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Improving Arterial Operations using Cooperative Adaptive Cruise Control (CACC)

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ABSTRACT

Cooperative Adaptive Cruise Control (CACC) allows for vehicles to safely travel in multi-vehicle strings with shorter gaps and respond almost simultaneously to speed changes in an environment with vehicle-to-vehicle (V2V) communications. This allows for improvements in capacity on freeways but also for congestion reduction on urban arterial corridors. This study investigated the potential mobility, benefits of CACC vehicle operations on urban arterials using a microscopic simulation developed based on realistic field experiments. A case study of the San Pablo Avenue corridor in Berkeley, California suggests that introducing CACC vehicles can reduce delay by up to 70%, at 100% market penetration of CACC equipped vehicles and without upgrades to the existing infrastructure of traffic signals. CACC vehicle strings can also reduce the number of stops by as much as 33% and the amount of time spent waiting at the signalized intersections by as much as 62%, which could potentially reduce fuel consumption and mitigate the environmental impact.

Keywords: Cooperative Adaptive Cruise Control (CACC), Arterial Corridor, Signalized Intersections, CACC String Operation

INTRODUCTION

Connected and automated vehicles (CAV) have the potential to improve the existing transportation infrastructure by reducing congestion, the number of accidents, and vehicle emissions. While vehicles will become fully automated and no longer require driver inputs in the future, fully automated vehicles will take decades to become readily available and widely adopted (*1*). However it is important to recognize that intermediate steps prior to full automation can bring significant benefits to the transportation systems. For instance, equipping vehicles with Cooperative Adaptive Cruise Control (CACC) can potentially improve mobility, reduce environmental impact, and enhance safety. CACC is the combination of Adaptive Cruise Control (ACC) and Vehicle-to-Vehicle (V2V) communication. ACC is a readily available vehicle automation system that automatically adjusts the vehicle speed using data collected from on-board sensors to maintain a safe following distance, though lane changes still need to be performed manually. However, its limited detection range prevents it from anticipating the traffic conditions beyond its immediate preceding vehicle, and such limitation often results in stop-and-go waves that decreases both the capacity and stability of traffic (*2*). Fortunately, this shortcoming can be mitigated by incorporating V2V communication, which allows the subject vehicle to broadcast its information to and collect information from its surrounding vehicles. Such capability enables vehicles to respond almost immediately to speed changes of multiple forward vehicles and therefore allows vehicles to safely travel in strings with shorter inter-vehicle time gaps (*3*). In fact, field experiments suggest that the average drivers adopt a 0.6 second inter-vehicle time gap in CACC strings but a 1.4 second inter-vehicle time gap when the vehicles are driven manually (*4*). Such shorter gap can potentially increase the freeway capacity by more than 90% when the market penetration of CACC vehicles reaches 100% (*5, 6*), based on results from simulation models that were calibrated according to realistic CACC field experiments (*7*).

We expect that the shorter gaps in CACC vehicle strings would increase the capacity of signalized intersections by increasing the saturation flow. In fact, a recent study (*8*) simulated an idealized queuing model and showed that platoons of connected vehicles could double the saturation flow and thereby reduce delay on urban arterials. However, this study could benefit from further improvements because the idealized queuing model cannot account for realistic vehicle behavior. Liu et al. (*9*) addressed this shortcoming by conducting a realistic microscopic simulation experiment of CACC vehicles at an isolated intersection; the simulation was calibrated based on CACC vehicle field tests (*7*) and the CACC vehicle string operation can increase the capacity of an isolated intersection by 67%, under existing signal controllers and timing plans. Despite the recent effort in quantifying the potential mobility benefit of CACC vehicles at signalized intersections, there has not been any realistic assessment of the potential benefit of CACC vehicle strings on the arterial corridors with multiple signalized intersections, under the existing infrastructure and algorithm for signalized intersections. This study is intended to realistically quantify the potential mobility improvements of the CACC vehicle strings on urban arterial corridors with multiple signalized intersections, when the existing signal controller and timing plans are in operation. This is extremely important as the results of this study would provide benchmark values for comparisons when developing and evaluating new signal control strategies for arterial corridors with CACC vehicle strings.

The rest of the paper is organized as follows, the next section discusses the simulation model for manually driven vehicles and CACC vehicle strings. The following section documents the approach for evaluating the benefit of CACC vehicle string through simulation of a real-world arterial corridor, followed by a section detailing the simulation results. The final section summarizes the study findings and discusses the next steps in the ongoing research.

