimum gap regulation distance (m) (200 m in this study)

3) Cooperative Merge-3: Speed Regulation: Once the on-ramp vehicle is released, a virtual leader (VL) and a virtual follower (VF) will be assigned to the on-ramp vehicle, as shown in Fig. 3(b). These are the two vehicles immediately before and after the identified gap on the mainline. The three vehicles aim to form a virtual platoon. Therefore, the on-ramp vehicle starts to regulate the speed with the reference speed v_f set as the current speed of the VL when Equation (1) is applied. When the speed of the on-ramp vehicle approximately equals the VL ($\pm 2m/s$ in this study), the on-ramp vehicle will change to the gap regulation mode with the VL, and the VF changes to gap regulation mode with the merge vehicle. Fig. 3(c) illustrates this regular case. However, if the merge vehicle cannot accelerate to be approximately as fast as the VL before the distance to the merge point becomes less than the minimum gap regulation distance, both the VF and merge vehicles are in gap regulation mode and follow the VL. However, they apply different following gaps: the merge vehicle applies an intra-platoon gap (0.7 seconds in this study), and the VF tries to keep the identified merge gap (e.g., 1.6 seconds in this study). This is to ensure sufficiently large gaps are available for merge. We let the VF follow VL, instead of following the merge vehicle as in the regular cases, because the merge vehicle is still slow (below the VL, VF, and general traffic speed at or before the merge area) and following the slow merge vehicle may cause the VF to significantly slow down. Therefore, in this case, we let the VF follow the VL and maintain the gap. Note that when the merge vehicle speed is close to the VL, the gap regulation mode will switch to the regular mode as shown in Fig. 3(c).

4) Cooperative Merge-4: Gap Regulation and Merge: The on-ramp vehicle will keep the relative intra-platoon gap with the VL, and Equations (2) through (4) are applied with $t_2 = 0.7s$. The VF begins following the on-ramp vehicle, as shown in Fig. 3(c) and Equations (2) through (4) are applied. The gap for VF in the gap regulation is dependent on the vehicle type of the VF and which vehicle the VF is following. When the vehicle reaches the pre-specified merge point at the acceleration lane, the vehicle can change lanes and merge into the right lane. After this point, the cooperative merge process is completed, and the CACC platooning logic kicks in to control how the new vehicle will join existing platoons. Note that because of the existence of on-ramps and off-ramps, vehicles may join and leave the platoons. Therefore, the platoons in the system do not always comprise ten vehicles, the preset maximum platoon length. Instead, the merge vehicles are usually able to join the platoon before or behind it and then continue the operation as a part of the CACC platoon.

In this study, two types of lane change behaviors are applied. One is a simplified lane change behavior, which is a part of the preferred lane change behavior for fulfilling cooperative merge (as discussed in the "Cooperative Merge" Section). If the identified gap can be maintained to let the on-ramp merging vehicle merge into the mainline, the merging vehicle will calculate the time gaps between itself and the virtual leader/follower. If both gaps meet the critical gap requirements (e.g., greater than 0.7 seconds in this study), then the subject vehicle will merge into the mainline immediately. If the identified gap cannot be maintained or is missed by the merging vehicle, the merging vehicle will switch to the "Necessary Lane Change" mode, which is controlled by VISSIM's lane change model and complete the lane change manually. The subject vehicle will try to seek a qualified gap to merge into the mainline manually. This model allows the subject vehicle to use a reduced safety distance during lane change to facilitate the merge. The reduced safety distance is 10% of the original safety distance in this study, which is calibrated by [44]. When the merging vehicle reaches the end of the acceleration lane of the merge area, the VISSIM's lane change model will let the vehicle forcefully merge into the mainline. However, it creates a large disturbance to the mainline traffic, similar to real-world conditions.

Note that multiple vehicles can be released if a large enough gap to accommodate multiple vehicles are identified. Also, the proposed algorithm also intrinsically creates gaps for vehicles if needed. For example, when we identify a gap of 1.6 seconds or above on the mainline, we release the vehicle, and the merging vehicle will form virtual platoons with the mainline virtual leader and virtual follower. The gap of 1.6 seconds is large enough, so the virtual follower may not need to slow down for gap creation. But if the gap threshold value is small (say, 0.8 second), the virtual follower on the mainline will need to slow down due to the virtual platooning rule to leave enough space for the merging vehicle (as the middle vehicle of the virtual platoon). This is indeed a gap creation process.

In the case studies of this paper, we also incorporated a variation of the cooperative merge strategy, which releases and creates gaps for on-ramp vehicles if this vehicle's waiting time at the ramp exceeds threshold σ. The original strategy without purposely releasing and creating gaps for on-ramp vehicles can be regarded as $\sigma = \infty$. Note that, under this updated strategy, once the merging vehicle is released, it will identify its virtual leader and follower at the pre-specified gap-identification location and start forming virtual platoons. Under this scenario, the virtual follower will need to slow down and create gaps for the merging vehicle.

C. Speed Harmonization

Speed harmonization is also referred to as I2V speed control in this study. It aims to control each individual vehicle's trajectory (i.e., providing each vehicle with real-time commands) at both basic freeway segments and merge areas to coordinate trajectories of vehicles and thus smooth traffic, particularly at bottleneck locations. This method can be used in conjunction with cooperative merge at merge areas to create gaps for merging vehicles effectively. Some other studies [30], [35] also discussed this idea.

