Effects of Vehicle-vehicle/ roadside-vehicle Communication on Adaptive Cruise Controlled Highway Systems

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***Abstract*—In this paper we study the effect of vehicle-vehicle/vehicle-roadside communication on the performance of adaptive cruise control (ACC) systems. Two simulation works are presented. One is a single ACC vehicle simulation using MATLAB/SIMULINK. A cut-in scenario and a braking scenario are tested. Communication greatly saves control effort in the former scenario, while has little effect in the latter. The other work simulates ACC controlled highway merging with SHIFT language. The results show beneficial effects of communication in terms of braking effort, waiting-to-merge queue length, and main lane traffic shock wave caused by merging.**

I. INTRODUCTION

In recent years lots of research efforts are underway with the goal of enhancing the safety and efficiency of highway/urban traffic under the aid of wireless communication and modern control techniques. Both ad hoc wireless network based vehicle-vehicle (V-V) communication and infrastructure-based roadside-vehicle (R-V) communication have attracted interest from researchers in wireless communication as well as in ground transportation study [1][2][3]. Aware of the great benefits such communication system could bring, FCC proposed the allocation of 5.9GHz band spectrum specifically to national ground transportation safety and productivity applications. The on-going standardization process of this Dedicated Short Range Communication (DSRC) band further inspires the research in the field [3].

Adaptive Cruise Control (ACC) systems are the first driver control assistance systems entering the market that have the potential to influence traffic flow characteristics. In conventional cruise control the vehicle is commanded to maintain a preset velocity, regardless of the traffic environment. With adaptive cruise control, the vehicle tries to maintain a desired range to the preceding vehicle and match the preceding velocity on basis of the measurement from forward sensors (typically millimeter wave radar or infrared laser). When V-V/R-V communication is conjoined with ACC, the system becomes Cooperative Adaptive Cruise Control (CACC) system. Besides the sensor measurements, CACC vehicles also receive messages communicated by the preceding vehicle and other relevant vehicles, and all these vehicles cooperatively perform control maneuvers. Much work has been done to the understanding the effects of ACC in traffic flow [4][5][6][7]. However the CACC concept is new and related literature is small, despite the high degree of interest toward it.

We aim to incorporate the V-V/R-V communication design and the ACC/CACC system design, and study the influence of such design on the behavior of highway vehicles on both microscopic and macroscopic level. We use simulation as the primary method. This choice is due to the difficulty in obtaining analytical solution to the problems in such complex systems as highway systems, and the difficulty and cost in collecting large fleet of ACC/CACC vehicles to perform experiment. The simulation results could be guidelines for future analytical and experimental work.

The rest part of the paper is organized as follows. Section II describes the key communication concepts we apply. Section III is the simulation scenario, and section IV is the system modeling for the simulation. Section V reports the results of simulation and our discussion. Section VI is the conclusion.

II. TWO KEY COMMUNICATION CONCEPTS

Two important communication concepts for V-V/R-V communication are applied in our work. However seemingly simple, they can help overcome many challenging difficulties in V-V/R-V communication.

The first one is location-based broadcast (LBB), in which the sender broadcasts a message to all the potential receivers in the communication range, and the physical location of the sender is written in the broadcast message. Each receiver processes the message to determine the relevance of the message and the proper response by itself. Useful information for the sender in processing the message include the relative physical position of itself to the sender (in front, behind, left lane, how far, etc.), the nature of the message (braking, lane changing, accident, congestion, etc.), and other information in the message (velocity, acceleration, etc.). By applying LBB we avoid the difficulty of location based addressing and location/address mapping. The realization of LBB requires sensor fusion and GPS/INS techniques. It should be noticed that LBB is only suitable for certain type of vehicle safety applications, and for some applications unicast is unavoidable.