RESEARCH APPROACH

Both the CACC vehicle strings and the manually driven vehicles were simulated using a commercial microscopic simulation software package AIMSUN (*10*). A micro Software Development Kit (microSDK) was used to incorporate an externally developed vehicle behavior model into the microscopic simulation. This externally developed vehicle behavior model, known as the PATH microscopic traffic flow model, captures both the car following and lane changing behavior of manually driven vehicles and CACC equipped vehicles, as well as the interaction between both types of vehicles. The PATH microscopic traffic flow model was developed based on the NGSIM oversaturated flow human driver model (*11*) and empirical data collected from a field experiment of realistic ACC and CACC car following behavior (*7, 12*). This model assumes that CACC equipped vehicles still perform lane changes and turning movements manually. Manually driven vehicle behavior in the PATH microscopic traffic flow model was calibrated using field data collected from an 18-kilometer freeway corridor during a typical weekday peak (*12*) and was cross-validated with another microscopic simulation model (*13*).

The ACC and CACC vehicle behavior have been validated using trajectory data from the field experiment (*7*). The traffic models provided a solid foundation for modeling the car following and lane changing behavior in mixed traffic with the CACC operation strategies. The PATH microscopic traffic flow model has been used extensively in recent simulation studies of CACC string operations on freeways and at isolated signalized intersections (*5, 6, 9*). The PATH model was further enhanced in order to simulate CACC strings on arterials with signalized intersections. The following strategies and assumptions were used to simulate CACC strings on arterial corridors:

- Drivers would manually accelerate when the traffic signal turns green. Once acceleration has begun, the ACC and CACC controllers are activated and the controllers would automatically maintain the desired speed and the desired time gap. The equipped vehicles would leave the intersection in CACC strings. The leader in the CACC string would operate in ACC mode; the followers would be in CACC mode and adopt shorter time gaps.
- The reaction time of the leading vehicle is 2 seconds. The followers would have lower reaction time when accelerating from the beginning of the green; the second vehicle in the string has a reaction time of 1.75 second, the third vehicle in the string has a reaction time of 1.5 second, the fourth vehicle in the string has a reaction time of 1.25 second, and the fifth and all vehicles that follow have reaction times of 1.0 second.
- Vehicles in CACC strings would treat red light as an idling vehicle downstream and manually decelerate (not performed by ACC and CACC controllers) to stop at the signalized intersections. This applies to the leaders and the followers in the CACC strings. If a follower in the CACC string encountered a red light after its leading vehicles in front have cleared the intersection, this particular follower would stop for the red light, split the CACC string, and become the leader of a new CACC string.
- Vehicles in CACC strings would treat yellow light as an idling vehicle downstream and manually stop (not performed by ACC and CACC controllers) at the signalized intersections if applying the maximum acceptable deceleration of 4.0 m/s^2 would allow the vehicle to stop at or prior to the stop bar at the signalized intersection. Otherwise the vehicles would proceed in the CACC strings and clear the intersection. If a follower in the

CACC string must stop in a yellow phase after its leading vehicles in front have cleared the intersection, this follower would split the CACC string, and become the leader of a new CACC string.

- Driver would manually decelerate and accelerate when performing permitted left turns (not performed by ACC and CACC controllers) to yield oncoming traffic and proceed through the intersection. There must be at least a 5 second gap between the vehicle that is attempting to make the permitted left turn and the oncoming vehicle in the opposite through direction. If the sufficient gap continues, multiple CACC equipped would accelerate and perform the left turn maneuver, and the ACC and CACC controllers would activate to allow for CACC string operations. Otherwise, the followers in the CACC string must stop, yield to the oncoming traffic, and split the CACC string and form a new string.

CASE STUDY: SAN PABLO AVENUE CORRIDOR

A real world arterial corridor was selected to evaluate the potential benefit of introducing CACC vehicle strings. A 3.25 kilometer section of San Pablo Avenue located in Berkeley, California was selected. The evening peak period (4:30 PM to 5:30 PM) was chosen for this study. The test site consists of ten signalized intersections, five of which are major intersections. The geometrics and lane configurations are shown in Figure 1. The arterial has a posted speed limit of 50 km/hr. All of the cross streets have posted speed limits of 40 km/hr. During the evening peak period, the northbound direction of San Pablo Avenue is oversaturated, with volumes to capacity ratios that are greater than 1.0 at all major intersections (as high as 1.18 at the intersection with Cedar Street). The southbound direction operates under capacity in the evening peak period. The northbound direction is more heavily traveled than the southbound direction since San Pablo Avenue is often used as an alternate route for the Interstate 80 freeway that is more congested in the northbound direction during the evening peak period.

