Evaluations of Managed Lane Strategies for Arterial Deployment of Cooperative Adaptive Cruise Control

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ABSTRACT

Evolving from adaptive cruise control, cooperative adaptive cruise control (CACC) is the most advanced generation of cruise control system. Enabled by an extra layer of communication under connected vehicle (CV) environment, CACC has gained an increasing attention due to its technology readiness that can achieve rapid deployment compared to other CV applications. Recently, combining with managed lane strategy, CACC has become a game changer to dramatically elevate the capacity of highway without any significant investment for lane-mile increase. Applying CACC for arterial managed lane strategy, this paper presents the findings obtained from the simulation-based evaluation results. Divided into three arterial managed lane strategy categories dealing with 1) mixed-traffic, 2) restricted CACC lane, and 3) dedicated CACC lane, a VISSIM-based simulation test bed is constructed with an actual corridor located in Fairfax, Virginia.

With intersection average stop delay, average speed, and throughput as the measures of effectiveness, simulation results show that the implementation of dedicated CACC lane strategies would be improper for the improvement of intersection performance until the market penetration of CACC reaches a sufficient level as much as the capacity of one driving lane. On the other hand, it is revealed that the mixed-traffic and restricted CACC lane strategies outperform the dedicated lane strategy, thereby resulting in 5% to 25% stop delay reductions, depending on the market penetration rates.

INTRODUCTION

Traffic congestion has added up to a cost of billions of U.S. dollars every year in terms of wasted time, energy, and productivity. According to the 2015 Urban Mobility Scorecard, travel delay due to traffic congestion led to 3 billion gallons of fuel and 7 billion hours wasted time (*1*). Besides, it is expected that traffic problems will keep growing, and by 2020, nationwide total delay will increase by an extra 1 billion hours, resulting in approximately 20 percent congestion cost increase(*1*). Numerous congestion mitigation strategies have been proposed for the past decades. Recently, implementing managed lane strategies has gained great attention as it is able to provide a high degree operational flexibility in response to rapidly changing condition (*2*).

Meanwhile, Connected and Automated Vehicle (CV/AV) technologies are quickly advancing and are expected to transform the transportation landscape. Particularly, through wireless connectivity and automated longitudinal control, Cooperative Adaptive Cruise Control (CACC) is envisioned to drastically improve roadway capacity by forming vehicular platoons with a much shorter headway that is unachievable by human driver in a safe manner. Previous studies have shown that CACC could improve traffic capacity and safety if widely adopted: connected vehicle applications could help prevent approximately 50 percent of intersection crashes, whereas in the left-turn cases, 36 to 62 percent of crashes could be prevented (3); full deployment of connected vehicle mobility applications have the potential to reduce congestion delay by one third (4). Obviously, CACC may work more effectively while providing measurably higher lane capacity if it is applied on managed lane.

However, studies have focused on CACC applications on traffic flows, demonstrating great potential of CACC on increasing roadway capacity (5 -9) and most of them emphasized on freeway traffic management. Especially, in the context of recurring congestion, combination of CACC deployment and managed lane strategies have been examined by previous studies. However, in terms of arterial traffic management, although studies have been conducted on the intersection management in a connected vehicle environment (*3*), few research efforts have been emphasized on the investigation of the impacts on managed lane for arterial deployment of CACC.

To fill this gap and further investigate the benefits of CACC application on arterials, this paper emphasizes the study of managed lane strategies on arterials in a connected vehicle environment. A dedicated CACC car following algorithm is developed for vehicle longitudinal. Scenario-based analysis is conducted, where various CACC deployment strategies are examined and compared against a set of measure of effectiveness.

The remaining paper is organized as follows. The literature review section summarizes related research on managed lane practice on arterials as well as CACC applications. The simulated network, CACC control algorithm and experiment design are explained in the methodology section, followed by the evaluation results. Finally, the findings are summarized together with future research in the section of concluding remarks.

LITERATURE REVIEW

Previous studies on CACC implementation primarily focused on the investigation of impacts on traffic flow, with an emphasis on freeway segment. Vander Werf et al. (*4*) found that CACC has the potential to double the highway capacity at a high market penetration based on the simulation results on a single-lane roadway segment. De Bruin et al. (*5*) tested the CACC system with three test vehicles and showed that the CACC system enabled anticipatory braking actions leading to a potentially mitigated shock waves and improved traffic flows. Schakel et al. (*6*) assessed the impacts of CACC on traffic flow stability and shockwaves with a modified intelligent driver model. The results from a field test with 50 vehicles showed a reduction in vehicle headways and speed variation. Shladover et al. (*7*) estimated capacity for freeway segments under different CACC market penetration and suggested that CACC was able to increase capacity greatly under high market penetration rates.

Few research has been conducted on managed lanes with CACC deployed. The effects of a dedicated lane for CACC vehicles were evaluated in the study conducted by van Arem et al. (*8*), where positive effects on highway capacity were revealed despite negative impact of lane changes due to platoons formed by CACC vehicles. However, deterioration in traffic performance with a low CACC market penetration (e.g., less than 40%) was found in their study. Arnaout and Bowling (*9*) presented a progressive deployment approach to demonstrate the impact of CACC on traffic dynamics, where a special CACC lane was modelled to allow other non-CACC vehicles to operate on. By enabling mixed traffics in CACC special lane, it was found that traffic dynamics (e.g., flow, average time traveled in the network, average speed) could be significantly improved with even a low market penetration of CACC (e.g., 20%). Focusing on the comparison of macroscopic and mesoscopic traffic modeling Fakharian Qom et al. (*10*) investigated the mobility impacts of CACC on managed lanes with various incentives, pricing strategies and access restrictions.

When it comes to arterial management, several studies investigated the intersection management with the concept of CACC have been reported. Lee and Park (*3*) developed a cooperative vehicle intersection control system to manipulate individual vehicle maneuver for safely crossing the intersection without a traffic signal. A similar study was conducted by Zohdy and Rakha (*11*) by employing a simulation model integrating optimization tool for seeking the optimal movement of CACC vehicles. Both studies showed that average intersection delay was dramatically reduced. Moreover, fuel consumption savings and greenhouse gas emission reduction could be observed under such connected vehicle environment.

