Simulation, Analysis, and Comparison of ACC and CACC in Highway Merging Control [1]

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Abstract

We comparatively assess the influence of adaptive cruise control (ACC) and cooperative adaptive cruise control (CACC) systems on highway traffic flow characteristics, with highway merging as an example. The primary goal is to study the design and implementation of vehicle-vehicle/roadside-vehicle communication system, which enhances an ACC system to a CACC one. In addition, the impact of market penetration of ACC/CACC vehicles and controller aggression are also evaluated. Two simulation works are presented. The microscopic study simulates a single ACC/CACC vehicle in cut-in scenario using MATLAB/SIMULINK. Simulation shows that CACC system saves control effort over ACC system. In the macroscopic work we simulate ACC/CACC controlled highway merging with SHIFT language. The results show beneficial effects of communication in both efficiency (average velocity) and cost (braking effort). The higher the market penetration of controlled vehicles the better the system performs. The aggressiveness of controller has mixed influence, which provides a tradeoff between efficiency and safety.

1 INTRODUCTION

In recent years lots of research efforts are underway with the goal of enhancing the safety and efficiency of highway/urban traffic with 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 benefit such communication system could bring, FCC allocates 5.9 GHz spectrum specifically to the national ground transportation safety and productivity. The on-going standardization process of this Dedicated Short Range Communication (DSRC) band further inspires the research activities 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 [4]. In conventional cruise control (CC) 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 with the preceding vehicle and to match the preceding velocity on basis of the measurement from forward-looking 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 information communicated by the preceding vehicle and other relevant vehicles. All these vehicles cooperatively perform control maneuvers. Both CC and ACC have appeared in market. Literature is well supplied with results in understanding the effects of ACC in traffic flow [5]-[8]. However the CACC concept is new and related literature is small, despite the high degree of interest towards it.

We incorporate the design of V-V/R-V communication system with that of the ACC/CACC system, and study the impact of such incorporation in controlling highway vehicle merging on both microscopic and macroscopic level. In addition, some other design parameters of the system, namely the market penetration and controller aggressiveness, are also studied to understand their effects. The research method we use is simulation. This choice is due, on one hand, to the difficulty in getting analytical solution to such complicated system as highway traffic, and on the other, to the hardship and cost in collecting large fleet of ACC/CACC vehicles to conduct experiment. The simulation results could be guideline for future analytical and experimental work.

The rest part of the paper is organized as follows. Sec-

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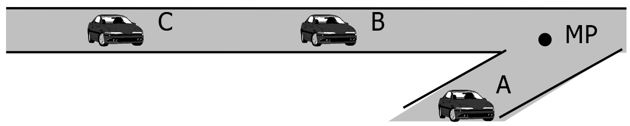

Figure 1: Highway Layout of HMC

tion 2 describes the simulation scenarios. Section 3 is the system modeling and implementation. Section 4 reports and discusses the results of simulation. Section 5 concludes the paper.

2 SIMULATION SCENARIOS

We conducted two complementary simulations. The first is the simulation of a single CACC (or ACC) vehicle, whose dynamic is thoroughly modelled. We study it in a cut-in scenario, which is the microscopic representation of the highway merging. The second study is the macroscopic simulation of two highways carrying CACC (or ACC) vehicles that merge. The vehicle model in the macroscopic study is simpler to save computational load. We describe the scenario simulated in these two works separately below.

2.1 One-vehicle CACC simulation (OVC)

In OVC, initially a CACC (or ACC) vehicle is following its preceding vehicle. Then a third vehicle in the adjacent lane cuts in between the two vehicles, and becomes the new preceding vehicle of the CACC (ACC) vehicle. Without communication, the ACC vehicle detects the cut-in vehicle when the latter passes the lane border. The ACC controller thus 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 approximately half of lane change time to slow down and make space for the cut-in vehicle. In CACC scheme we assume the cut-in vehicle and the CACC vehicle to have V-V communication capability, while the “old” preceding vehicle do not have to communicate.

2.2 Highway Merging CACC Simulation (HMC)

In HMC, 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 Figure 1. In the figure cars B and C are the main lane vehicles, and car A is in the merge-in lane.

The merge-in procedure in the simulation is the following.

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 merging car, car A broadcasts a message to all the main lane vehicles within its 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. If A is stationary at the merge-in point when it becomes the head (e.g. when there is a queue formed in the merging lane), we assume a metering light at the MP commands A to wait for a certain amount of time before it attempts to merge. The length of the time the head merging vehicle waits is set to be the reciprocal of the input flow rate of the merging lane. For example, for merge-in lane flow rate of 1200 vehicles/hour/lane, the average waiting time is about 3 seconds.

