Mobility and Energy Consumption Impacts of Cooperative Adaptive Cruise Control (CACC) Vehicle Strings on an Urban Freeway Corridor

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ABSTRACT

Cooperative adaptive cruise control (CACC) vehicle string operation has potential to significantly improve the mobility and energy consumption performance of congested freeway corridors. This study examined the impacts of CACC operations on vehicle speed and fuel economy of the 13-mile SR–99 corridor northbound from Elk Grove to SR–50, near Sacramento, CA. The study evaluated the performance of the busy urban corridor under various CACC market penetration scenarios and traffic demand inputs. The CACC string operation was also analyzed when wireless vehicle awareness device (VAD) and CACC managed lane (ML) strategies were implemented. The case study revealed that the average speed increased by 70 percent when the CACC market penetration changed from 0 to 100 percent. The highest average fuel economy was achieved under the 30 percent CACC scenario, where it was 5 percent higher than in the baseline scenario. However, as the CACC market penetration reached 100 percent, fuel economy was 11 percent lower than the baseline because of higher travel speeds. When CACC market penetration reached 100 percent, the corridor could accommodate 30 percent more traffic without experiencing reduced average speed. Results also indicate that equipped the manually driven vehicles with wireless VADs to enable them to lead CACC strings increased the average speed by 8 percent when the CACC market penetration was 20 percent or 40 percent, while the fuel economy had a minor decrease. The ML strategy decreased the corridor performance when implemented alone because it attracted CACC vehicles to make additional lane changes to merge into and out of the managed lane.

Keywords: Cooperative Adaptive Cruise Control (CACC), CACC String Operation, Mobility Impacts, Energy Consumption, Freeway Corridor

INTRODUCTION

Cooperative Adaptive Cruise Control (CACC) is a Connected Automated Vehicle (CAV) system that offers automated car following and platooning capabilities for equipped vehicles. The system uses Dedicated Short-Range Communications (DSRC) to enable real-time vehicle to vehicle (V2V) information interchange with 100 milliseconds update interval (*1*). This allows a CACC vehicle to quickly respond to speed variations of the preceding CACC vehicle, enabling the subject vehicle to adopt less than 1 second car following time gaps while operating in CACC vehicle strings in the freeway traffic stream (*2*). Since the CACC headway can be as short as half the headway of a typical human driver (*3*), the freeway facility could theoretically serve twice as many CACC vehicles as manually driven vehicles. In addition, because all followers in a string can consistently respond to the speed changes of the string leader, it helps dampen traffic disturbances, which could otherwise propagate upstream and develop into traffic congestion. The flow smoothing effect of CACC strings is expected to improve the energy efficiency of the freeway traffic flow. Our previous studies have quantified the following traffic mobility and energy efficiency benefits of CACC at an isolated freeway on-ramp bottleneck (*4-5*):

- 92% freeway pipeline capacity increase under 100% CACC market penetration;
- 50-67% freeway on-ramp bottleneck capacity increase under 100% CACC market penetration; and
- 12-16% reduction in average vehicle energy consumption under 100% CACC market penetration.

The above findings were identified at an isolated freeway segment where the mainline traffic stream was only affected by the merging flow from a single on-ramp. However, the impact of CACC on real-world freeway corridors may be substantially different because the spatiotemporal congestion pattern of a corridor can often be attributed to the interplay among multiple bottlenecks of the corridor. It is likely that CACC improves the output flow of a minor bottleneck while a downstream major bottleneck cannot accommodate the resulting extra input demand. As a result, the traffic congestion of the major bottleneck is further intensified, making the congestion region grow backward and eventually clog the output flow of the minor bottleneck. Because CACC potentially has both positive and negative impacts on the freeway corridor performance, it is necessary to examine such impacts to identify the best implementation strategies of the advanced system.

To address the above challenge, this study performed a comprehensive CACC case study on the 13-mile (21-km) SR–99 freeway corridor to the south of Sacramento, California. The impacts of the CACC string operation on average speed and average vehicle energy consumption were quantified using a state-of-the-art microsocpic traffic simulation model (*4*). The research also investigated the benefits of CACC management strategies that aimed to increase the CACC string numbers in the traffic stream. The study results revealed trends of CACC impacts under various market penetration rates and traffic demand input levels. Those findings are expected to be critical to design CACC implementation strategies for real-world freeway corridors.

LITERATURE REVIEW

The development and evaluation of CAV have been gaining momentum in recent years. Many representative studies have aimed to explore the impacts of CAV systems on freeway traffic. Some of them aimed to explore the relationship between the CAV characteristics and freeway capacity analytically. For example, in Ghiasi et al. (*6*), the researchers presented an analytical model that described the capacity of a single lane freeway as a function of the CAV market penetration, platoon intensity, and headway distributions. The study found that the freeway capacity increased with the CAV market penetration and platoon intensity only when the headway between a CAV and a manually driven vehicle was smaller than the average of headways between two CAVs and two manually driven vehicles. This finding gave a useful guideline when designing the car following strategies for CAVs. A similar study is found in Chen et al. (*7*) where the capacity of a freeway segment was depicted as a function of CAV market penetration rate, platoon size, inter/intra-platoon spacing, and different lane policies. The model was further used to determine the lane policy that maximized the roadway capacity by exploiting the CAV platooning capability. Talebpour and Mahmassani (*8*) developed a simulation framework that could depict the interactions of manually driven vehicles, connected manually driven vehicles, and automated vehicles. Their stability analyses indicated that both connected vehicles and automated vehicles could maintain a string stable flow only when the speed was very low (e.g., less than 5 m/s). In case studies with a one-lane freeway, the automated vehicles were found to outperform the connected vehicles in terms of increasing the stability region and freeway capacity.

