2010 American Control Conference
Marriott Waterfront, Baltimore, MD, USA
June 30-July 02, 2010

Design and Field Testing of A Cooperative Adaptive Cruise Control System

Fanping Bu, Han-Shue Tan and Jihua Huang

***Abstract*—This paper describes the development of an Cooperative Adaptive Cruise Control (CACC) experimental system with vehicle-to-vehicle communication based on a car with factory installed ACC system. The controller design will be introduced in detail on how to incorporate the information shared through wireless communication link. The structure of the proposed CACC controller and an indirect adaptive Model Predictive Control (MPC) based gap regulation controller are presented. Experimental results from field testing at both vehicle proving ground and public highway are shown to verify the effectiveness of the proposed controller design.**

I. Introduction

ADAPTIVE cruise control (ACC) systems are now commercially available on high-end vehicles. Compared with conventional cruise control (CC) systems which regulate vehicle speed only, An ACC system [1] allows drivers to maintain a desired cruise speed if there is no preceding vehicle as well as a desired following gap with respect to a preceding vehicle. The ACC system senses the range (i.e., relative distance) and range rate to the preceding vehicle with a radar or LIDAR sensor. Such information is used to generate appropriate throttle or brake command to maintain a preset following gap to the preceding vehicle. With the development of wireless communication technology such as Dedicated Short Range Communication (DSRC), a vehicle can exchange information with its surrounding vehicles through vehicle-to-vehicle communication. As an enhancement to ACC systems, a cooperative adaptive cruise control (CACC) system further incorporates vehicle-to-vehicle communication to make use of rich preview information about the preceding vehicle. Previous research has shown that CACC systems could achieve tighter following gaps, more smooth and "natural" ride in comparison to ACC systems [2]. Other benefits of CACC technology include improvement of traffic safety and traffic efficiency.

ACC systems have been studied extensively from highway speed to stop-&-go. An extensive review can be found in [3]. In [4], a CACC system design and test results are presented. Instead of local range sensors, Global Positioning System (GPS) is used to provide the positions of the preceding vehicle and the following vehicle; upon receiving the positions of the preceding vehicle through vehicle-to-vehicle communication, the following vehicle computes relative positions for ACC control. However, GPS problems such as signal blockage or multipath may cause performance degradation, especially around urban areas. Model predictive control (MPC) [5] is a control framework which can optimize performance criterion under multiple design constraints. The formulation of MPC usually results in a constrained optimization problem which can be solved by various solvers [6]. Due to its complexity of computation, MPC used to be applied on chemical process control where plant dynamics is slow and real-time computation requirement is not that stringent. With computer getting cheaper and more powerful, MPC has extended its applications to other fields such as vehicle control [7]. MPC [1, 8-12] has been employed to develop ACC systems.

The CACC system described in this paper is developed under a California PATH research project on methods for mitigating congestion via the application of Intelligent Transportation Systems (ITS). The primary focus of this project is a human factor study on driver experiences of different time gaps, especially relatively short time gaps, with CACC systems in live traffic. Since CACC systems are not commercially available yet, two Infinity FX45s that are equipped with ACC systems are retrofitted with the CACC system designed by California PATH. The factory installed ACC system has three relatively long time gap settings, 2.2, 1.5 and 1.1 second time headway, which are not sufficient for the proposed human factor study. Therefore, the objective of CACC system design is to enable shorter time gap settings from 0.6 s to 1.1 s under live traffic on public road for the purpose of the human factor study. Hence, this paper is not intended to provide solutions for a generic CACC design; instead, it aims to describe how we formulate a real-world application with multiple constraints into a control problem and presents the successful field testing at both vehicle proving ground and public highway.

This paper is organized as follows: Section II describes CACC system setup retrofitted on the two Infinity FX45s; Section III details CACC controller design including design challenges, the controller structure, and the time-gap regulation controller based on the indirect adaptive MPC; Section IV presents experimental results from field testing at NISSAN Arizona vehicle proving ground and public highway around San Francisco, CA; Section V concludes the paper.

Fanping Bu is with California PATH, University of California at Berkeley, Richmond, CA 94804 (phone: 510-665-3589; fax: 510-665-3537; e-mail: fanping@ path.berkeley.edu).

