Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Design, Tuning and Evaluation of Integrated ACC/CA Systems

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Abstract: This paper describes design, tuning and evaluation of integrated Adaptive Cruise Control with Collision Avoidance (ACC/CA). The control scheme is designed to control the vehicle so that it would feel natural to the human driver during normal safe driving situations and to completely avoid rear-end collision in vehicle following situations. Driving situations are divided into safe, warning and dangerous mode and three different control strategies have been used depending on driving situations. The driving situations are determined using a non-dimensional warning index and time-to-collision. A confusion matrix method based on manual driving data is used to tune the control parameters of the integrated ACC/CA system. Using a simulation and a validated vehicle simulator, vehicle following characteristics of the controlled vehicle are compared to real-world manual driving radar sensor data. A Hardware-in-the-loop Simulation (HiLS) was developed and used for an evaluation of integrated ACC/CA System. Finally the integrated ACC/CA system is implemented in a real vehicle and has been tested in both safe traffic and the severe braking situation. It is shown that the proposed control strategy can provide with natural following performance similar to human manual driving in both high speed driving and low speed stop-and-go situations and can prevent the vehicle-to-vehicle distance from dropping to an unsafe level in a variety of driving conditions.

1. INTRODUCTION

Advanced driver assistance systems (ADAS) like Adaptive Cruise Control (ACC), Lane-keeping support, Collision Warning and Collision Avoidance (CW/CA), assisted lane change, automated parking assist have been active topics of research and development since the 1990's. During this time, sensors, actuators, and other enabling technologies have greatly advanced (Fancher, P. *et al*, 2000, 2004, Iljima, T. *et al*, 2000, Wang, J. *et al*, 2004, Baloga, T. 2006). These systems are believed to reduce the risk of accidents, improve safety and enhance comfort and performance for drivers. While several automakers have already introduced features like adaptive cruise control in their top of the line cars, many others are pursuing research to introduce ACC and other advanced features like collision warning and avoidance systems into their products. An enhancement to the cruise control of today's car is ACC systems, which can detect the preceding vehicle and automatically accelerate and decelerate the vehicle to maintain a specified spacing between the two vehicles. The goal of a vehicle cruise control system, such as ACC, is a partial automation of the longitudinal vehicle control and the reduction of driver workload during low speed driving in busy urban traffic as well as at high speeds on highways. While development of passive safety technology has led to effects that are much safer in the event of a collision, they cannot reduce the changes of a collision in vehicle following situation. Worldwide statistics shows a decreasing trend in number of fatalities in car accidents but an increased number of accidents. Rear-end collision, for example, account for about 1.8 million crashes annually which is 28 percent of all crashes. As the driver is limited in recognizing, deciding and operating in dangerous traffic situation, accidents are practically inevitable. However, many of accidents can be avoided if the human driver limits can be overcome by automating some parts of the driving tasks. This initiative has encouraged extensive research in collision warning and collision avoidance systems that can improve passenger safety and reduce losses by preventing the accidents. When the driver fails to perform the necessary emergency maneuver, a collision avoidance system will take the control and brake the car to avoid a collision. In order to avoid rear-end collision and improve driver's comfort in a various traffic situations, it is necessary to integrate ACC system and CA system. Since the integrated ACC/CA systems always work with a human driver co-existing, this system must be useful to the driver and the system's operation need to be acceptable to the driver (Goodrich, M.A. *et al*, 2003). In this context, the target of the proposed ACC/CA system is to achieve naturalistic behaviour of the controlled vehicle and to achieve safe vehicle behaviour in severe braking situation in which large deceleration are necessary. This paper presents an integrated control structure and a method for tuning parameters of integrated ACC/CA system based on manual driving data. The integrated ACC/CA system is also implemented in a real vehicle and shown that the proposed control algorithms can provide satisfactory performance.