In order to achieve this ideal trajectory smoothing paradigm, we need to be capable of detecting the speed drop and predicting the corresponding shock wave propagation and queue dissipation. Then we need to control the CAV to follow a smooth trajectory so that it properly leads the vehicle queue and enters the bottleneck right after the queue clears. In the case of a downstream speed drop, if the congestion is moderate, the algorithm will seek to smooth the traffic, let the queue dissipate, and then allow the following CAVs to pass the bottleneck smoothly at a reasonable speed. Otherwise, if traffic is too congested and the queue is not anticipated to dissipate in a short period of time, the CAVs will guide the upstream traffic to avoid hitting the downstream queue at a sudden full stop by slowing down and smoothly joining the downstream queue.

The 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, such that traffic and queue status can be predicted. Then, recommended trajectories are generated by assuming homogeneous traffic conditions between each sensor or probe vehicle. Note that this trajectory-based harmonization strategy is a real-time action that is updated frequently for each vehicle (e.g., every 2 seconds). Therefore, at the beginning of each time increment, queue characteristics are updated based on newly detected traffic conditions, so the actions taken by CAVs may be modified based on the updated data. Note that in this study, we assume in the managed lane that 100 percent of vehicles are connected vehicles (at least equipped with VADs), and therefore real-time traffic conditions at any location can be estimated using the data of all probe vehicles that pass the location during a specified duration. With probe data available for 100 percent of the vehicles, we can define "virtual detectors" anywhere in the network and collect corresponding traffic information. This study does not focus on how to use these data to best estimate traffic status. In our simulation, we have full information on the system, and therefore we extract the information directly to generate I2V speed control commands. For detailed information on the estimation and more advanced trajectory construction, interested readers can refer to an earlier publication for detailed information [34].

This study adopts a heuristic approach for speed commands generation, building on [35]. We set many virtual loop detectors along the speed harmonization segment (e.g., 2 kilometers before the merge area). The traffic speed is monitored at these points and the values are calculated as the arithmetic mean of the speed of the past 5 minutes. Two components are considered in the process: global and local commands. First, the speed harmonization algorithm gradually slows the vehicle down based on the difference in traffic conditions at the vehicle's current location and the bottleneck location. We apply a simple linear speed transition algorithm to obtain the global harmonization commands, as shown in:

$$v_{des} = v_{cur} + \left(v_{pre} - v_{cur}\right) \times \left(1 - \frac{d_{cur}}{L}\right) \tag{6}$$

where,

v_{cur} : current speed of the subject vehicle (m/s)

v_{pre} : prevailing speed in the merge area (m/s)

d_{cur} : the distance between the current position and the boundary of speed harmonization area

L : total length of the speed harmonization area

Second, the algorithm also has the CAVs follow local harmonization commands, subject to the differences in the front vehicle's distance and speed. The algorithm uses the data from the densely deployed virtual detectors to predict the trajectory of the front vehicle (CAV or VAD vehicle) and the trajectories of all preceding vehicles before the merge area. When the front vehicle is predicted to be slower at a certain speed threshold (i.e., slow front vehicle), then local harmonization is triggered to issue a spatiotemporal linear speed command using a method like that shown in Equation (6), except that the distance and speed are measured for the front vehicle at the predicted slow moment in the future. This ensures that the CAV does not tightly follow the front vehicle to join the congestion.

When the CAV is very close to the front vehicle (i.e., less than a threshold, such as 50 meters in distance gap) and the speed difference is less than a specified value (e.g., 5 m/s), the CAV will be asked to slow down in a linear fashion using a method similar to that in Equation (6), except that the distance and speed are measured for the front vehicle at the current moment. For a CAV approaching the front vehicle at a high speed, this local harmonization ensures operational safety and let the CAVs more smoothly join the queue.

D. Integrated Application Process

The three CAV applications are also integrated together during real-time operations, referred to as integrated CAV operations. The pseudo-code for the integrated application process is shown below. The CACC module first determines the CACC status and corresponding operational mode and calculate the desired speed v_{CACC} for the specific CACC mode. If the vehicle is within the speed harmonization zone or I2V speed control is activated, the speed harmonization module calculates the alternative speed v_{SH} based on Equation (6), and the desired speed is set to $v_{CACC} = v_{SH}$.

When the subject CAV approaches the merge area, the cooperative merge module is activated. This module then releases an on-ramp vehicle when a qualified gap is identified on the mainline upstream of the merge area. For mainline vehicles, if the subject vehicle is a VL, the CACC module keeps calculating and sending speed and corresponding acceleration commands to control the VL; if the subject vehicle is a VF, the VF follows the VL and keeps the identified gap when the on-ramp vehicle is controlled by speed regulation mode; when the on-ramp vehicle switches to the gap regulation mode, the VF begins to follow the on-ramp vehicle and is controlled by gap regulation mode. One exception is discussed above that the VF follows the VL even the on-ramp vehicle is in gap regulation mode (when the on-ramp vehicle speed does not match the VL). For released on-ramp vehicles, if the on-ramp vehicle reaches the target speed or the boundary of the gap regulation segment (defined in the cooperative merge algorithm), it will start the gap regulation mode; otherwise, it is controlled by the speed regulation mode.