Han-Shue Tan is with California PATH, University of California at Berkeley, Richmond , CA 94804.

Jihua Huang is with California PATH, University of California Berkeley, Richmond CA 94804.

II. SYSTEM DESIGN AND DESCRIPTION

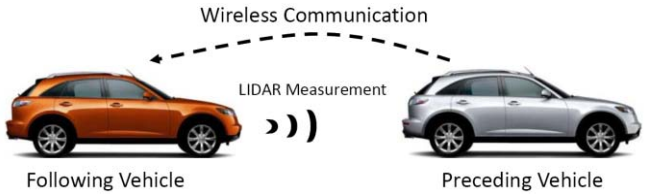

Fig. 1 CACC Formation

The CACC system designed by PATH consists of two Infinity FX45s, as shown in Fig.1. One FX45, driven by a PATH staff, serves as the CACC preceding vehicle, while the other serves as the CACC following vehicle which is driven by test subjects during this human factor study. Both FX45s are equipped with factory installed ACC systems, which use LIDAR to detect vehicles in front and measure relative distance and speed. All the vehicle information such as vehicle speed, engine/transmission state, brake state, and LIDAR measurements can be accessed through vehicle CAN bus. The CACC system designed by PATH is essentially an add-on system retrofitted on the two FX45s.

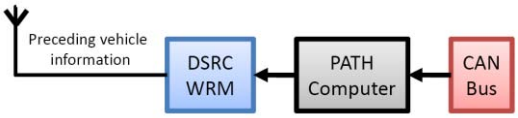

Fig. 2 Preceding Vehicle Configuration

Fig.2 shows the configuration for the preceding vehicle. A PC104 computer is installed to interface with vehicle CAN bus. A DSRC Wave Radio Module (WRM) supplied by DENSO is used to broadcast the state information of the preceding vehicle, such as vehicle speed, throttle percentage, brake percentage, gear position, and engine speed etc.

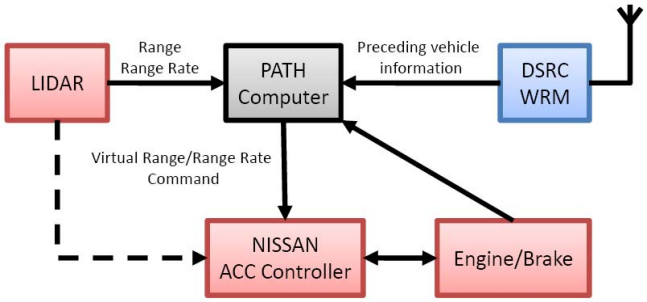

Fig. 3 Following Vehicle Configuration

Fig.3 shows the configuration for the following vehicle. A (PATH) PC104 computer which hosts the CACC control receives the information of the preceding vehicle from the DSRC WRM and accesses the information of the following vehicle through its CAN bus. In order to control the time gap between the following vehicle and the preceding vehicle, it is necessary for the PC104 computer to actuate the engine and brake system of the following vehicle. Ideally, direct access to the engine and brake system will provide more freedom for the CACC controller design. However, actuating engine/brake directly would involve extensive modifications to the existing vehicle hardware and software, which is not preferred under this project.

Also shown in Fig.3 is the factory installed ACC system. Its LIDAR sensor sends the relative distance and speed of the preceding vehicle to the NISSAN ACC controller through the CAN bus (dashed line in the figure). A simple way for implementing the cooperative vehicle longitudinal control is that the prototype CACC controller intercepts the LIDAR sensor measurement information and sends out its own virtual relative distance and speed commands to the NISSAN ACC controller instead. For example, if the following vehicle follows the preceding vehicle at exactly the set time gap, a virtual relative distance command that is smaller than current LIDAR measurement will increase the actual time gap between the preceding vehicle and following vehicle. Although this includes the existing NISSAN ACC controller in the CACC control loop and poses additional difficulties for the CACC controller design, it requires minimal modifications to the existing NISSAN ECU firmware and was therefore adopted in the system design.

III. CACC CONTROLLER DESIGN

The design objectives of the CACC controller are to maintain the time gap (i.e. from 0.6 s to 1.1s) set by driver under all traffic conditions and to provide riding comfort at least comparable to manual driving. There are several difficulties inherent in the design of the CACC controller. First of all, the controller does not have direct access to vehicle's engine and brake system. This greatly limits the freedom of the controller design. Second, the control loop has to include NISSAN's ACC controller, which we know little about and is hard to identify. Finally, the braking capability that can be actuated is limited to 0.3g by the NISSAN system.

