Cooperative Adaptive Cruise Control in Real Traffic Situations

Vicente Milanés, Steven E. Shladover, John Spring, Christopher Nowakowski, Hiroshi Kawazoe, and Masahide Nakamura

***Abstract*—Intelligent vehicle cooperation based on reliable communication systems contributes not only to reducing traffic accidents but also to improving traffic flow. Adaptive cruise control (ACC) systems can gain enhanced performance by adding vehicle–vehicle wireless communication to provide additional information to augment range sensor data, leading to cooperative ACC (CACC). This paper presents the design, development, implementation, and testing of a CACC system. It consists of two controllers, one to manage the approaching maneuver to the leading vehicle and the other to regulate car-following once the vehicle joins the platoon. The system has been implemented on four production Infiniti M56s vehicles, and this paper details the results of experiments to validate the performance of the controller and its improvements with respect to the commercially available ACC system.**

***Index Terms*—Adaptive cruise control (ACC), connected vehicles, cooperative ACC (CACC), cooperative vehicles, intelligent driving, intelligent transportation systems (ITS).**

I. Introduction

SIGNIFICANT developments in advanced driver assistance systems (ADAS) have been achieved during the last decade. Intelligent systems based on on-board perception/detection devices have contributed to improving road safety [1]. The next step in the development of ADAS points toward vehicle-to-vehicle (V2V) communications to obtain more extensive and reliable information about vehicles in the surrounding area, representing cooperative intelligent transportation systems (ITS). Using wireless communication, potential risk situations can be detected earlier to help avoid crashes, and more extensive information about other vehicles' motions can help improve vehicle control performance. Research projects have been conducted throughout the world to define the requirements for an appropriate vehicular communication system and its possible applications [2].

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Although most of the V2V cooperative ITS applications have been focused on improving collision avoidance and safety [3], the extension of the commercially available adaptive cruise control (ACC) system toward the cooperative ACC (CACC) system has a high potential to improve traffic flow capacity and smoothness, reducing congestion on highways. By introducing V2V communications, the vehicle gets information not only from its preceding vehicle—as occurs in ACC—but also from the vehicles in front of the preceding one. Due to this preview information, oscillations due to speed changes by preceding vehicles can be drastically reduced. Benefits from including communications in ACC systems have been widely studied in recent years [4]–[6].

Prior experimental results using vehicle–vehicle cooperation to improve vehicle-following performance were achieved by the California Partners for Advanced Transit and Highways (PATH) in 1997 [7], [8] when a platooning maneuver involving eight fully automated cars was carried out using wireless communication among vehicles, mainly for longitudinal control, and magnetic markers in the infrastructure, mainly for lateral control. Based on the idea of a leading vehicle guiding several followers, the Safe Road Trains for the Environment (SARTRE) European Union project has developed virtual trains of vehicles in which a leading vehicle with a professional driver takes responsibility for each platoon [9]. That concept of the professional driver in the first vehicle was originally developed in the European project called CHAUFFEUR [10].

Specifically related to CACC implementations in production cars, two important projects were recently conducted in the Netherlands. The Connect & Drive project, funded by the Dutch Ministry of Economic Affairs, carried out a CACC demo using six passenger vehicles [11] adopting a constant time gap spacing policy. For the Grand Cooperative Driving Challenge competition in 2011, nine heterogeneous vehicles from different European research institutions tried to perform a two-lane CACC platoon [12]. This competition revealed some of the most important problems to be solved before bringing this technology into production, including communication systems reliability. From the control point of view, most of the implementations were based on proportional proportional-derivative feedback/feedforward controllers [13]–[15] or model predictive control techniques [16], [17].

When it comes to designing a CACC system, string stability plays a key role [18]. The goal is designing a system able to reduce disturbances propagated from the leading vehicle to the rest of the vehicles in the platoon. There are two different approaches to car-following gap regulation, i.e., one based

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Fig. 1. Experimental M56s vehicles.

on constant spacing or one based on constant time gap. A comparative study between them, where CACC stability was discussed, was presented in [19]. Several papers have dealt with string stability analysis and simulations [20]–[22], based on simplified theoretical models of ACC vehicle-following behavior, and have shown encouraging results. However, real production ACC systems have significant response delays that have not been represented in the prior theoretical analyses but which destabilize vehicle-following responses. Consequently, those theoretical analyses have produced unrealistically optimistic estimates of the traffic stability impacts of ACC.

In previous PATH research, a CACC involving two vehicles was tested with very favorable results [6], [23], [24]. Building on that previous work, this paper describes a new control system design and implementation that is integrated in four production vehicles. A constant time-gap car-following strategy was implemented similar to the commercial ACC, but with the availability of significantly shorter time-gap settings. This is achievable because V2V communications permit tighter control of vehicle spacing and guarantee string stability, so that intervehicle time-gap settings significantly shorter than the production ACC time-gap settings are comfortable and acceptable to drivers [24]. The whole system was then tested in real traffic scenarios in order to compare its performance with the production ACC system installed in the vehicles. Cut-in and cut-out maneuvers were also tested to evaluate the controller under regular traffic circumstances, emulating everyday traffic situations.

The rest of this paper is organized as follows: Section II presents a brief explanation about the production vehicles used in the experimental phase, the control architecture implemented on each vehicle, and the vehicle model. The control system that has been implemented based on a gap-closing controller and a gap regulation controller is explained in Section III. Several experiments to validate the proposed systems are included in Section IV. Finally, some concluding remarks are given in Section V.