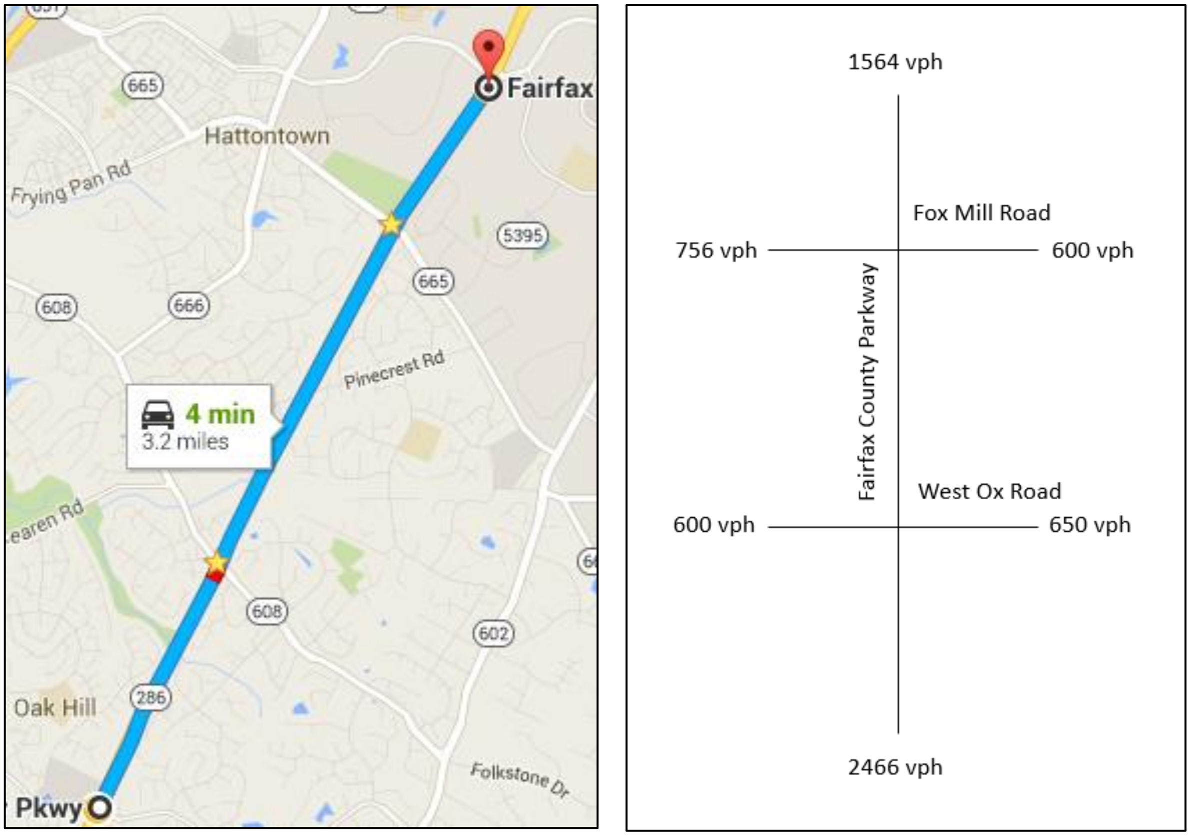
Lee et al. (*12*) tested the mobility and environmental impacts of CACC implementation by comparing a traditional pre-timed signalized intersection to a cooperative intersection with intelligent traffic signal control and CACC equipped vehicles. Enabled by communication between CACC vehicles and traffic signal, the goal of their proposed system was to minimize vehicle acceleration/deceleration through dynamic signal timing adjustment. Their study showed that with the implementation of CACC in a low volume intersection, the cooperative scenario substantially reduced average vehicle delay, green gas emission, and fuel consumption. Guler et al. (*13*) proposed a similar control algorithm for an intersection of two one-way-streets and evaluated the benefits under different CACC market penetration rates considering platooning and signal flexibility. Through optimizing vehicle departure times based on collected arrival times, the total intersection delay was minimized. Their study showed that average delay decreased as the penetration rate increased, however, the returns on additional penetration rates diminished after 60% penetration.

Revealed from literature review, despite its potential to improve intersection capacity and mitigate congestion, few studies have been conducted on managed lanes especially for arterial under connected vehicle environment.

METHODOLOGY

Simulation Network

The primary goal of the arterial evaluation is to assess the potential benefits of CACC technology when deployed on a signalized corridor. The intersection chosen is a segment of Fairfax County Parkway located in Fairfax County, Virginia as shown in FIGURE 1(a). The segment of the 2-lane Parkway is approximately 3 miles long. Intersecting at West Ox Rd. and Fox Mill Rd., the Parkway permits both protected left-turn and permitted right-turn movements. Two vehicle categories, GP and CACC vehicles, are considered. The demands on the mainline are directional with 2500 vehicle/hour (vph) for the northbound (NB) direction and 1500 vph for the southbound (SB) direction as stated in FIGURE 1(b). It is noted that the base demands of both major directions are under capacity, judging from the unadjusted saturation flow rate of 1800 veh/hr/ln. (*14*) .