2. *Head merging vehicle drives to or waits at merge-in point*

   After receiving the warning message from the head merging vehicle, each main lane vehicle determines the relevance of the message to itself. If a main lane vehicle C (see Figure 1) finds that at the anticipated time vehicle A arrives in the main lane the latter will cut in between C and its current preceding vehicle B, car C regards the message as relevant. In response to the relevant message, C brakes promptly but smoothly to increase the gap between itself and vehicle B. If a car finds a message irrelevant, it simply discards it.

3. *Head merging vehicle waits for acceptable gap in main lane*

   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 main lane traffic is too busy such that the head merging vehicle has to wait for excessively long time, a queue of waiting cars forms in the merge-in lane.

4. *Head merging vehicle merges in*

   The head merging vehicle merges in the gap it feels safe. At this instant, the main lane vehicle right behind it sees the merging vehicle, and responds by necessary braking. The head merging vehicle's initial velocity in the main lane is designed to be that of the main lane vehicle right in front of it. Now the second vehicle in the merging lane, if any, becomes the new head merging vehicle, and we are back in step one and the above procedure is repeated.

3 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 is built using SHIFT, a language developed by California PATH for describing dynamic network of hybrid automata [9].

3.1 Vehicle Models

The OVC uses the vehicle model of a BMW test vehicle [10]. The model includes the following components: longitudinal vehicle dynamics, wheel dynamics, unlocked engine dynamics, torque converter, lockup logic, gear shifting, and throttle/brake actuator. Each part of the model is experimentally validated with the vehicle driven in test track or urban streets. The parameters are either estimated from experiment results or provided by the manufacturer. The well-studied vehicle model enables us to observe the performance of the controller under the influence of the nonlinear dynamics of the mechanical components of a vehicle. The details of modeling and validation of each component of the vehicle model are summarized in [10].

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.

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

The model consists 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.

3.2 Controller Design

We describe the vehicle following controller for ACC and CACC system in this subsection.

3.2.1 ACC Controller: We use ACC controller showed in equation (2) in the simulation.

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

In the equation $r(t)$ and $\dot{r}(t)$ are the range and range rate, and $r_d(t)$ is the desired range. The desired acceleration a_{des} is the control command. Controller gains k_v and k_p are designed with the sliding surface technique in order to regulate the range error and range rate error. 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 [10]. The acceleration commanded by the controller is a measure of control effort. For the same level of performance on range error and range rate responses, better controller design demands less control effort. The acceleration of the ACC/CACC controllers is bounded to between -3m/s/s and 2m/s/s for safety and comfort purpose, but such limits do not apply to human drivers (see details in [4]).

Instead of the commonly used time-gap 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 OVC test vehicle [10].

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

We observe that the increasing rate of this desired range is smaller than the time-gap model when the velocity is high.

3.2.2 CACC Controller: When CACC scheme is applied, we modify the desired range properly and use controller of the same structure as described above to track this modified desired range. Both in OVC and HMC, whenever a CACC vehicle receives a "relevant" 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).

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

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 before cut-in/merging vehicle's arrival, such that the CACC vehicle decelerates as aggressively as necessary without having to brake excessively hard.

3.3 Other models in HMC

There are more models in HMC since it simulates much more complicated system than OVC. The highway is one lane and limited access, with only passenger cars on it. The vehicle following could be controlled by human, ACC, or CACC. The human driver model is the cognitive model based on COSMODRIVE proposed by Song and Delorme [11]. 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 modelled. 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 [12] for the human decision making in merging. In CACC, the relevant main lane vehicles try to make a more acceptable gap for the merging vehicle when the latter arrives, but it is the human driver of the merging vehicle who makes the decision to merge or not. The communication system modeling applies the concepts of location-based broadcast and event-driven communication [13]. We show the powerfulness of this seemingly simple implementation of communication in the results below.

4 RESULTS AND DISCUSSIONS

4.1 Results of OVC

The range and velocity for ACC and CACC systems are shown in Figure 2. The velocity of the preceding vehicle remains to be 12.5 m/s in the simulation. At the beginning of simulation the follower (i.e. the CACC or ACC vehicle) is 150 meters behind the preceding vehicle and driving at 25 m/s. The follower brakes to track the preceding velocity. The cut-in happens at 10 second, making the range to drop instantaneously. The range after this instant becomes the range to the new preceding vehicle. For simplicity we set the cut-in vehicle's longitudinal velocity to be the same as the old receding vehicle. There is little difference on the range, though the velocity of CACC vehicle responds earlier than that of the ACC vehicle.