Other studies exploited the benefits of specific CAV applications. Rios-Torres and Malikopoulos (*9*) proposed a centralized controller to coordinate the merging traffic. This controller minimized the level of acceleration of vehicles in both the freeway mainline and the on-ramps by allowing them to enter the merging area without conflict. In their simulation studies, the algorithm could decrease the travel time by 7.1% to 13.5%, and the total fuel consumption by 48.1% to 52.7%. Xie et al. (*10*) reported a similar centralized automated merging system that coordinated the merging behaviors of fully connected automated systems. The algorithm aimed to maximize the speed of all vehicles in the control region. The simulation studies identified that the proposed system was able to maintain high travel speed for all vehicles with the increase of on-ramp demand. It also brought throughput benefit to the on-ramp bottlenecks. Letter and Elefteriadou (*11*) developed a centralized merging algorithm that aims to maximize the overall speed of fully connected and automated vehicles. They identified 7% to 36% in travel time reduction and 4% to 53% speed increase due to the proposed algorithm. The algorithm was found to have largest benefit under 1 second minimum gap and 2200 vehicles per hour traffic demand level.

The impact of CACC on traffic flow performance has been investigated as well. In an early study, van Arem et al. (*12*) identified the benefit of CACC for a lane-drop bottleneck in terms of increasing the average speed and reducing the shockwaves. The freeway capacity was found to be only slightly increased. In Shladover et al. (*13*), the capacity impact of CACC was tested in a simulated single lane freeway. A quadratic increase trend of capacity was identified with the CACC market penetration. A 97% capacity increase was found when the CACC market penetration changed from 0% to 100%. Liu et al. (*14*) analyzed the multilane freeway merge capacity using a CACC model developed based on empirical CACC test datasets. The study quantified the freeway capacity under various CACC market penetrations and traffic demand levels. The results indicated that the CACC string operation could bring about quadratic capacity increase regardless of the level of on-ramp traffic input.

While most of the existing CACC studies were conducted for isolated freeway bottlenecks, this study extends the impact analysis of CACC to a complex freeway corridor. The traffic and vehicle energy consumption influence of CACC string operation were identified under various CACC market penetrations, CACC string operation strategies, and corridor traffic demand levels. The methodology and findings of the study are presented as follows. The next section gives a brief description of the simulation model that depicts the behaviors of CACC vehicles and manually driven vehicles. The following section describes the study network and existing traffic management strategies. The next section presents the impacts of the CACC string operation on freeway corridor speed and energy consumption under various traffic demand inputs, CACC market penetrations and CACC management strategies. The last section provides concluding remarks about the research.

SIMULATING MANUALLY DRIVEN AND CACC VEHICLES

A state-of-the-art simulation modeling framework was used in the study to depict the longitudinal and lateral interactions between manually driven vehicles and CACC vehicles. The modeling framework as developed based on the NGSIM oversaturated flow human driver model reported in Yeo et al. (*15*) and the ACC/CACC car following model developed based on the ACC/CACC field test data. (*16-17*) The human driver model was calibrated using field data collected in the study freeway corridor (*18*) and its modeling capability was cross-validated with the MOTUS microsimulation model (*19*). The ACC/CACC model was derived from trajectory data obtained from tests on a real-world CACC string. (*17*) The lane changing behaviors of CACC vehicles and the algorithms for implementing the VAD and ML strategies were described in Liu et al. (*4*) The simulation framework was implemented in Aimsun via its microSDK interface, replacing the default Aimsun models of driving behavior with the models cited above. The researchers applied the Aimsun tool to code the study freeway corridor and visualize the simulation experiments. The built-in demand generation functions were adopted to provide various traffic demand inputs for the freeway network. The Aimsun database interface recorded the simulation results.

The baseline simulation model depicts the behaviors of human drivers. Microscopic car following behaviors and lateral vehicle interactions with nearby vehicles determine the overall traffic pattern at the macroscopic level. In the proposed model, a driver's car following and lane changing behaviors are partitioned into fundamental driving modes (or movement phases):

- CF: Regular car following mode.
- LC: Lane change mode, which includes discretionary lane change (DLC), active lane change (ALC) and mandatory lane change (MLC).
- ACF: After lane changing car following mode (a driver temporarily adopts a short gap after a lane change maneuver).
- BCF: Before lane changing car following mode (a driver speeds up or slows down to align with an acceptable gap in the target lane).
- RCF: Receiving car following mode (a driver temporarily adopts a short gap after a vehicle from the adjacent lane merges in front).
- YCF: Yielding (cooperative) car following mode.

As depicted by FIGURE 1, at the beginning of each simulation update interval, the model of a subject driver will determine the driving mode based on a set of car following and lane changing rules. Each driving mode is associated with specific car following and lane changing algorithms, which are used to determine the driver's speed and position at the end of the update interval. Such an update process is executed iteratively for every modeled vehicle in the simulation environment, resulting in a trajectory for each manually driven vehicle over the simulation period.