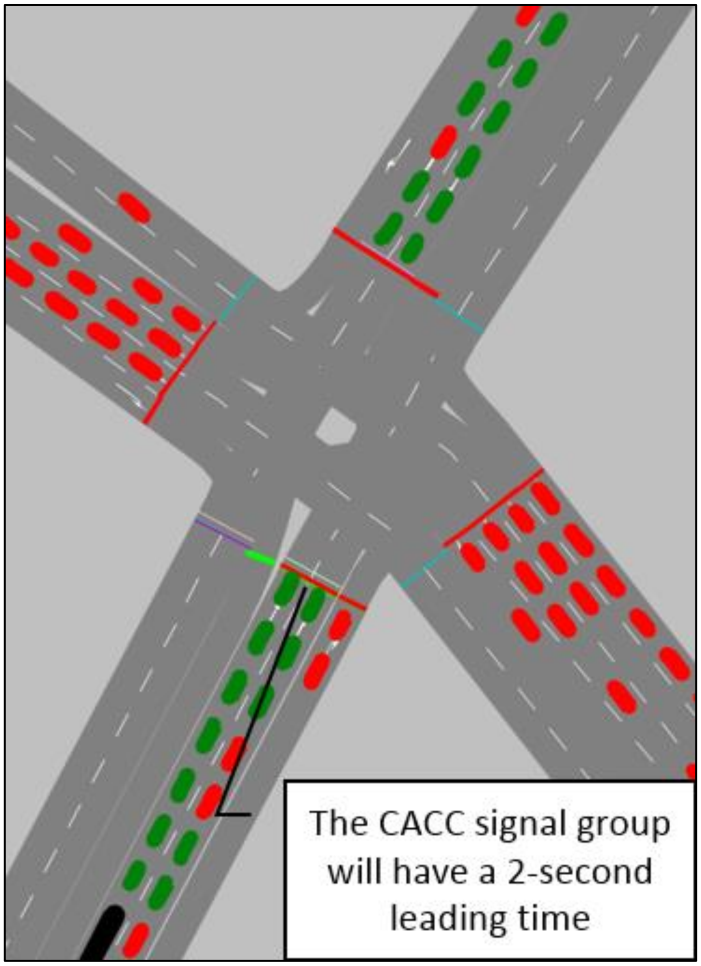


(a) Simulation network

(b) Network static demand

FIGURE 1 Segment for CACC arterial deployment simulation

In the simulation test bed, a CACC vehicle makes a decision with respective to the current signal status once it is within 400ft upstream of an intersection. That is, if the signal of the downstream intersection is red or amber, the cruising CACC vehicle in the platoon will switch off the CACC mode; if the signal status is green, the CACC vehicles maintain platoons cursing mode with short headways to pass the intersection. If a signal head turns from red to green, CACC vehicles waiting at the stop line do not experience the 2-second start-up loss time, assuming the infrastructure-to-vehicle capability of the intersection. This was implemented by a virtual set of signal heads in VISSIM as shown in FIGURE 2. A detailed decision flow chart for each CACC vehicle during each scanning interval is shown in FIGURE 3.



The CACC signal group will have a 2-second leading time

FIGURE 2 Simulation of saving of start-up loss time of CACC

CACC Car Following Algorithm

The CACC controlling algorithm is the modified MIXIC(*15*) car following model and the lane change behavior of a CACC vehicle is controlled by VISSIM(*16*). CACC cruising mode is switched on and off based on the distance to the immediate intersection and corresponding signal phases. When switched off (e.g., waiting in a queue), a CACC vehicle is controlled by VISSIM's Wiedemann driver model(*16*). Once the green phase resumes, the platooning among immediate CACC vehicles resumes to pass the intersection. Two types of headways are applied in the controlling algorithm: 0.6 seconds headway between CACC vehicles within a platoon and 2.0 seconds headway between a CACC platoon leader and its immediate preceding GP vehicle. In view of the lane changing of the arterial network, the maximum platoon size is set to 5 vehicles to prevent long platoons which may impact the lane changing of GP vehicles. The core logic of a CACC vehicle is presented in FIGURE 3.

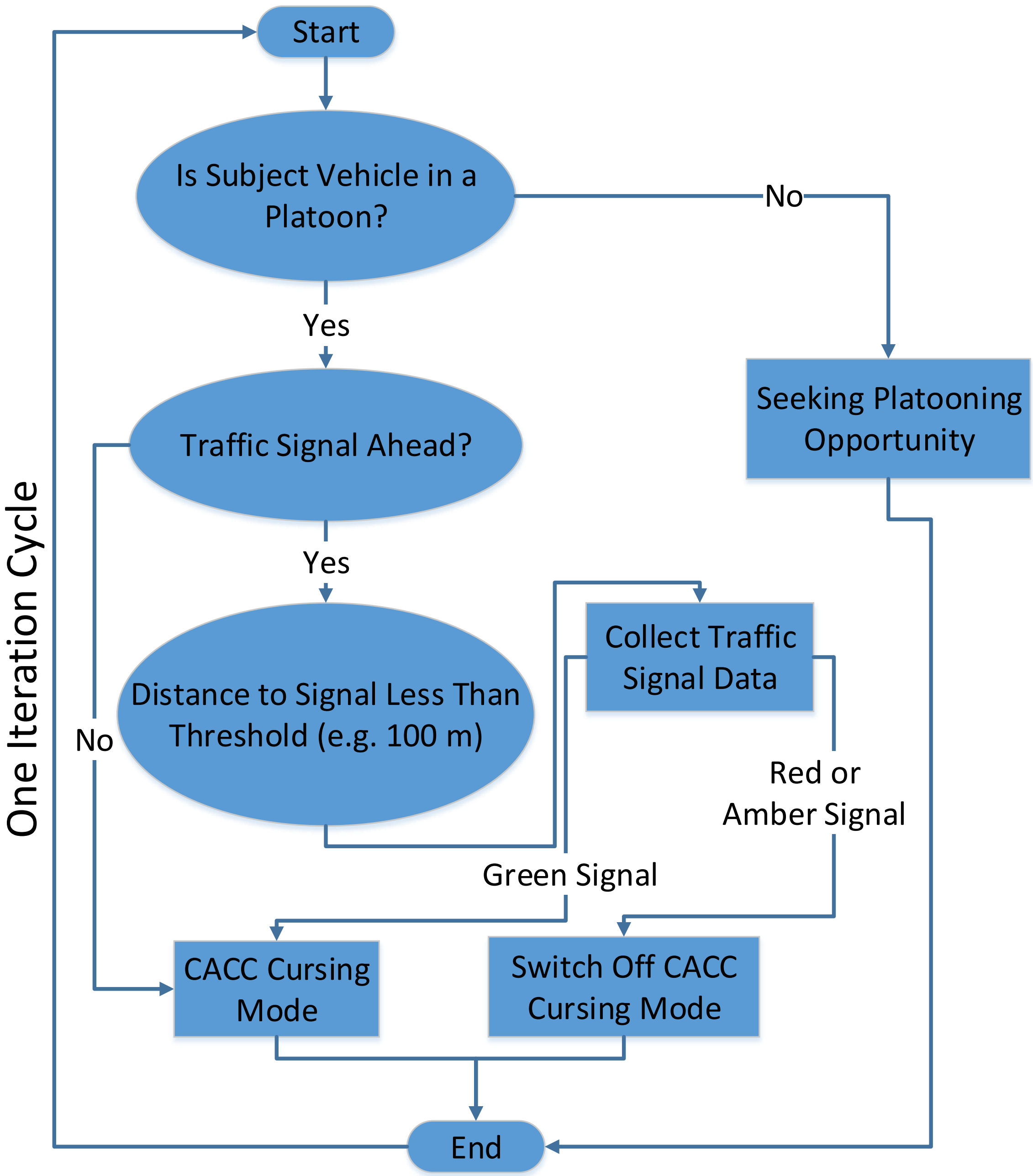


FIGURE 3 CACC decision algorithm in arterial simulation

Experiment Design

Five different deployment strategies (shown in Table 1) were evaluated with wide range CACC market penetration rates (MPRs) ranging from 10% to 90% with 10% increment for the mixed lane use type strategy. In case of dedicated CACC lane strategies, MPRs ranging from 10% to 70% was applied to avoid unrealistic lane utilization imbalance. For the dedicated lane use strategies, it is necessary to mention that a buffer zone, located in the upstream at an intersection is created in order to accommodate lane changing preparation for turning vehicles in the intersection. FIGURE