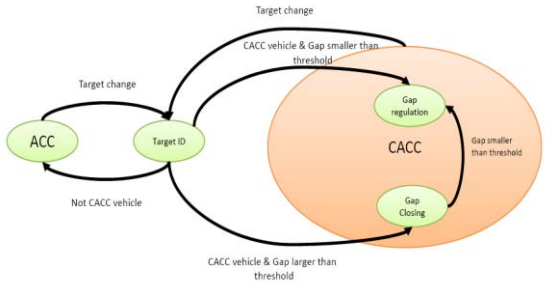

Fig.4 State machine of the CACC controller

A. State Machine of the CACC Controller

Fig.4 illustrates the state machine for the prototype CACC controller. When the vehicle in front of the following vehicle is not the CACC preceding vehicle with wireless communication, the LIDAR sensor measurements will be forwarded to the NISSAN ACC controller directly and the function of factory installed ACC system will be restored. Whenever the CACC preceding vehicle is identified as the vehicle directly in front, the controller enters the CACC mode.

The function of target identification mode is to identify if the target detected by the ACC LIDAR is the CACC preceding vehicle with wireless communication. This problem would be much more complicated if there are multiple vehicles with DSRC wireless communication around. Since there are only two DSRC equipped vehicles during our testing, a simple method is adopted for the target identification purpose. Experimental results show that the relative speed from the LIDAR sensor has about 0.5 s delay compared with vehicle speed from DSRC communication when the CACC preceding vehicle is in front of the following vehicle directly. This characteristic is used by the simple method to confirm the target identity.

B. Design of the Gap Closing Controller

When the relative distance between two vehicles is much larger than the desired time gap, controller saturation will occur if a high-gain CACC gap regulation controller is engaged immediately. Such controller saturation induces oscillating responses which make the driver uncomfortable. One way to resolve this problem is to introduce controller switching. A CACC gap closing controller will be engaged before the relative distance reaches a predetermined threshold value. The CACC gap closing controller is a "semi" open loop controller. A simple trapezoidal trajectory of the relative speed is planned with respect to relative distance as shown in Fig.5. All the parameters (e.g. Δv and $D_{threshold}$) can be tuned to provide different driver comfort levels and avoid controller saturation when transitioned to CACC gap regulation controller.

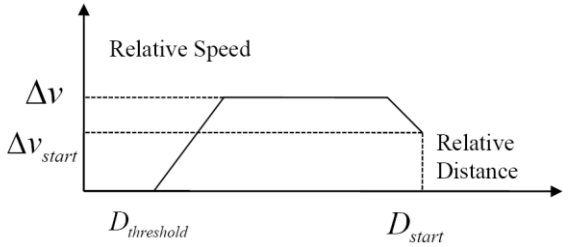

Fig.5 Trajectory planning for the CACC gap closing controller

C. Design of the Gap Regulation Controller

1) Controller Structure and System Modeling

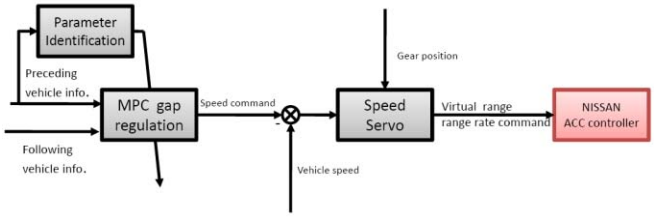

Fig.6 Gap regulation controller structure

The gap regulation controller is the focus of the CACC control design. To address the design difficulties we mentioned at the beginning of this section, the following measures are adopted as shown in Fig.6. Firstly, a high-gain inner speed servo loop is constructed so that the vehicle speed can response to the speed command fast enough. The resulting dynamics of the closed inner speed servo loop can be approximated by a first order linear system. Therefore, the dynamics of NISSAN ACC controller is masked inside the inner speed loop; secondly, the gap regulation is formulated into a MPC control framework to satisfy stringent performance criteria under various constraints such as limitation on brake actuation; finally, an online adaptation method is used to compensate for parameter uncertainties in the system. Since speed servo design is not the focus of this paper, only MPC gap regulation controller design will be presented.