The other concept we study is “intermediate communication”. In this kind of communication, the transmission of a message is driven by particular events, e.g. cut in, merging, braking of preceding vehicle, etc. On the

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other hand the time-driven communication is regarded as full communication, in which vehicles transmit certain information (e.g. position, velocity, acceleration, road condition, etc.) to target receivers in every certain period of time (e.g. 100msec) [3][4]. When large number of senders are competing for the channel, as is the case in V-V communication, intermediate communication can help reduce the load of channel and simplify the communication protocol design. However intermediate communication convey less information than full communication thus is not good enough for some applications. One scenario we simulate is found to be such an example.

III. SIMULATION SCENARIOS

Two simulation studies are reported in this paper. The first is the simulation of the response of a single CACC vehicle to the changing highway traffic environment, and the second study simulates two highways carrying CACC vehicles that merge.

A. One-vehicle CACC simulation (OVC)

Two scenarios, Braking and Cut-in, are simulated in the OVC simulation.

In Braking scenario, two vehicles are driving in the same lane with the follower being either an ACC or CACC vehicle. In the simulation, the preceding vehicle brakes and the follower applies a proper braking in response to maintain the desired range and match the preceding velocity. In ACC scheme, the follower measures the range and range rate with forward sensors. The range rate is differentiated by the on-board computer to obtain acceleration, and the braking of the preceding vehicle is detected from the change in acceleration. With V-V communication, whenever the preceding vehicle brakes, it transmits a “brake light” message to the CACC following vehicle. The CACC vehicle, upon receiving the message, brakes strongly enough for safety but not enough for passenger discomfort. Response time is increased by replacing the sensor delay and computational delay with the shorter communication delay.

In Cut-in scenario, initially an ACC/CACC vehicle is following its preceding vehicle. Then a vehicle in an adjacent lane cuts in between the two vehicles, and becomes the new preceding vehicle of the ACC/CACC vehicle. Without communication, the ACC vehicle would detect the cut-in vehicle when the latter passes the lane border. The ACC controller then commands the vehicle to brake, often abruptly, to make space in front for the cut in vehicle. With CACC system using V-V communication, the cut-in vehicle transmits the equivalent of a “turning light” message to the CACC vehicle at the instant it starts to cut in from the center of the adjacent lane. The CACC vehicle then has 2-3 seconds (half of lane change time) to slow down and make space for the cut-in vehicle.

B. Highway Merging CACC Simulation (HWC)

In HWC, vehicles merge into the main lane from a merge-in lane, and the two lanes join at a merge-in point (MP), as illustrated in Fugre 1. Cars B and C are the main lane vehicles, and car A is in the merge-in lane.

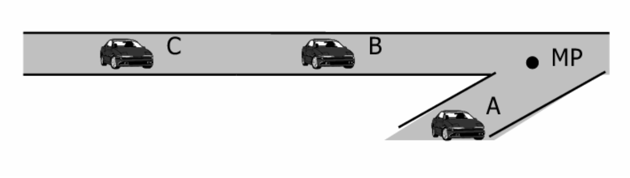

Figure 1. Highway Merging Scenario

Some or all of the main lane vehicles are ACC/CACC controlled while others are driven by humans. The percentage of the ACC/CACC vehicles in the main lane is controllable.

The procedure of merge-in is as follows.

1)Head merging vehicle is generated

At the instant the first vehicle in the merge-in lane enters the main lane, the second vehicle in the lane becomes the new “head merging vehicle”. For presentation convenience, assume car A in Fig 1 is the new head merging vehicle. In CACC system, at the instant it becomes the head car, A broadcasts a message to all the main lane vehicles within the communication range. The communication could be realized by either V-V communication with A being the broadcaster, or R-V communication with the aid of a roadside station close to MP. The message contains the position of the merge-in point and the time taken for vehicle A to enter the main lane. If A is driving at the instant it becomes the head merging vehicle, this time is needed for A to drive from its position at that instant to merge-in point. The distance it travels in this period of time is equal to the range between A and its old preceding vehicle, i.e. the last head merging vehicle. If A is already waiting at the merge-in point when it becomes the head, we assume a metering light at the MP commands A to wait for a certain amount of time before it attempts to merge. The benefit of this necessary waiting is evident from the simulation results.

