# Leveraging existing High-Occupancy Vehicle lanes for mixed-autonomy traffic management with emerging connected automated vehicle applications

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Transportation agencies have started including phased deployment of connected and automated vehicle (CAV) technologies in their transportation plans and programs. While theoretical analyses have indicated significant benefits of CAVs for improving system performance, deploying these technologies at existing or adapted highway facilities concerns more than technological issues. This study introduces the concepts and operational strategies of using managed lanes, High-Occupancy Vehicle (HOV) lanes in particular, for mixed-autonomy traffic management. The study enhances existing and develops new algorithms for three selected freeway CAV applications as a CAV technology integration, including speed harmonization, cooperative adaptive cruise control (CACC), and cooperative merge. Instead of evaluation on a synthetic segment, this study reports a large-scale simulation-based real-world case study to investigate CAV early deployment opportunities on Interstate 66 outside the Beltway. The simulation results show that, for all scenarios, individual and bundled CAV applications can significantly improve traffic performance in terms of delay and throughput. CACC platooning is the most effective individual strategy to improve traffic performance. The bundled CAV applications can benefit the system, even with low CAV market penetration, and fully handle more than 130 percent of the existing demand with high CAV market penetration rates. Additionally, left-side dedicated ramps and shared managed lane operational strategies are also beneficial, even during early deployment stages.

Keywords: connected automated vehicles (CAV); managed lane; High-Occupancy Vehicle (HOV); cooperative adaptive cruise control (CACC); cooperative merge; speed harmonization; dedicated ramp

## Introduction

Oversaturation occurs when more vehicles use a road than the capacity (i.e., demand is greater than supply). Regardless of its original cause(s), excess congestion leads to unstable traffic flow, which is followed soon by breakdowns and bottlenecks. These congestion events bring unwanted impacts, including wasted fuel, increased emissions, decreased travel time reliability, delays to emergency vehicles, and higher accident risk.

Emerging connected and automated vehicle (CAV) technologies offer promising and flexible solutions to traffic congestion. CAVs may be equipped with a suite of technologies ranging from preliminary vehicle automation (i.e., automated decision making at the vehicle level using onboard sensors) to a connected ecosystem in which vehicles and roadside infrastructure communicate wirelessly among themselves. Since managed lane facilities are often equipped with traffic sensors, communication networks, and tolling equipment (Yin et al., 2009; Zhang et al., 2009; de Palma and Lindsey, 2011), which can be leveraged to support CAV initiatives, managed lane operators have a unique opportunity to leverage their facilities as early deployment sites for CAV to improve the traffic system performance.

The motivation of this study is to investigate the effectiveness of CAV deployment in enhancing existing traffic system performance with different managed lane operational strategies. This study aims to evaluate the potential benefits of implementing CAV applications in existing or upgraded facilities and determine appropriate managed lane operational strategies correspondingly. Since more than three dozen CAV application concepts have been developed (Siegel et al., 2017; Guanetti et al., 2018; Elliott et al., 2019; ITSJPO, 2019), three of them are applied in this study due to their effectiveness (Shladover et al., 2012; Naus et al., 2010; Ntousakis et al., 2016; Letter and Elefteriadou, 2018; Malikopoulos et al., 2018; Learn et al., 2017; Ma et al., 2017; Zhou et al., 2017; Guo et al., 2019): cooperative adaptive cruise control (CACC), speed harmonization, and cooperative merge.

CACC is able to reduce traffic congestion by improving highway capacity and throughput and attenuating traffic flow disturbances. Since ACC has had little effect on lane capacity (Shladover et al., 2012; Milanés et al., 2014), the CACC systems could allow the mean following time gap to decline from about 1.4 seconds when driving manually to approximately 0.6 seconds with utilizing vehicle-to-vehicle (V2V) communication (Nowakowski et al., 2010), resulting in an increase in highway lane capacity.

Speed harmonization involves gradually lowering speeds upstream of a heavily congested area in order to reduce the stop-and-go traffic, which may also be used to reduce vehicle speeds, either delaying or preventing the onset of traffic congestion. The simulation results in previous literature found significant travel time reductions (e.g., a 10-percent reduction corridor-wide and a 35-percent reduction on localized bottleneck segments) at CAV penetration rates of 10 percent or higher, which concurred with other simulation-based studies (Talebpour et al., 2013).

Cooperative merge leverages V2V and V2I communications to enable CAVs to safely merge into the traffic with less impact on mainline traffic (Chou et al., 2016; Raboy et al., 2017). It helps CAV to identify upcoming acceptable gaps or signal mainline traffic to create an acceptable gap by cooperating with each other. Chou et al. (2016) tested two cooperative automated merging strategies with I2V and V2V correspondingly. The results show that the I2V case 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. A recent Federal Highway Administration (FHWA) study (Raboy et al., 2017) also successfully validates a cooperative lane change maneuver driven by a proof-of-concept field experiment.

Based on the previous simulation studies in a single managed lane, the bundled application of these three aforementioned CAV applications can further improve the traffic performance with existing highway facilities as compared with using individual CAV application (Ma et al., 2018). These vehicle connectivity and automation technologies could allow consistent speeds to be maintained throughout the facility, thereby increasing the traffic demand levels that the roadway can support. The increased throughput and capacity of the managed lanes could also potentially benefit parallel general-purpose lanes as traffic shifts to the managed lane. Smoothed, optimized speeds would also create a reduction in fuel consumption, harmful emissions, and highway crashes.

Litman (2017) indicates that the CAV may not be predominant in traffic until the 2040s to 2050s; therefore the traffic flow will consist of conventional vehicles, connected vehicles (CVs) and CAVs in a long period. In this transition period, CAVs and CVs can benefit the traffic system performance with gradually increasing market penetrations before the fully-autonomy (i.e., all presented vehicles are CAV) is achieved; therefore the traffic system can be regarded as a 'mixed-autonomy' system since conventional vehicles coexist with CVs and CAVs. To ensure a smooth transition from conventional human-driven traffic to mixed-autotomy traffic with gradually increasing market penetration rate of CVs and CAVs, the alternative operational strategies are also worthy of investigation to adapt the changes to realize CAV benefits, especially at the early deployment stages. For example, based on the results in the previous study (Ma et al., 2018), low market penetration of CAV may not contribute to traffic performance enhancement. This is mainly because conventional vehicles cannot cooperate with CAVs and involve stochastic driving behaviors that may disturb CAVs' operations. To resolve this issue, one possible alternative strategy is to create a "high-penetration" environment by offering CAVs eligibility to using existing managed lanes such that CAVs can concentrate at a certain part of the traffic stream, interact and platoon with each other, and therefore positively impact the traffic system performance.

The purpose of this paper is to investigate deployment opportunities of CAV technologies and alternative managed lane strategies on existing and adapted facilities in the mixed-autonomy traffic system. This study conducts simulations on a real-world network to examine the effectiveness of CAV deployment and corresponding managed lane operational strategies in enhancing traffic system performance. Both infrastructure operational and CAV technological strategies are simulated, evaluated, and discussed. On the CAV technological side, this study evaluates the effectiveness of each individual CAV application and their combinations. On the infrastructure operational side, the case study evaluates the potential benefits of dedicated ramps and a realistic management lane concept – CV/CAV eligible HOV lanes – where CVs, CAVs, and HOVs (which can be human-driven or CV/CAV) can access the left-side managed lane. The remainder of this paper is organized as follows: Section 2 provides detailed descriptions of the technologies and operational strategies. Section 3 covers the simulation experiments and results, including the model calibration, design of simulation, simulation results for different scenarios, and discussion of implications. Section 4 concludes this paper and proposes future research topics.

## CAV Applications and operational strategies

### *Cooperative Adaptive Cruise Control/Platooning*

The car-following behavior of CACC-equipped vehicles is significantly different from human-driven behaviors. CACC-equipped vehicles can form platoons with stable and short following gaps. This study adopts the CACC control logic developed by Milanes and Shladover (2014) and Liu et al. (2018) and incorporates recent results from the Federal Highway Administration (FHWA) High-Performance Vehicle Stream project (2015). This study focuses on the impact of the car-following behavior of CACC operations at the early stages of deployment and does not explicitly consider lane changes for platooning; therefore the lateral behaviors are modeled the same as human-driven behavior. If a CACC-equipped vehicle intends to change lane, the longitude behavior will be regulated by CACC control logic, and the lateral behavior is controlled by the conventional lane change model. Therefore, the CACC behavior is SAE Level 1 Automation with longitudinal control. The cooperative merge and speed harmonization applications discussed later are also Level 1.