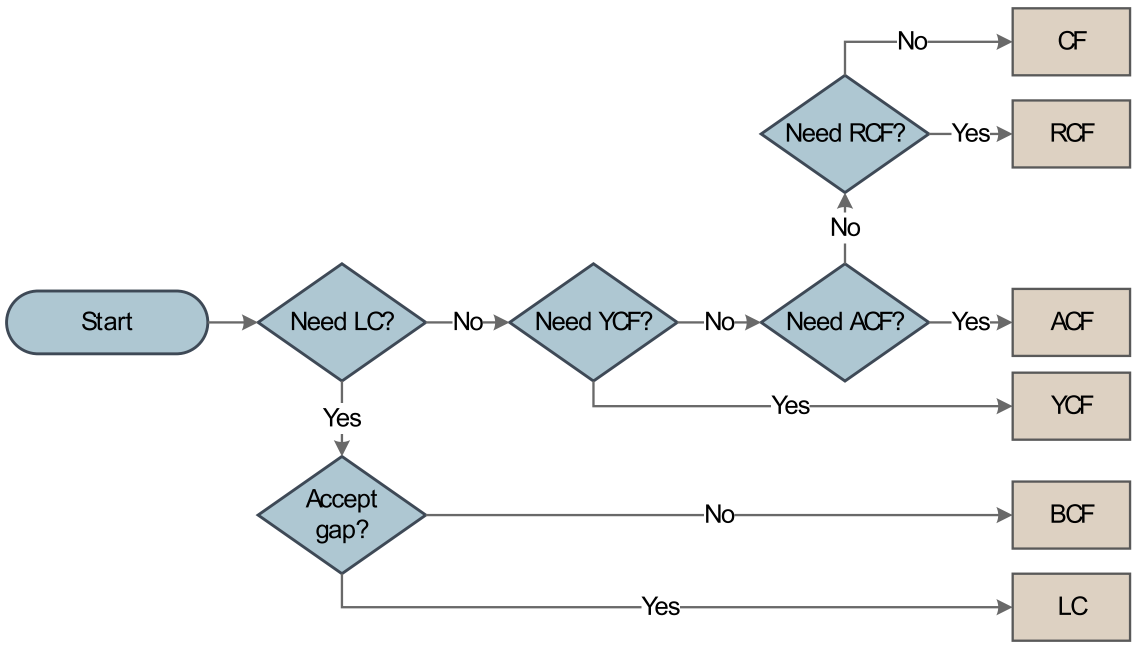


FIGURE 1 Human-driver model structure.

The human driver models were used to depict the car following and lane changing behaviors of passenger cars and heavy-duty trucks. For passenger cars, the models were applied for manually driven vehicles and ACC/CACC vehicles when they were not operating under the ACC/CACC mode. The behaviors of trucks were always modeled by the human-driver models. In this study, we did not consider truck platooning scenarios. All trucks were assumed to be manually driven. (Scenarios concerning passenger car CACC strings together with truck CACC strings will be tackled in future research).

This study adopted the models developed in Milanes and Shladover (*17*) to depict the ACC and CACC car following behaviors. CACC vehicles exhibit significantly different car following behavior from manual drivers and can form strings that allow them to follow the preceding vehicles with short gaps. Drivers of CACC equipped vehicles can also exit their closely coupled string and switch off CACC to make lane changes or exit the freeway. The modeling framework for CACC vehicles is highlighted in FIGURE 2. Although CACC system implementation relies on information received from the leading vehicle in the CACC string as well as from the immediately preceding vehicle, the empirical models used in the simulation provide a simplified description of the closed-loop vehicle-following dynamics that are achieved relative to the immediately preceding vehicle. This simplified approach is suitable for modeling a large number of CACC vehicles.

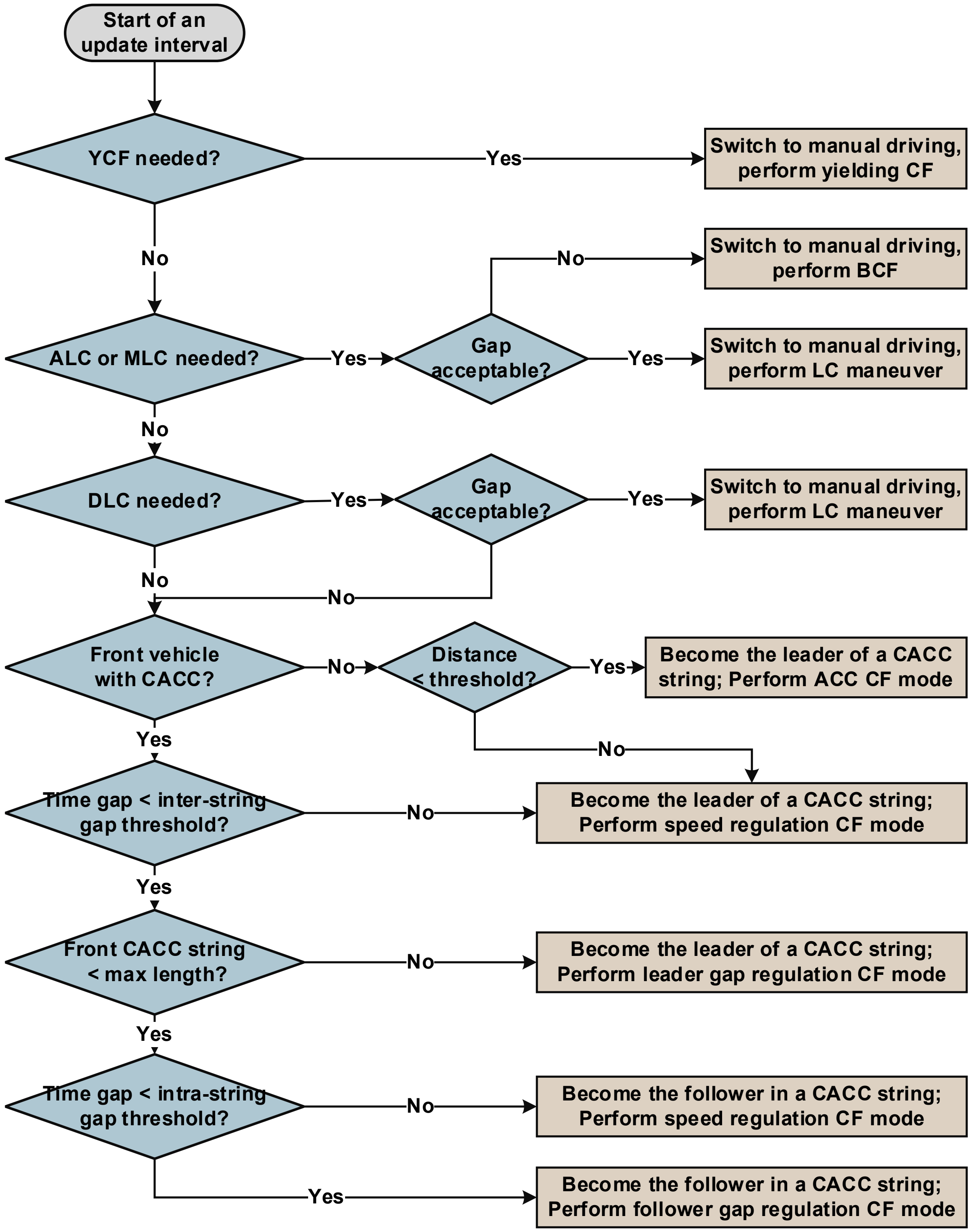


FIGURE 2 Car following and lane changing dynamics of cooperative adaptive cruise control-equipped vehicles.