With the inner loop speed controller, the dynamics of the following vehicle can be written as

$$\begin{cases} \dot{x}_f = v_f \\ \dot{v}_f = -\tau v_f + \tau v_c \end{cases} \quad (1)$$

where x_f and v_f represent the position and speed of the following vehicle respectively, v_c is the speed command considered as control input for the gap regulation controller and τ is the time constant of the first order dynamics. The dynamics of preceding vehicle can be written as:

$$\begin{cases} \dot{x}_p = v_p \\ \dot{v}_p = \frac{1}{m} f(u_p, i_p) - \frac{c}{m} v_p^2 + \frac{d}{m} \end{cases} \quad (2)$$

where x_p and v_p represent the position and speed of the preceding vehicle respectively, $f(u_p, i_p)$ represents the traction force generated by either throttle or brake command u_p and is a function of gear position i_p, c is the air drag coefficient, m represents vehicle mass and d represents lumped disturbances that are not modeled in (2) (e.g. tire-road friction).

The relative distance between the preceding vehicle and the following vehicle can be expressed by $x_r = x_p - x_f$. Therefore, the design objective of the gap regulation controller is to minimize gap regulation error represented by

$$e_1 = x_r - v_f t_{HW} \quad (3)$$

where t_{HW} represents the time gap setting (from 0.6 s to 1.1 s) selected by the driver. The available sensing information for the controller design includes v_f and x_r from following vehicle's CAN bus, as well as v_p, u_p, and i_p from DSRC vehicle-to-vehicle communication. With the additional information (e.g. speed, throttle/brake command, and gear position of the preceding vehicle) from DSRC communication, the CACC system is expected to be capable of regulating a tighter time gap and providing smoother ride compared with the factory installed ACC system.

In general, the traction force $f(u_p, i_p)$ in (2) is a nonlinear function of the throttle/brake command u_p and gear position i_p. It can be approximated by following expressions:

$$f(u_p, i_p) \approx \begin{cases} \alpha_{i_p} u_p & for\ throttle\ command \\ \alpha_b u_p & for\ brake\ comand \end{cases} \quad (4)$$

where α_{i_p} is a constant for throttle command at a corresponding gear position i_p and α_b is a constant for brake command. The approximation error can be lumped into the lumped disturbance d. Define the state variables as $x =$

$[x_r, v_p, v_f]^T$, equations (1-2) can be expressed in state-space form as:

$$\begin{cases} \dot{x}_1 = x_2 - x_3 \\ \dot{x}_2 = \theta_1 u_p - \theta_2 x_2^2 + \theta_3 \\ \dot{x}_3 = -\tau x_3 + \tau u \end{cases} \quad (5)$$

where $u = v_c$ is the control input and the unknown parameter vector is

$$\theta = [\frac{\alpha}{m}, \frac{c}{m}, \frac{d}{m}]^T \quad (6)$$

with α defined as

$$\alpha = \begin{cases} \alpha_{i_p} & for\ throttle\ command\ and\ gear\ i_p \\ \alpha_b & for\ brake\ comand \end{cases} \quad (7)$$

2) Parameter Identification Online

To address parametric uncertainties shown in the second equation of (5), an indirect adaptation approach is adopted in which unknown parameters are identified online and the identified values are then used in the later controller design. To use common online system identification methods, it is desirable to obtain a static model for the prediction error that is based on the state *x* and is linearly parameterized in terms of the parameter estimation error. Since the measurement of the preceding vehicle's acceleration ($\dot{x}_2$) is either not available or too noisy, a first order filter is added to transfer the dynamic relationship to a static relationship:

$$\begin{aligned} \dot{x}_2 &= \theta_1 u_p - \theta_2 x_2^2 + \theta_3 \\ \dot{x}_2 + a x_2 &= \theta_1 u_p - \theta_2 x_2^2 + \theta_3 + a x_2 \\ x_2 - \frac{a}{s+a} x_2 &= \theta_1 \left(\frac{u_p}{s+a}\right) + \theta_2 \left(-\frac{x_2^2}{s+a}\right) + \theta_3 (\frac{1}{s+a}) \end{aligned} \quad (8)$$