978-1-1234-7890-2/08/$20.00 © 2008 IFAC

10.3182/20080706-5-KR-1001.1741

2. DESIGN OF INTEGRATED CONTROLLER

The overall structure of an integrated ACC/CA system is shown in Fig 1. The integrated ACC/CA system monitors two indexes, x and TTC^{-1}, and determine the driving situation, for example, 'safe', 'warning' or 'dangerous' (Yi, K. *et al*, 2007). According to the driving situation, an upper-level controller of the integrated ACC/CA system determines the desired acceleration. In safe driving, the integrated ACC/CA system controls the vehicle to provide smooth naturalistic vehicle behaviour similar to normal driving of a human driver. In dangerous situation or in unexpected events, the integrated ACC/CA system uses large decelerations to maintain safe vehicle-to-vehicle clearance. A low-level controller manipulates the throttle-brake actuators such that the vehicle acceleration tracks the desired acceleration. The throttle-brake control laws were based on the reverse dynamics (Yi, K., *et al*, 2002, 2006).

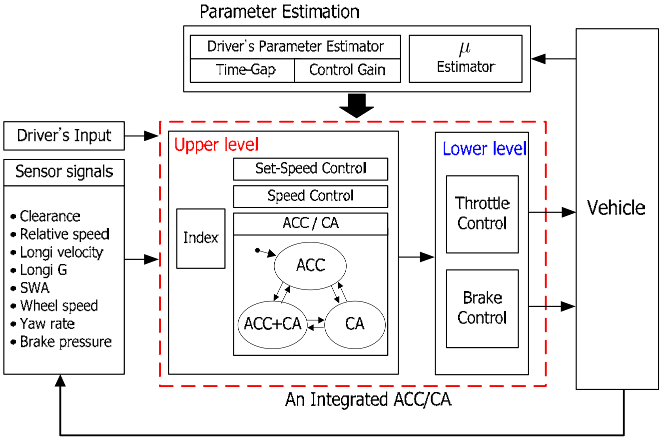


Figure.1 The structure of an integrated ACC/CA system

2.1 Driving Situation and Control Modes

A non-dimensional warning index (x) and an inverse TTC (TTC^{-1}) are used to evaluate driving situations. Most collision warning/collision avoidance systems in existence use a similar algorithm based on braking critical distance and warning critical distance [11]. The non-dimensional warning index uses braking and warning critical distances which are functions of vehicle velocity, relative velocity, tire-road friction, a system delay, and a minimum headway time. The non-dimensional warning parameter, x, used in this study is defined as follows.

$$x = \frac{c - d_{br}}{d_w - d_{br}} \quad (1)$$

where c is the actual clearance between vehicles, d_{br} and d_w are the braking critical distance and the warning critical distance, respectively. The warning and braking critical distances are defined as follows

$$\begin{aligned} d_{br} &= v_{rel} \cdot T_{delay} + f(\mu) \cdot \frac{(2v_s - v_{rel})v_{rel}}{2a_{\max}} \\ d_w &= v_{rel} \cdot T_{delay} + f(\mu) \cdot \frac{(2v_s - v_{rel})v_{rel}}{2a_{\max}} + v_s \cdot T_{h,\min} \end{aligned} \quad (2)$$

where v_{rel} is the relative velocity between subject and preceding vehicles, T_{delay} is the system delay, a_{max} is the maximum deceleration of vehicle under normal road condition, v_s is the subject vehicle velocity, $f(\cdot)$ is the friction scaling function, μ is the estimated value of the tire-road friction coefficient, and $T_{h,min}$ is a minimum headway time. A piece-wise linear function of the following form is used for the friction scaling function. The tire-road friction coefficient can be estimated using various methods and the estimated friction coefficient can be used for the adaptation of our proposed ACC algorithm [12,13]. The inverse TTC is related with the visual cues that might guide driver headway maintenance. The looming concept, as described in human-factor studies, is employed in the analysis of human perception and longitudinal control behavior in the driving situations. The looming effect was first investigated by Hoffman and Mortimer in 1996 and was one of key factors in human-centered design of an ACC-with-braking and forward-crash-warning system conducted by Fancher et al. [2]. The size of the image projected onto the eye of the subject following driver depends on the range to the observed object, i.e., the preceding vehicle. If there is relative motion between the vehicles, the range will change. Since the width of the preceding vehicle, w, is constant and can be represented as

$$w = R \cdot \theta \quad (3)$$

the rate of change of range is related to the rate of change of the angle, θ, occluded by the image as projected onto observer's eye, i.e., the driver's eye as follows: The looming effect is represented by the ratio of occluded angle to the rate of change of that angle, i.e. $\theta / \dot{\theta}$,. Therefore, the looming effect can be represented as

$$\frac{\theta}{\dot{\theta}} = \frac{R}{-\dot{R}} = \frac{c + l}{v_s - v_p} = TTC + \delta \quad (4)$$

where c is the clearance between the vehicles and l is the distance between the front bumper and the driver's eye. The driver's sensation of looming is related with the range and range rate, which can be measured by the sensor employed in ADAS.