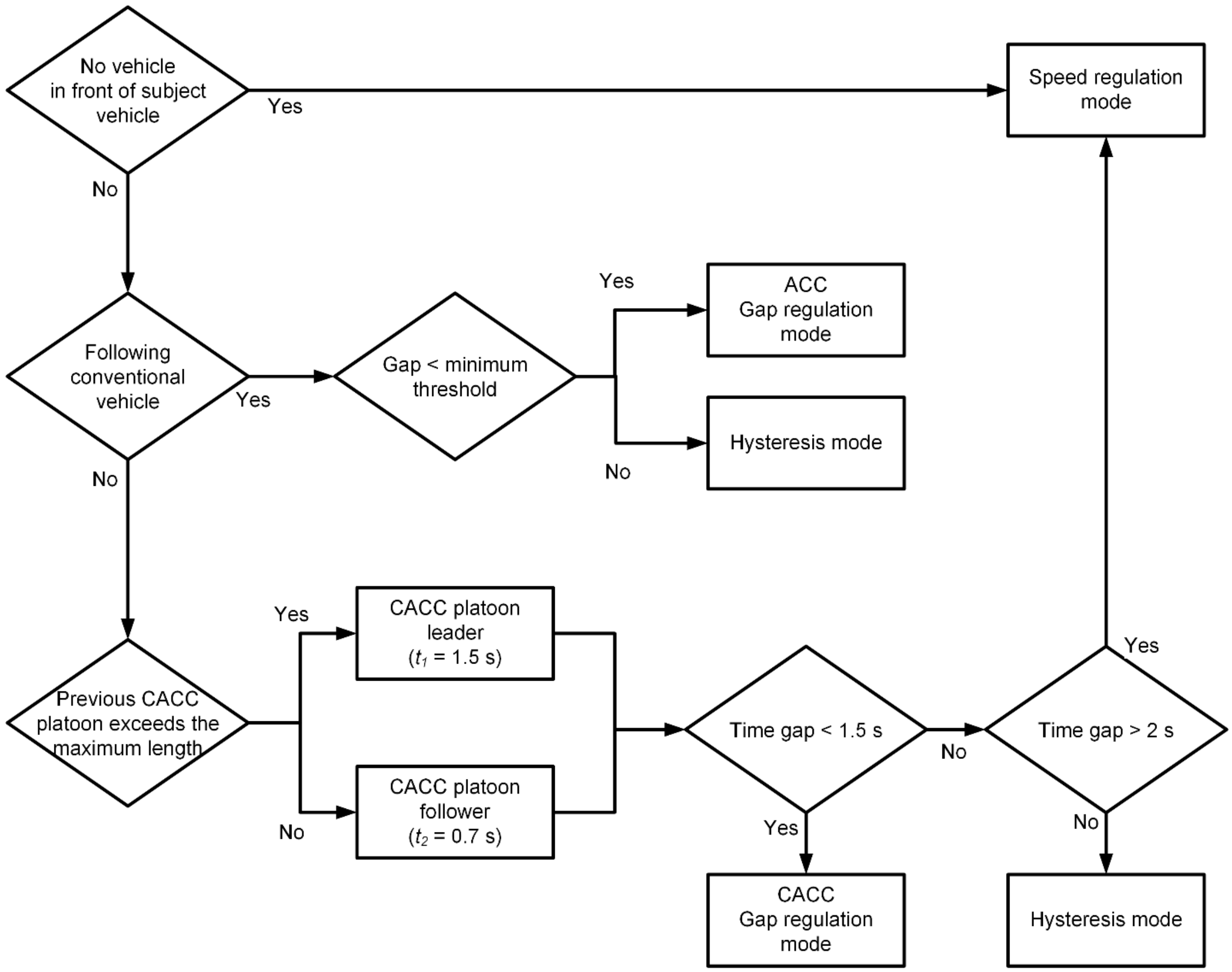



**Figure 1.** Car following logic for vehicles equipped with cooperative adaptive cruise control.

As shown in **Figure 1**, if there is no vehicle in front of the subject CAV, it will apply the speed regulation mode to regulate the driving behavior. This mode keeps the subject CAV cruising with target speed to reduce unnecessary oscillations, as shown in Equation (1) (Liu et al., 2018):

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

where $k_1$ is the control gain of the difference between current speed $v_{sv}$ and free-flow speed $v_f$ and determines the acceleration $a_{sv}$. The control gain $k_1$ is set to 0.4 $s^{-1}$ in this study (Liu et al., 2018).

If the preceding vehicle is a conventional vehicle, the subject CAV will switch to the ACC mode to regulate the driving behavior. If the subject CAV is too close to the preceding vehicle (i.e., the detected clearance distance is smaller than a given minimum following threshold), it will switch to the ACC gap regulation mode to maintain a safe following time gap $t_{hw}$, as shown in Equation (2) (Liu et al., 2018). Otherwise, the CAV will repeatedly implement previous control logic to ensure consistent driving behavior.

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

where $k_2 = 0.23\ s^{-2}$ and $k_3 = 0.07\ s^{-1}$ are control gains on following distance difference and speed difference, respectively (Liu et al., 2018). The headway $d$, preceding vehicle length $L$, and preceding vehicle speed $v_l$ are considered in Equation (2).

If the preceding vehicle is a CAV, the subject vehicle will switch to the CACC mode and communicate with the preceding vehicle to exchange critical information (e.g., speed, location, platoon size). If the length of the previous CACC platoon is less than the maximum allowable platoon length, the subject CAV will catch up with the preceding CACC platoon and become a platoon follower; therefore the intra-platoon gap $t_2$ (0.7 seconds in this study) is applied to tightly follow the preceding CAV. Otherwise, the subject CAV becomes a CACC platoon leader and applies the inter-platoon gap $t_1$ (1.5 seconds in this study) to follow the preceding CAV. The specific regulation mode depends on the actual time gap between the subject CAV and its preceding CAV. If the time gap is larger than a given threshold (2 seconds in this study), the subject CAV will apply speed regulation mode, as shown in Equation (1). Otherwise, it will apply the CACC gap regulation mode to keep a safe following distance with the determined following gap (i.e., inter-platoon gap or intra-platoon gap) by implementing Equation (3)-(6) (Liu et al., 2018).

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

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

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

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

where $k_p = 0.45\ s^{-1}$ and $k_d = 0.0125$ are gap error control gains (Milanés and Shladover, 2014).

Due to the linearity of the above models, the vehicles cannot handle emergency braking to avoid collisions. The forward collision warning algorithm (Kiefer et al., 2003) developed by the Collision Avoidance Metrics Partnership (CAMP) is included in the C/ACC car following modes to determine whether the gap between the subject vehicle and the preceding vehicle is sufficient for safe car following. If the crash warning is activated, it implies that a crash will happen if both the subject vehicle and the preceding vehicle keep their current acceleration speeds for the next few seconds. The algorithm will use a conventional car-following model (e.g., Wiedermann 99) that guarantees collision-free to generate emergency deceleration commands until the crash warning is deactivated.

In this study, as a benchmark, we chose a maximum string length of 10 vehicles, as recommended in Liu et al. (2018). Shorter string lengths would result in more CACC strings, which can lead to lower freeway capacity because inter-string gaps are larger than the gaps between consecutive vehicles within the string (Bujanovic and Lochrane, 2018). On the other hand, long CACC strings would make it more difficult for other vehicles to perform certain maneuvers, such as merging and lane changing, particularly when they need to merge into or leave the freeway.

### *Speed Harmonization*

This study adopts the segment-based I2V speed harmonization, as proposed in FHWA (2016). When an imminent or existing congestion at a bottleneck is detected, to avoid hitting the downstream queue at a sudden full stop, the upstream CAV should slow down moderately and pass the bottleneck smoothly at a reasonable speed just as the downstream queue dissipates. 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 similar smooth manner. As a result, the platoon of vehicles following this CAV will pass the bottleneck with a larger throughput rate due to reduced time headway at high speed, less fuel consumption due to smoothed trajectories, and less collision risk due to harmonized vehicle speeds.

This 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. It is assumed that traffic detectors are available at bottleneck locations to monitor the real-time traffic condition to calculate the arithmetic mean of speed and occupancy of the past 3 minutes at these locations. Within a bottleneck area, the speed-based algorithm tends to generate advisory speeds 10 to 50 percent higher than measured bottleneck speeds. This approach does not claim system optimization yet emphasizes simplicity and practical field implementation. A simple linear algorithm is applied to generate the recommended speed $u_m(k)$ at time step k, as shown in Equation (7) (FHWA, 2016):

$$u_m(k) = \alpha_m \times \bar{v}_m(k) \tag{7}$$

where $\alpha_m$ is proportional control gain of the arithmetic mean of speed in bottleneck area $m$. The value of $\alpha_m$ is set to $\alpha_m = 1.3$ in this study after evaluations of the effects of alternative values.

Second, when an imminent or existing congestion is detected, this algorithm intends to generate a lower recommended speed than the measured arithmetic mean of the speed of the bottleneck area to smooth the upstream traffic. This algorithm is triggered by the measured occupancy of the bottleneck area, as shown in Equation (8) (FHWA, 2016):

$$u_{m+1}(k) = \begin{Bmatrix} V_{free}\,, & if\ o_m(k) < \sigma_{sw} \\ \beta_m \times \bar{v}_m(k) & if\ o_m(k) \geq \sigma_{sw} \end{Bmatrix} \tag{8}$$

Where,

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

$V_{free}$: free-flow speed.

$\beta_m$:  proportional control gain in section m, where $\beta_m \in [0.7,0.9]$, $\beta_m = 0.8$ in this study

$o_m(k)$: occupancy in bottleneck section $m$.

$o_{cri}$: critical occupancy in bottleneck section $m$.

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

It is critical to mention that in a legacy algorithm of speed harmonization for human-driven traffic (FHWA, 2016), the value of critical occupancy in the bottleneck section $o_{cri}$ stays constant as a basic attribute of the traffic stream. With CAV traffic, however, $o_{cri}$ varies depending on the market penetration of CAVs because the fundamental diagrams shift with different market penetration rates. In this study, initial simulation runs are conducted to obtain the capacity and critical density values under different market penetration rates of CAVs.

***Cooperative Merge***

Cooperative merge aims to cooperatively operate both mainline vehicles and merging vehicles to create qualified gaps at merging areas through V2V and/or V2I communications. When the merging vehicle requests to merge or a merging vehicle is detected, a gap should be created to let merging vehicle to merge into the mainline. The creation of gaps relies on the situations described below, letting mainline vehicles to cooperatively change the lane or slow down to create qualified gaps.

There are four scenarios that the vehicle may potentially encounter to activate the cooperative merge. Please note that the algorithm process uses many parameters, and their values have been determined by selecting those that can generate the best system performance during initial simulation runs on simplified and actual I-66 networks.

*Case 1*

As shown in Figure 2 (a), there is a vehicle (Vehicle B) on the target lane in front of the merging vehicle (Vehicle A). If Vehicles A and B have similar speed (i.e., small speed difference $\Delta v$), the merging Vehicle A will slightly slow down and merge into the mainline. In this study, the range of speed difference is $-1.0\ m/s\ < \Delta v < 0.1\ m/s$ and the deceleration rate of merging Vehicle A is a constant value of $-0.5\ m/s^2$.

*Case 2*

As shown in Figure 2 (b), if Vehicle A intends to merge into mainline and Vehicle B on the target lane is behind A, then B will be advised to cooperatively change lane to adjacent lane to create a safety and acceptable gap for Vehicle A to merge into. This cooperative merge will be activated once the following conditions are met:

(1) The new lane will not affect Vehicle B to complete its original route.