II. Experimental Vehicles

Four production Infiniti M56s (see Fig. 1) were used as the experimental vehicles. These vehicles are rear-wheel drive with a 420-hp 5.6-L V8 gasoline engine. They were factory equipped with lidar-based ACC, lane departure warning, and blind spot detection systems. Additionally, a 5.9-GHz dedicated short-range communication (DSRC) system with a differential Global Positioning System (GPS) incorporated in a wireless safety unit

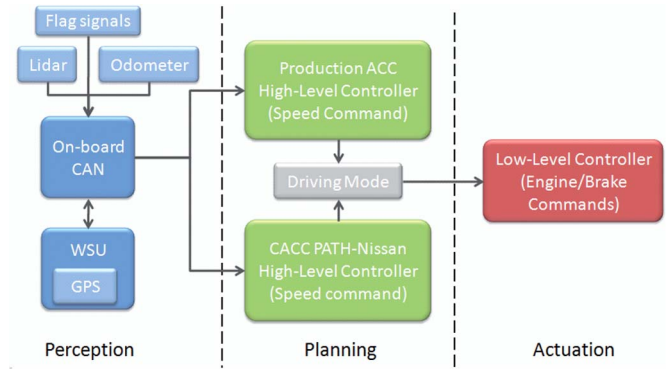

Fig. 2. Control architecture block diagram.

(WSU) was supplied by DENSO. Control was implemented through a dSpace MicroAutoBox, which received data from both the WSU and the production vehicle's controller area network (CAN). In particular, lidar data from the first and immediately preceding vehicles and data from on-board vehicle sensors—speed, acceleration, and yaw rate—were used by the control computer.

A. Control Architecture

As previously stated, a factory installed ACC controller was available in the vehicles. This controller sends target speed commands to the vehicle's actuators. The same control variable is available for the CACC system, but it needs to act through the commercial system that controls the throttle and brake pedals, i.e., the low-level controller. This constraint somewhat limits the options when it comes to designing the controller since the low-level controller could not be modified, but it still provides adequate dynamic range for controlling the vehicle under nonemergency transient conditions. Fig. 2 shows the block diagram for the vehicle control architecture. It consists of a classical robotics control architecture divided into three stages.

1) **Perception** phase where all information from the sensors installed in the vehicle is received. Two sources can be distinguished. On one hand, information coming from the WSU system, where all data communicated by other vehicles in the platoon—speed, acceleration, distance to preceding vehicle, current time gap, control activation, and so on—are received and included on the CAN bus data structure. These data also include detection and assignment of the vehicle position sequence in the platoon, which is carried out by the WSU using its GPS with wider area augmentation system differential corrections. On the other hand, information is obtained from the on-board sensors, such as factory available lidar measurements (relative distance to the preceding vehicle), odometer (current speed) and acceleration, and flag signals (to get information about the interaction of the driver with the driver interface such as activation or deactivation of the system or gap setting selection). The driver interface buttons, located on the right side of the steering wheel, are also used for the CACC controller.

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2) **Planning** stage includes the high-level controller. Both controllers, i.e., the commercial ACC system and the newly developed CACC system, are available during the tests so the driver can switch between them in real time. For switching, the control code reads the CAN bus information coming from the transmission mode selection button, i.e., eco-driving mode, sport mode, standard mode, or snow mode. When the sport mode is chosen, the high-level controller will take the CACC controller output. When any of the other modes is chosen, the production ACC controller output will be sent to the low-level controller. The CACC controller code has been developed in MATLAB/Simulink and is loaded in the vehicle using a dSpace MicroAutoBox, which is connected to the vehicle via the CAN bus, where the target speed commands are sent. The CACC controller can be deactivated in the same way as the commercial ACC, either using the driver interface buttons or pressing the brake pedal.
3) **Actuation** phase is in charge of executing target reference commands coming from the planning stage. As previously stated, this low-level controller is in charge of converting the target speed commands into throttle and brake actions, using the factory ACC controller.

B. Vehicle Model

The vehicle dynamic model, to be used for evaluating vehicle performance from the string stability point of view, is identified based on its step responses to different speed changes. For these tests, a simple open-loop controller is in charge of generating speed target commands to the vehicle. Once the vehicle is stably driving at its current target speed, a new speed command for an accelerating or braking maneuver is sent to the vehicle. The Infiniti M56s vehicles are equipped with a powerful engine that produces fast and strong responses to changes in the target speed command. Considering this, a second-order response model can be extracted from the experimental test data, where two different dynamic responses are clearly evident in the behavior of the vehicle during the accelerating and braking phases. Overshoot occurs on the braking response since a high engine braking force, particularly in the sport driving mode where the CACC controller was designed, is added to the friction braking action. Two second-order models with time delay were identified from the test data, with the following structure:

$$F(s) = \frac{k}{s^2 + 2\theta\omega_n s + \omega_n^2} e^{-T_d s} \tag{1}$$

with k, θ, ω_n, and T_d being the static gain, damping factor, natural frequency, and time delay, respectively. Parameters for both models, i.e., braking and acceleration responses, are defined in Table I. They are obtained using the MATLAB System Identification Tool, which permits selection among different candidate transfer functions. This transfer function for representing vehicle behavior was chosen as a tradeoff between simplicity (second-order model) and goodness of fit (over 95%). Responses for both models to a speed change are depicted in Fig. 3. One can appreciate how well the model fits the response of the real vehicle. This model incorporates both the dynamics of the vehicle and the low-level controller in charge of managing throttle and brake actions.