2)Main lane vehicles process the message

After sending the warning message, it takes sometime for A to enter the main lane. During this period of time, each main lane vehicle determines the relevance of the received message. If a main lane vehicle C finds that at the anticipated time the head merging vehicle A arrives in the main lane, A will cut in between C and its current preceding vehicle B, it regards the message relevant. Vehicle C then brakes to increase the gap between itself and vehicle B. The response time is generally long enough for a main lane vehicle to make a “good” gap. For example, for merge-in lane flow rate of 1200 vehicle/hour/lane, the average response time is about 3 seconds. If a car finds a message irrelevant, it simply discard it. This is in accordance with the principle of location based broadcast.

3)Head merging vehicle waits for acceptable gap

When it arrives at the MP, the head merging vehicle stops and observes the gap between the passing vehicles in the main lane. It waits to merge in until an acceptable gap appears. If the head merging vehicle has to wait for rather long time, a queue of waiting cars will be formed in the merge-in lane.

4)Head merging vehicle merges in

The head vehicle merges in the gap if it feels safe. Its initial speed is equal to the main lane vehicle in front. At this instant, the main lane vehicle right behind it sees the merging vehicle, and responds by braking.

IV. SYSTEM MODELING AND DESIGN

This section describes the models implemented in the simulation and the controller design. The OVC models are implemented with MATLAB/SIMULINK software package. The HMC simulation was built using SHIFT, a language developed by California PATH for describing dynamic network of hybrid automata [8].

1)Vehicle Model

The OVC uses the vehicle model of a BMW test vehicle [9]. The model includes longitudinal vehicle dynamics, wheel dynamics, unlocked engine dynamics, torque converter model, lockup Logic, gear shifting, and throttle/brake actuator models. Each part of the model is experimentally validated with the test vehicle driven in test track or urban streets. The well- studied vehicle model enables us to grasp the performance of the controller under the influence of the nonlinear dynamics of vehicle mechanical components.

In HMC, due to the large number of simulated components and the complication of the scenario, we use the simple longitudinal vehicle model in (1) to save computation load.

$$\begin{aligned} \ddot{x}(t) &= a(t) \qquad (1) \\ \tau\dot{a}(t) + a(t) &= u(t) \end{aligned}$$

The model composed of a double integrator and a first-order lag, where $x(t)$ and $a(t)$ are respectively the position and acceleration, and $u(t)$ is the commanded acceleration from the controller.

2)Controller

The ACC controller (2) is designed with the sliding surface technique in order to regulate the range error and range rate error.

$$a_{des} = k_v \dot{r}(t) + k_p (r(t) - r_d(t)) \qquad (2)$$

In the equation r and $\dot{r}$ are the range and range rate, and r_d is the desired range. The desired acceleration a_{des} is the control command, and k_p and k_v are the controller gains. Gain scheduling is used to deal with different relation of the range and range rate. The rule is that for shorter range and more negative range rate, the controller reacts more aggressively [9]. The acceleration commanded by the controller to the vehicle is a measure of control effort. For the same level of performance on range error and range rate responses, better controller design should demand less control effort. The acceleration of the ACC/CACC controllers is bounded to -3m/s/s to 2m/s/s for safety and comfort purpose. It should be noticed that the braking capacity of human driver uses the distribution in [12] and is not bounded like that of ACC/CACC vehicles.

Instead of the commonly used headway model for the desired range, we use the desired range defined by (3), which is a curve fitting result of human driver behavior provided by the manufacturer of the test vehicle [9].

$$r_d(t) = t_h * v^{k_0} + offset = 6.33 * v^{0.48} + 2 \qquad (3)$$

Both in the cut-in scenario of the OVC and the HWC, whenever a CACC vehicle receives a message warning it of a vehicle cutting in front in t_{cut-in} time, it changes the desired range in the way described in (4).

$$\tilde{r}_d = \left[1 + \frac{(t - t_s)}{t_{cut-in}}\right] * r_d + \frac{(t - t_s)}{t_{cut-in}} * L \qquad (4)$$

In the equation, r_d is the desired range defined in (3), $\tilde{r}_d$ is the modified desired range for the CACC controller, t_s is the instant of the receipt of the warning message, t_{cut-in} is the estimated time left for the arrival of the cut-in vehicle, and L is the vehicle length. This modified desired range means to command the controller to increase the gap to the preceding vehicle linearly with time during the time the cut-in vehicle is changing lane or merging in.