(2) The speed difference $\Delta v_{AB}$ between Vehicle A and Vehicle B is less than the maximum speed difference $\Delta v_{max}$, where $\Delta v_{AB} = v_A - v_B$. The maximum speed difference is $\Delta v_{max} = 10.8\ km/h$ (i.e., $3\ m/s$) in this study.

(3) The collision time does not exceed the maximum collision time $t_\sigma$, and B's speed has increased less than the maximum speed difference $\Delta v_{max}$. The maximum collision time is $t_\sigma = 10\ s$ in this study recommended by PTV VISSIM.

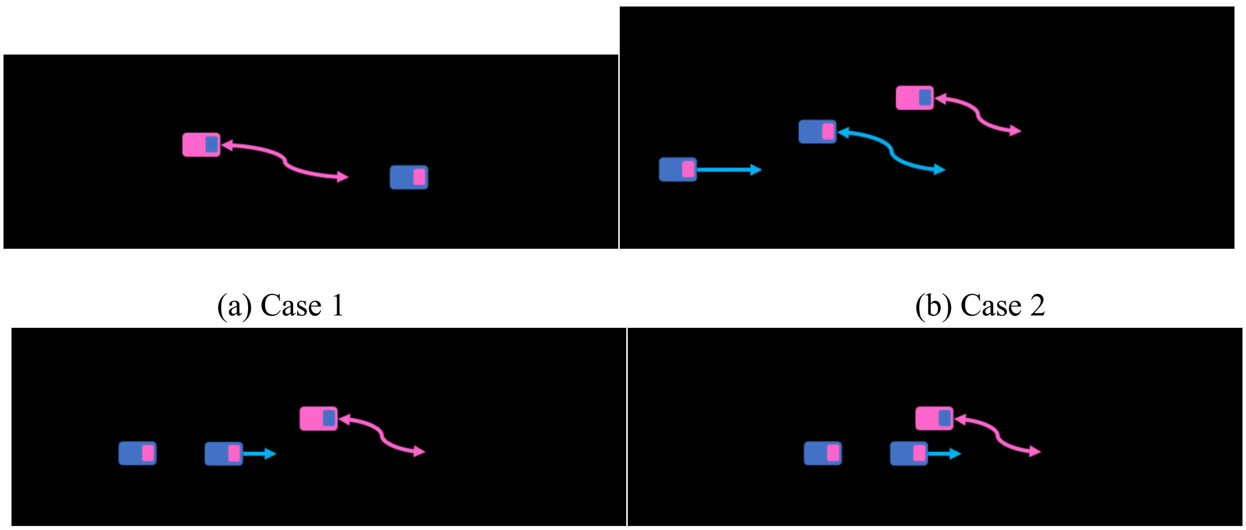
Case 3 and Case 4 involve the situation that the mainline vehicle cannot change lane into the adjacent lane due to the requirements in Case 2 cannot be met. Therefore, the mainline vehicle needs to reduce speed to create a gap and allow the merging vehicle to merge into the mainline.

*Case 3*

As shown in Figure 2 (c), on-ramp Vehicle A intends to merge into mainline and the mainline vehicle B is behind A. Then Vehicle B will slow down and create an acceptable gap to let on-ramp Vehicle A merge into the mainline. Meanwhile, the following vehicle C will also cooperatively slow down to keep a safe following distance from Vehicle B. Vehicle B and C can be independent vehicles and can also possibly be a CACC platoon in many cases.

*Case 4*

Figure 2 (d) shows another situation that when the on-ramp Vehicle A requests to merge, the mainline Vehicle B is too close to slow down. Then B will take no action and keep its speed. The following Vehicle C will slow down and let A merge into the mainline.



(a) Case 1 (b) Case 2

(c) Case 3 (d) Case 4

Figure 2. Illustration of different cooperative merging cases.

***Bundled CAV Application***

The aforementioned CAV applications, when bundled together, are expected to generate higher benefits (Ma et al., 2018). This section briefly describes the operational process of the bundled application.

The desired speed of CAV $v_{des}$ is initially set to speed limit $\overline{v}$ when it enters the network. The CACC logic determines the platoon status (i.e., platoon leader or follower) first and decides which mode should be applied based on the preceding vehicle type, platoon status, and current following gap. Then the CACC logic calculates acceleration or deceleration rate with the desired speed $v_{des} = \overline{v}$ and control the vehicle to stably maintain the optimal following gap.

If speed harmonization is activated, an updated speed guidance $v_{SH}$ will be calculated and distributed to CAVs within the speed harmonization zone instead of the original speed limit $\overline{v}$. Cooperative merge can also impact speed guidance. If the mainline traffic is signaled to implement cooperative merge by reducing speed (i.e., Case 3 or 4), an updated speed guidance $v_{CM}$ will be calculated and sent to the subject CAV. Therefore, an alternative speed guidance $\hat{v}$ will be applied instead of $\overline{v}$, where $\hat{v}$ is defined by Equation (9).

$$\hat{v} = min\{\overline{v}, v_{SH}, v_{CM}\} \tag{9}$$

Then $v_{des}$ is set to $v_{des} = \hat{v}$ and applied in CACC control logic to regulate the car following behavior.

If CAV needs to change lane for the cooperative merge (i.e., Case 2 of cooperative merge), the lane change behavior is regulated by conventional 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.

***Connected Vehicle Behavior***

Compared with CAV, CV is only capable of communicating wirelessly to exchange critical vehicle information (e.g., speed, location)  with other CVs, CAVs, and infrastructure. The CVs cannot be automatically controlled and are still maneuvered by human drivers. In this study, a driving behavior model is proposed to adapt CV driving behavior, which is different from either CAVs or conventional vehicles.

The proposed CV driving behavior model is based on Wiedemann 99 model with calibrated parameters (Miller-Hooks et al., 2012), which is also used to model conventional vehicle driving behavior in this study. For the CACC application, a CV can be a platoon leader since it can transmit vehicular information to the following CAVs, which enables the CAVs to perform CACC logic. However, the CV itself cannot be the platoon follower because it cannot be automatically controlled.

In this study, we assume all CV drivers comply with the speed harmonization and cooperative merge guidance because of the personalized message delivered to the vehicle. For speed harmonization, a CV driver will reduce its speed once it received the speed guidance. However, unlike the CAV, CVs' desired speeds are heterogeneous in the traffic stream. The speed harmonization command is only the desired speed for all CVs. The actual CV speeds follow a pre-specified distribution with the desired speed (i.e., commands from the speed harmonization algorithm) as the distribution mean. Therefore, CVs still show heterogeneous behaviors in the traffic. For cooperative merge, CVs can either send merge requests to mainline traffic or receive merge requests from merging vehicles. If a CV in the mainline traffic receives a cooperative merge request, it will respond to this request and implement the cooperative merge manually (i.e., implementing the recommended speed by the cooperative merge algorithm). If a CV intends to merge into the mainline, it will the signal mainline traffic and finds a qualified gap to merge into the mainline manually.

### *Operational Strategies with Managed Lanes*

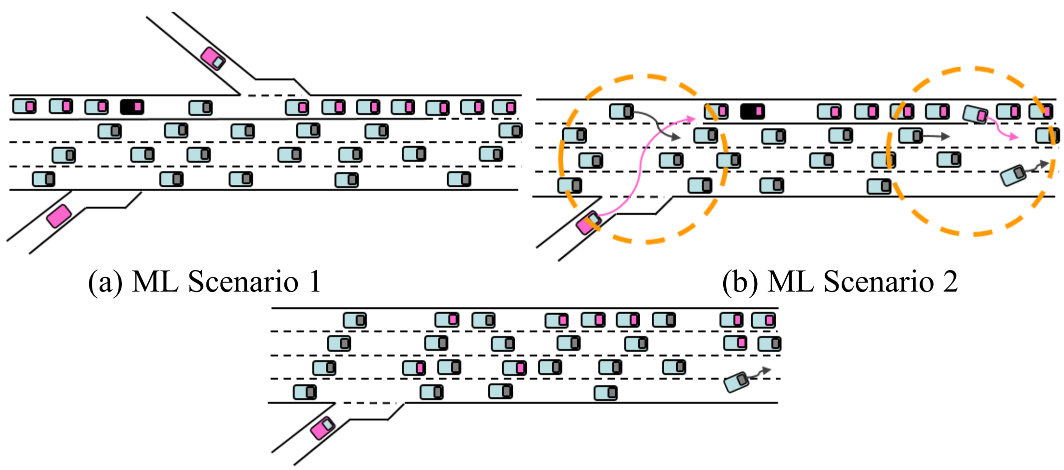
The goals of managed lane operations overlap with the goals of the CAV applications. While each managed lane project is implemented with its own set of goals and performance measures, in general, all managed lane operations aim to provide superior traffic performance (typically measured in terms of travel speeds and travel-time reliability) to that of adjacent general-purpose lanes, which are not subject to the same level of active management. The CAV strategies proposed in this study present a mechanism to increase the efficiency of available managed lane capacity and to improve traffic performance without significant capital investment.

Three scenarios for infrastructure are analyzed in this study. The main idea is to convert the existing HOV2 lanes, on which only vehicles with 2 or more than 2 persons in the car eligible, as the managed lane that also allows CVs or CAVs to access the lane. Different from the CAV-dedicated managed lane (Liu et al., 2018), this study investigates a CV/CAV eligible HOV lane, meaning that CVs and CAVs can have access to the existing HOV lane, even if the CVs or CAVs are single-occupancy vehicles. Also note that any HOVs, human-driven or CV/CAV, can still access the managed lanes. Therefore, this study investigates the mixed traffic scenario where both human-driven vehicles or CVs/CAVs may co-exist on any part of the network. Although the existence of human-driven traffic on managed lanes may negatively impact the CAV traffic performance, the mixed traffic condition in this case study is considered more realistic in the short run when early deployment of CAVs can be directly incorporated into the transportation network and the benefits of important network users, particularly HOVs, are not sacrificed. And it is also important to know how significant the negative impacts of human-driven vehicles are.

Another infrastructure component of interest is the left-side dedicated ramps that are connected to the managed lane. Because more vehicles will have access to the left-side managed lane, vehicles may make multiple lane change maneuvers to access the managed lane and therefore create a man-made weaving section that can reduce the highway capacity and increase safety risks. Therefore, constructing the dedicated ramps can reduce such negative effects and can be considered as a part of the CAV infrastructure strategy.