TABLE I
ACCELERATING AND BRAKING MODEL PARAMETERS

	k	θ	ω_n	T_d
Accelerating	0.156	0.661	0.396	0.146
Braking	1.136	0.5	1.067	0.287

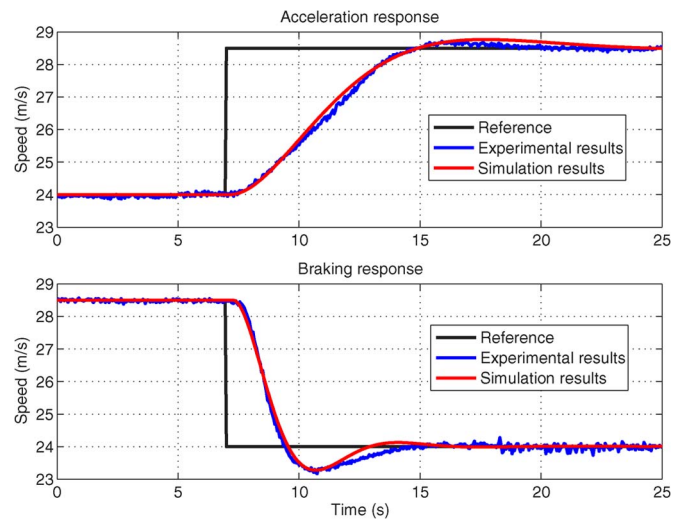

Fig. 3. Vehicle's longitudinal dynamics response for acceleration and braking maneuvers.

III. Control Design

The goal of the CACC controller is maintaining the driver-desired time gap to the preceding vehicle in any traffic circumstance, with both smoothness and accuracy. The ACC driver interface is used to manage the CACC controller. It includes buttons for activating and deactivating the ACC controller, three gap settings, and the option of setting, increasing, or decreasing the cruise control speed, in case no vehicle is detected in front of the ego-vehicle. For the ACC factory system, the available gap settings are 1.1, 1.6, and 2.2 s. For the CACC system, the shortest gap is set at 0.6 s. This value has been chosen based on estimates of the separation needed to enable crash avoidance under emergency conditions, as well as previous tests of acceptance by drivers from the general public [24]. The other two available CACC gap settings are 0.9 and 1.1 s. There were two limitations when designing the CACC controller: It is not possible to access or modify the low-level controller, and acceleration and deceleration are limited to maximum values (0.1 and 0.28 g, respectively) by the low-level controller.

The controller has been divided into two stages. The first stage occurs when the CACC system is activated, and there is no vehicle in front of it, or the ego-vehicle is far away from the preceding one. In these cases, the vehicle is usually following its set speed so an approaching maneuver has to be carried out before switching to a car-following policy. This controller—the gap-closing controller—has to be as smooth as possible to permit a good transition to the gap regulation controller. It is also used in case of cut-out maneuvers when a vehicle in the

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middle of the platoon decides to leave and the following one has to cover the cut-out vehicle gap.

Once the vehicle has joined its predecessor, the second-stage controller—the CACC gap regulation controller—is in charge of implementing the car-following policy depending on the time gap selected by the driver. Three different time gaps are available, following the production ACC structure. This controller is also in charge of managing cut-in maneuvers when a nonequipped vehicle merges into the platoon. Both controllers have been designed to be consistent with how a human driver handles each driving situation.

A. Gap Regulation Controller

Once the vehicle is close enough and the gap-closing maneuver has finished, the system switches to the gap regulation controller, which is the core of the CACC control system. Commercially available ACC systems try to reduce the gap error (x_e) between the ego-vehicle and the preceding one. Information from the lidar/radar is used to reduce gap error (x_e) between desired time gap (t_g) and relative distance $(x_r = x_p - x_f)$, where x_p is the current position of the preceding vehicle, and x_f is the position of the ego-vehicle, following the expression

$$x_e = x_r - v_f t_g \tag{2}$$

where v_f is the speed of the ego-vehicle. For this purpose, a controller, $K_P(s)$ based on a standard PD-control structure [25], [26], can be easily adjusted to get stability with respect to the immediately preceding vehicle; however, as previously demonstrated [27], this is not enough to guarantee string stability.

Exchanging information among vehicles using wireless communications permits improving the vehicle's response as well as significantly reducing time gaps, keeping safety. When it comes to designing a CACC system, string stability is one of the main goals. It can be defined as the system's ability to reduce perturbations downstream, avoiding that leading vehicle speed changes cause amplification in the rest of the vehicles [28]. According to [29], it can be defined as

$$|SS(s)| = \left|\frac{X_i(s)}{X_{i-1}(s)}\right| \leq 1, \qquad i \geq 2 \tag{3}$$

where i indicates the position of the vehicle in the platoon.

Fig. 4 shows the CACC controller block diagram, where $G(s)$ represents the vehicle model; terms $P_P(s)$ and $P_L(s)$ correspond to the car-following policy with respect to the preceding and the leading vehicle, respectively; terms $K_P(s)$ and $K_L(s)$ represent time-gap error regulation controller for the preceding and the leading vehicle, respectively; U_i and U_{i-1} correspond to the control action for the ego-vehicle and the preceding vehicle (coming from the wireless communication system), respectively; the term $D(s) = e^{-\delta s}$ represents the time delay in the wireless communication; and X_i, X_{i-1}, and X_0 represent the positions of the ego-vehicle, the preceding, and the leading vehicle position in the platoon. The controller is formed by three main terms: One of them is in charge of keeping the current speed, but instead of using the ego-vehicle or preceding vehicle speed [23], the preceding vehicle target speed (U_{i-1}) is used as a feedforward term. This permits improving the vehicle response time to speed changes and reducing delays in the transition between throttle and brake actuations. The other two terms try to keep the errors with respect to preceding vehicle $K_P(s)$ and leading vehicle $K_L(s)$ as small as possible. Both terms correspond to a classic PD structure defined as