Algorithm 1 Bundled Application Algorithm

```
vehMode ← get_CACC_Status // get the CACC status
    and operation mode
v_C_Acc ← cal_CACC _speed(vehMode) // calculate the
    desired speed in CACC platoon
If Speed Harmonization is applied
    v_SH ← cal_SH_speed
End
If Cooperative Merge is applied
    If on-ramp vehicle released
        If not the VL
            If Gap Regulation
                v_Coop ← cal_Gap Regulation_speed
            Else
                v_Coop ← cal_Speed Regulation_speed
            End
            If not the VF
                If meet merge conditions
                    Preparing to merge into the gap
                End
            End
        End
    End
End
v_desired = Min(V_CACC, V_SH, v_Coop)
v_desired = Cal_Acc(v_desired)
Send_Command(v_desired, α_desired)
```

If a CAV needs to change lane for the cooperative merge, the lane change behavior is still regulated by the conventional human lane change model. However, during the lane change process, all the longitudinal maneuvers are still governed by the above-mentioned process, including collision avoidance. This means that this study focuses on longitudinal control of all automated vehicles.

IV. Simulation Scenarios and Results

The goal of the simulation is to investigate the effectiveness of different CAV applications under the same simulation environment. It is also of interest to understand the performance of integrating CAV technologies together. Three analysis scenarios are identified and investigated in this study. First, we are interested in implementing the state-of-the-art CACC

TABLE I
ADJUSTED DRIVING BEHAVIOR PARAMETERS

Parameter	Definition	Default Value	Calibrated Value
CC2	Longitudinal oscillation: oscillation factor gains on following distance	4 m	12 m
CC4	Negative speed difference: negative speed difference during the following process	-0.35	-0.1
CC5	Positive speed difference: positive speed difference during the following process	0.35	0.1
SDRF	Safety distance reduced factor: reduce safety distance during lane change	0.6	0.1
LBD	Look back distance	250 m	1000 m

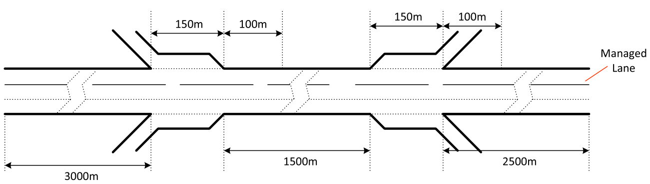


Fig. 4. Sketch plot of a simple network.

algorithm that reflects realistic CACC operations and evaluating its effectiveness using a separate traffic simulator VISSIM. We want to understand the pipeline capacity of CACC, which is the best performance of the managed lane, and set it as a benchmark when incorporating other technologies, such as cooperative merge and speed harmonization. Further, CACC traffic stream performance varies under different CAV market penetration rates, which also impacts the effectiveness of other technologies.

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

Third, the effects of speed harmonization when it is integrated with other CAV technologies are also of interest in this study. There are two potential effects that speed harmonization can have to improve traffic efficiency. One effect is to delay or reduce the slow-down or stop-and-go occurrences at the merging area. The other is its ability to help create larger gaps by slowing upstream vehicles down before the merge area and let merging vehicles to more smoothly join the mainline traffic.

The assumed simulation network is a simple 3-lane freeway segment with an on-ramp and an off-ramp (see Fig. 4). The freeway mainline is 7 kilometers long. There is a 2-kilometer 'warm-up' mainline segment in the beginning. The simulated vehicles will use this segment to reach a stable car-following state after entering the network. This segment also allows CACC vehicles to form stable CACC vehicle platoons in the CACC analysis cases. There is an on-ramp 3 kilometers downstream from the beginning of the network. An off-ramp is located 4.65 kilometers from the network beginning. Both the on-ramp acceleration lane and off-ramp auxiliary lane are 150 meters long. Data collection point locations: the first location O1 is 500 meters downstream from the end of the on-ramp. Since this study is interested in the performance of managed lanes, in our simulation, we only study the left most managed lane and the corresponding dedicated ramps. The bottom part of the network is for general purpose traffic and provided for illustration purpose.

The experiments are simulated in VISSIM 10.07, a microscopic traffic simulation tool. The driver model API (Application Programming Interface) and COM (Component Object Model) interface are applied to model CAVs to realize the longitudinal control functions of the CACC, speed harmonization, and cooperative merge logic. For each simulation run, we collected 60-minute performance after a 15-minute warm-up period, and the free-flow speed is 104 km/h (65 mph).

The VISSIM internal model, i.e., the Wiedemann 99 model, is applied to simulate the car-following behavior of VAD vehicle in the VISSIM. To simulate driving behavior realistically, the parameters of the driver model usually need to be calibrated, and several previous studies have calibrated various parameter sets using real-world data [45]–[48]. In this study, calibrated parameters from [49] are used. This study suggests five parameters are adjusted from the VISSIM default, including longitudinal oscillation (CC2), negative speed difference (CC4), positive speed difference (CC5), safety distance reduced factor (SDRF), and maximum lookback distance (LBD). The adjusted driving behavior parameter values are listed in Table I. All other parameters assume default values in VISSIM, such as CC1 (inter-vehicle gap mean) = 0.9 seconds.