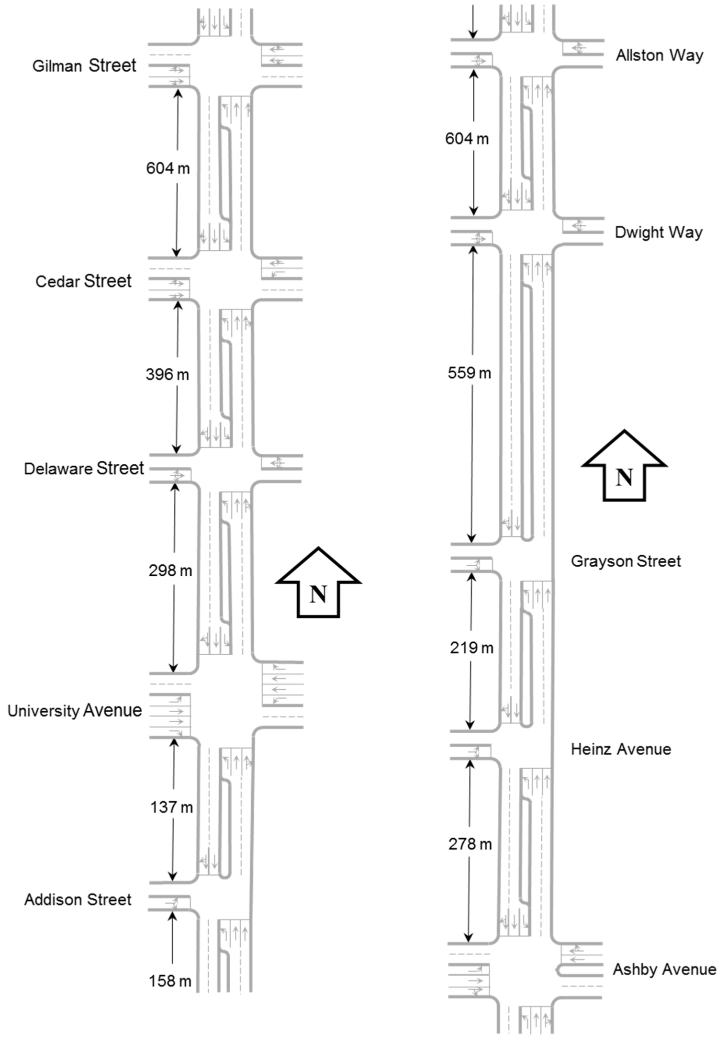
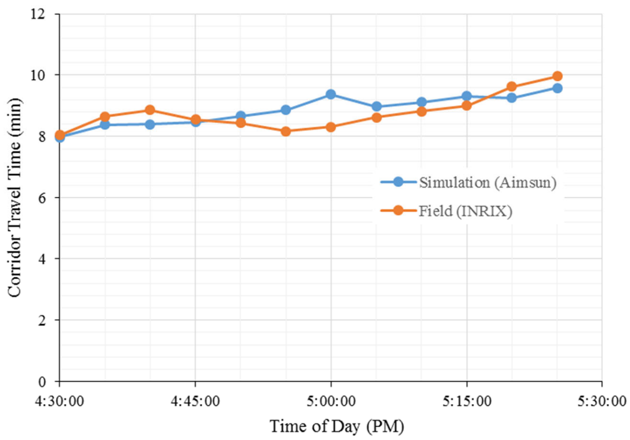


Figure 1 San Pablo Avenue corridor.

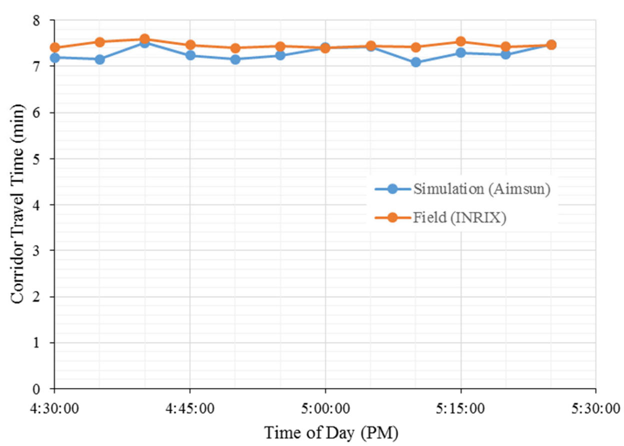
The signalized intersections of this corridor operate with fixed time plans and a common cycle length of 110 seconds to provide progression to the northbound direction. Minimum greens times at each intersection satisfy the required pedestrian crossing time.