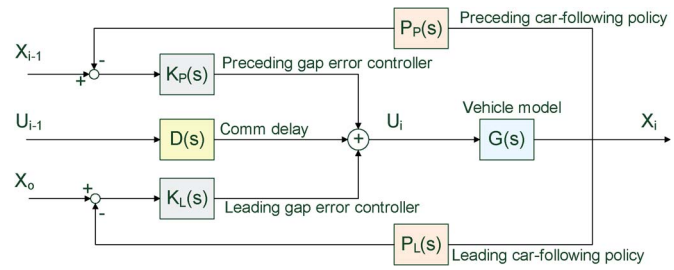

Fig. 4. CACC control structure block diagram.

$$K_P(s) = k_1 s + k_2 \tag{4}$$

$$K_L(s) = k_3 s + k_4 \tag{5}$$

where car-following policies can be defined as

$$P_P(s) = h_P s + 1 \tag{6}$$

$$P_L(s) = h_L s + 1 \tag{7}$$

with h_P and h_L being the time-gap target values with respect to the preceding and leading vehicles, respectively.

As previously stated, the vehicle clearly exhibits different dynamics in the acceleration and braking phases that can be modeled by second-order functions $sG(s) = F(s)$ so the position $X_i(s)$ for a vehicle in the platoon can be determined as

$$X_i(s) = G(s)U_i(s) \tag{8}$$

where $U_i(s)$ is the target speed command for that vehicle. Assuming the vehicles start from rest and using (8), the relation between the ego-vehicle and the preceding one is given by

$$X_i(s) = \frac{D(s) + G(s)K_P(s)}{1 + G(s)\left[K_P(s)P_P(s) + K_L(s)P_L(s)\right]} X_{i-1}(s). \tag{9}$$

Following the criteria defined for string stability, the goal is to keep the Bode magnitude below the unity gain of both vehicle dynamics, i.e., acceleration and braking responses. Control gains were first modified using tuning tools from MATLAB/Simulink to fulfill the requirements. Final tuning was carried out in the experimental vehicle in order to get not only an accurate response from the car-following policy point of view but also a smooth riding quality from the driver perspective. Table II shows the final parameters selected for the preceding and leader car-following policy controllers. The same parameters were used for accelerating and braking maneuvers since good responses were obtained for both dynamics, and they fulfilled string stability criteria. Control gains of the controller in charge of minimizing the error with respect to

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TABLE II
K_P AND K_L CONTROLLER PARAMETERS

k_1	k_2	k_3	k_4
0.45	0.25	0.15	0.1

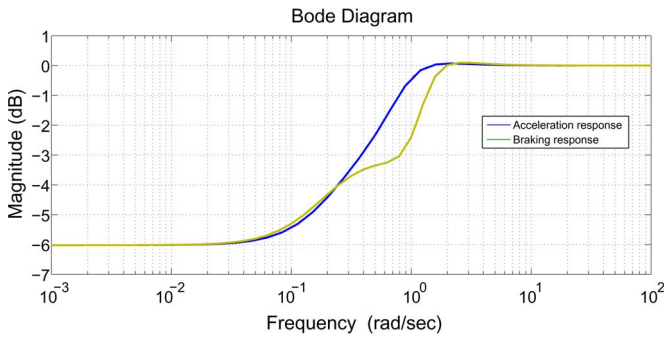

Fig. 5. String stability frequency analysis.

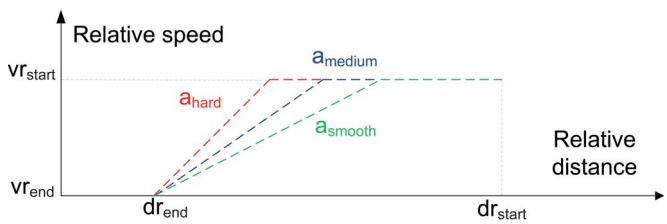

Fig. 6. Gap-closing controller operation.

the leading vehicle are smaller than the ones in the controller that tries to reduce the error with respect to the preceding one. This is consistent with the need to ensure safety (avoiding potential impact with preceding vehicle) and to reduce the perceived variability of the gap relative to the preceding vehicle to promote driver confidence in the system.

Fig. 5 shows responses for both dynamics, i.e., acceleration and braking, in the frequency domain, showing that the string stability criterion is fulfilled. The difference in both dynamics is also reflected in the frequency analysis. For the controller design, it was assumed that there is no delay in the wireless communication system, i.e., $D(S) = 1$. This assumption was subsequently confirmed during the experiments, when the packet loss percentage was insignificant. Effects of packet loss on string stability are out of the scope of this paper.