In addition to the scenarios in which CACC vehicles were randomly distributed in the traffic stream, this research considered two traffic management strategies that aimed to increase the CACC market penetration locally. The two strategies are defined as:

- **Implementation of Vehicle Awareness Device (VAD) on manually driven vehicles.** The VAD vehicles have wireless communication capability to broadcast real-time information regarding their operation status and route choice. Although they don't have an automated controller to perform the car following task, they can serve as the leader of CACC vehicle strings. With this strategy, the probability for CACC vehicles to travel in the CACC mode greatly increases at low market penetration of CACC. It thus offers incentives for users to equip with CACC, even when the CACC market penetration is low.
- **CACC Managed Lane (ML) strategy**. The managed lane strategy has been widely used to serve high-occupancy vehicles or drivers willing to pay a toll, with the purpose of improving the overall efficiency of the highway system. The CACC ML strategy adopts a similar operational concept that only allows CACC vehicles and VAD vehicles to enter the managed lane. It physically separates the CAV traffic stream and the regular traffic. As the CACC and VAD vehicles concentrate in the managed lane, they will have a higher probability of traveling in CACC strings. The managed lane also reduces the interaction between the CACC vehicles and manually driven vehicles, so the CACC strings are less likely to be interrupted in the managed lane.

The human-driver models discussed above are directly used to depict the behavior of VAD vehicles. In this case, the car following and lane changing behaviors of VAD vehicle drivers are the same as the drivers of conventional vehicles, even when the VAD vehicle is leading a CACC vehicle string. To capture the connectivity of VAD vehicles, we have implemented a communication module that allows CACC vehicles within 1,000 feet (300 meters) of a host VAD to receive its real-time speed, location, and acceleration information. We assumed a perfect communication environment that enables CACC vehicles to receive the VAD information without communication delay or packet loss when the CACC vehicle is in communication range. The traffic effects of communication imperfections will be a subject for future research, but these effects are not expected to be large based on the ability of existing wireless technologies to serve the modest data communication needs of CACC.

The ML strategy is achieved by using the anticipatory lane changing model we developed in a previous study (*4*). When the strategy is active, drivers of CACC vehicles entering from an on-ramp will be motivated to merge into the managed lane if the average speed of the managed lane is higher than the speed of the general-purpose lane. The motivated CACC drivers will follow the anticipatory lane changing behavior—they will actively search for downstream gaps for making lane changes. In the meantime, they will accept smaller car following gaps and higher desired speed to increase the probability of identifying an acceptable gap. If a CACC vehicle is making an anticipatory lane change, it will use the manual driving mode. The vehicle is therefore temporarily unable to perform CACC string operation. While the managed lane attracts CACC vehicles, it does not allow manually driven vehicles to merge into it unless they are equipped with VADs. This creates a dedicated lane for CACC and VAD vehicles only.

STUDY FREEWAY CORRIDOR

The SR–99 corridor to the south of Sacramento, California, has been selected as the study corridor. The 13-mile (20-km) corridor starts at the on-ramp of Elk Grove and extends to the off-ramp toward the SR–50 freeway. It contains 16 on-ramps and 12 off-ramps as shown by FIGURE 3. The study segment contains three lanes with one high-occupancy vehicle (HOV) lane and two general purpose lanes in each direction upstream of the Calvine Road interchange, while an additional general-purpose lane is added downstream of that interchange. The on-ramp merging and weaving sections located downstream of the Elk Grove Blvd. interchange, as well as the off-ramp at the US-50 freeway interchange, contribute to the recurrent traffic congestion observed during the morning peak in this corridor. This peak period typically begins at 6:30 a.m. and ends around 9 a.m., and the morning congestion pattern is the result of the high demand for suburb-to-downtown trips during the morning hours. The free flow speed is 65 mph for the freeway and 45 mph for the ramps.

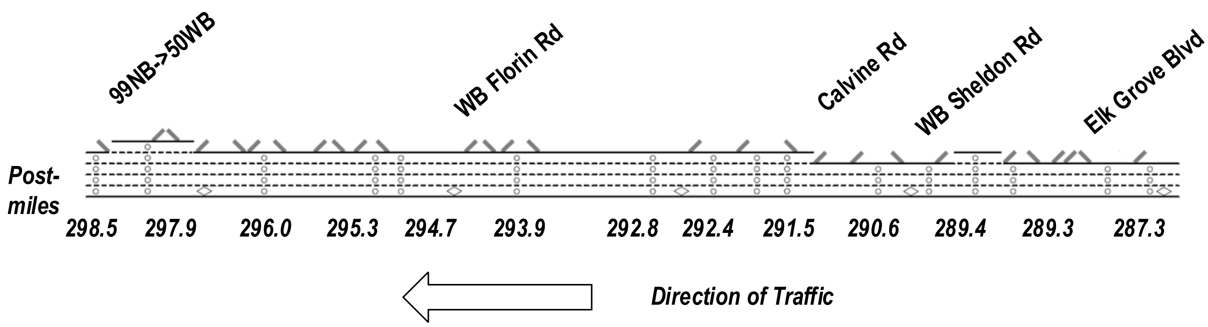


FIGURE 3 The study site on the SR–99 freeway south of downtown Sacramento, CA.