4 illustrates the 5 CACC lane use deployment strategies. The traffic flow data is collected every 600 seconds and the simulation time is 4200 seconds with 600 seconds warming-up period for each replication. 5 replications for each MPR in each deployment strategy were conducted.

Table 1 CACC Arterial Deployment Strategies

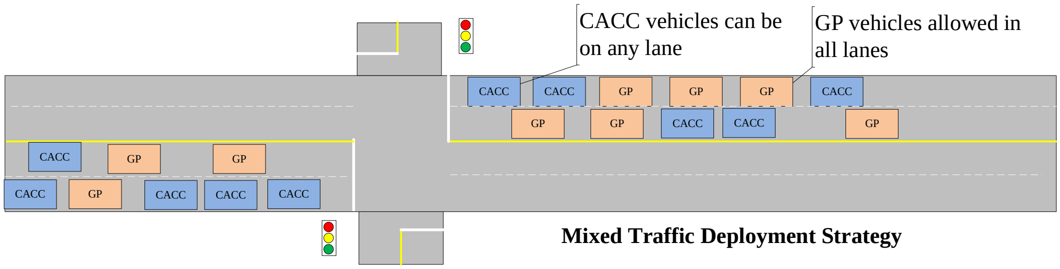
Category	**ID**	**Deployment Strategy**	**Right Lane**	**Left Lane**	**Market Penetration Rate (MPR)**	**Replication**
Base Case	0	Base Case	GP Only	GP Only	0%	5
Mixed Lane Use	1	Mixed Traffic	CACC + GP	CACC + GP	10%~90%	5
	2	Restricted-to-right-lane	CACC + GP	GP only	10%~90%	5
	3	Restricted-to-left-lane	GP only	CACC + GP	10%~90%	5
Dedicated Lane Use	4	Dedicated Right Lane	CACC only	GP + CACC	10%~70%	5
	5	Dedicated Left Lane	GP + CACC	CACC only	10%~70%	5

The advantages of CACC includes: 1) instant start at the moment of green signal, 2) consistent platoon progression across the intersection, 3) much shorter inter-platoon vehicle headway (e.g. 0.6s). The simulation test is designed to answer for the following questions:

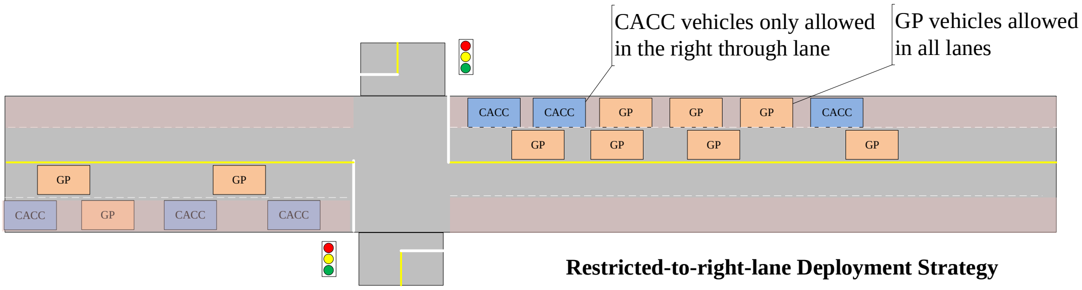
- Does the introduction of CACC vehicles reduce the average stop delay
- How do CACC vehicles perform and contribute to the overall intersection performance
- What is the improvement and maximum throughput for each intersection with CACC
- Among 5 CACC deployment strategies, which are the most effective under current demand and network setting

Assumptions made for the simulation are summarized as follows:

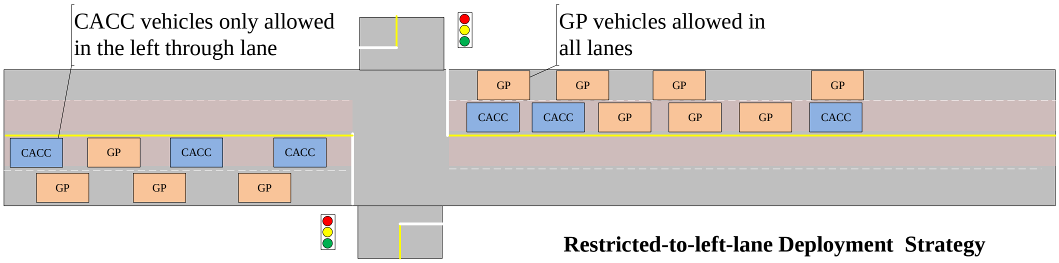
- Only mainline through traffic has CACC vehicles and the MPR is calculated based on the percentage of CACC vehicle in the through move movements.
- The demands of the network remain unchanged when CACC is available for deployment
- Seamless DSRC connectivity between CACC vehicles, and between CACC vehicles and intersection signal controller.
- The V2V and V2I communication is perfect (e.g. no packet loss, no interference)