This study estimates the CACC pipeline capacity under different percentages of CAV market penetration. When data are collected to draw fundamental diagrams under each mar-

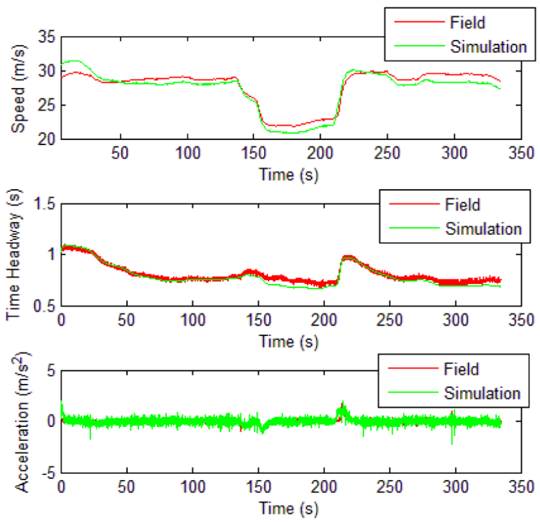
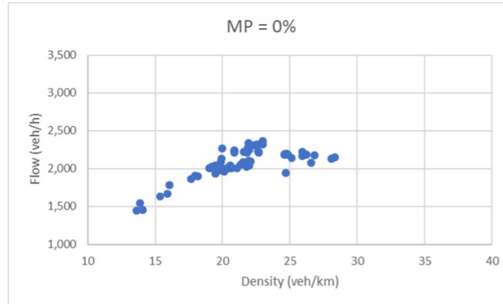


Fig. 5. Model validation.

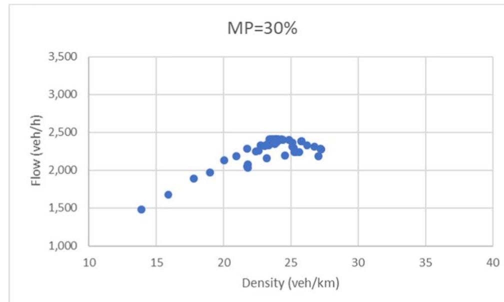
ket penetration scenario, traffic input demand varies from 2,000 vphpl to 4,000 vphpl to generate different conditions. We collected data of each 15 minutes (after the simulation warm-up period) and used the four times of each 15-minute volume data to represent a valid data point to draw the fundamental diagram.

Note that different CAV market penetration rates are only applied to mainline traffic. Since the VAD vehicle cannot perform the cooperative merge in this study, the CAV market penetration rate of on-ramp traffic is fixed at 100%. This is corresponding to the policy that VAD vehicles can only use the managed lane by merging from the general-purpose lane because manual VAD vehicle merge from the dedicated ramps, if allowed, may cause disturbance to the mainline managed lane traffic and even affect CAV cooperative merge operations. We leave the scenario of mixed traffic on the dedicated ramps to future analyses. We believe the strategy of only allowing CAVs to use the dedicated ramps will maximize the benefits.

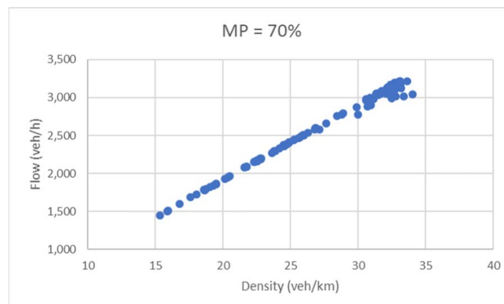
We validated the selected CACC model [42] by comparing simulation results and field test data. The field data were collected from a real-world on-road experiment by using the FHWA CARMA platform (https://highways.dot.gov/research/research-programs/operations/CARMA) and five-vehicle experimental fleet in July 2018, representing the latest CAV hardware and software [50]. The selected experimental location is a 17.7-kilometer (11-mile) segment on I-95 Express Lanes. As shown in **Fig. 5**, the speed, acceleration, and time headway profiles of simulation and field data match each other well. It is expected that the simulated acceleration is not as noisy as the field data, but their mean and variance are similar.



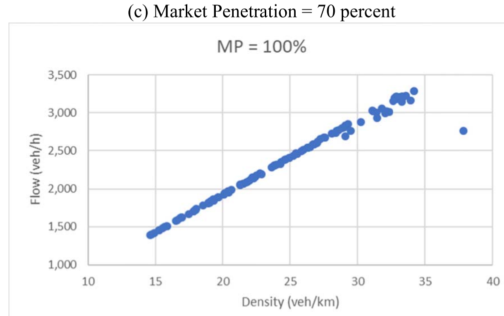
(a) Market Penetration = 0 percent



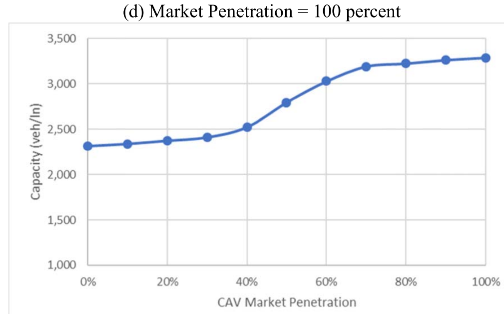
(b) Market Penetration = 30 percent



(c) Market Penetration = 70 percent



(d) Market Penetration = 100 percent



(e) Pipeline Capacity under Different Market Penetration

Fig. 6. CACC pipeline capacity analysis.