The on-ramps of the study corridor are metered using a local responsive ramp metering (LRRM) and a coordinated ramp metering (CRM) algorithm in order to control the flow of on-ramp traffic and mitigate the peak hour congestion (*18*). The LRRM is used for the five upstream on-ramps of the SR–99 corridor (some interchanges have several on-ramps). An optimized CRM algorithm has been implemented for the 11 downstream ramp meters. The CRM algorithm is essentially different from LRRM in that LRRM determines the ramp meter (RM) rate for an on-ramp based only on the local mainline occupancy/flow of its immediate upstream mainline detectors, while CRM determines the meter rate by looking at mainline occupancy/flow of the whole corridor and the demands at all on-ramps. The CRM algorithm implemented in this corridor was developed based on an optimal control approach (*18*). The objective function was the difference between total vehicle hours traveled (VHT) and total vehicle miles traveled (VMT):

$$\text{VHT-}\alpha\text{VMT} \tag{1}$$

where α is a positive number that converts the unit of VMT into VHT. The VHT term allows the CRM to minimize the overall freeway mainline travel time. However, if there is only the VHT term, the CRM will simply execute the lowest metering rate, leading to excessive delay for the on-ramp traffic. To address this problem, the objective function also includes the negative VMT term. In this case, the system will maximize the vehicle miles travelled by encouraging as many on-ramp vehicles to enter the freeway as possible. Intuitively, the implemented algorithm intends to control the SR–99 corridor as a long discharging section in the sense that the downstream should not be more congested than the upstream traffic on average. This is the best way to dump the overall traffic in the fastest manner.

IMPACTS OF THE CACC STRING OPERATION

This study examined traffic performance and vehicle fuel consumption on the SR–99 corridor under three cases. Case 1 explored the impacts of CACC under various CACC market penetrations.

The traffic demand input of this case was the real-world traffic volume observed in a typical morning peak at the study site. Case 2 examined the effects of the VAD and ML strategies on the corridor performance. In this case study, the average speed and vehicle fuel consumption with and without the ML and VAD strategies were compared. It was assumed that all manually driven vehicles were equipped with VAD when the VAD strategy was active. The final case identified the CACC impacts when the traffic demand input increased. The demand input increase ranged from 5% to 40% in 5% increments.

Effects of CACC at Different Market Penetration Rates

The effects of the CACC vehicle stings on average vehicle speed and average vehicle fuel economy are shown in FIGURE 4. The data were collected in 6-hour simulation runs that lasted from 5:00 AM to 11:00 AM. The simulation experiments contained both the peak hours and the free flowing times before and after the peak hours. The calculation also counted vehicles in both the freeway mainline and on/off-ramp lanes. In this case, the results represented a conservative estimation of CACC impacts. If the analysis only considered peak hour data, the CACC effects were expected to be higher than the presented levels.

The speed curve shows that the average vehicle speed increases nearly linearly as CACC market penetration grows. At the 100 percent CACC level, the average speed is about 56 mph, which is 70% higher than the baseline condition speed at the 0 percent CACC level. The average speed of 56 mph is close to free flow speed, which indicates that traffic congestion is nearly eliminated when all vehicles are equipped with CACC. As traffic congestion decreases with the increase of the CACC market penetration, the average vehicle energy fuel economy first improves. But when the CACC market penetration is 40 percent or higher, the vehicle fuel economy starts to decrease as the CACC market penetration increases.

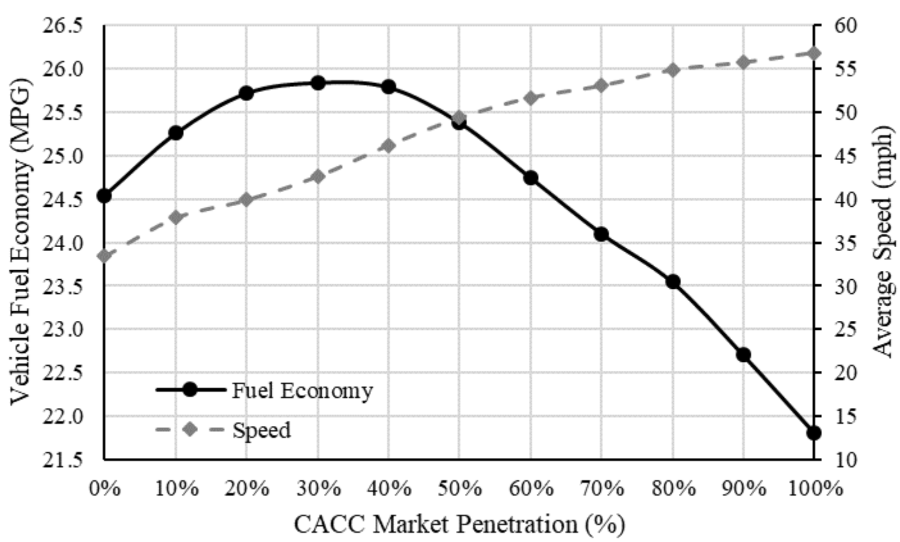


FIGURE 4 Average speed and fuel economy under various cooperative adaptive cruise control market penetration rates.

When traffic flow changed from a congested state to an uncongested state (when the market penetration rate of CACC vehicles increased from 0 percent to 40 percent), vehicles had fewer acceleration-deceleration cycles due to the improvement of the traffic flow smoothness. However, as traffic flow became faster when CACC market penetration reached beyond 40 percent, the vehicles started to travel at high speeds. The increase in speed resulted in a decrease in fuel economy. This finding was different from the results of the isolated bottleneck where the vehicle fuel economy increased with the CACC market penetration (*4*). The major difference between the two analysis was that the traffic flow was always congested in the isolated bottleneck analysis, regardless of the CACC market penetration rates, while the traffic stream became free flowing in the corridor analysis as the CACC market penetration reached 40 percent. The fuel economy benefit of CACC was not significant under free flow conditions because the design of the CACC controller did not explicitly consider fuel consumption minimization. As the CACC market penetration rate grew, more vehicles in the traffic stream could operate using the CACC mode. Such an observation indicates that the CACC vehicle following control algorithm should be explicitly designed to improve the energy efficiency of the CACC fleet.