The three scenarios are illustrated in Figure 3. The key features of them are summarized below:

- ML Scenario 1
  - Dedicated Ramp for HOVs, CVs, and CAVs
  - Existing one-lane managed lane for HOVs, CVs, and CAVs
  - HOVs, CVs, and CAVs can access ramps on both sides
- ML Scenario 2
  - Existing ramp for all vehicles
  - Existing one-lane managed lane for HOVs, CVs, and CAV
- ML Scenario 3
  - Existing ramp for all vehicles
  - Existing one-lane managed lane for HOVs only



(a) ML Scenario 1 (b) ML Scenario 2

(c) ML Scenario 3

Figure 3. Illustration of three operational scenarios.

## Simulation results and analysis

### *Model Calibration*

The experimental simulation network is I-66 Westbound between interchange I495 (MM64) and US-29 (MM 51), six interchanges on this 13-mile long section as shown in **Figure 4**. And there is an HOV lane on the left side through this network. Speed and volume data were collected by RTMS trailers along with major mainline segments. On- and off-ramp volume data are collected by cameras. Initial calibration was performed to narrow down parameter set candidates by using a Latin Hypercube Sampling Design (LHD) approach. A total of 500 scenarios created by LHD were evaluated by PTV VISSIM with 5 replications for each scenario to choose the best candidate scenario. The selected candidate was fine-tuned to obtain the final simulation model. OD matrices are used by VISSIM to specify travel demand. The I-66 freeway network has ten zones. Zones 1 and 10 are the starting and ending points of the corridor. Zones 2 to 9 contain the intermediate interchanges. Two of the zones are only applicable to the existing HOV vehicles (i.e., exits for westbound, entrances for eastbound). The field-collected data in this study could identify how many vehicles traveled between some, but not all, OD pairs. To fill in the gaps, OD matrices were estimated using the QueensOD software. Results indicate an excellent correlation between estimated and field-measured OD trips. **Figure 5** (a) and (b) show example results of simulation validation. On the selected links, the comparison between estimated traffic flow and traffic counts match each other well. We also use INRIX data to validate the simulation, as shown in **Figure 5** (c), and the results show that the simulated link travel times also match the data well. Simulation experiments were performed 10 times to account for stochasticity.

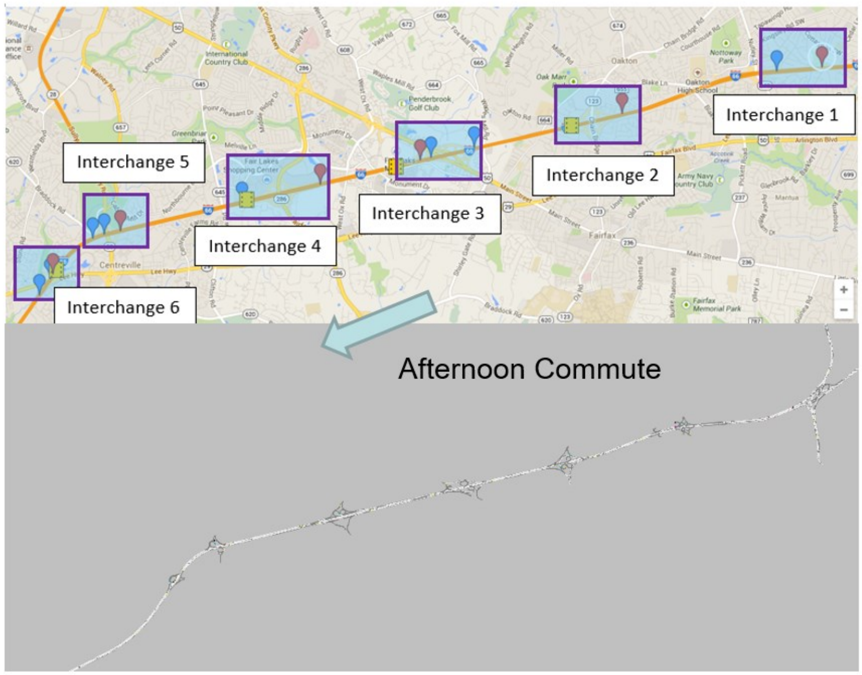
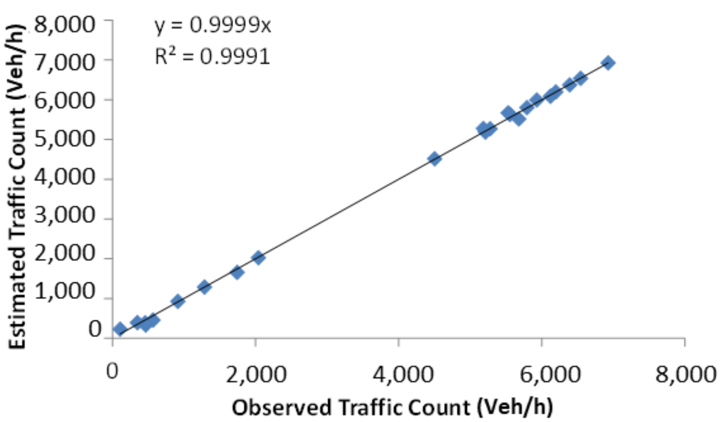
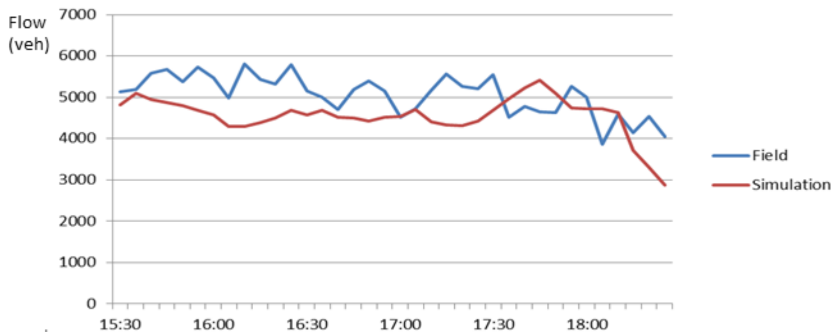


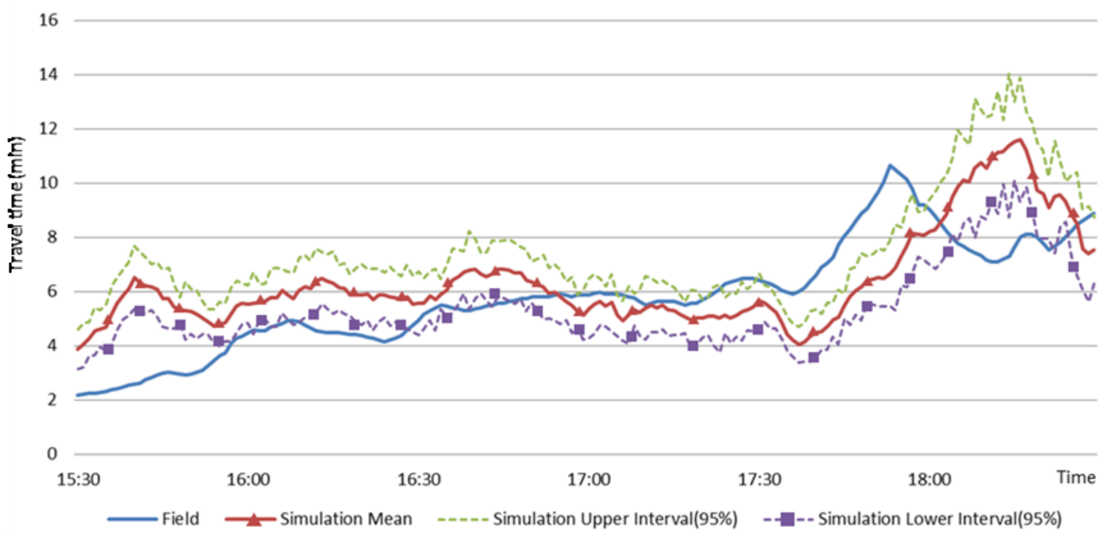

**Figure 4** I-66 Westbound simulation network




(a) Comparison of Estimated Flow and Observed Flow: 3:00 p.m. – 3:15 p.m.




(b) Calibration Results of traffic counts




(c) Calibration Results of Speed and Travel Time

**Figure 5** Calibration Results of the I-66 Simulation Network

### *Simulation Results*

In this study, three scenarios are simulated to investigate different operational strategies of existing or upgraded freeway facilities. Four different market penetrations (MP) of 0%, 33%, 67%, and 100% are tested, which the MP is calculated by Equation (10).

$$MP = \frac{number\ of\ CVs + number\ of\ CAVs}{number\ of\ vehicles} \times 100\% \tag{10}$$

Since CV has different driving behaviors with CAV, the CAV market penetration ($MPA$) is proposed to represent the proportion of CAV in the traffic flow and is defined by Equation (11). CAV market penetration can be also regarded as the autonomy level of the traffic system.

$$MPA = \frac{number\ of\ CAVs}{number\ of\ vehicles} \times 100\% \tag{11}$$

Therefore the CV market penetration (MPC) can be defined as,

$$MPC = \text{MP} - \text{MPA} = \frac{number\ of\ CVs}{number\ of\ vehicles} \times 100\% \tag{12}$$

Five CAV market penetration levels of 0%, 25%, 50%. 75% and 100% are applied in this study to represent different autonomy levels. Eleven different traffic compositions are conducted by combining different MPs and MPAs and selecting all possible pairs $\Gamma = \{(mp, mpa)|\ mp \in MP, mpa \in MPA,\ mpa \leq mp\}$. For example, (0.33, 0.25) indicates that 33% of all traffic is CV or CAV, which 25% of all traffic is CAV and 8% of all traffics is CV. If there are 100 vehicles in the traffic stream, there are 8 CVs, 25 CAVs, and 67 conventional vehicles.

Combining three different operational strategies and two different traffic demand levels (100% and 130% of calibrated volume), 66 different scenarios are investigated. Each scenario is run three times with different random seeds, which affect the oncoming traffic pattern. The simulation period is 5 hours and PTV VISSIM is used in this study as the simulation platform. The VISSIM driver model DLL interface and COM interface are used to realize the bundled CAV application logic.