where a is a positive constant. Define $y = x_2 - \frac{a}{s+a} x_2$ and $\Omega = [\frac{u_p}{s+a}, -\frac{x_2^2}{s+a}, \frac{1}{s+a}]^T$, then the static relationship can be expressed as

$$y = \Omega^T \theta \quad (9)$$

Define the estimation of y as $\hat{y}$ and the parameter estimation of θ as $\hat{\theta}$, the parameter estimation error can be expressed as $\tilde{\theta} = \hat{\theta} - \theta$ and the model prediction error can be expressed as $\varepsilon = \hat{y} - y = \Omega^T \tilde{\theta}$. Based on the least square method, the parameters can be updated as:

$$\dot{\hat{\theta}} = Proj_{\hat{\theta}}(-\Gamma \frac{\Omega \varepsilon}{1 + \nu Trace\,(\Omega^T \Gamma \Omega)}) \quad (10)$$

where adaptation gain matrix $\Gamma = \mathrm{diag}\{\gamma_1, \gamma_2, \gamma_3\}$ is updated by

$$\dot{\Gamma} = \lambda \Gamma - \frac{\Gamma \Omega \Omega^T \Gamma}{1 + \nu Trace\,(\Omega^T \Gamma \Omega)} \quad (11)$$

where $\lambda < 0$ is the forgetting factor. To ensure the identified parameters will always stay in a predetermined bound, the parameter projection in Eq. (10) is defined by:

$$Proj_{\hat{\theta}}(*) = \begin{cases} 0 & if\ \hat{\theta} = \theta_{max}\ and * > 0 \\ 0 & if\ \hat{\theta} = \theta_{min}\ and * < 0 \\ * & otherwise \end{cases} \quad (12)$$

where θ_{min} and θ_{max} are the lower and upper limits of parameter estimation respectively.

3) MPC Controller Design

To carry out MPC controller design, the discrete time representation of the continuous model (5) is obtained as

$$\begin{cases} x_1(k+1) = x_1(k) + \big(x_2(k) - x_3(k)\big)T \\ x_2(k+1) = x_2(k) + (\theta_1 u_p - \theta_2 x_2^2 + \theta_3)T \\ x_3(k+1) = x_3(k) + \big(-\tau x_3(k) + \tau u(k)\big)T \end{cases} \quad (13)$$

where T is the sampling period. The constraints in the discrete time can be expressed as

$$\begin{aligned} x_1(k) &> d_{safe} \\ v_{max} > u(k) &> 0 \\ a_{max} > \tfrac{x_3(k+1) - x_3(k)}{T} &> a_{min} \end{aligned} \quad (14)$$

The first constraint means that the relative distance between two CACC vehicles will always be larger than a safety threshold d_{safe} ; the second constraint shows the limit on the control input (i.e., speed command for the following vehicle) be between 0 and maximal speed v_{max} ; The last constraint imposes an acceleration bound for enhancing rider comfort and for avoiding control input saturation.

A quadratic form of cost criterion is used for the optimization problem as shown in following equation:

$$\begin{aligned} J(k) = \sum_{n=1}^{N} (&\rho_e e_1^2(k+n) + \rho_u \Delta u^2(k+n) \\ &+ \rho_v \Delta v^2(k+n)) \end{aligned} \quad (15)$$

where ρ_e , ρ_u and ρ_v are positive weighting constants, $\Delta u(k+n) = u(k+n) - u(k+n-1)$ and $\Delta v(k+n) = x_2(k+n) - x_3(k+n)$. Hence, minimizing the cost criterion achieves the following simultaneous: minimizing the time gap error, smoothing out the control input and thereby providing better riding comfort, and speeding up the response of the following vehicle to the speed change of the preceding vehicle. The control input can be derived by solving the optimization problem of minimizing the cost criteria defined in (15) subject to the constraints defined in (14).

IV. EXPERIMENTAL RESULTS

To fine tune the control design and controller parameters, two testing trips were made to the Nissan's vehicle proving ground in Arizona. At the end of the second field trip, a series of scenarios was performed to test the performance of the final controller.