This research also examined the string operation based on the results shown in FIGURE 5. It shows that the probability of a CACC-capable vehicle actually operating in a CACC string increases with CACC market penetration. This was expected because CACC vehicles had more opportunity to form strings as market penetration rates rose. However, the string probability curve became flatter as the CACC market penetration increased. Even when all vehicles were CACC capable, the string probability was about 80 percent, indicating that the remaining 20 percent CACC vehicles could not travel in strings. This was because the desired speeds of CACC vehicles were different. Some CACC vehicles could not close the gap with the preceding CACC vehicle due to its smaller desired speed. It was also possible that CACC vehicle strings were nearby but traveling in different lanes. The CACC drivers did not wish to make lane changes to join the strings. In both cases, a local or regional CACC string-forming algorithm that provides those isolated vehicles with string formulation guidance will be very useful. The string forming information can help the isolated vehicles plan their trajectories and eventually join the string. When the CACC market penetration was low (e.g., 10 percent or 20 percent), the string probability was higher than the theoretical string probability (theoretical string probability is equal to the CACC market penetration rate). The reason was that the CACC vehicles tend to stay within the string once they joined a string leader. They would not make discretionary lane changes to exit the string even if the adjacent lanes had higher speed than the current lane. As a result, there were more CACC vehicles joining the strings than vehicles leaving the strings during a unit time over the SR–99 corridor.

The shape of the average string length curve is different from the shape of the string probability curve. The string length increased linearly with CACC market penetration. In the simulation, the maximum permitted string length was 15 vehicles. However, the average string length was substantially less than the maximum string length even when all vehicles were CACC capable. In mixed traffic, where manually driven vehicles could cut into or cut out from the strings, it was difficult for strings to reach the maximum length limit. In addition, the CACC vehicles were generated with different desired speeds, representing a distribution of driver preferences. The CACC string followers may not continue to follow the string leader if the leader had a higher desired speed. This led to string splits, thereby reducing the average string length.

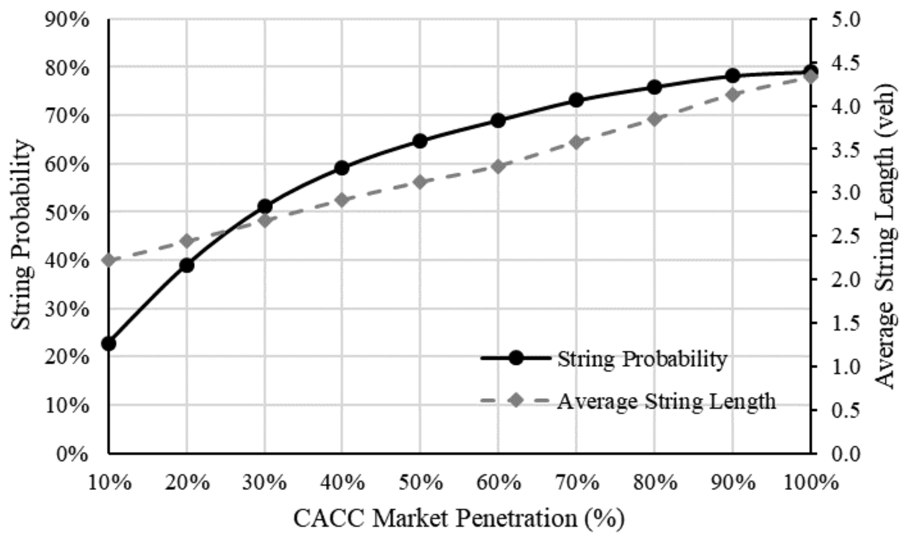


FIGURE 5 String probability and average string length under various CACC market penetrations.

Effects of Vehicle Awareness Device and CACC Managed Lane Strategies

The impacts of VAD on speed and vehicle fuel economy are shown in FIGURE 6 and FIGURE 7. The application of VAD had significant effects on average vehicle speed when the CACC market penetration was 40 percent or lower. In those scenarios, CACC vehicles had difficulty finding string leaders because they were randomly distributed in the traffic stream. After VAD was deployed, the VAD vehicles could serve as the string leaders, enabling isolated CACC vehicles to enter and operate in a string. The increase of CACC strings helped stabilize the traffic flow and increase overall speed. When CACC market penetration was greater than 40 percent, it became easier for CACC vehicles to identify CACC vehicle leaders (i.e., the string probability was 70 percent or more, see FIGURE 5). In this case, the connectivity capability of VAD vehicles was less utilized, and the influence of VAD strategy on speed therefore decreased. On the other hand, the VAD strategy had a minor negative influence on the vehicle fuel consumption. This again could be attributed to the lack of energy minimization algorithm in the CACC controllers.

FIGURE 6 and FIGURE 7 show that the ML strategy alone did not help improve either freeway speed or fuel efficiency. The strategy motivated CACC vehicle drivers to make lane changes to the managed lane, causing traffic disturbances in the general-purpose lanes. Particularly for an urban freeway corridor, those CACC vehicles needed to make three or four consecutive lane changes before they could merge into the managed lane. Such frequent lane changing behaviors could substantially decrease the stability of the traffic flow. In previous studies where the ML strategy was implemented at a simple on-ramp bottleneck, it was determined that the strategy brought about substantial speed and energy improvements (*5*). This was because the majority of simulated CACC vehicles had already traveled in the managed lane when they were released into the simulation network. Those vehicles did not cause lane changing disturbances to traffic. The study results imply that the ML strategy can be used to enhance corridor performance if it is possible to reduce the impact of the lane changes made by CACC vehicles. One potential way to resolve this challenge is to provide dedicated on-ramps for the managed lanes. With dedicated on-ramps, CACC vehicles can directly merge into the managed lane without disrupting the traffic stream in the general-purpose lane. In the meantime, the CACC vehicles can concentrate in the managed lane, generating efficient traffic flow with CACC string operations. When the ML and VAD strategy were combined, it only offered small benefit compared to the VAD-only scenario. Both the VAD and ML strategy slightly decreased the vehicle fuel economy because those strategies allowed more vehicles to operate in CACC mode.