Two measurements, network throughput and total delay, are used to evaluate the traffic system performance. The network throughput is defined as the total number of vehicles that arrived at their destinations within the simulation period. And the total delay is defined as the sum of individual vehicle delays. The individual delay is calculated by Equation (13),

$$t_s^i = \frac{d}{v_{free} - v_{avg}} \tag{13}$$

where $t_s$ is accumulated delay of vehicle $i$ at the time step $s$, $d$ is traveled distance, $v_{free}$ is free-flow speed, and $v_{avg}$ is the average speed for traversing distance $d$. Therefore the total delay at time step s can be calculated by equation (14).

$$T_s = \sum_{i=1}^{I} t_s^i \tag{14}$$

where $I$ is the total number of vehicles that are in or has left the network.

Since the results of two different traffic demand levels show the similar trends, we only present the results of 130% demand level scenarios in *Analysis* 2 to 4 to ensure the readability of the paper.

*Analysis 1 – CACC Pipeline Capacity*

CACC can significantly improve throughput. Since this study involves five different MPA levels of 0%, 25%, 50%, 75%, and 100%, the CACC pipeline capacity under each of those different percentages of MPA rates is estimated. 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. The capacity is tested on a 7-mile simplified freeway segment with 4 lanes. The traffic input demand varies from 1,400 vphpl to 4,000 vphpl to generate different conditions. The data are collected every 15 minutes after a simulation warm-up period of 15 minutes. The capacity is represented by four times of the maximum 15-minute-volume collected from all simulation runs for one market penetration scenario.

As shown in Figure 6, the results demonstrate a significant increase in capacity with the increase of CAV market penetration. The benchmark (0 percent) capacity is 1,780 vphpl, and the maximum CACC pipeline capacity is around 3,227 vphpl, an increase by 81.2 percent. At the

CAV market penetration rates of 25 percent, 50 percent, and 75 percent, the capacity has increased by 14.0 percent, 25.9 percent, and 48.0 percent, respectively.

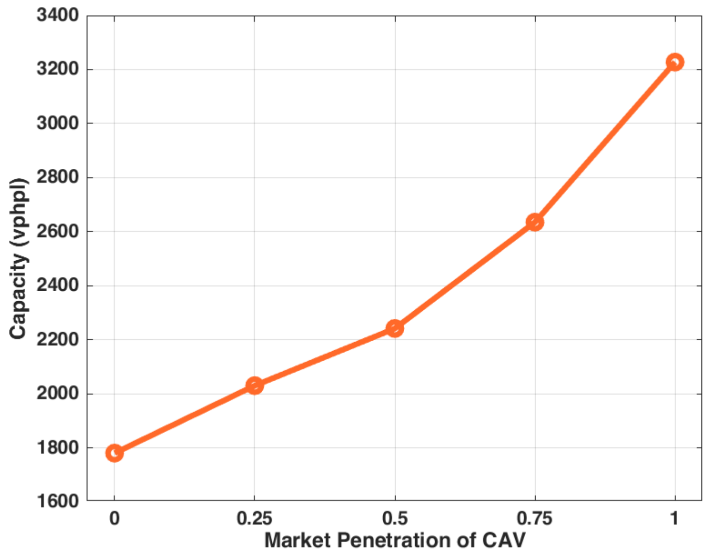



**Figure 6.** Cooperative adaptive cruise control pipeline capacity under different CAV market penetration rates.

*Analysis 2 – Cooperative Adaptive Cruise Control, Speed Harmonization, and Cooperative Merge*

CACC can significantly improve traffic performance in terms of both network throughput and total delay. As shown in Figure 7, the increasing trend of throughput is obvious when the market penetration increased from 0 percent to 50 percent. From 50 percent to 100 percent, the throughputs have not changed significantly with the increasing CAV market penetration because the input volume is less than the capacity of corresponding mixed traffic. The descending trend of delay is significant. This is mainly because that CACC can form CAVs strings with small gaps, maximizing the use of the existing facility and reduces disturbances or oscillations in traffic flow. Also, it is noted that CACC platoons also have the capability of stabilizing traffic flows because of the unique control algorithms and faster, smoother response of any CACC vehicle to the front vehicle's changes in speed.

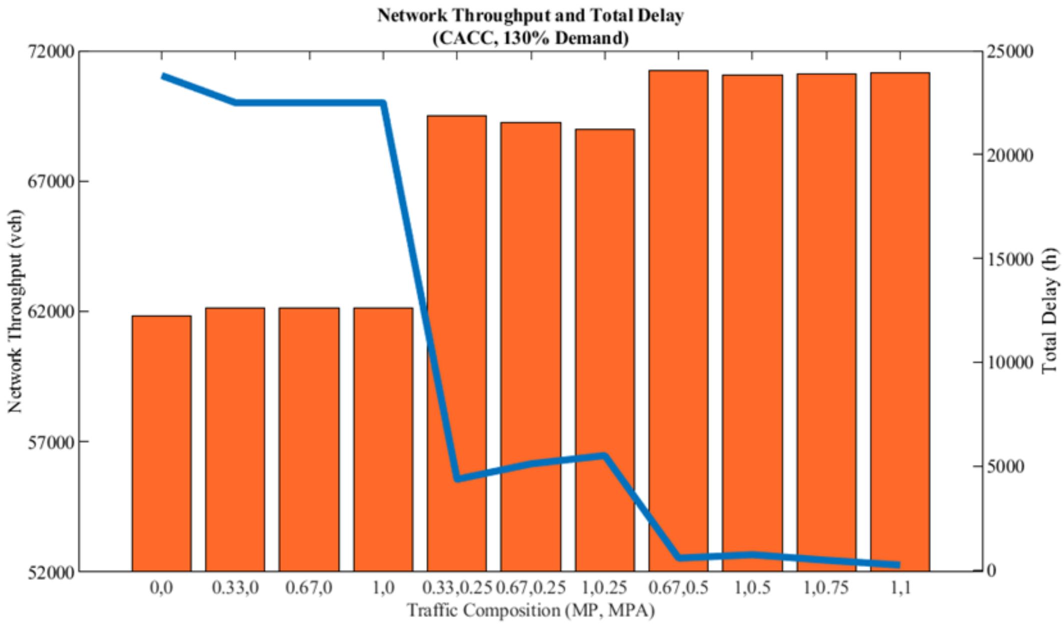



**Figure 7**. Performance of applying CACC

As shown in Figure 8, speed harmonization can help reduce the delay and increase throughput by smoothing the upstream traffic and discharging existing queues at the bottleneck areas. Comparing (0, 0), (0.33, 0), (0.67, 0) and (1, 0) cases, delay decreases with the increase of market penetration, but the throughput does not significantly change. As discussed before, if the speed harmonization algorithms are not designed carefully, the slowdown effect of speed harmonization may cause negative benefits in throughput and delay (FHWA, 2016). When the market penetration is fixed and the CAV penetration rates increases, such as (0.67, 0), (0.67, 0.25), (0.67, 0.5), both throughput and delay decrease significantly. This is mainly because AVs assume the deterministic behavior of ACC/CACC mode and can maintain relatively stable following distances with prespecified, deterministic inter- and intra-platoon gaps. This stabilizing effect can directly impact the traffic system performance.

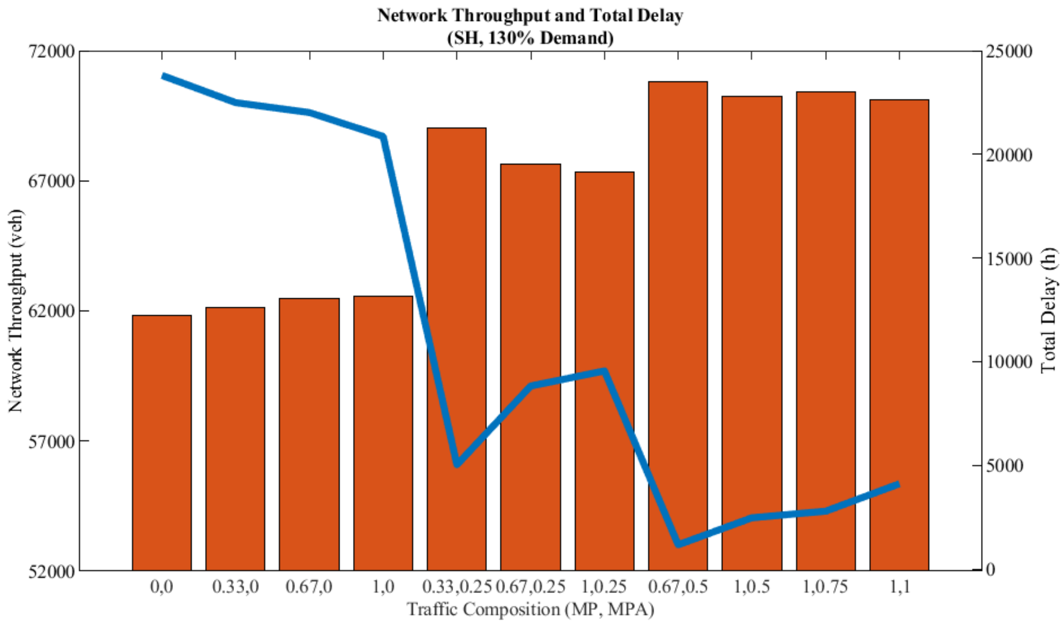



**Figure 8**. Performances of applying speed harmonization

Cooperative merge aims to facilitate merge area operations by creating gaps for merging vehicles. As shown in Figure 9, the cooperative merge can also improve traffic performance in terms of delay and throughput. This proves the effectiveness of the cooperative merge algorithm and the corresponding parameters in this study. Note that if the parameters selected in the algorithm are not optimized, initial simulation runs show that the creation of gaps may become too frequently and then negatively impact the entire traffic performance.