B. Gap-Closing Controller

For approaching the preceding vehicle, a simple linear function depending on the relative speed and distance between vehicles and the desired deceleration has been used. It can be configured according to the driver's preference. Fig. 6 shows the gap-closing controller operation, where dr_{start} represents the initial intervehicle distance when a preceding vehicle is detected, vr_{start} indicates relative speed between vehicles, dr_{end} represents the distance when the controller switches to the gap regulation mode, and vr_{end} indicates the final relative speed equal to zero. The ego-vehicle braking maneuver depends on the desired deceleration, i.e., a_{smooth}, a_{medium}, or a_{hard} in the graphic. This parameter can be configured to match the driver's preferences. The smoother the deceleration, the

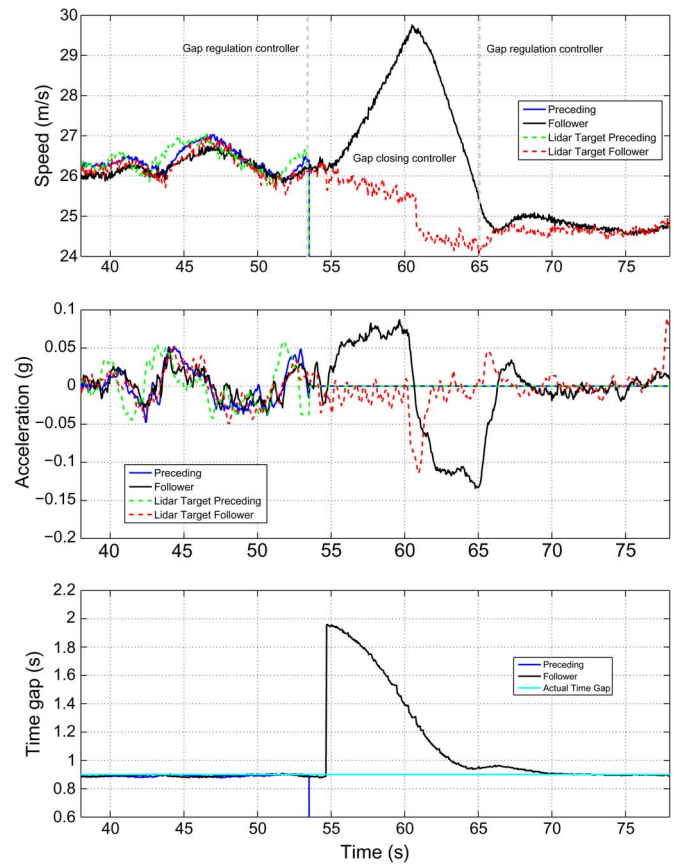

Fig. 7. Preceding-car approaching maneuver in a cut-out scenario.

earlier the vehicle starts to brake. The controller has been tested both following a set speed before joining a platoon and in a cut-out maneuver when the vehicle initially switched from the gap regulation controller to the gap-closing controller and then switched again to the gap regulation controller. Since this second option involves more complex situations, results of an experiment for this situation are included to show the behavior of the gap-closing controller.

Fig. 7 depicts the performance of the gap-closing controller during a three-vehicle CACC test. The top graph plots the evolution of the speeds of the vehicles and their forward vehicle speeds estimated from the lidar range measurements. The middle graph plots the vehicles' accelerations during the experiment. The bottom graph represents the time gaps between vehicles during the test. For notation, the leading vehicle is the first vehicle during the whole test, the preceding vehicle (solid blue line) is the one that starts the platoon in the second position and then cuts out, and the follower vehicle (solid black line) is the one that begins in the third position and then performs the approaching maneuver. The preceding and follower vehicles are driving under CACC control with a time gap of 0.9 s and a set speed of 31.1 m/s. Forward vehicle speeds estimated from the lidar range measurements of the preceding vehicle (dotted green line) and the follower (dotted red line) are also shown.

During the first 54 s, preceding and follower vehicles are driving in CACC following the leading vehicle in the platoon. One can appreciate how the speed estimated from the lidar range measurements of the follower (dotted red line) is tracking

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the preceding vehicle's speed (solid blue line). Close to 54 s, the preceding vehicle changes lane (cuts out) so both its speed and lidar measurement have been removed for the sake of clarity. One can appreciate how the follower detects that its preceding vehicle has cut out and a sharp change in the time gap occurs. At that point, the system switches between the gap regulation controller and the gap-closing controller. The follower starts to smoothly accelerate in order to close the gap with the leading vehicle. Considering the deceleration parameter constraint for this test −0.1 g, the vehicle starts to brake smoothly to create a new two-vehicle platoon with the leading vehicle. The new target vehicle is driven by a human driver so some speed changes—as occurs in real traffic driving—during the gap-closing maneuver are seen. It can be observed how the vehicle switches again to the gap regulation controller close to 65 s, where a change in the deceleration is observed. Then, the vehicle finishes the gap-closing maneuver, perfectly fitting the desired time gap.

IV. Experimental Results

The CACC system was implemented in four Infiniti M56s vehicles equipped with 5.9-GHz DSRC for wireless communication. Several trials were carried out with the vehicles to validate the proposed approach and the designed controller. In particular, three different test results are shown here. The first experiment consists in evaluating the behavior of the car-following policy while the driver is changing the gap settings. The second experiment shows a realistic situation on highways when the ego-vehicle is following a leader, and another vehicle wants to take the next exit, executing both a cut-in and a cut-out maneuver in a relatively short period of time. The third experiment compares the CACC performance of the four vehicles following a moderate but realistic speed change profile with the performance of the production ACC system under the same conditions.

A. Gap Setting Changes Test

For testing controller behavior when the driver chooses to change the gap setting, only two vehicles were used, one of them acting as the leading vehicle and the other one running the CACC controller. Fig. 8 shows this test result. The upper plot shows the speed of both vehicles during the test, the middle plot depicts the acceleration, and the gap setting chosen by the driver is shown in the bottom graph, compared with the actual gap.