Fig.7 shows a scenario when the following car was approaching the preceding car and the time gap setting was changed from 1.1 s to 0.9 s. Both the actual time gap and the speed show that, under the control of the CACC controller, the following car approached the preceding car smoothly and the time gap was then well regulated at 0.9 s.

Fig.8 shows a scenario when the preceding car braked at about 0.16 g while the following car was approaching. With the feed-forward information (including the brake and throttle of the preceding vehicle) from the wireless communication, the CACC controller reacted very quickly. Therefore, the following car responded to the speed change of the preceding car quickly and regulated the time gap at the desired time gap setting in the gap regulation mode.

To further illustrate the advantages of the feed-forward information from wireless communication, Fig.9 shows a

scenario when the preceding car repeatedly made braking and acceleration transitions. The largest magnitude of braking is around 0.25 g, which is close to the maximum capability of the brake actuator (0.3g). As shown in Fig. 9, the following car was always able to track the preceding vehicle's speed, even with this aggressive braking and acceleration. Fig. 10 also show that the following vehicle braked almost immediately after the preceding car braked with the information provided via wireless communication.

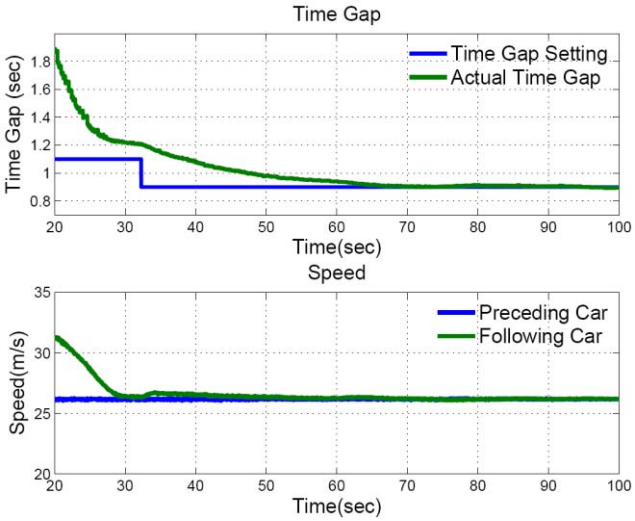

Fig.7 Proving ground test: steady state performance

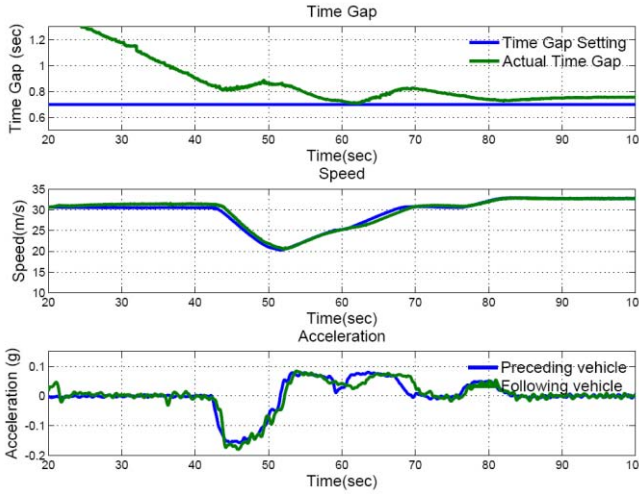

Fig. 1 Preceding car braking while following car approaching

As part of the performance testing, a three-car platoon was formed to test the string stability effect and compare the performance between the conventional ACC controller and the CACC controller. A manually driven Infiniti G35 led the platoon and the preceding Infiniti FX45 followed it with the factory ACC controller turned on. The following Infiniti FX45 followed the preceding FX45 with the CACC controller turned on. The lead G35 made aggressive braking and acceleration repeatedly. As shown in Fig. 11, the ACC equipped preceding FX45 tracked the lead G35's speed with a much larger time lag compared with the CACC equipped following FX45's tracking performance. Therefore, the ACC equipped preceding FX45 exhibited a much larger variation in time gap regulation as well. More importantly, the amplification of the time gap variations for the conventional ACC shows a potential loss of string stability, which is compensated successfully by the CACC's enhanced vehicle following capability.