Comparing cases (0.33, 0.25), (0.67, 0.25) and (1, 0.25), an interesting phenomenon can be found that at the same low CAV market penetration rate of 0.25, the traffic performance is getting worse with the increase of the market penetration. This is because in this study CVs also perform cooperative merge. When the CV market penetration increases, more vehicles are eligible for cooperative merge, and they create gaps for on-ramp vehicles. As CV's driving behavior (i.e., manually driving behavior) is quite stochastic and incurs errors, the lane change, acceleration, and deceleration process can have an impact on the mainline traffic performance. However, this phenomenon is gone when the CAV market penetration becomes high because of the stabilizing effect of AV traffic flow originated from deterministic machine driving behavior coded in the ACC/CACC vehicle algorithms.

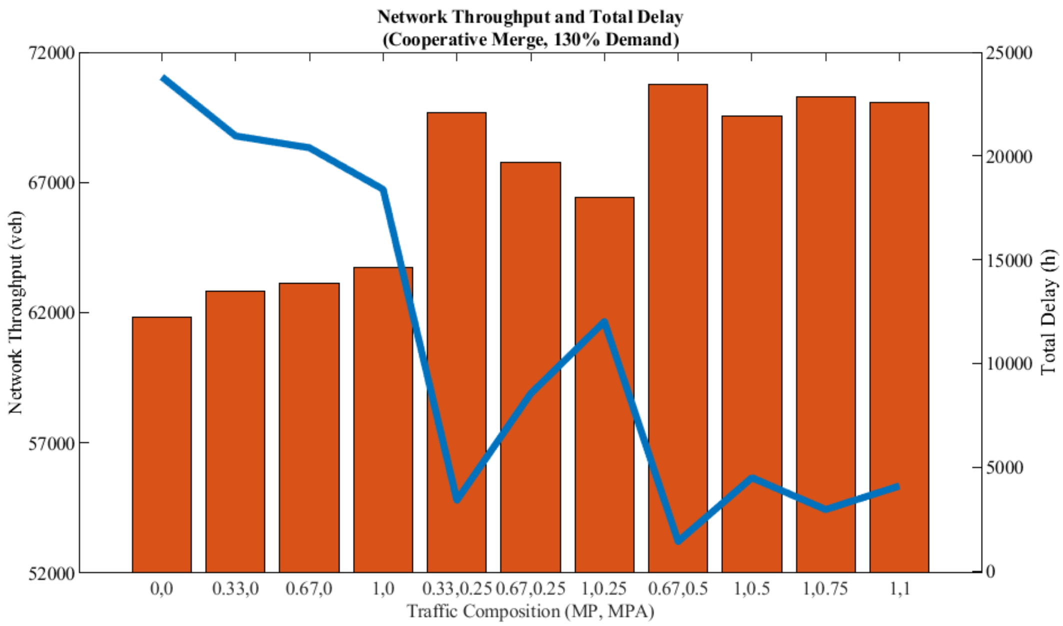



Figure 9**.** Performances of applying cooperative merge

Table 1 shows the results of applying CACC, speed harmonization, and cooperative merge separately for the ML Scenario 1. For the overall performance, CACC performs significantly better than the other two applications, because CACC can efficiently utilize existing facility capacity and reduce disturbances on the mainline. Note that when CAV penetration is 0 percent, i.e., (0, 0), (0.33, 0), (0.67, 0) and (1,0) cases, there is no CAV and thus CACC is not applied. The results of these cases can be regarded as base cases. It can be found that there is a slight difference in traffic performance between (0, 0) and other 0 percent CAV penetration cases. This is because, in the (0, 0) case, only HOVs, about 30 percent of total traffic volume, can use the managed lane and dedicated ramps; and in other 0 percent CAV cases, about 50 percent of total traffic volume, including both HOVs and CVs, can utilize the managed lane and dedicated ramps. This rebalanced volume could slightly relief the congestion at the merge area and results in a 0.5 percent throughput increase and 5.52 percent of delay reduction.

Table 1. Results of CACC, Speed Harmonization, and Cooperative Merge Cases

| Case | CACC | | Speed Harmonization | | Cooperative Merge | |
|---|---|---|---|---|---|---|
| | Network TH (veh) | Delay (h) | Network TH (veh) | Delay (h) | Network TH (veh) | Delay (h) |
| 0,0 | 61,828 (0.00%) | 23,808.20 (0.00%) | 61,828 (0.00%) | 23,808.20 (0.00%) | 61,828 (0.00%) | 23,808.20 (0.00%) |
| 0.33,0 | 62,136 (0.50%) | 22,495.15 (-5.52%) | 62,133 (0.49%) | 22,493.52 (-5.52%) | 62,804 (1.58%) | 20,963.30 (-11.95%) |
| 0.33,0.25 | 69,516 (12.43%) | 4,367.58 (-81.66%) | 69,020 (11.63%) | 5,032.74 (-78.86%) | 69,695 (12.72%) | 3,412.22 (-85.67%) |
| 0.67,0 | 62,136 (0.50%) | 22,495.15 (-5.52%) | 62,491 (1.07%) | 22,015.76 (-7.53%) | 63,119 (2.09%) | 20,395.98 (-14.33%) |
| 0.67,0.25 | 69,248 (12.00%) | 5,110.94 (-78.53%) | 67,655 (9.42%) | 8,828.23 (-62.92%) | 67,774 (9.62%) | 8,542.69 (-64.12%) |
| 0.67,0.5 | 71,237 (15.22%) | 572.71 (-97.59%) | 70,822 (14.55%) | 1,172.15 (-95.08%) | 70,758 (14.44%) | 1,427.67 (-94.00%) |
| 1,0 | 62,136 (0.50%) | 22,495.15 (-5.52%) | 62,545 (1.16%) | 20,864.48 (-12.36%) | 63,743 (3.10%) | 18,389.62 (-22.76%) |
| 1,0.25 | 68,988 (11.58%) | 5,511.25 (-76.85%) | 67,318 (8.88%) | 9,558.41 (-59.85%) | 66,416 (7.42%) | 12,019.20 (-49.52%) |
| 1,0.5 | 71,047 (14.91%) | 737.72 (-96.90%) | 70,233 (13.59%) | 2,475.64 (-89.60%) | 69,556 (12.50%) | 4,498.56 (-81.11%) |
| 1,0.75 | 71,093 (14.99%) | 470.25 (-98.02%) | 70,424 (13.90%) | 2,793.13 (-88.27%) | 70,273 (13.66%) | 2,964.61 (-87.55%) |
| 1,1 | 71,166 (15.10%) | 238.41 (-99.00%) | 70,098 (13.38%) | 4,116.97 (-82.71%) | 70,064 (13.32%) | 4,100.12 (-82.78%) |

Network TH = Network Throughput

*Analysis 3 – Performances of Bundled CAV Applications*

Figure 10 shows the comparison of traffic performance between the bundled applications and single CAV applications of ML Scenario 1. As shown in Figure 10, bundling CACC and speed harmonization can further improve traffic performance than applying only CACC or SH. As **Error! Reference source not found.** shows, bundling CACC and speed harmonization can help increase 0.49 to 15.38 percent of throughput and reduce 5.52 to 100.18 percent of delay. The bundled application can improve 1.37 to 15.73 percent of throughput and reduce 10.53 to 100.17 percent of delay. The performance of the bundled application is better than the combination of CACC and speed harmonization only when the CAV market penetration is less than 50 percent. When the CAV market penetration is greater than 50 percent, a longer CACC string can be formed than the low CAV market penetration scenario, efficiently using the facility capacity and improving the capacity the facility can support. Under low CAV penetration conditions, the mainline is not congested, and there are more qualified gaps for on-ramp vehicles to use, while there are less qualified gaps when the CAV market penetration is high.

As shown in Figure 11 and Figure 12, Scenario 2 and 3 have shown the same trends when the applications are compared with one ML scenario, and therefore their results are not discussed separately.

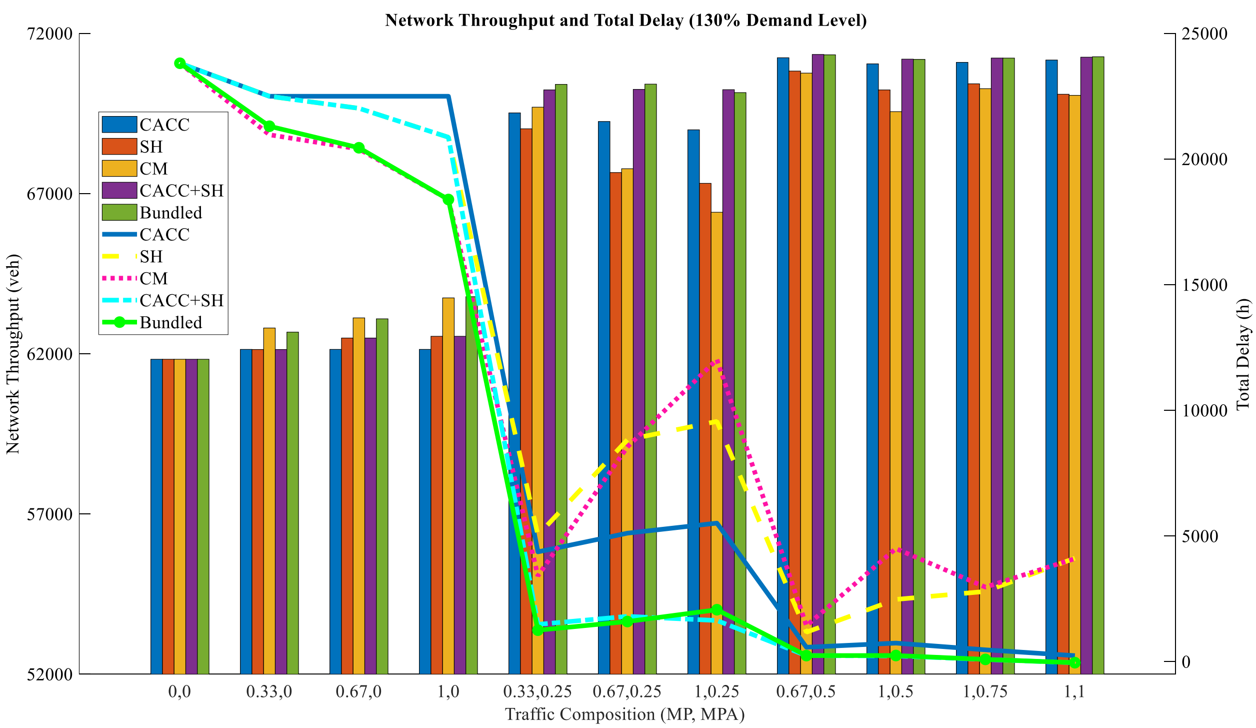



Figure 10. Performances Comparison between Single Application and Bundled Applications, Scenario 1