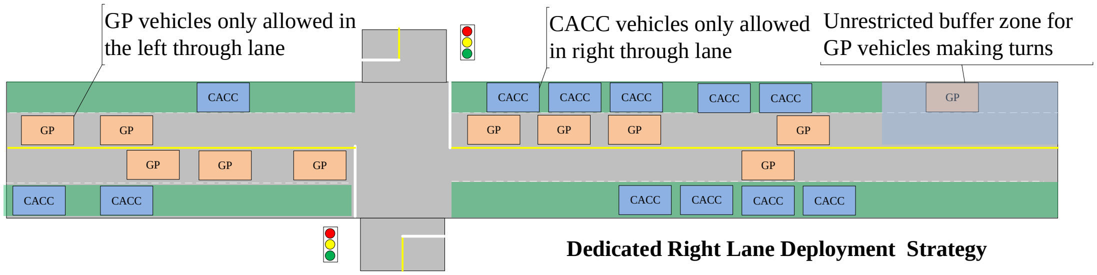
Mixed Traffic Deployment Strategy



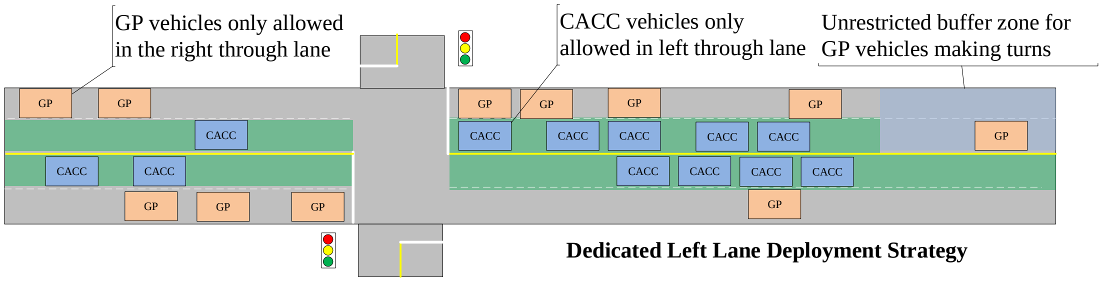
Restricted-to-right-lane Deployment Strategy



Restricted-to-left-lane Deployment Strategy



Dedicated Right Lane Deployment Strategy



Dedicated Left Lane Deployment Strategy

FIGURE 4 Illustrates for CACC deployment strategies

Measure of Effectiveness

Despite the potential transformations CACC could bring, from motorists' standpoint, they are more likely to make their decision of whether using CACC primarily based on more individual level-orientated Measures of Effectiveness (MOEs): whether CACC decrease the delay caused by the intersection and/or whether CACC could dampen the speed variation upstream of an intersection, making the riding experience more comfortable. Being able to provide such information is vital in informing the motorists to adapt CACC. MOEs selected for the evaluation in this paper are tailored to intersection performance evaluation, which are average stop delay, network average speed, intersection throughput. The definitions of the selected MOEs are listed in **Table 2**.

Table 2 Simulation Measure of Effectiveness

Measure of Effectiveness (MOE)	Definition
Average Stop Delay	The average delay in seconds within certain distance (e.g. 100m) upstream of an intersection when a vehicle comes to a complete stop due to signal control and queue
Network Average Speed	The average speed of vehicles traveling within the network
Throughput	The sum of vehicles (e.g. through movement, left-turn movement) passing an intersection

EVALUATION

For each MPR under each lane deployment strategy, the simulation was conducted for 5 replications. The proposed MOEs are subsequently summarized and analyzed.

Average Intersection Stop Delay

The stop delay measures the delay incurred due to stops occur at a signalization intersection. The average stop delays for both intersections are shown in FIGURE 5 and 6 with the baseline of 0%, respectively. For the Fox Mill Rd intersection, reductions have shown at MPR of 20% for Strategy 1, 2, and 3; whereas Strategy 4 and 5 shown an increase in average stop delay due to imbalance lane utilization. At MPR of 30%, Strategy 4, and 5 obtained a lower-than-baseline value. However, after 50% of MPR, the average stop delay of dedicated CACC lane cases started to increase, while those of Strategy 1, 2, and 3 continued to decrease and reached maximum reduction of approximately 25% at Strategy 3.

For the West Ox Rd Intersection, which has a higher demand, the trend of average stop delay exhibited a similar pattern to the Fox Mill Rd intersection . It is worth pointing out that the effect of implementing CACC at this intersection is more apparent: 10% reduction was achieved at 10% MPR, compared to Fox Mill Rd intersection. The reduction of average stop delay researched up to 25% at MPR 70% for Strategy 2. The average stop delays for Strategies 1 and 3 were leveled off at 80% MPR for a 20% and 25% reduction, separately. Strategies 4 and 5 both achieved reduction at 40% MPR and then keep reducing to the lowest value of 18% at 70% MPR.