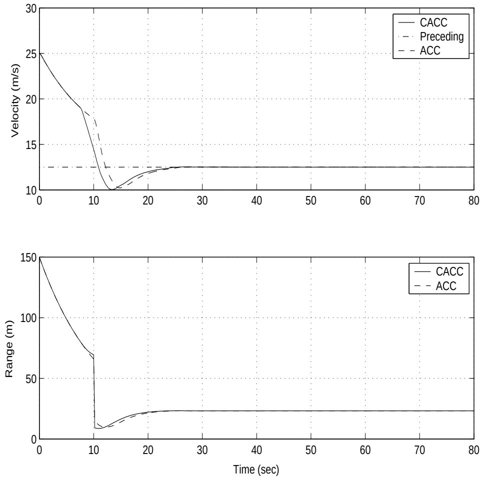

Figure 2: OVC: Range and Velocity for ACC and CACC vehicles

Figures 3 and 4 are respectively the acceleration of the ACC vehicle and CACC vehicle. In both figures, the horizontal axis is time in second and vertical axis is acceleration in m/s/s. 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 -2.5 m/s/s to slow down. After this hard brake, the velocity of the ACC vehicle decreases to a safe value. The acceleration thus goes back to the normal value, and finally converges to zero as the ACC goal is achieved. On the other hand, in Figure 4, 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 of the cut-in vehicle. Because the CACC vehicle has longer response time, it brakes much more softly than the ACC vehicle. The braking effort is smaller than 0.5 m/s/s, and the sharp notch shortly after 10 second in Figure 3 disappears. Combining the observation of Figures 2- 4, we see that the V-V communication helps save large amount of control effort without sacrificing controller performance, which means more safety and comfort for the passenger.

4.2 Results of HMC

In Figures 5 and 6, we compare the performance for four cases: CACC system with strong controller, CACC system with weak controller, ACC system with strong controller, and ACC system with weak controller. We expect to observe the role played by V-V/R-V communication as well as by controller aggressiveness in this set of results.

The system simulated in Figure 5 has 100% market penetration of controlled vehicles (i.e. 100% CACC vehicles if the system is CACC and 100% ACC vehicles if the system is ACC). The Figure shows the cumulative probability distribution function of the average velocity, therefore the y-value is the portion of vehicles with average velocity lower than abscissa. We simulate the system for long enough time for 30 minutes trip time of vehicles, thus typically about 1,000 vehicles appear in the simulation. This assures that the statistics we present here are significant. We observe clearly that

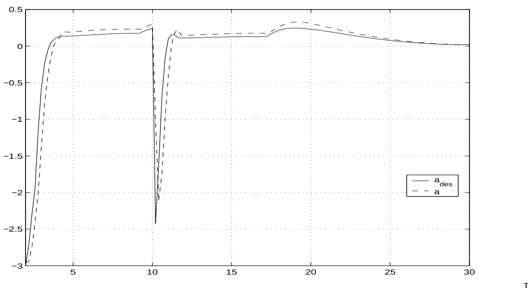

Figure 3: OVC: Acceleration of ACC vehicle

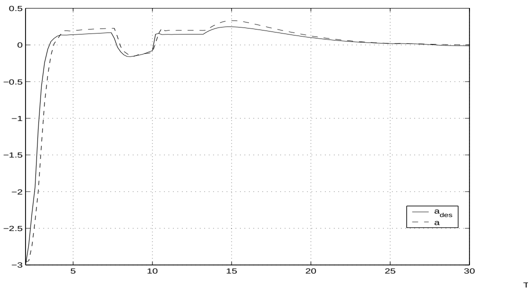

Figure 4: OVC: Acceleration of CACC vehicle

in term of average velocity, strong controller performs better than weak controller (given that both are ACC or both are CACC), and for the same controller aggressiveness CACC system outperforms ACC system. For instance, the percentage of vehicles with average velocity smaller than 15 m/s is respectively about 10%, 25%, 40%, and 58% for CACC with strong controller, ACC with strong controller, CACC with weak controller, and ACC with weak controller.

CACC system performs better than ACC system due to the benefit of communication. With V-V/R-V communication the main lane vehicles know about the merging in advance, therefore the relevant vehicle brakes smoothly in longer response time. Its followers also have a smoothed brake period and their average velocity do not suffer so much from the merging disturbance as in the system where vehicles do not prepare for the merging. Strong controller respond more promptly to the disturbance than weaker controller. Therefore the more aggressively controlled vehicles are disturbed for shorter time.