Table 2. Performance Results of Scenario 1 at 130 Percent Demand Level.

| Case | CACC Only | | SH Only | | Cooperative Merge Only | | CACC + SH | | Bundled Application | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Network TH (veh) | Delay (h) | Network TH (veh) | Delay (h) | Network TH (veh) | Delay (h) | Network TH (veh) | Delay (h) | Network TH (veh) | Delay (h) |
| 0,0 | 61,828 (0.00%) | 23,808.20 (0.00%) | 61,828 (0.00%) | 23,808.20 (0.00%) | 61,828 (0.00%) | 23,808.20 (0.00%) | 61,828 (0.00%) | 23,808.20 (0.00%) | 61,828 (0.00%) | 23,808.20 (0.00%) |
| 0.33,0 | 62,136 (0.50%) | 22,495.15 (-5.52%) | 62,133 (0.49%) | 22,493.52 (-5.52%) | 62,804 (1.58%) | 20,963.30 (-11.95%) | 62,133 (0.49%) | 22,493.52 (-5.52%) | 62,675 (1.37%) | 21,301.99 (-10.53%) |
| 0.33,0.25 | 69,516 (12.43%) | 4,367.58 (-81.66%) | 69,020 (11.63%) | 5,032.74 (-78.86%) | 69,695 (12.72%) | 3,412.22 (-85.67%) | 70,234 (13.60%) | 1,482.48 (-93.77%) | 70,406 (13.87%) | 1,251.18 (-94.74%) |
| 0.67,0 | 62,136 (0.50%) | 22,495.15 (-5.52%) | 62,491 (1.07%) | 22,015.76 (-7.53%) | 63,119 (2.09%) | 20,395.98 (-14.33%) | 62,491 (1.07%) | 22,015.76 (-7.53%) | 63,090 (2.04%) | 20,445.62 (-14.12%) |
| 0.67,0.25 | 69,248 (12.00%) | 5,110.94 (-78.53%) | 67,655 (9.42%) | 8,828.23 (-62.92%) | 67,774 (9.62%) | 8,542.69 (-64.12%) | 70,250 (13.62%) | 1,802.01 (-92.43%) | 70,414 (13.89%) | 1,595.93 (-93.30%) |
| 0.67,0.5 | 71,237 (15.22%) | 572.71 (-97.59%) | 70,822 (14.55%) | 1,172.15 (-95.08%) | 70,758 (14.44%) | 1,427.67 (-94.00%) | 71,340 (15.38%) | 240.08 (-98.99%) | 71,329 (15.37%) | 240.20 (-98.99%) |
| 1,0 | 62,136 (0.50%) | 22,495.15 (-5.52%) | 62,545 (1.16%) | 20,864.48 (-12.36%) | 63,743 (3.10%) | 18,389.62 (-22.76%) | 62,545 (1.16%) | 20,864.48 (-12.36%) | 63,781 (3.16%) | 18,387.38 (-22.77%) |
| 1,0.25 | 68,988 (11.58%) | 5,511.25 (-76.85%) | 67,318 (8.88%) | 9,558.41 (-59.85%) | 66,416 (7.42%) | 12,019.20 (-49.52%) | 70,241 (13.61%) | 1,637.05 (-93.12%) | 70,150 (13.46%) | 2,064.93 (-91.33%) |
| 1,0.5 | 71,047 (14.91%) | 737.72 (-96.90%) | 70,233 (13.59%) | 2,475.64 (-89.60%) | 69,556 (12.50%) | 4,498.56 (-81.11%) | 71,194 (15.15%) | 226.84 (-99.05%) | 71,186 (15.14%) | 243.37 (-98.98%) |
| 1,0.75 | 71,093 (14.99%) | 470.25 (-98.02%) | 70,424 (13.90%) | 2,793.13 (-88.27%) | 70,273 (13.66%) | 2,964.61 (-87.55%) | 71,228 (15.20%) | 85.93 (-99.64%) | 71,227 (15.20%) | 89.51 (-99.62%) |
| 1,1 | 71,166 (15.10%) | 238.41 (-99.00%) | 70,098 (13.38%) | 4,116.97 (-82.71%) | 70,064 (13.32%) | 4,100.12 (-82.78%) | 71,255 (15.25%) | -43.68 (-100.18%) | 71,268 (15.27%) | 42.22 (-100.18%) |

Network TH = Network Throughput

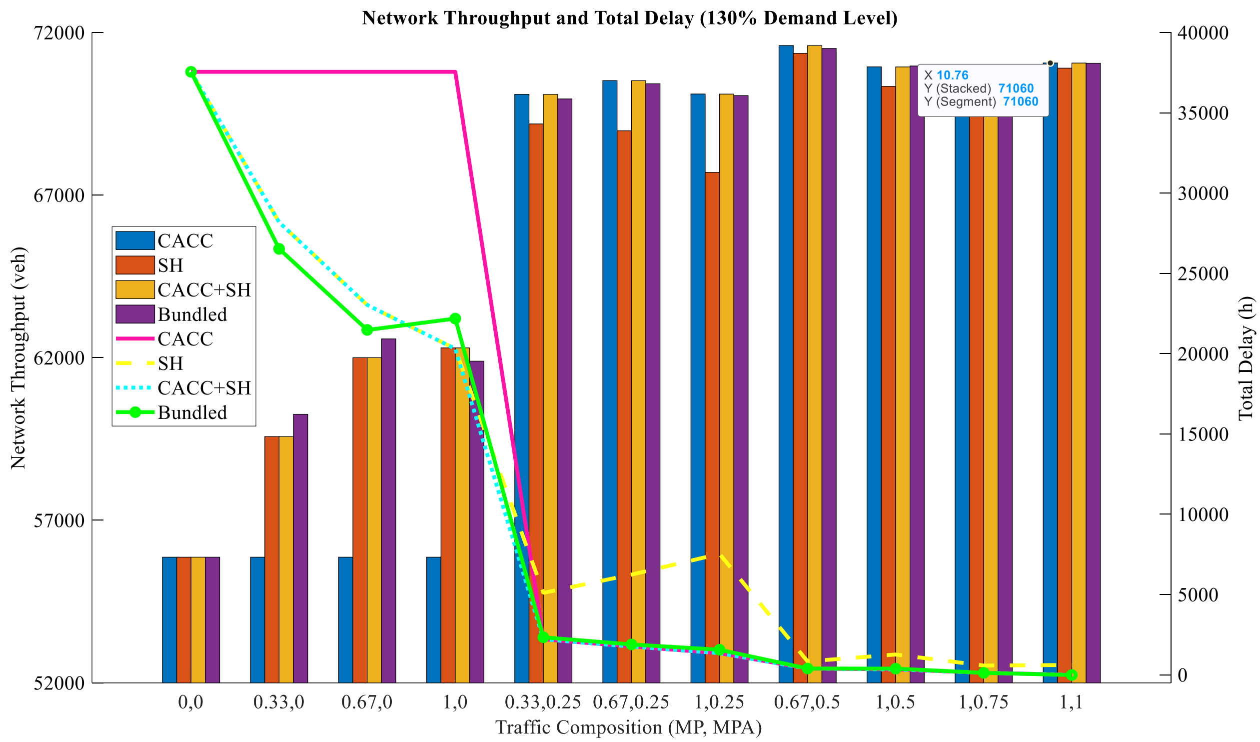



Figure 11. Performances Comparison between Single Application and Bundled Applications, Scenario 2

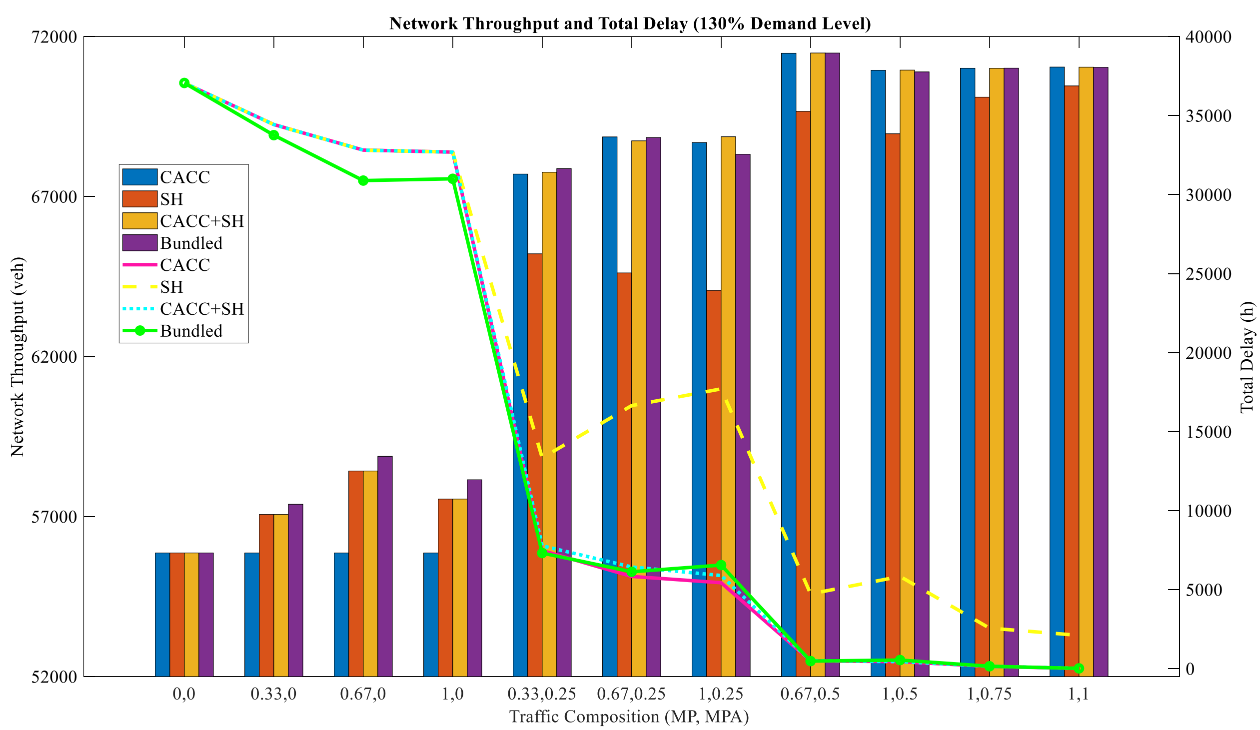



Figure 12. Performances Comparison between Single Application and Bundled Applications, Scenario 3

*Analysis 4 – Comparison of Different ML Scenarios*

In this section, results from three ML scenarios are compared to understand if there are significant differences between the infrastructure scenarios. As shown in Figure 13, the ML 1 scenario's performance is significantly better than the ML 2 and ML 3 scenarios, indicating the benefits of constructing dedicated ramps for CVs, CAVs, and HOVs. This reduces the formation of weaving traffic at the on- and off-ramp areas and therefore is beneficial in terms of both delay and throughput.