A. Analysis 1-CACC Pipeline Capacity

The density-flow rate diagrams under each market penetration rate are presented in **Fig. 6**(a)-(d). The maximum flow is considered to be maximum capacity, which is 3,288 vphpl in this study. The results also demonstrated a significant increase in capacity with the increase of the market penetration of CACC vehicles. At the market penetration rates of 30%, 50%, 70% and 100%, the capacity increased by 4.1%, 20.7%, 37.8% and 42.0%, respectively. The CACC pipeline capacity under different market penetration rates is shown in **Fig. 6** (e).

We hope to mention that we have used different random seeds for all simulation scenarios to account for the stochasticity of the traffic systems, and all data from different runs using different random seeds are included in the fundamental diagrams. The arriving patterns of upstream traffic are different from each other with different random seeds [52]. It can be seen that we can easily see the congestion dynamics under the 0% and 30% MP scenarios. However, the congestion dynamics are not clear when the MP is high. This is mostly because the traffic performance (e.g., stability) and highway capacity are much improved. In those cases, we cannot see an obvious breakdown of traffic. While we still see some congestion dynamics under the 70% MP, we do not see that under 100%. It is likely because the input of the vehicles is limited, and the traffic will not break down under normal and high traffic input (as high as the limit of the simulation software), meaning that the capacity may have exceeded the limit of input of simulation. The parameter of standstill distance (CC0) is set to 1.5 meters, and the following distance in time (CC1) is set to 0.9 seconds for VAD vehicle. Although this driving model is not applied for CAV, it influences the input volume in VISSIM [52]. Since the vehicle length is about 4.8 meters, the average headway is about 1.12 seconds, therefore lead to a limit of input volume of about 3,214 vphpl. It is also highly likely to happen in the future when the managed lane vehicle input is limited at the entrance of the managed lane before which only human-driven capacity volume is possible, meaning that the input of the managed lane at the entrance is limited by the human-driven traffic capacity. The same phenomena of the fundamental diagrams have been reported by the literature [33], which reported no breakdown during high market penetration (above 70%).

Also, **Fig. 6**(e) shows that the capacity increase trend flattens out when the MP gets higher than 70%. This is due to the vehicle composition assumption of the simulation. In the paper, we assume all vehicles on the managed lanes are at least VAD-equipped, which can serve as platoon leaders. When the MP reaches around 70%, almost all the platoons use VAD vehicles as the leader. We also only use regular human-driven behavior for VAD vehicles, which does not cause too much additional disturbance. Therefore, by the time MP reaches 70%, most of the vehicles are in relatively long platoons, and most of the roadway capacity has been exploited. It is easy to understand and has been shown in our simulation that, if VAD vehicles are replaced with non-VAD vehicles, this trend line can take the shape of an exponentially increasing curve because higher MPs indicate higher probabilities of forming platoons.

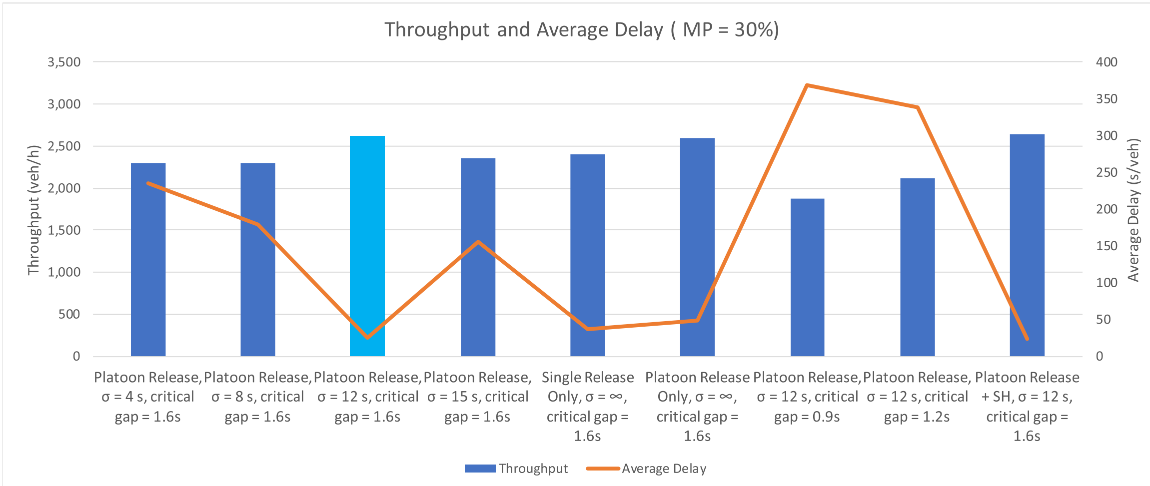
B. Analysis 2–CACC and Cooperative Merge

Vehicles entering via on-ramps bring disturbance to the mainline managed lane. Their impacts mainly depend on the mainline managed lane volume. Lighter traffic volume on the managed lane can provide more and longer gaps that will be available for vehicles from the on-ramp to merge into. This section aims to compare managed lane performance with and without cooperative merge.