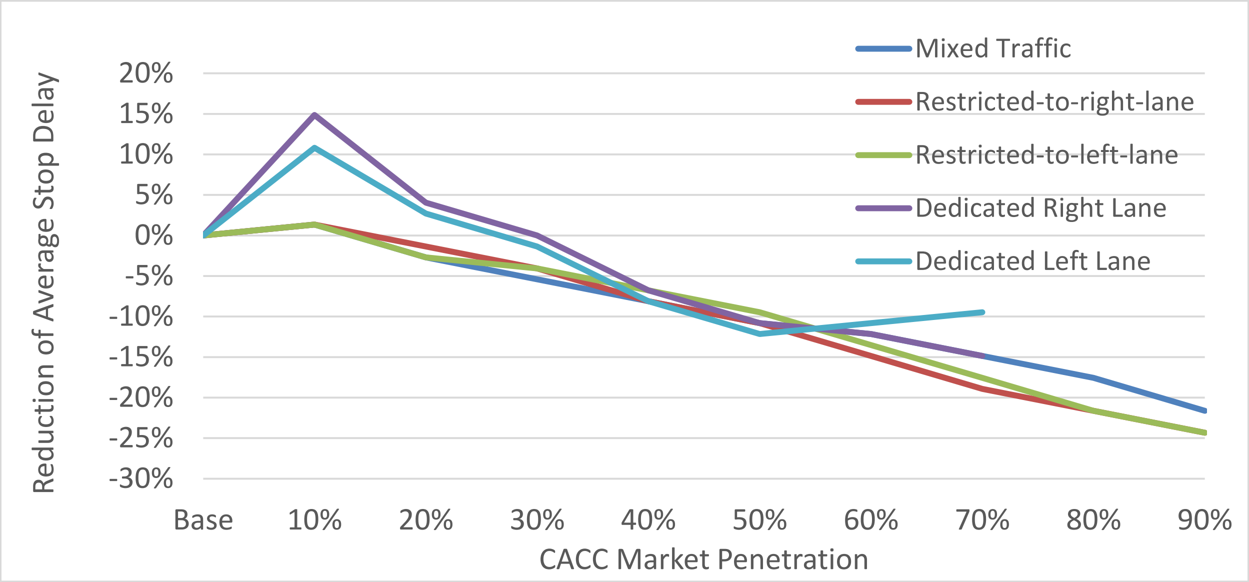


FIGURE 5 Reduction of average stop delay at Fox Mill Rd intersection

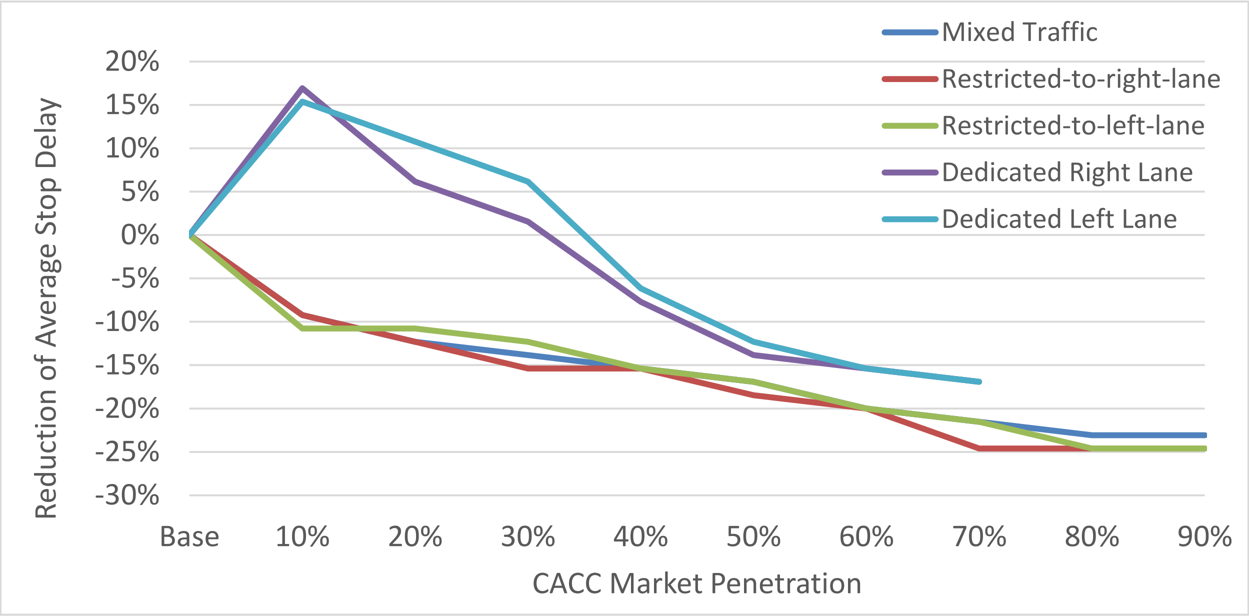


FIGURE 6 Reduction of average stop delay at West Ox Rd intersection

Network Average Speed

For the same stretch of roadway, the speed is the reciprocal of travel time, the authors chose speed instead of travel time as MOE. In this section, the average speeds, a straightforward performance measure for mobility. The speed of the entire network is presented in FIGURE 7. The difference of the posted speed limit and average speed is needed to be clarified. Unlike the post speed limit, the latter measures the actual operating speed of vehicles, accounting for control delays, vehicle interactions etc. It is typical that the average speed is lower than the posted speed limit, which is 50mph in the simulation network. In Strategy 1, Strategy 2, and Strategy 3, the average speeds slightly decrease by 1 mph for scenarios at 10% MPR. The maximum average speed is 41 mph, observed at 90% MPR in mixed traffic deployment strategy. For two dedicated lane strategies, the average speeds drop to the lowest point at 10% MPR and an approximately 35% reduction in speed was observed. Starting at 20% MPR, the speed increase and return to the value of baseline at 50% MPR. When the MPR is above 50%, the average speed becomes steady. The speed for Strategies 4 and 5 are slightly higher than 3 other strategies at mid-range MPRs. But, Strategies 1 to 3 show a more overall balanced performance in terms of average speed at each level of MPR.

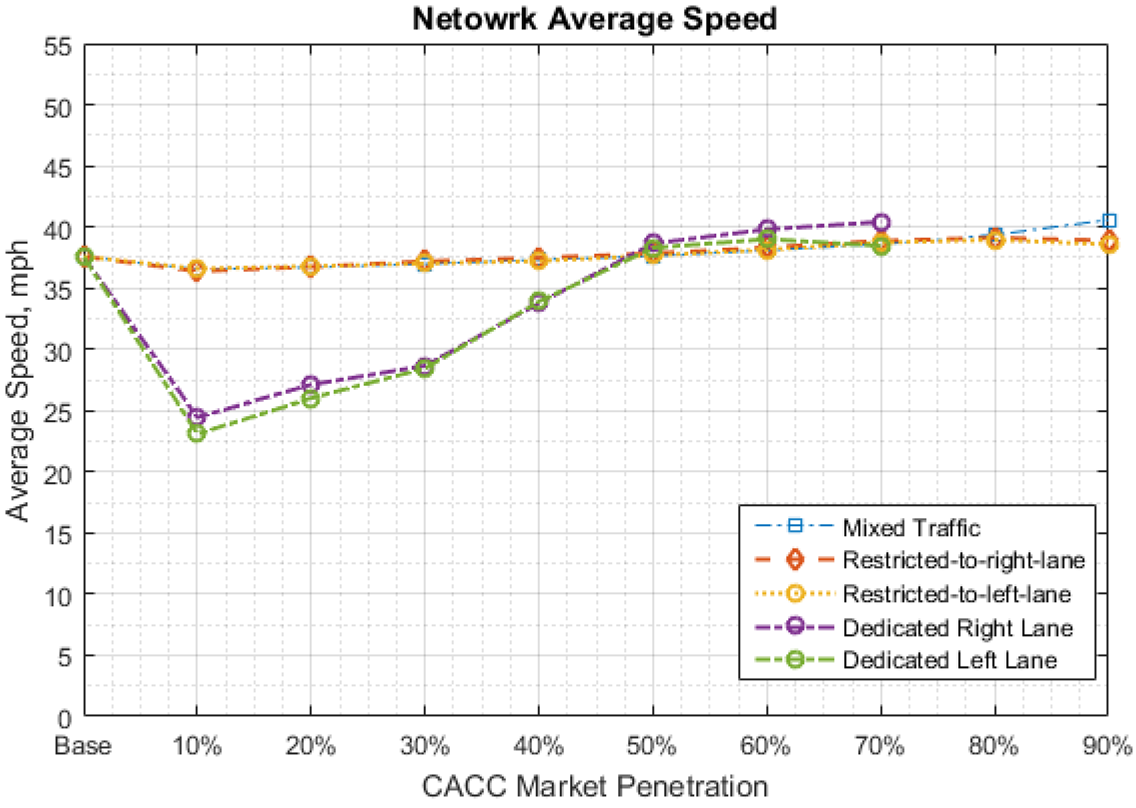
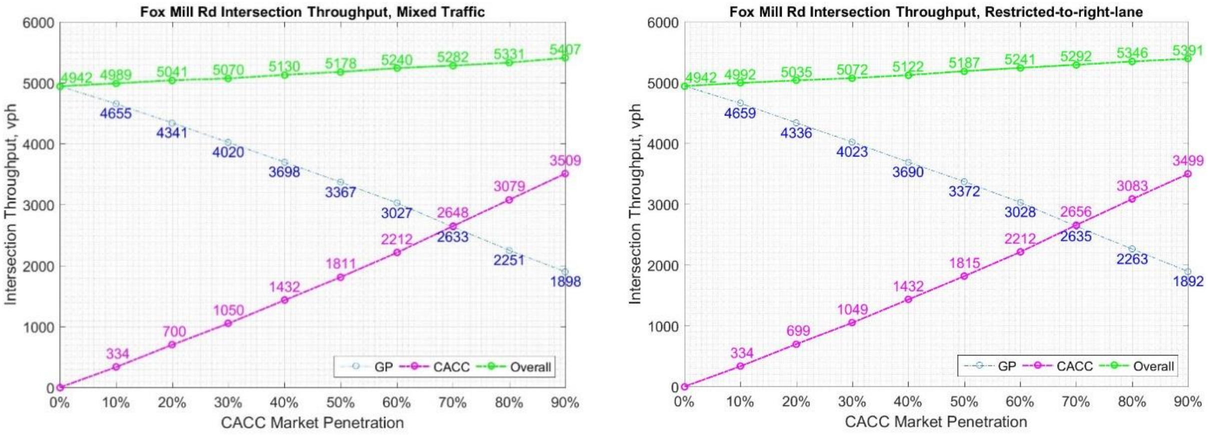