During the test, the leader accelerates and brakes slightly, emulating real traffic behavior. The experiment starts with a gap of 1.1 s, which is the longest CACC gap available on the driver interface. Around 58 s, the driver changes to the middle gap setting, i.e., 0.9 s. The follower accelerates smoothly to reduce the gap. One can appreciate this transition in the time gap plot where no overshoot or sharp change occurs. The vehicle exhibits a similar behavior when it goes from the middle to the shortest gap −0.6 s. Then, the vehicle comes back to the longest gap. In this case, it is driving at 0.6 s behind the leading vehicle when the reference gap is 1.1 s so a significant deceleration

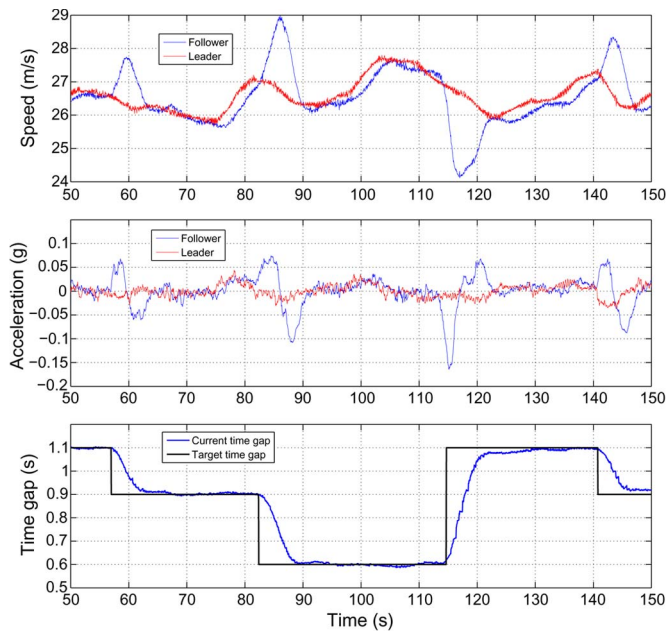

Fig. 8. Responses to changes in gap setting.

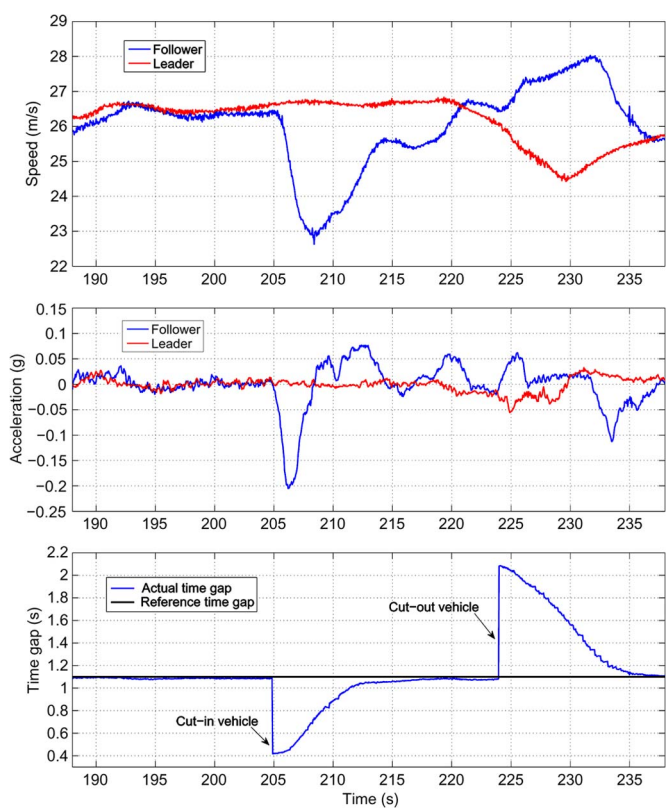

Fig. 9. Cut-in and cut-out vehicle response with CACC control.

is observed on the part of the follower in order to achieve the desired gap. One can appreciate how time gap transitions among different gap settings are smooth, and once the desired gap has been reached, the car-following policy is well maintained. Finally, around 100 s, it can be noticed that there appears to be some lag in the speed response of the follower as the leader accelerates. Although this might intuitively appear as a

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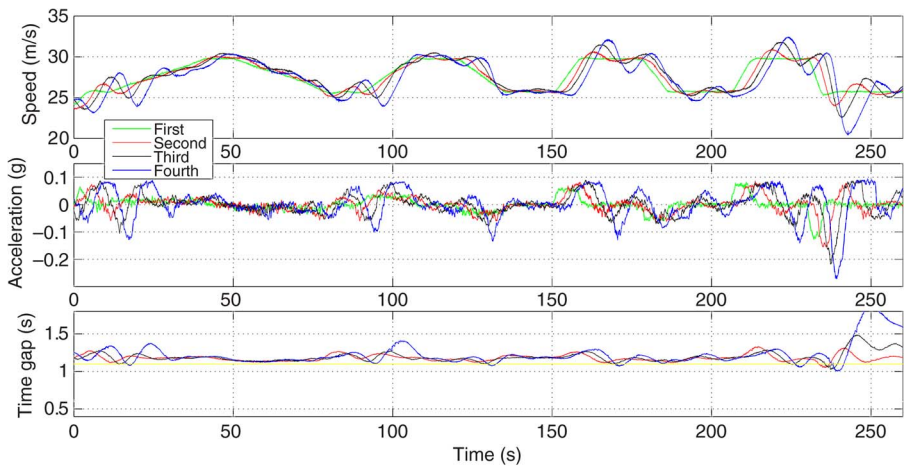

Fig. 10. Four-vehicle ACC test results with speed profile in the leading vehicle.

delay in the response, the lag is actually an artifact of using a constant time-gap car-following policy instead of a constant-spacing car-following policy. As speed increases, so does the desired intervehicle distance. Examining the associated time-gap plot, one can see that the time gap remained constant during the lead vehicle acceleration.