3)Other models in HMC

In HMC, the highway is one lane and limited access, with only passenger cars on it. The vehicle following could be controlled by either human or ACC/CACC. The human driver model is the cognitive model based on COSMODRIVE proposed by Song and Delorme [10]. Human drivers do not respond to the V-V/R-V communication messages. The lateral motion of vehicles and geometry of merge-in ramp are not modeled. Both in ACC and CACC system, merging is human controlled, because automatic controlled merging is not realizable in the near future. We use the probabilistic model of Ahmed [11] for the human decision making in merging. In this model, when seeing a good gap the driver of the merging vehicle has a higher probability to merge in, but a good gap cannot guarantee a merging. Other factors (e.g. relative speed, distance to the point where the merging has to be completed, and processing delay) are also considered in the model. In CACC, the relevant main lane vehicles try to make a more acceptable gap for the merging vehicle when it arrives, but it is human driver who makes the decision to merge or not.

V. SIMULATION RESULTS

Figures 2 and 3 are the acceleration of the ACC vehicle and CACC vehicle in cut-in scenario of OVC. The x-axis is time in seconds, and y-axis is the acceleration in m/s/s. The solid line is the desired acceleration and the dashed line is the actual acceleration. The cut-in happens at 10 second for both ACC and CACC cases. The ACC vehicle detects the cut-in vehicle shortly after 10 second, and then has to apply a hard brake of approximately –2.5 m/s/s to slow down. After this hard brake, the velocity of the ACC vehicle decreases to a safe value, and the acceleration then goes back to the normal value. On the other hand, in Figure 3, because of the V-V communication, the CACC vehicle responds 2.5 seconds before the vehicle in the adjacent lane cuts in, which is half of the lane change time. Because the CACC vehicle has longer response time, it brakes much less than the ACC vehicle. The braking effort is smaller than 0.5 m/s/s, and the sharp notch in Figure 2 disappears. The two cases have quite similar performance on the range and range rate response, which we do not show here. Therefore the V-V communication helps save large amount of control effort, which means more safety for the vehicle, and less discomfort for the passenger.

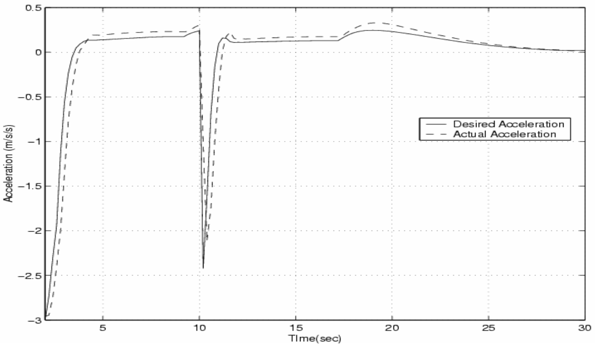

Figure 2. Accleration of ACC vehicle in OVC: Cut-in scenario

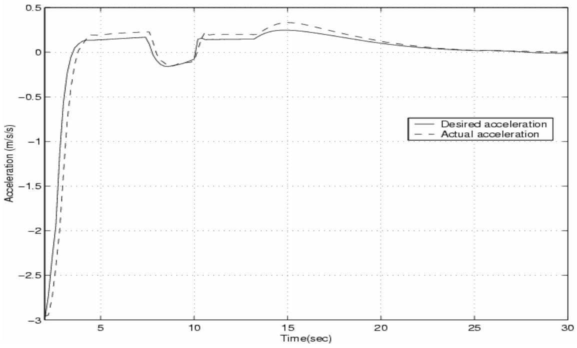

Figure 3. Acceleration of CACC vehicle in OVC: Cut-in scenario

Figure 4 is the range error and range rate of the ACC/CACC controller in the braking scenario of OVC. Little difference could be observed to draw clear conclusion. The control effort comparison shows the same result, which we omit here. The reason may be that the quality of the forward sensor implemented in the simulation is quite high and the response time gained by addition of communication is not long enough for the mechanical components to yield much difference in performance. From the simulation we build, it looks that intermediate communication does not help a lot in a scenario like the braking warning.