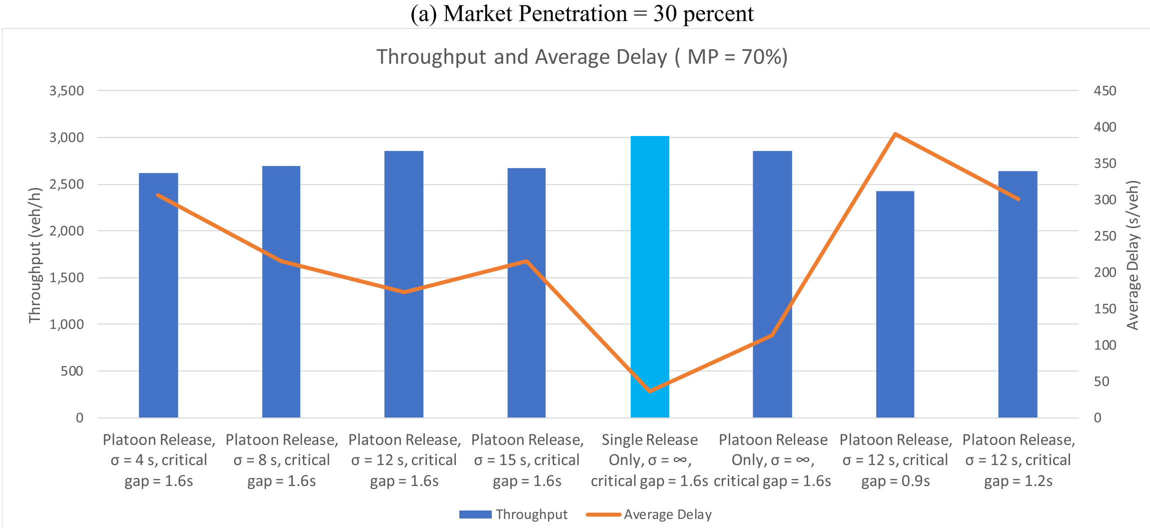
Several sensitive analyses have been conducted to find out the optimal critical gap and releasing strategies. First, we compared two strategies that release either one on-ramp vehicle for any identified gaps and multiple vehicles depending on the sizes of the qualified gaps. The critical gap for one vehicle is set as 1.6 seconds. As shown in Fig. 7, releasing and operating more than one merging vehicle can increase traffic performance for 100% and 30% market penetration cases. For the 70% case, the result is worse than releasing only one vehicle. This is mainly because, in this scenario, most CACC platoons are formed with a VAD leader and CAV followers. Then the qualified gaps are usually identified between two CACC platoons (i.e., the inter-platoon gap). Thus, most virtual followers are VAD vehicles. They cannot maintain the identified gaps, especially under the congested situation. Even though the same situation can also happen in the 30% case, the mainline density is relatively lower than the 70% case, which could tolerate some disturbance.

We also tested the updated releasing strategy that releases and creates gaps for on-ramp vehicles if this vehicle's waiting time at the ramp exceeds threshold σ. We selected four different levels of σ, which are 4, 8, 12, and 15 seconds, representing the minimum guaranteed ramp metering rates of 900, 450, 300, and 240 veh/h, respectively. The strategy that only releases vehicle when big enough gaps are identified can be regarded as $\sigma = \infty$. The results show that the performances of σ =12 seconds are better than others in both 100% and 30% cases. The scenario of $\sigma = 12$ seconds can be seen as a balance point where more on-ramp vehicles can be released with only moderate disturbance to the mainline traffic. That can help reduce both the number of waiting vehicles and total waiting times so that the average delay of the entire system decreases and the throughput increases. For the case of 70% market penetration, as we discussed in the last paragraph, the frequent release on-ramp vehicles cause significant disturbance to the mainline traffic because many of the identified gaps may disappear when the follower does not create gaps. In this case, the case of $\sigma = \infty$ performs the best because fewer vehicles are released, and they are only released when there are potential gaps.