A microscopic simulation network was built in the AIMSUN (*10*) using the most up to date road geometry, lane configurations, and speed limits of the 3.25 kilometer section of San Pablo Avenue. City of Berkeley provided recently collected (May 2015) typical evening peak period traffic counts of each intersection, and they were used as inputs for demand and turning percentages in the microscopic simulation. City of Berkeley also provided the latest signal timing plans, which were used as inputs in the microscopic simulation.

The microscopic simulation uses the PATH microscopic traffic flow model to replicate real world driver behavior. The simulation was calibrated to existing conditions on San Pablo Avenue; field data for typical weekday evening peak period travel times, which were collected from INRIX (*14*), were compared with the travel times simulated in AIMSUN. As shown in Figure 2, the calibration results showed satisfactory agreement between the simulated and field observed total corridor travel times for both directions.



(a) Northbound



(b) Southbound

Figure 2 Field vs. simulated total corridor travel time on San Pablo Ave.

Simulation tests of the San Pablo Avenue corridor were conducted to determine the potential benefit of CACC vehicle strings. Five replications of the microscopic simulation runs with different random number seeds were made using the existing demand, turning percentages, and signal timing plans. The simulation tests were performed for 0%, 20%, 40%, 60%, 80%, and 100% market penetration of CACC equipped vehicles. The following performance metrics were used to analyze the simulation results:

- Delay per distance traveled (sec/km) on both San Pablo Avenue and the cross streets shown in Figure 1. This refers to the time spent in addition to the time it would take if the vehicle were able to travel at a constant speed equivalent to the posted speed limit. This may include time spent at idle and during acceleration and deceleration.
- Average speed (km/hr) along San Pablo Avenue. This is also an indication of the travel time along San Pablo Avenue.
- Number of stops per distance traveled (#/km) on both San Pablo Avenue. The average number of stops also indicates the frequency of acceleration and deceleration, which is an indirect measure of fuel consumption and emissions.
- Stop time per distance traveled (sec/km) on both San Pablo Avenue. The stop time indicates the amount of time spent idling, which is also an indirect measure of fuel consumption and emissions.

Commented [HL1]: And the cross street?

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RESULTS AND DISCUSSION

Simulation results of the potential benefits of CACC vehicle strings are shown in Figures 3 and 4. CACC vehicle strings significantly reduced the average delay on San Pablo Avenue and the cross streets, at all market penetrations. Significant benefits can be realized at higher CACC market penetrations.

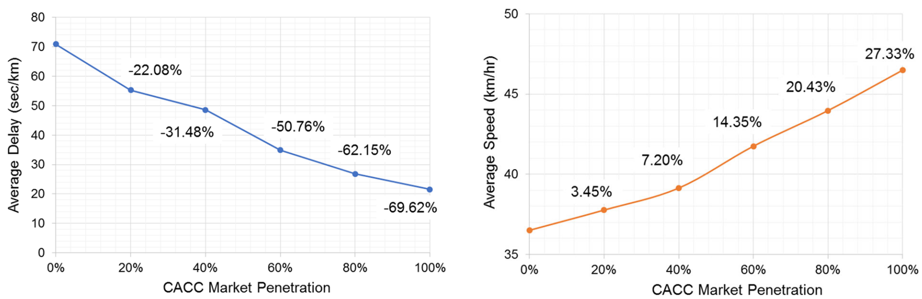

Figure 3 Average delay and average speed at varying levels of CACC market penetrations.

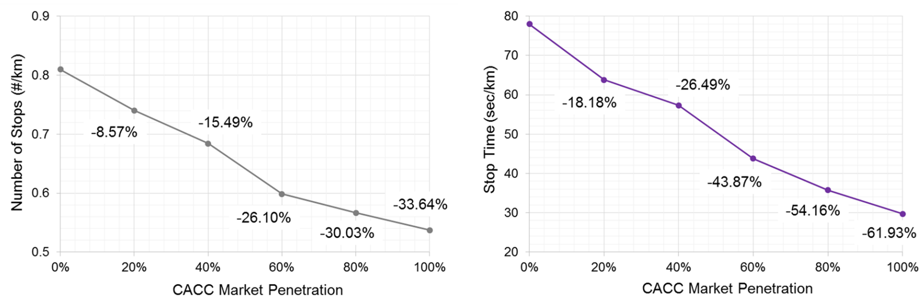

Figure 4 Number of stops and stop time at varying levels of CACC market penetrations.