B. Cut-In and Cut-Out Test

A regular situation, if the CACC platoon is driving in the rightmost lane on a highway, is that sudden and unexpected cut-ins occur when other vehicles want to enter or leave the highway. In these situations, a vehicle carries out both a cut-in and a cut-out maneuver in a short period of time. In this experiment, the system response to those situations is shown.

For the sake of clarity, a two-vehicle CACC platoon response is shown in this test, but the test has been successfully performed for a four-vehicle CACC platoon. For safety reasons, the chosen gap setting is 1.1 s. Fig. 9 shows vehicle behavior during this experiment. As in the previous one, the upper graph shows vehicle speeds, the middle graph shows vehicle accelerations, and the bottom graph depicts the current and reference (desired) time gaps.

At the beginning, the leader is driving at a constant speed, and the follower is perfectly tracking the leader's speed at the desired gap. Around 205 s, a cut-in vehicle merges between them. This vehicle is detected by the lidar, as revealed by the sudden change in the time gap, whose value decreases to 0.42 s. The follower brakes in order to increase the gap to the new vehicle, and after a few seconds, it reaches the desired gap. Then, around 224 s, the cut-in vehicle cuts out by doing another lane change. Again, that movement is detected by the lidar, and a sudden increase in the time gap occurs. The follower accelerates smoothly to achieve the desired gap with the original leader. One can notice the smooth transition toward the desired time gap in both the cut-in and cut-out maneuvers without any abrupt behaviors. The hardest deceleration occurs when the vehicle cuts in, but this is because the time gap is drastically reduced, creating a potential safety hazard that needs to be reduced as quickly as possible. It is also important to note that deceleration is always within the comfort range, which is set at ± 0.2 g [30].

C. Four-Vehicle Test

The last experiment shows the comparison between the production ACC system and the newly developed CACC controller. To this end, an automatic speed profile was designed and implemented on the leader car. It consisted of the following series of speed changes. In the first cycle, the vehicle drives at 25.5 m/s for 10 seconds; then, it accelerates at a constant acceleration of (1/80) g to reach 29.5 m/s speed. The speed remains constant for 10 seconds, before the vehicle starts to decelerate at a constant rate of (1/80) g to come back to a constant speed of 25.5m/s for 10 seconds. The second cycle repeats the same acceleration and deceleration curve with a constant acceleration of (1/40) g and 15 s of driving at a constant speed at the top and bottom of each acceleration or deceleration event. The third and fourth cycles repeat the same pattern at (1/20) and (1/10) g with 20 s of driving at a constant speed between acceleration and deceleration events. This profile emulates a real driving situation in moderately congested traffic, where repeated accelerations and decelerations happen. The speed variations have been constrained for this test so that it could be conducted safely on a public highway, mixed with other traffic.

Fig. 10 shows the ACC system response to this profile, with the gap between vehicles set to 1.1 s, the shortest available on the production ACC. Before starting the profile, all vehicles drove with the ACC system activated and in a stable state. The leading vehicle drove as close as possible to the initial speed, i.e., 25.5 m/s, and then activated the profile.

Upon acceleration, note the oscillations, mainly on the third and fourth cars in the platoon, in both the vehicle speed and time gap, before stabilizing around 30 s at a constant time gap. In the subsequent acceleration cycles, note that the third and fourth car response delays are considerably larger, and the overshoots in the speed during the last two accelerations caused an amplification downstream along the platoon. A considerable delay, which is close to 15 s, can also be noted in the response of the last car of the platoon. Finally, from the fourth vehicle

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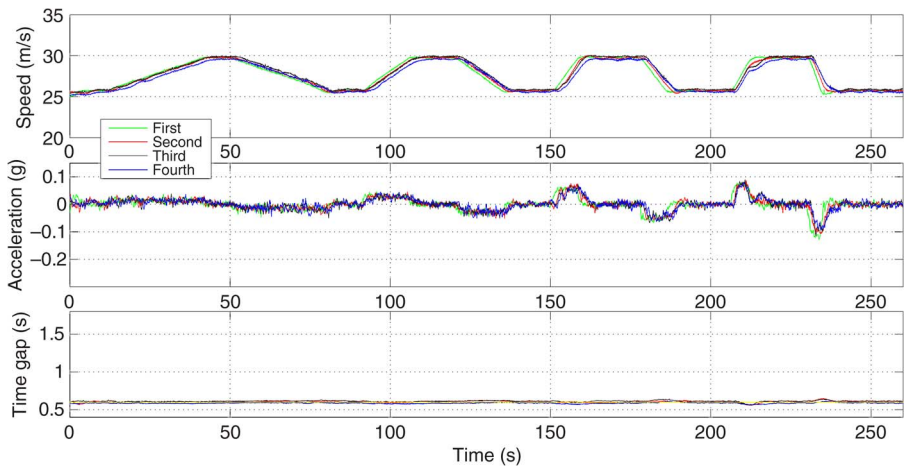

Fig. 11. Four-vehicle CACC test results with speed profile in the leading vehicle.