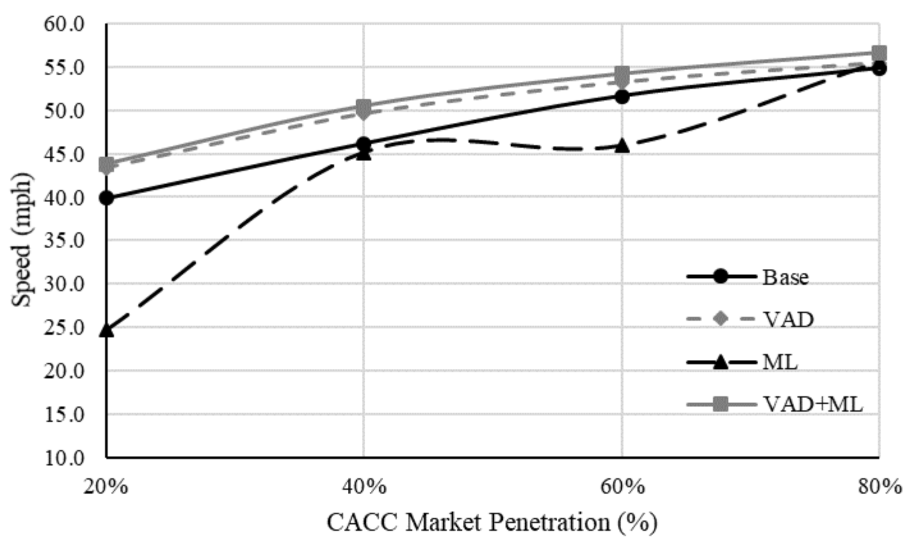


FIGURE 6 Vehicle speeds under the influence of vehicle awareness device and managed lane strategies.

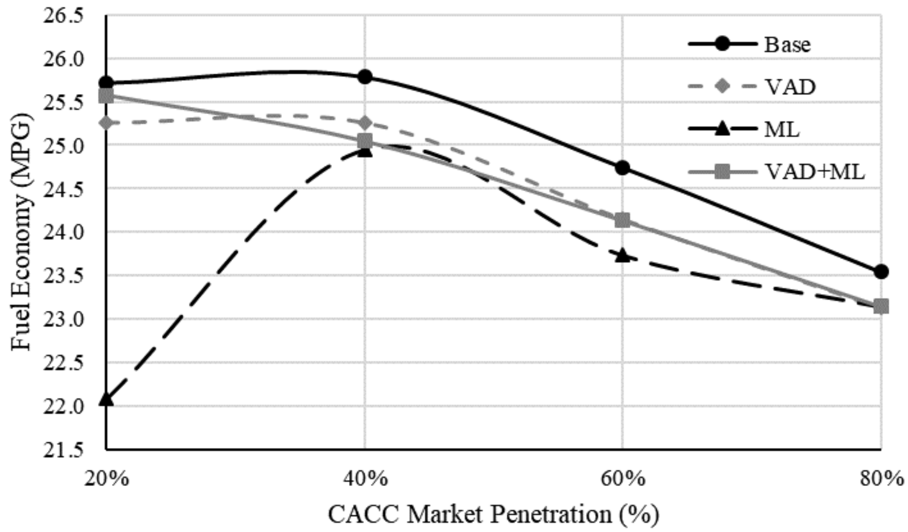


FIGURE 7 Fuel economy under the influence of vehicle awareness device and managed lane strategies.

Effects of Traffic Demand Increase

This study examined the performance of the SR–99 corridor when the traffic demand was increased by 5 to 40 percent. The purpose of the analysis was to identify the amount of extra traffic input the corridor could accommodate with the CACC string operation while maintaining the same average speed observed at the 0 percent CACC baseline case. The results are shown in TABLE 1. In the table, N/A means that the simulated traffic becomes over congested that the simulation run could not be handled by a computer with an Intel i7 processor and 32 GB memory.

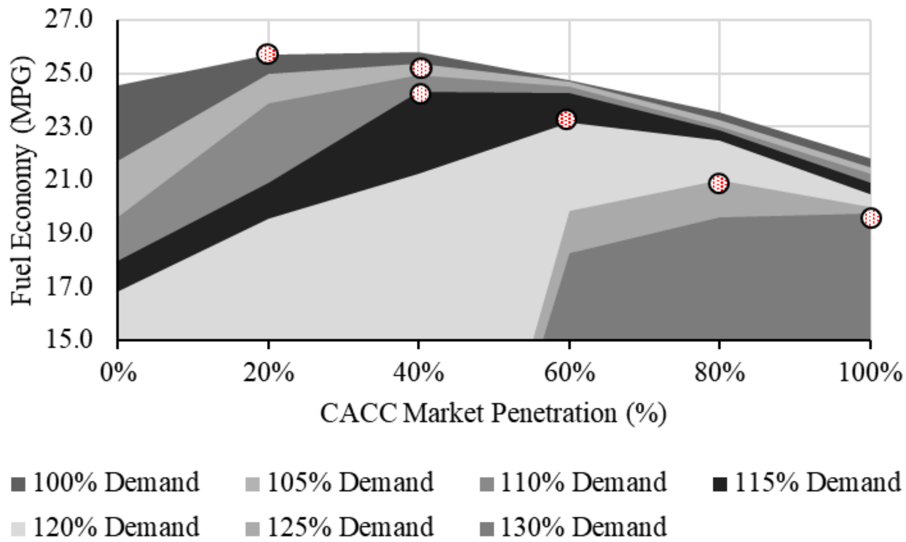
As TABLE 1 shows, the gray cells represent the maximum traffic demand the corridor can serve (henceforth the achievable corridor capacity) while maintaining a similar average speed to that observed under the baseline 0 percent CACC case. The achievable corridor capacity increased linearly with the CACC market penetration. The capacity gain was not as significant as the improvement identified at an isolated freeway on-ramp bottleneck (*4*). At the isolated bottleneck, the freeway pipeline capacity could increase by more than 90 percent when the CACC market penetration rate grew from 0 percent to 100 percent. On the SR–99 corridor, the entire network became very congested in the 100 percent CACC scenario when the traffic demand was increased only by 30 percent. The comparison suggests that it is difficult to extend the same level of CACC benefit observed at individual bottlenecks to larger freeway corridors. One reason is that CACC does not improve bottleneck performance consistently along the corridor. While it has significant effect on bottlenecks with smaller disturbances caused by on/off-ramp traffic, its effectiveness is reduced at bigger bottlenecks where the traffic flow is frequently interrupted by entering and exiting traffic. In many cases, CACC improved some upstream mild bottlenecks, allowing those bottlenecks to release more vehicles downstream. This increased the input flow for downstream heavy bottlenecks. As a result, those heavy bottlenecks became more congested. The traffic congestion at those sites eventually propagated upstream, negatively impacting the operation of the upstream bottlenecks. Because of the spatial development of the congestion region, the benefit of CACC was largely offset. Such an observation suggests the need to develop speed harmonization strategies that can dynamically adjust the input and output flow of individual bottlenecks by providing tailored speed limits to CACC vehicles. In this case, it could maintain efficient operation at the busiest bottlenecks using the CACC capability while avoiding the backward propagation of queues. Consequently, the performance of the entire corridor could be improved.