As shown in Figure 3, at a relatively low CACC market penetration of 20%, average delay was reduced by 22.08%; and average delay can be reduced by approximately 70% when the CACC market penetration reaches 100%. Such observation agrees with the results shown in Lioris et al. (*8*) and Liu et al. (*9*), as the CACC market penetration increases, there would be more CACC vehicle strings. This allows vehicles to follow with shorter gaps thereby achieve higher saturation flow. The higher saturation flow translates to higher capacity at the signalized intersections, as demonstrated in the simulation experiment at an isolated intersection (*9*). In fact, the capacity of the signalized intersection increases linearly with CACC market penetration (*9*). This also correlates with the observation that average delay decreases linearly with increasing CACC market penetration. The significant improvement can also be attributed to the fact the San Pablo Avenue is oversaturated in the northbound direction under existing conditions (0% market penetration of CACC equipped vehicles).

Furthermore, as expected the average speed on San Pablo Avenue increases linearly with increasing CACC market penetration, which agrees with the trend that average delay decreases with higher CACC market penetration. As the CACC market penetration increases, the average speed on San Pablo Avenue approaches closer to the 50 km/hr speed limit, which indicates more time spent on cruising and less on delay due to stopping at signalized intersections, and this can be explained by the results shown in Figure 4. Both the number of stops and the stop time per distance traveled decrease approximately linearly as the CACC market penetration increases. As the number of stops and the stop time decrease with higher CACC market penetration, less delay is incurred from deceleration and waiting at signalized intersection, thereby increasing the average speed. In addition, the reduction in the number of stop and stop time indicate that there would be less frequent deceleration and accelerations and idling near and at the signalized intersection. This also implies that CACC vehicle strings could potentially reduce fuel consumption and vehicle emissions because acceleration, deceleration, and idling contribute to significantly higher fuel consumption and emissions than cruising at constant speeds. Although a promising insight, more accurate emissions and energy consumption models would be required to precisely quantify the environmental benefits of operating CACC vehicle strings on arterial corridors.

CONCLUSIONS AND RECOMMENDATIONS

Emerging technologies in vehicle automation and connectivity could potentially improve the existing transportation system. Prior to full automation, an intermediate step such as equipping vehicles with Cooperative Adaptive Cruise Control (CACC), a combination of Adaptive Cruise Control (ACC) and Vehicle-to-Vehicle (V2V) communication, can improve mobility and reduce congestion. CACC enables vehicles to respond almost immediately to speed changes of multiple forward vehicles. This allows vehicles to safely travel in strings with shorter inter-vehicle time gaps, which can significantly increase capacity and reduce congestion.

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We expected that the shorter gaps in CACC vehicle strings would increase the saturation flow and therefore lead to higher capacity and lower delay at the signalized intersections. A microscopic simulation experiment, which was calibrated based on field tests of CACC vehicle strings, demonstrated that significant mobility improvements can be achieved at a real world arterial corridor San Pablo Avenue in Berkeley, California. Simulation of the existing signal controller and timing plans and evening peak demand showed that average delay decreases linearly as the market penetration of CACC equipped vehicles increases, and this is consistent with the observation that average speed increases linearly with the market penetration of CACC equipped vehicles. In fact, the average delay can decrease by as much as 70% when the market penetration of CACC equipped vehicles reaches 100%, and the average speed along the San Pablo Avenue corridor can increase by as much as 27.33% at the 100% CACC market penetration. These observations are supported by the reduction in the number of stops and stop time observed at higher market penetrations of CACC equipped vehicles. Fewer number of stops and less time stopped at the signalized intersection led to less acceleration, deceleration, and idling at and near the signalized intersections, which meant higher speeds, lower travel time, and therefore less delay. Overall, CACC equipped vehicles can bring substantial mobility benefits when operating under current infrastructure.

Although the potential mobility benefits of CACC vehicles can be extremely promising even under the current transportation infrastructure, further improvements can be made to enhance and maximum the benefit of CACC vehicles. We suggest future research to develop new signal timing optimization approaches to specifically account for CACC vehicles strings that yield significantly higher saturation flows, at various levels of market penetrations. Furthermore, the simulation test in this study demonstrated that CACC vehicles can reduce the number of stops as well as the amount of time spent idling, but an accurate estimate of the potential reduction in fuel consumption and emissions is yet to be found. We recommendation future research to precisely measure and simulation the fuel consumption and emissions of CACC vehicle strings at varying levels of market penetrations, when operating on urban arterial corridors. This could be accomplished using detailed trajectory data and emissions models that accurately capture speed fluctuations

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AUTHOR CONTRIBUTION STATEMENT

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

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