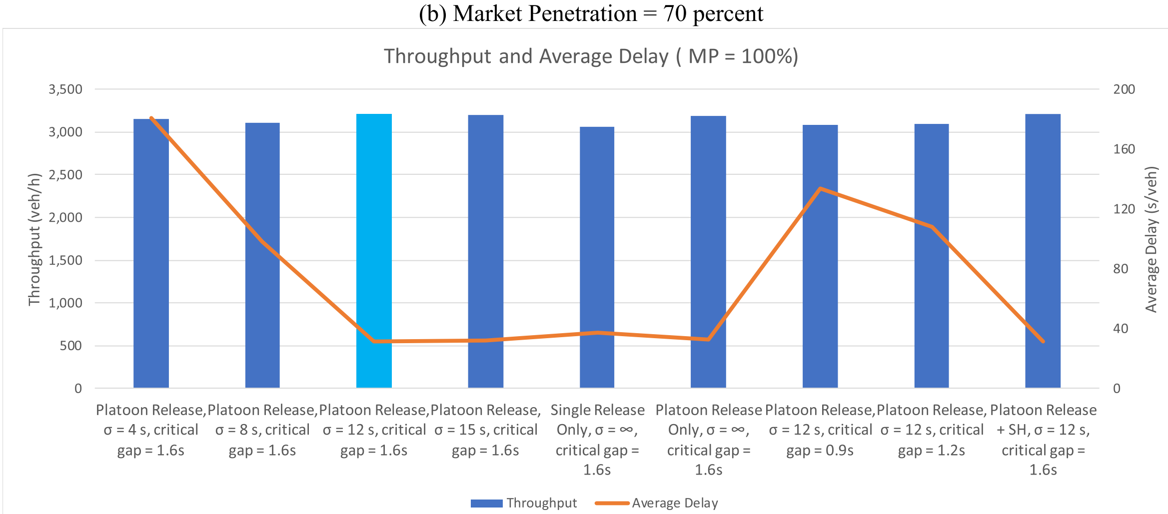
Note that in the case studies, the merge algorithm only allows merge vehicles to join gaps over a threshold. This threshold is set at 1.6 seconds in this study, which is slightly higher than the inter-platoon gap. If the threshold is too large, the roadway is not fully utilized. As shown in Fig. 7, two smaller thresholds, 0.9 and 1.2 seconds, are tested. It can be found, as expected, that if the threshold is too small, the virtual follower needs to slow down frequently during congestion to create gaps for the merging vehicle due to the virtual platooning process of the cooperative merge, therefore causing significant disturbance to the local traffic. In this paper, this value has been selected through many simulation runs under different scenarios (e.g., congestion level) to ensure the merging maneuver does not cause significant disturbance to



(a) Market Penetration = 30 percent



(b) Market Penetration = 70 percent



(c) Market Penetration = 100 percent

Fig. 7. Sensitive analysis.

the local traffic and the corresponding throughput and delay are best on average across the trail runs.

Table II shows selected simulation results with combined CACC and cooperative merge under different CAV market penetrations. The managed lane input (ML) volume is around 85% of the pipeline capacity, such that additional vehicles are allowed to enter the segment through on-ramps. The merge input volume is generated by actual simulation runs with

TABLE II
SELECTED RESULTS WITH COMBINED CACC AND COOPERATIVE MERGE

MP	ML Volume (vphpl)	Merge Volume (vphpl)	Throughput (Coop / Non-coop, vphpl)	Average Delay (Coop / Non-coop, seconds)	Pipeline Capacity (vphpl)	Improvement of Throughput (%)	Reduction of Average Delay (%)	Reduction from Pipeline Capacity (%)
100%	2800	436	3214	31.32	3288	12.77	80.88	-2.25
			2850	163.82				-13.32
70%	2700	289	3012	36.74	3192	19.61	67.15	-5.64
			2518	111.87				-21.11
30%	2050	610	2616	25.48	2412	10.66	72.42	+8.46
			2364	92.40				-1.99
0%	1970	382	-	-	2316	N/A	N/A	-10.49
			2073	132.23				

MP = market penetration rate. ML = managed lane.

cooperative merge algorithms, and it is partly dependent on the available merging gaps. We use the same merge volume for the corresponding non-cooperative merge of the same MP scenarios to compare results with the cooperative merge.

As we see, the system improvement due to the cooperative merge is dramatic when the market penetration is at 100%. The throughput improvement is 12.77% (from 2,850 vphpl to 3,214 vphpl) and the delay reduction is 80.88% (163.82 seconds to 31.32 seconds). For the 70% MP scenarios, we release a single vehicle based on release gaps, instead of multiple-vehicle platoon release, because this strategy performs better as shown and discussed above. The throughput improvement at 70% is larger than in other cases, but the average delay is slightly worse. But with lower penetration rates such as 30%, the benefit of cooperative merge still maintains at a good level. It is mainly because the low penetration rates mean additional gaps that merging vehicles can use to merge into the traffic since the desired gaps between manual vehicles are usually larger than the critical gap (i.e., 1.6 sec) used in this study. But a lot of these gaps cannot be maintained because of the human-driven virtual followers. Therefore, the net benefits of cooperative merge under lower MP rates are smaller than under high MP rates, though by a small margin.

In terms of reduction from pipeline capacity, it is intuitive that the 100% case is better than 70% because the 100% MP allows full cooperation and, therefore, less disturbance from the merging traffic to the mainline. However, under lower penetration, the reduction in capacity is not obvious. This is because 1) the pipeline capacity is not high, and many gaps are available for merging, and 2) more CAVs entering the network from ramp actually increases the percentage of cooperation more than other high-MP cases.

C. Analysis 3–Effects of Speed Harmonization

For all the scenarios in Analysis 2, this section evaluates them again with the addition of speed harmonization. Speed harmonization effects are also analyzed with and without a cooperative merge.

Table III shows the simulation results with integrated CACC, cooperative merge, and speed harmonization under different CAV market penetrations. We use the same method for generating the managed lane and on-ramp traffic volumes. Speed harmonization is effective from 1,500 meters upstream of the merging area. The length of the speed harmonization zone is obtained through multiple trial runs, which shows the 1,500-meter zone gives the best performance. The speed harmonization algorithm is implemented as automatic speed control of CAVs, and therefore VADs are not affected by speed harmonization directly, but they may be harmonized by nearby CAVs. Also, note that speed harmonization is only activated when the merge area average speed is below 80 km/h (50 mph); otherwise, the mainline delay will drastically increase.