Figures 5 and 6 are the trajectories of vehicles in the main lane between 900 second and 1000 second for ACC and CACC HMC simulation. Each curve corresponds to the trajectory of one vehicle. The x-axis is time in seconds and the y-axis is the position in meters. The merge-in point is at 510 meters, and the horizontal line at 510 meter represents queued vehicles. Merging vehicles can be identified by curves which lie entirely above this line. We can see clearly in Figure 5 a shock wave propagating upstream, i.e. in the opposite direction of the traffic. However this shock wave is smoothed in Figure 6. The reason lies in two facts. First is that the relevant main lane vehicle receives the warning message well in advance, thus it can brake gently to increase the gap to preceding vehicle. Second is when the merging vehicle enters the main lane, the gap it is in is already large enough for safety, and the main lane vehicles behind it do not need to brake hard, as they have to do in ACC scheme.

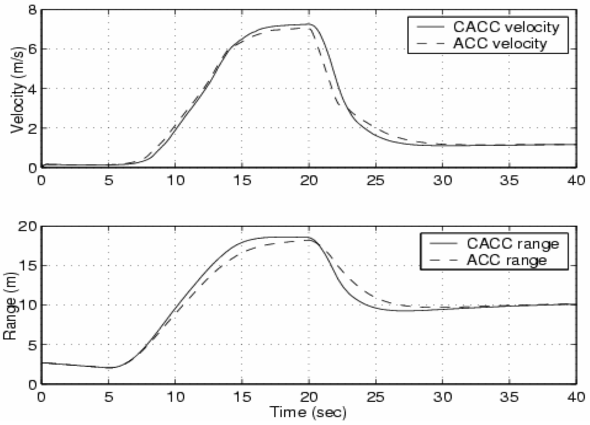

Figure 4. Range and Range Rate in OVC: Braking Scenario

We repeat the simulation with various market penetration of the ACC (CACC) vehicle. Figures 7 and 8 summarize the market penetration effect in braking effort. In both figures the vehicles other than ACC/CACC ones are human-driven. In Figure 7, the “mean maximum braking effort” vs. percentage of ACC (CACC) vehicle is shown. In the duration of simulation each vehicle has a maximum braking effort. The mean maximum braking effort is the average, over all vehicles appearing in the simulation, of the vehicle's maximum braking effort. It is used as a measure of the average braking effort of all vehicles. In the figure, the solid line stands for the CACC case, and the dashed line stands for the ACC case. Evidently we can see the following facts. The more ACC vehicles in the highway, the smaller the average braking effort is. With the same percentage of ACC vehicles, CACC performs better than ACC in saving the braking effort. This result is consistent with that of cut-in scenario of OVC, due to the similarity of merge-in and cut-in.

Figure 8 shows the length of the queue of the waiting to merge vehicles in the merge-in lane from 600 to 1000 second. Results for four cases are plotted here. The top curve is for 50% ACC main lane vehicles. In the middle, two curves standing for 100% ACC and 50% CACC are quite close to each other. The bottom curve is for 100% CACC. The queue length keeps increasing because we intentionally inject large input flow exceeding the capacity of the highway. Clearly, the larger the percentage of ACC (CACC) vehicles, the shorter the waiting queue. For the same percentage, the queue in CACC highway is up to 5 vehicles shorter than in ACC highway. Due to the communication, the relevant main lane vehicles have longer time to make a good gap in front. By the time the merging vehicle arrives at MP, it is more likely to see an acceptable gap and merge in than reject the gap and wait. Therefore in average the merging cars wait shorter in CACC highway, and the queue behind it is shorter if exists at all.