Figure 6 compares the same four cases as in Figures 5, but focusing on the maximum braking effort, i.e. the minimum negative acceleration exerted by a vehicle in the duration of simulation. Shown here are the CDF's of the maximum braking effort. Observation is that for given controller, integration of V-V/R-V communication saves braking effort, while for a given system (either with or without communication), weak controller utilizes less braking effort than strong controller (except for some small braking effort values). For example, the percentage of vehicles exerting maximum braking effort larger than 1.5 m/s/s (minimum negative acceleration smaller than -1.5 m/s/s) is approximately 8%, 20%, 30%, and 50% for CACC with weak controller, ACC with weak controller, CACC with strong controller, and ACC with strong controller.

Figure 7 shows the average maximum braking effort vs. percentage of controlled vehicle for various cases. The former value is obtained by averaging the maximum braking effort of all main lane vehicles appeared in the simulation. In all the cases presented here, whenever we say the market penetration of ACC is *X*%, the other 1-*X*% vehicles in highway is human-driven. The same goes for CACC system, i.e. ACC and CACC vehicles are never mixed. Evidently from the figure that for both ACC and CACC systems, the higher the market penetration the smaller the average braking effort. With the same percentage of controlled vehicle, CACC system spends less braking effort than ACC system. Also for the same market penetration, either in a CACC system or ACC system, a weak controller saves control effort over a strong controller.

Communication makes the CACC vehicle aware of the merging in advance, therefore the irrelevant vehicles could ignore the merging vehicle and the relevant vehicle could brake smoothly in longer time. The chance of abrupt braking is decreased, and all the following vehicles brake less hard than in the scenario without communication. The result shown here agrees with the microscopic OVC results. For a given disturbance a stronger controller responds more aggressively, sometime over-responds. Therefore although it makes the system less disturbed, as shown in Figure 5, this benefit is gained with cost in braking effort. Hence we have a tradeoff here. On one hand we have efficiency, and on the other safety and passenger comfort. We leave as a future work the design of controller achieving optimal relationship between these two aspects.

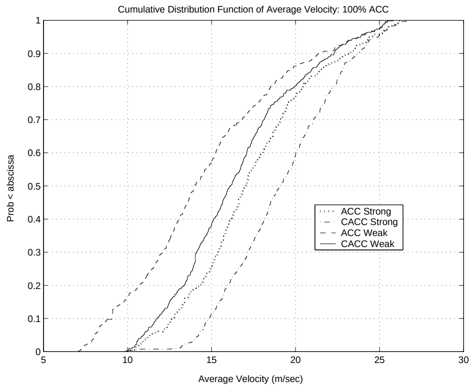

Figure 5: HMC: CDF of Average Velocity (Market Penetration = 100%)

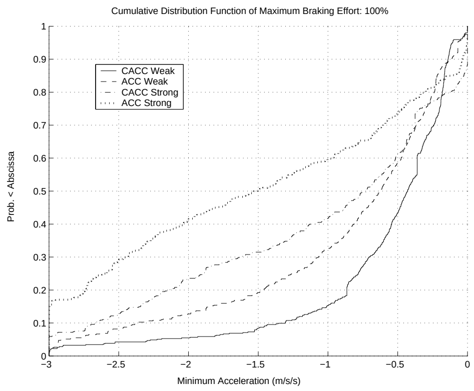

Figure 6: HMC: CDF of Maximum Braking Effort (Market Penetration = 100%)

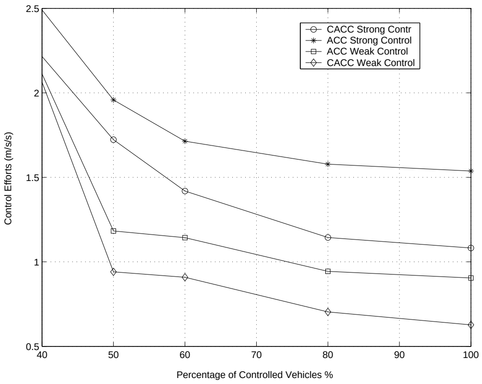

Figure 7: HMC: Average Maximum Braking Effort

5 CONCLUSION

In our simulation of highway merging control, vehicle-vehicle/Roadside-vehicle communication brings benefit to highway traffic by increasing average velocity and decreasing braking effort. Given all other conditions same, A CACC system always outperforms an autonomous ACC system. Higher market penetration is beneficial for both ACC and CACC systems in terms of average vehicle velocity and braking effort. An aggressive controller design increases the average velocity, therefore enhances the efficiency. However a weaker controller saves braking effort, thus making the system safer and more comfortable.

The many encouraging results justify the motivation of implementing V-V/R-V communication to vehicles control applications. The important future work is to design protocols as well as hardware to realize such communication with high Quality of Service and low cost.

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