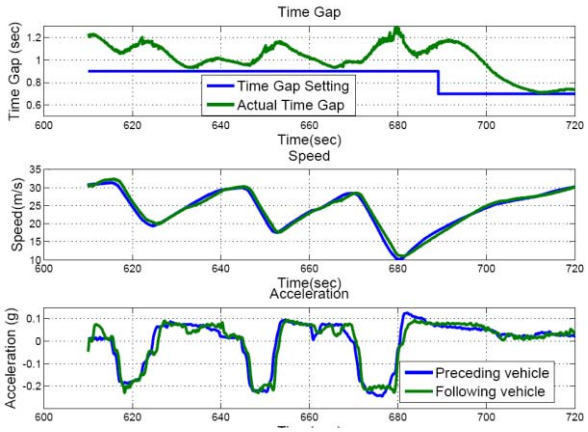

Fig. 9 Preceding car brakes and accelerates repeatedly

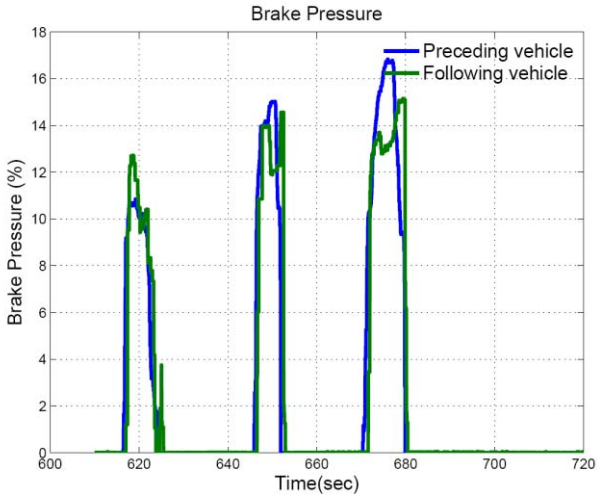

Fig. 10 Brake pressure percentage when preceding vehicle brakes and accelerates repeatedly

Fig. 12 shows the testing result on a section of public highway in live traffic with the smallest gap setting of 0.6 s. Again, the CACC controller performed well and tracked the desired time gap setting with just a relatively small steady state error.