FIGURE 7 Network average speed

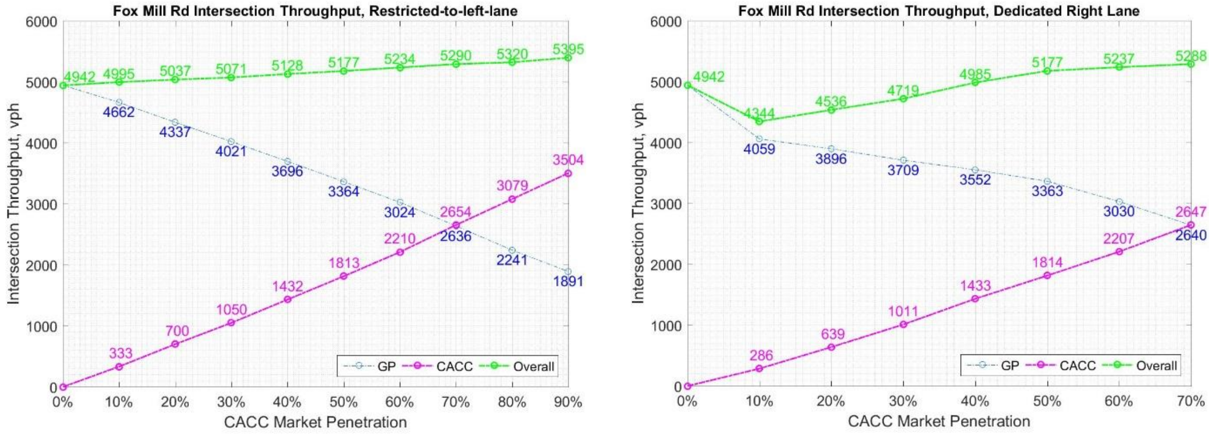
Throughput

Despite that only through movements contain CACC traffic, the simulation results are evaluated in an overall intersection level. The throughput patterns in relationship with CACC MPR of two intersection exhibit similar trends. We only presented the throughput for Intersection at Fox Mill Rd and Fairfax Co. Parkway in FIGURE 8. As seemed in FIGURE 8(a), (b) and (c), for Strategy 1, Strategy 2, and Strategy 3, where CACC vehicles are mixed with GP vehicles, the throughput at the overall intersection increases almost linearly as the MPR of CACC increases. The throughput reaches the highest value of 5,407 vph at 90% MPR in FIGURE 8(a). The throughputs of Strategy 2 and Strategy 3 are only marginally less than Strategy 1: the throughput for Strategy 2 is 5,391 vph and the throughput for Strategy 3 is 5,395 vph at 90% MPR. Comparatively, in the dedicated lane cases (i.e. Strategy 4 and Strategy 5) where one lane is used for CACC vehicles exclusively, the throughputs at the intersection drops at 10% MPR as shown in FIGURE 8(d) and (e) and start to increase back to the base case level until 40% MPR. When MPR reaches over 40% MPR, the throughputs for the entire intersection increase linearly. The maximum throughputs achieved for Strategy 4 and Strategy 5 are 5288 vph and 5264 vph respectively at 70% MPR. The dedicated lane deployment strategies (Strategy 4 and 5) do not yield better performance than the other three lane use deployment strategies at high MPRs.