Comparison of ML 2 and ML 3 results indicates that allowing CVs/CAVs to access the existing HOV lane is beneficial to the system delay and throughput, even when the market penetration rates of CVs/CAVs are small. This benefit, however, is relatively minor compared to the additional benefit brought by the construction of dedicated ramps (ML 1). In other words, the weaving effects in ML 2 are quite dramatic and cancels a large portion of the CAV benefits.

The fact that both ML 1 and ML 2 outperforms ML 3 in terms of both throughput and delay implies the benefit of the CAV managed lane strategies. Concentrating CAVs in a single lane can help realize early deployment opportunities. Additionally, it is proved through this simulation that CAV dedicated lanes are not necessary for realizing early deployment benefits. Even 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), the benefits of deploying CAVs can still be achieved.

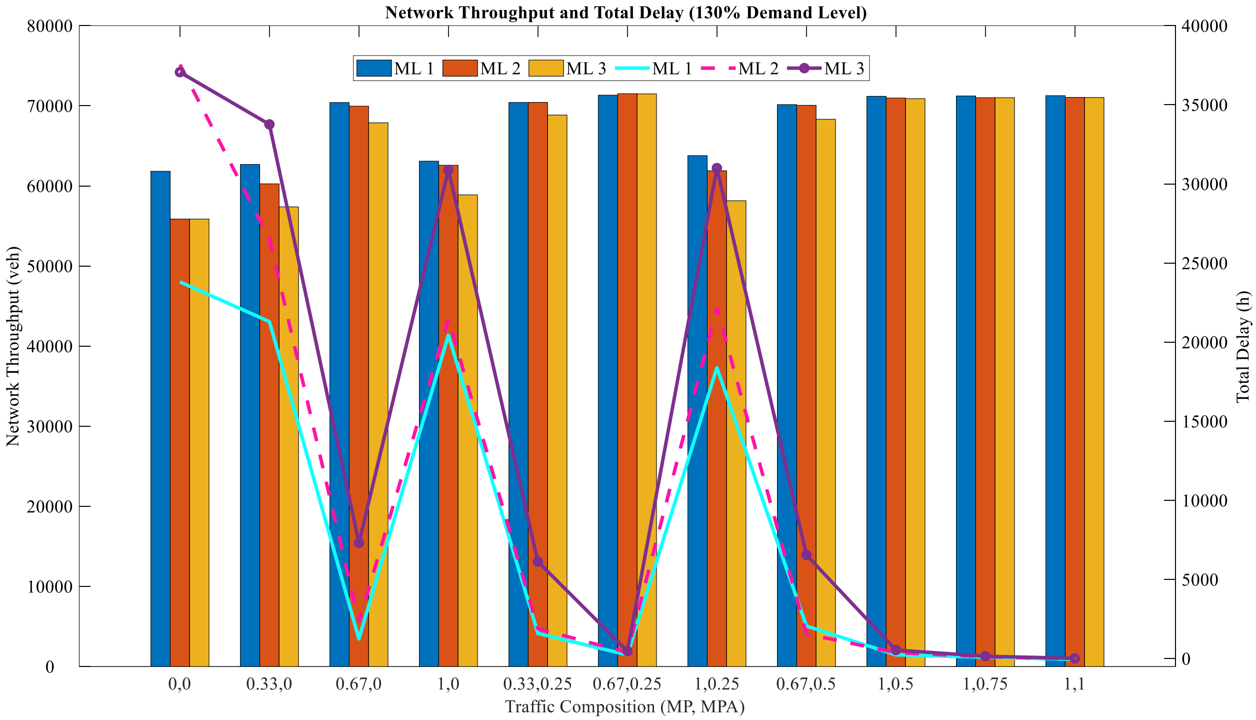



Figure 13. Performances Comparison among Different Scenarios

***Discussion of implications***

Based on the simulation results, multiple key observations and implications are summarized as follows:

- For all scenarios, individual and bundled CAV applications can significantly improve the traffic performance in terms of delay and throughput in most of the cases.
- 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. Through the capacity analysis, the effect of CACC continues to increase as the market penetration rates increase (81.2 percent increase for the 100 percent penetration scenario).

- Speed harmonization, by its nature, can help smooth mainline traffic, increase throughput and reduce delay in most of the cases. Because the speed harmonization relies on monitoring of the real-time traffic state to avoid breakdown, it is critical that the existing speed harmonization algorithm is updated to reflect the mixed-autonomy traffic conditions. Legacy algorithms may deteriorate the traffic performance.
- Cooperative merge can positively impact traffic performance by reducing force-in merge occurrences and smooth the merging process. In the I-66 case study, the mainline vehicles will slow down or make lane changes, when appropriate, to create safe gaps for the 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 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 market penetration rates, if deployed, can handle the 130 percent demand scenario, indicating that the resultant highway capacity with high market penetrations of CAVs is greater than the 130 percent of the current demands. Additionally, even with low CAV market penetration rates, there are still system benefits in early deployment stages, and this applies to both V2V applications (i.e., CACC) or I2V applications (i.e., speed harmonization and cooperative merge).
- In many cases, even though when CACC is not implemented, the system performance still improves when CAV market penetration increases. This is because of the traffic stabilizing effect originated from the deterministic behavior of CAVs as compared to the stochastic behavior of human drivers. For example, cooperative merge with CVs is

implementable, but it deteriorates the system performance because the slowdown and lane change processes of human drivers create too much disturbance to the system. Meanwhile, the deterministic behavior of AVs makes these processes more stable.

- Scenario ML 1 performs better than ML 2 and ML 3, and ML 2 outperforms ML 3 for low and medium market penetration cases, indicating that the dedicated ramps and managed lane operation strategy are beneficial. While this conclusion is intuitive because these two infrastructure-side enhancements reduce weaving and increase the chance of platooning, the significance of the result is that it proves the effectiveness of a more realistic scenario (at least for the I-66 case study) where human HOV traffic is still allowed to access the dedicated ramps and managed lane to continue to enjoy their benefits. This conclusion was only made for CAV-dedicated managed lanes in the past (e.g., Liu et al., 2017). There are a large number of such existing HOV facilities in the country, and the results of this case study prove the early deployment benefits with limited infrastructure adjustment.
- In this case study, it is found that all three applications, when applied individually or bundled together, are all beneficial to the system performance. Although for the reasons mentioned above, CACC platooning (V2V CAV operations) generates most of the benefits, it is interesting to find that speed harmonization and cooperative merge (two I2V traffic control strategies) further improves this benefit when the CAV market penetration is low to medium. This reiterates the agency's role in realizing early deployment benefits of CAV applications. Also, even if CACC is not implemented for certain reasons, speed harmonization and cooperative merge, when applied individually,

have significantly positive impacts, indicating the feasibility of incorporating them as parts of the next-generation active traffic management systems.

**Conclusion**

Connected and automated vehicles hold the potential for substantial improvements to traffic safety, travel time reliability, driver comfort, roadway capacity, environmental impacts, and users' overall travel experience. As managed lanes have evolved from simple restriping and signage improvements to more sophisticated intelligent transportation systems (ITS) and toll system deployments, they present as ideal testbeds for V2I and V2V communications, and vehicle automation technologies as well as potential first locations for their deployment.

This study conducts simulation on a real-world corridor I-66 in Northern Virginia and aims to investigate the effectiveness of CAV deployment in enhancing existing traffic system performance. The simulation results show that all three CAV applications, when applied individually or bundled together, are all beneficial to the system performance. CACC platooning generates most of the benefits, and it is also interesting to find that speed harmonization and cooperative merge further improves this benefit when the CAV market penetration is low to medium. Also, even if CACC is not implemented for certain reasons, speed harmonization and cooperative merge, when applied individually, have significantly positive impacts, indicating the feasibility of incorporating them as parts of the next-generation active traffic management systems.

Last but not least, while this study is simulation-based analysis with assumed or partially calibrated CV/CAV behavior models, some of the simulation results and insights have been proved and validated by previous experiments conducted at FHWA. The stabilizing effect of AVs has been validated during the speed harmonization experiment on I-66 inside the Beltway conducted in 2015 (Ma et al., 2016) and the bundled CACC and cooperative merge experiment (Ma et al., 2019) conducted in 2018. The efficiency of platooning and cooperative merge has also been tested and confirmed in the previous experiment (Ma et al., 2019), which is in line with the simulation assumption and has the potential to generate system-level benefits.

Although many insights have been obtained, multiple areas of the future of research are recommended to improve the modeling and simulation. As the connected automated vehicle data become increasingly available, the aforementioned CAV models need to be constantly enhanced to increase model validity. Besides, in this case study, only selected infrastructure and CAV technological strategies are simulated and evaluated as a first-step analysis. There are other interesting scenarios that may be further simulated. And more performance measurements, such as safety and environmental impact, need to be considered. Therefore, the multiple goals need to be optimized simultaneously and the complexity of operation will increase significantly (Li and Sun, 2018; Li and Sun, 2019).

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