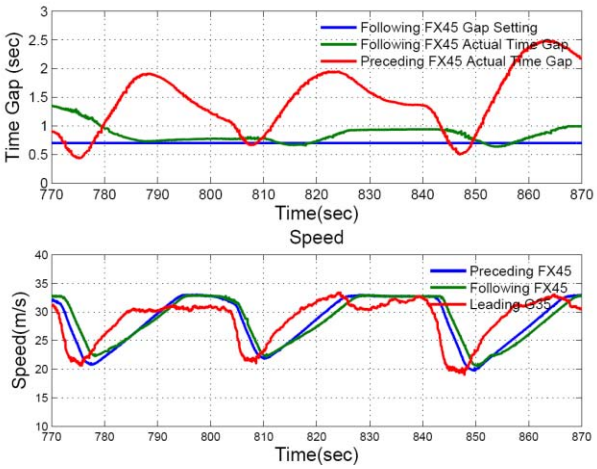

Fig. 11 Three car platoon test

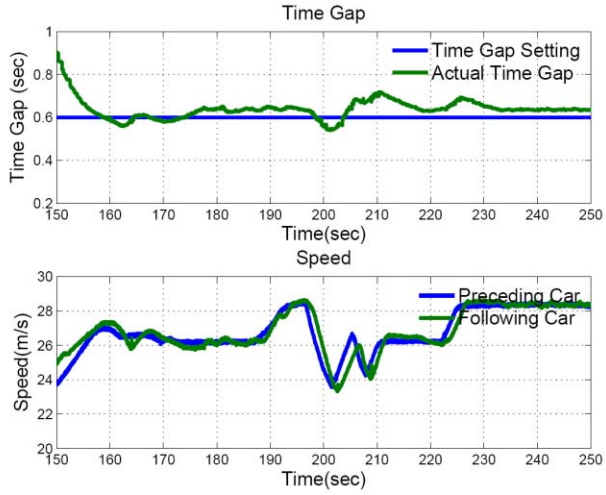

Fig. 12 Public highway testing result

V. Conclusion

This paper describes the design, implementation, and testing of a CACC system on two Infiniti FX-45 vehicles that were provided by Nissan Motor Company. The CACC system has been developed by adding a wireless vehicle-vehicle communication system and new control logic to an existing commercially available ACC system. The CACC is intended to extend the vehicle-following capabilities of ACC to provide drivers with vehicle-following time gaps shorter than those provided by commercial ACC systems. A CACC controller structure is proposed and a gap regulation controller is designed based on the indirect adaptive MPC. The gap regulation controller utilizes additional information from the DSRC wireless communication for the enhanced following performance. Extensive field testing was conducted on both vehicle proving ground and public highway. Testing results show consistent performance under different scenarios and demonstrate its advantages over the conventional ACC system. The enhanced performance makes it possible for the CACC equipped vehicle to operate at time gaps between 0.6 s and 1.1 s, compared to a range of 1.1 s to 2.2 s with the ACC system; these shorter CACC time gaps could enable significant increases in highway capacity. The currently on-going human factor study with the CACC system will provide insights on drivers' experiences with different time gaps, especially those shorter time gaps.

Acknowledgment

The authors would like to thank Hiroshi Kawazoe, Hiroshi Tsuda and Junko Buxton of Nissan Technical Center North America for the valuable discussions and for their support on vehicle testing. The authors would also like to thank Delphine Cody, Steve Shladover, Sue Dickey, Dave Nelson, Thang Lian and Benedict Bougler of California PATH for supports and discussions.

References

[1] G. Naus, J. Ploeg, R. van de Molengraft, and M. Steinbuch, "Explicit MPC design and performance-based tuning of an Adaptive Cruise Control Stop-&-Go," in *Intelligent Vehicles Symposium, 2008 IEEE*, 2008, pp. 434-439.

[2] B. v. Arem, C. J. G. v. Driel, and R. Visser, "The Impact of Cooperative Adaptive Cruise Control on Traffic-Flow Characteristics," *IEEE Transactions on Intelligent Transportation Systems,* vol. 7, pp. 429-436, 2006.

[3] A. Vahidi and A. Eskandarian, "Research advances in intelligent collision avoidance and adaptive cruise control," *Intelligent Transportation Systems, IEEE Transactions on,* vol. 4, pp. 143-153, 2003.

[4] D. d. Bruin, J. Kroon, R. v. Klaveren, and M. Nelisse, "Design and Test of a Cooperative Adaptive Cruise Control System," in *IEEE Intelligent Vehicle Symposium*, Parma, Italy, 2004, pp. 392-396.

[5] J. M. Maciejowski, *Predictive Control with Constraints*: Prentice Hall, 2002.

[6] M. Diehl, H. Ferreau, and N. Haverbeke, "Efficient Numerical Methods for Nonlinear MPC and Moving Horizon Estimation," in *Nonlinear Model Predictive Control*, 2009, pp. 391-417.

[7] P. Falcone, H. Eric Tseng, F. Borrelli, J. Asgari, and D. Hrovat, "MPC-based yaw and lateral stabilisation via active front steering and braking," *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility,* vol. 46, pp. 611 - 628, 2008.

[8] V. L. Bageshwar, W. L. Garrard, and R. Rajamani, "Model predictive control of transitional maneuvers for adaptive cruise control vehicles," *Vehicular Technology, IEEE Transactions on,* vol. 53, pp. 1573-1585, 2004.

[9] D. Corona and B. De Schutter, "Adaptive Cruise Control for a SMART Car: A Comparison Benchmark for MPC-PWA Control Methods," *Control Systems Technology, IEEE Transactions on,* vol. 16, pp. 365-372, 2008.

[10] D. Corona, M. Lazar, B. De Schutter, and M. Heemels, "A hybrid MPC approach to the design of a Smart adaptive cruise controller," in *2006 IEEE International Conference on Control Applications*, 2006, pp. 231-236.

[11] D. Corona, I. Necoara, B. De Schutter, and T. van den Boom, "Robust hybrid MPC applied to the design of an adaptive cruise controller for a road vehicle," in *Decision and Control, 45th IEEE Conference on*, 2006, pp. 1721-1726.

[12] G. Naus, R. van den Bleek, J. Ploeg, B. Scheepers, R. van de Molengraft, and M. Steinbuch, "Explicit MPC design and performance evaluation of an ACC Stop-&-Go," in *American Control Conference, 2008*, pp. 224-229.