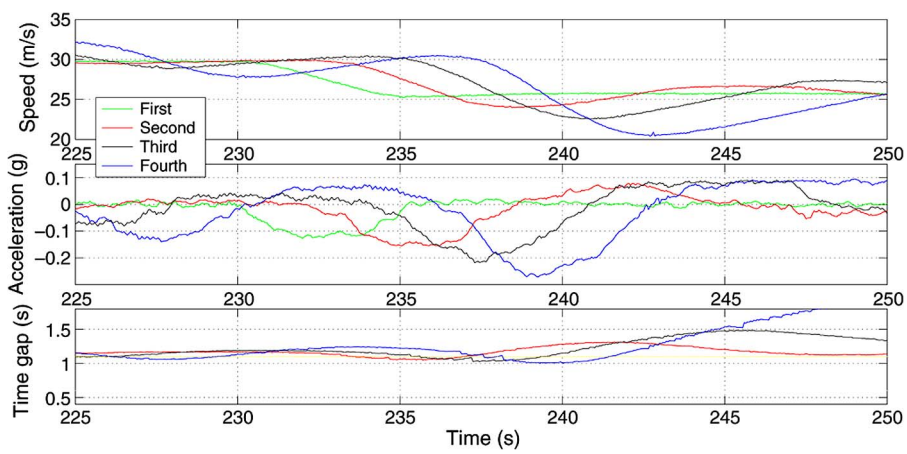

Fig. 12. Detail of the last deceleration for the ACC test using the speed profile.

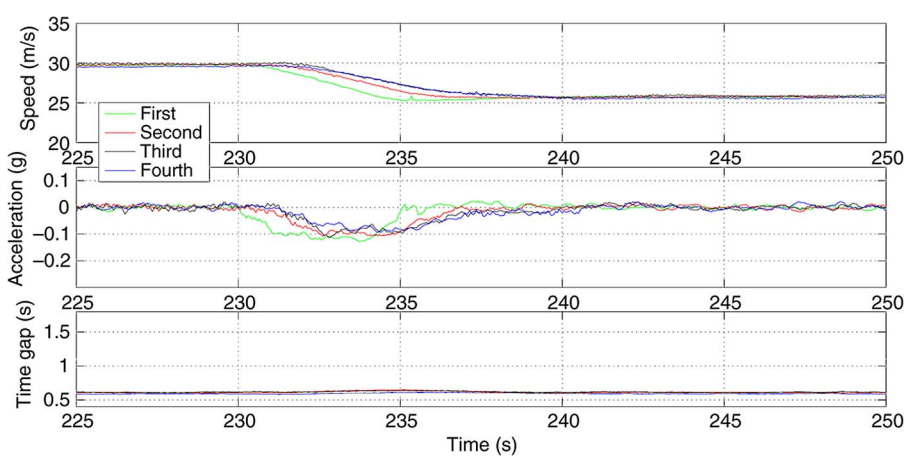

Fig. 13. Detail of the last deceleration for the CACC test using the speed profile.

driver's perception, his vehicle does not appear to be following any gap control policy because of the unstable behavior during the last speed change.

It is worth noting that this ACC system is not a degradation of our CACC controller from removing the feedforward but is the commercially available ACC that has been working in production cars with really good acceptability on the part of the drivers. It was designed with serious consideration of string stability, unlike many other ACC systems, and is actually more stable than some other commercially available systems. However, even its stability-enhancing design features are not able to overcome the challenges associated with the lack of information available about the motions of the vehicles ahead of the immediately preceding vehicle.

The same profile was tested for the CACC controller, and Fig. 11 shows the results using the same time scale as for the

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ACC test results. For this test, the shortest gap, i.e., 0.6 s for CACC, was used. One can appreciate how the overshoot of the third and fourth vehicles during the last two speed changes was eliminated. Additionally, there is no appreciable delay in the vehicles' responses, and the car-following policy is perfectly tracked by all vehicles in the platoon. These results clearly show how CACC control improves on ACC results for vehicle-following, and there is potential to significantly improve traffic efficiency and safety.

Figs. 12 and 13 detail the final braking transient when the leading car braking rate equals 0.1 g. On the ACC graphic, the response delay is clearly seen since the last vehicle in the platoon (solid blue line) is still accelerating during the period in which the leading vehicle is braking. Both the significant delay and the amplification are observed in the acceleration graph. Most striking is the fact that the leading vehicle braking, i.e., 0.1 g, is amplified by the last car to 0.3 g, causing an uncomfortable behavior from the driver and passenger point of view. In contrast, the CACC graphic shows how the leading vehicle braking is attenuated by the last car, and the deceleration is actually lower than the initial 0.1-g disturbance during the event. The accurate tracking of the time gap policy for the hardest braking during the speed profile is also worth noting.

V. Conclusion

This paper has presented the design, development, implementation, and testing of enhancement to commercially available ACC systems, based on introducing V2V communications, to produce CACC. The system has been implemented in four production Infiniti M56s vehicles equipped with DSRC devices for information exchange among vehicles. The CACC controller design takes advantage of wireless communication information, introducing feedforward terms in the control logic, to enable significant reductions in intervehicular gaps. The system has been tested on public roads showing good performance. First, reduced gap variability was demonstrated. Then, the ability to gracefully handle unequipped vehicles cutting in and out was also validated. Finally, a comparative study between the production ACC system performance and the new CACC controller was carried out. The CACC clearly showed improvements in response time and string stability, indicating the potential for a CACC system to attenuate disturbances and improve highway capacity and traffic flow stability. Ongoing and future research on this topic is mainly focused on assessing the potential magnitude of improvements that a CACC system might have on traffic response, both with respect to ACC and as a function of market penetration.

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