Similar to the results in Table II, the improvement of the cooperative merge, when speed harmonization is implemented, is significant when the MP is at 100%. The throughput improvement is 9.54% (from 2,934 vphpl to 3,214 vphpl) and the delay reduction is 79.59% (153.46 seconds to 31.32 seconds). Other trends are also similar to those in Table II. In the extreme case of 0% penetration rate, the performance is exactly the same as in Table II because speed harmonization does not affect VAD vehicles. Similarly, the reduction in capacity compared with the CACC pipeline capacity is also most significant when the CAV penetration rate is 100%, but the cooperative merge is much better than the non-cooperative merge scenario, implying the importance of cooperative merge.

The effect of speed harmonization can be reflected in multiple aspects. Compared with Analysis 2 in Table III, the average delay further reduced significantly in most of the cases because of the smoothing and breakdown prevention effects. Note that the effect of speed harmonization more significant when the cooperative merge is not implemented. This is intuitive because there is already not much space for improvement after CACC and cooperative merge is implemented. The same argument can be made to explain why there is no further improvement for the 100% MP scenario. Additionally, we notice that the changes in throughput after implementing speed harmonization, with and without cooperative merge, is quite limited, close to zero. This is in line with the simulation result obtained in [53], indicating greater delay improvement and small throughput benefits, unless the algorithm is specifically designed for throughput enhancement. The last two columns of Table III show the comparison of overall system performance. These interesting results further

TABLE III
SELECTED RESULTS WITH BUNDLED CACC, COOPERATIVE MERGE AND SPEED HARMONIZATION

MP (%)	ML Volume (vphpl)	Merge Volume (vphpl)	Throughput (Coop / Non-coop, vphpl)	Average Delay (Coop / Non-coop, seconds)	Pipeline Capacity (vphpl)
100	2800	436	3214	31.32	3288
			2934	153.46	
70	2700	440	2942	32.38	3192
			2484	65.10	
30	2050	617	2647	23.75	2412
			2244	75.85	
0	1970	382	-	-	2316
			2073	132.23	

MP (%)	Improvement of Throughput (%)	Reduction of Average Delay (%)	Reduction from Pipeline Capacity (Coop / Non-coop, %)	Throughput Compared with Analysis 2 (Coop / Non-coop, %)	Average Delay Compared with Analysis 2 (Coop / Non-coop, %)
100	9.54	79.59	-2.25	0.00	0.00
			-10.77	+2.95	-6.32
70	15.57	50.26	-7.83	-2.32	-11.87
			-22.18	-1.35	-41.81
30	15.22	68.69	+9.74	+1.18	-6.79
			-6.97	-5.08	-17.91

MP = market penetration rate. ML = managed lane.

confirm the importance of bundling application together to realize the greatest potential of each component application.

V. CONCLUSION AND FUTURE RESEARCH

The emergence of CAV technologies offers extensive opportunities to advance safety, mobility, and reliability on the US roadways. The market penetration of these vehicles is, however, expected to be low in the next decade, and as such, their potential benefits may not be fully realized. The use of managed lane facilities can support the realization of these benefits at early deployment stages. This study focuses on deployment stages of low market penetration and evaluates how the proposed integrated application of speed harmonization, cooperative adaptive cruise control (CACC), and cooperative merging is operated to improve existing system performance.

This study proposes an integrated algorithm for the integrated CAV application. Through microscopic simulation, this study estimates capacity shifts under CAV market penetrations, providing operational insights and guidance for traffic management centers to control the volume on the managed lanes to maintain the desired speed. Particularly, the study examines the effectiveness of CACC, CACC plus cooperative, and the addition of speed harmonization, under different penetration rates. Simulation results show the effectiveness of the integrated application to enhance system throughputs and reduce delay, even with low CAV penetration rates. The speed harmonization only shows significant effectiveness with high CAV penetration, but the potential safety benefits it brings to the system, though not evaluated in the study, can be quite significant.

Future research directions have been identified. First, additional simulation analysis should be conducted to understand other impacts on the system, such as safety benefits. Also, this study assumes a 100% communication success rate, and it is interesting to study the potential consequences when the communication performance is compromised. This may not only lead to safety concerns but also cause frequent status changes between platooning and human-driven modes, therefore resulting in unstable platoons and oscillatory traffic. Fourth, all merging vehicles on the left-side dedicated ramps are assumed to be CAVs to ensure their cooperative behavior. This assumption is made for our purpose of creating high- performance traffic streams on managed lanes but can be relaxed in future studies. It is interesting to investigate the system performance when the merging traffic, from either left-side or right-side ramps, is a mix of conventional vehicles, VAD vehicles, and CAVs. Non-CAVs may cause traffic disturbances in the merging area, and it is worth investigating how the integrated freeway CAV application handles the disturbances and smooths the traffic. Fifth, it is critical to evaluate the integrated application in a well-calibrated real-world network to understand the effectiveness of complex traffic and geometric settings. The research team is currently conducting a case study using an Interstate 66 network, a 21-kilometer (13-mile) freeway segment outside the Interstate 495 Beltway near Washington, D.C.

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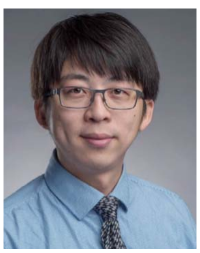

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