VI. CONCLUSION

In conclusion, for the types of ACC applications we studied, V-V/R-V communication brings great benefits. The benefits can be observed in terms of efficiency (waiting-to-merge queue length), safety (shock wave, braking effort, etc.) and passenger's comfort (braking efforts). Simple communication concepts like location based broadcasting and intermediate communication could work very well in these applications. But for some applications such effects are not obvious. The simulation works can serve as the guideline for further experimental work. For example, the braking scenario and similar applications should not be the focus of future experiment. Besides the experiments, how to design protocol to realize such communication with high Qos and low cost is another direction of future work.

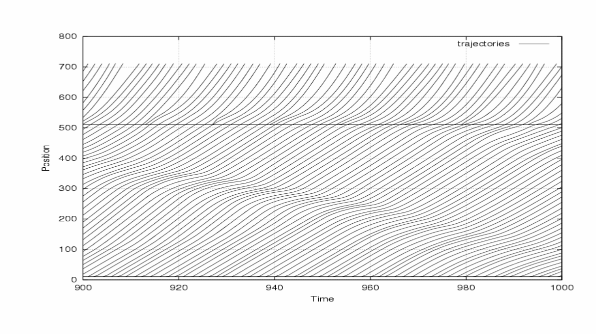

Figure 5. Trajectories of Main Lane Vehicles in ACC Highway Merging

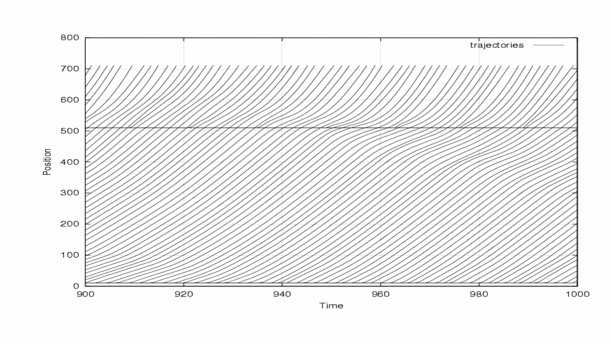

Figure 6. Trajectories of Main Lane Vehicles in CACC Highway Merging

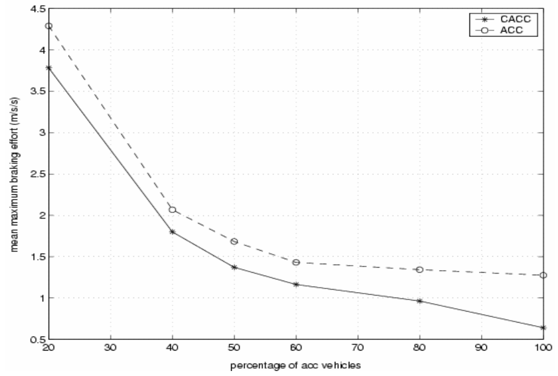

Figure 7. Average Braking Effort for Different Market Penetration of ACC/CACC in HWC

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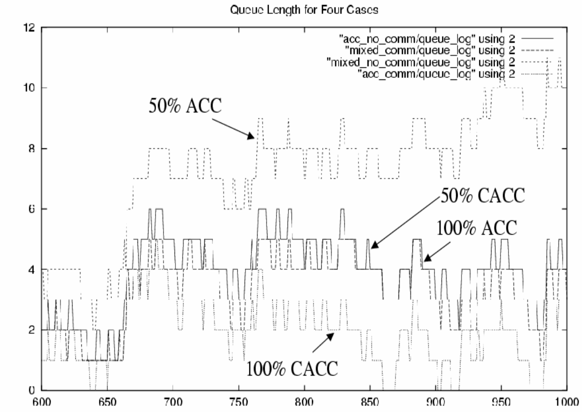

Figure 8. Queue Length of Waiting-for-Merge in HWC