TABLE 1 Average Speed under Different Traffic Demand Inputs (mph).

CACC MPR (%)	100% Demand	105% Demand	110% Demand	115% Demand	120% Demand	125% Demand	130% Demand
0	33.4	22.8	17.6	14.8	13.1	N/A	N/A
20	39.9	32.6	26.1	18.2	16.0	N/A	N/A
40	46.2	39.8	34.6	28.7	18.9	N/A	N/A
60	51.6	46.9	42.2	35.1	27.3	17.0	14.0
80	54.8	52.5	48.3	43.3	34.2	23.5	19.2
100	56.8	54.3	52.5	49.9	44.6	35.2	32.7

Note: MPR = market penetration rate

The impacts of CACC on vehicle fuel economy are depicted in FIGURE 8 under various demand inputs. The white circles indicate the peak vehicle fuel economy for each individual demand scenario. The peak point gradually shifts towards higher CACC market penetration as the demand increases. This implies that the energy consumption benefit of CACC is associated with the traffic demand level. The increase of demand leads to worse levels of traffic congestion, which requires higher concentration of CACC strings to resolve. The vehicle fuel economy reaches the peak point when the congestion is mostly alleviated by the CACC string operation. Afterwards, the traffic stream becomes more free flowing with the further increase in CACC market penetration. As a result, the energy consumption benefit of CACC starts to decline.



Note: no data points for 40 percent or less CACC market penetration scenarios when the demand is 125 percent or higher. The simulation runs of those scenarios could not be completed due to the extreme congestion. The fuel economy of those scenarios is expected to be significantly worse than the displayed points.

FIGURE 8 Fuel economy under various demand inputs and CACC market penetrations.

CONCLUSION

In this research, a simulation-based case study was completed to investigate the effectiveness of CACC for mitigating or solving existing transportation problems related to congestion and fuel consumption for a specific urban freeway corridor. The performance of the 13-mile SR–99 corridor was analyzed under various CACC market penetration scenarios, traffic demand inputs, and CACC management strategies. This study revealed that the average speed of the concerned freeway corridor increased linearly with CACC market penetration. The average speed increased by 70 percent (from 34 mph to 56 mph) when CACC market penetration changed from 0 to 100 percent. The CACC application positively impacted vehicle fuel efficiency, with the highest average MPG of 26 achieved under the 30 percent CACC market penetration scenario. This was 5 percent higher than the baseline 0 percent CACC scenario. As CACC market penetration reached 100 percent, the MPG dropped to 22, which was 11 percent lower than the baseline MPG. CACC string operation improved MPG in the low to medium CACC market penetration scenarios because it mitigated traffic congestion. As the traffic flow became more stable, the overall vehicle energy efficiency improved. When CACC market penetration exceeded 40 percent, traffic ran at higher speeds, which reduced average vehicle fuel economy.

When CACC market penetration reached 100 percent, the simulated corridor allowed about 30 percent more traffic to enter the network without experiencing increased travel time. This was much lower than the capacity increase (i.e., 90 percent) simulated with a simple on-ramp bottleneck. The major reason was that the performance improvement of an isolated bottleneck on a freeway corridor increased the output flow to the downstream segments, leading to mobility reduction of downstream bottlenecks. As a result, the improvement of isolated bottlenecks did not necessarily bring about a benefit of the same magnitude for the entire corridor. This observation suggests a need to develop corridor-level traffic flow management strategies (e.g., speed harmonization) to coordinate the input and output flow of each bottleneck. It also indicates the limitations in trying to apply results from models of simple freeway segments to predict the impacts along a complicated corridor. It will be necessary to explicitly model and simulate the traffic volumes and geometries of each corridor in order to produce realistic estimates of the impacts of CAV alternatives such as CACC.

This case study also considered the VAD and ML strategies. The VAD strategy could enhance CACC string operation by increasing string probability. With this strategy, CACC vehicles could locate a string leader more easily when more manually driven vehicles were equipped with VAD. The strategy had the greatest influence when the CACC market penetration rate was 20 percent or 40 percent. In those scenarios, the average speed increased by 8 percent, while the fuel economy had a minor decrease. When CACC market penetration increased, CACC vehicles could more easily find CACC string leaders, reducing the effect of the VAD strategy. The ML strategy, on the other hand, decreased corridor performance when implemented alone. As the strategy was active, it attracted CACC vehicles to make lane changes to merge into the managed lane. This caused disturbances to the general-purpose lanes, making the traffic flow in the general-purpose lanes unstable. One option to address the challenge could be to use dedicated on-ramps that allow CACC vehicles to enter the managed lane directly.

The findings of this study point to several challenges that could hinder the widespread deployment of CACC in freeway corridors. To fully take advantage of CACC capability, it is necessary to implement the CACC string operation with systematic traffic control and management approaches that coordinate the speed of the CACC strings and enhance the formation of CACC strings. Those research questions are worthy to investigate in future studies.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: H. Liu, X.Y. Lu, S.E. Shladover; data collection: H. Liu; analysis and interpretation of results: H. Liu, X.Y. Lu, S.E. Shladover; draft manuscript preparation: H. Liu, S.E. Shladover. All authors reviewed the results and approved the final version of the manuscript.

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