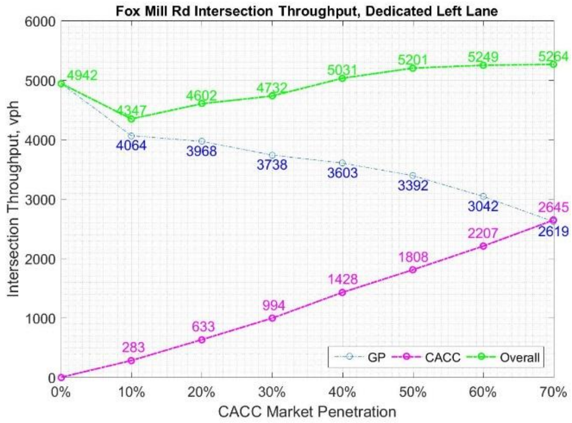
(a) Throughput at Fox Mill Rd intersection in mixed traffic deployment

(b) Throughput at Fox Mill Rd intersection in restricted-to-right-lane deployment



(c)Throughput at Fox Mill Rd intersection in restricted-to-left-lane deployment

(d) Throughput at Fox Mill Rd intersection in dedicated right lane deployment



(e) Throughput at Fox Mill Rd intersection in dedicated left lane deployment

FIGURE 8 Intersection throughput at Fox Mill Rd and Fairfax Co. Parkway

The percentage of throughput improvement in comparison to the base case for the Fox Mill Rd intersection is shown in FIGURE 9. Noticeably, the slope of the curve maintains almost constant at positive rates for Strategies 1, 2, and 3 and improvement of throughput was observed even at MPR as low as 10%. With negative impact at low MPR (i.e. 10% to 40%), Strategy 4 and 5 reach the same level of throughput improvement at 50% MPR and continues to increase the same rate as Strategy 1, 2, and 3 did.

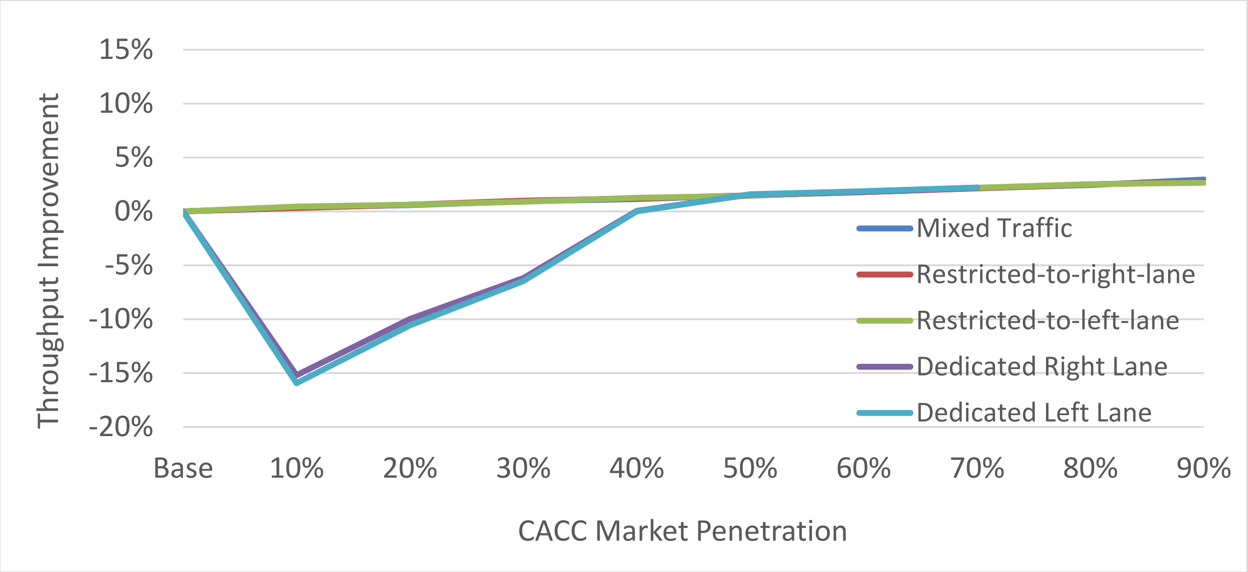


FIGURE 9 Throughput improvement at Fox Mill Rd intersection

Based on the above discussion, Strategies 1, 2, and 3 are recommended for CACC deployment in signalized arterials in the near future. At low MPR ranges (less than 40%), Strategies 1, 2, and 3 outperform Strategies 4 and 5 in all three MOEs. At the midrange MPR ranging from 50% to 70%, the performance of all strategies are at the same level. The dedicated land deployment strategies were not tested at MPRs above 70%. The authors anticipate that more other factors (e.g., more advance signal control systems) need to be considered in the future when CACC reaches a high MPR and believe it may create bias when extrapolating based on current signal control practices.

CONCLUDING REMARKS

Five different CACC lane use deployment strategies are proposed and subsequently evaluated in a signalized arterial corridor with 2 intersections with pre-timed signal plans. Considering 3 selected performance measures, dedicated lane deployment strategies (i.e., Strategies 4 and 5) appeared undesirable for CACC deployment on signalized arterial, especially under low MPRs. Implementing a dedicated CACC lane under low MPR would likely degrade the system performance caused by a lane use imbalance as GP vehicles are forcibly moved to one lane. In addition, dedicated lane deployment strategies do not provide the necessary flexibility for turning vehicles: all the lane change activities are restricted to the designated buffer zone. Given the current demand is maintained, deploying CACC in one lane with either mixing (i.e., Strategy 1) or restricted (i.e. Strategies 2 and 3) managed lane strategy appears to be desirable options for the reasons below:

1. The benefits of CACC technology were observed even at MPR as low as 10% in mixed-traffic, restrict-to-right lane, and restrict-to-left lane strategies.
2. Mixed-traffic, restrict-to-right lane, and restrict-to-left lane strategies did not create the significant reduction of the throughput of GP vehicles in low MPR scenarios. Moreover, a great margin for improvement in mixed traffic deployment strategies is expected, as the demand of the network grows in the future.
3. A smoother and unrestricted traffic flow was yielded especially for turning vehicles which have to get to the left or right lane for the desired turning.

In addition, the following measures may be taken to fully realize the potential benefits of CACC technology.

1. With proven improvements to the network performance, CACC technology should be introduced to the minor street traffic as well.
2. The signal plan may need to be optimized or change to adaptive control to accommodate the new CACC traffic pattern.
3. The turning movements of the major street approach could be restricted to one lane to eliminate the need for buffer zones by geometric reconfiguration of the intersection. (e.g. all-turns from right lane etc.). After the necessary geometric reconfiguration, the dedicated lane deployment strategies may be a better option.
4. Currently, CACC vehicles are subjected to the same speed limit as the human-driven vehicles. A flexible/variable speed limit, which may be higher, combined with dedicated lane use deployment strategy could potentially yield a promising enhancement on mobility

Lastly, the current level of demand, which is below the capacity of the corridor, may not be ideal to fully demonstrate the potency of CACC technology: CACC vehicle traffic is able to reach a throughput beyond what is achievable by human-driven traffic even under congested network.

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