In manual driving, 98% of the accelerations are in a range between -2.17 and 1.77 m/s^2. Driver and passengers feel significantly uncomfortable when the vehicle deceleration is greater than 3~4 m/s^2. Drivers use large deceleration greater than -4 m/s^2 only when they really need to apply severe braking to prevent the vehicle-to-vehicle distance from dropping to an unsafe level. In this context, driving situations are evaluated using the vehicle accelerations. When the magnitude of the vehicle decelerations is greater than 4 m/s^2, the driving situation is considered to be a 'severe braking or dangerous situation'. When the magnitude of the vehicle decelerations is smaller than 2 m/s^2, the driving situation is considered to be a 'safe situation'. To design an integrated ACC/CA system reflecting human driver's characteristics, the driving situations are divided by comfort-mode (Mode-1), large deceleration-mode (Mode-2) and severe braking-mode (Mode-3) and as follows.

$$\textit{Mode-1}: \textit{Comfort Mode} \ (a > -2\,[m/s^2]\ )$$
$$\textit{Mode-2}: \textit{Large deceleration Mode} \ (a > -4\,[m/s^2]\ )$$
$$\textit{Mode-3}: \textit{Severe Braking Mode} \ (a > -8\,[m/s^2]\ )$$

The non-dimensional warning index and the inverse TTC are used to determine the control modes as follows:

$$\begin{aligned} &\text{Control Mode-1} \ (x \geq \alpha_1 \text{ and } TTC^{-1} \leq iT_1) && \Rightarrow ACC \\ &\text{Control Mode-2} \ (\alpha_2 < x \leq \alpha_1 \text{ or } iT_1 < TTC^{-1} \leq iT_2) && \Rightarrow ACC + CA \\ &\text{Control Mode-3} \ (x \leq \alpha_2 \text{ and } iT_2 < TTC^{-1}) && \Rightarrow CA \end{aligned}$$

where iT_1 and iT_2 are inverse TTC thresholds and α_1 and α_2 warning index thresholds. The non-dimensional warning index and the inverse TTC were used to evaluate driving situations. It is important to determine appropriate threshold values for the warning index and TTC^{-1} for each mode. Warning and braking that are given with too much safety margin is likely to make the driver feel them annoying or nonsense. Warning and braking that is too late are likely to make the driver feel unsafe. Therefore, the parameters for transition of the driving mode should be determined based on manual driving data.

2.2 Desired Acceleration for Control Modes

Basically, linear optimal control theory has been used to design the desired acceleration in normal preceding vehicle following situations. Using integrators to model the vehicles, a state space model for the controlled and preceding vehicles can be written as follows:

$$\dot{x} = Ax + Bu + \Gamma w = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ -1 \end{bmatrix} u + \begin{bmatrix} \tau \\ 1 \end{bmatrix} w \qquad (5)$$

where τ is the linear coefficient, i.e., time gap. The states are $x^T=[x_1,\ x_2]=[\ c_d - c\ \ v_p - v_c\ ]$, the input, u, is the controlled vehicle acceleration and the disturbance, w, is the preceding vehicle acceleration. c_d and c are the desired range clearance and actual clearance between the preceding and controlled vehicles and v indicates velocity. Subscripts, p and c, indicate the preceding and the controlled vehicles, respectively. The gains for the state feedback law, $u=-kx$, are chosen to minimize the cost function:

$$J = \int_0^\infty \left(x^T Q\, x + u^T R\, u \right) dt \qquad (6)$$

The weighting matrices, Q and R, are defined as follows:

$$Q = \begin{bmatrix} \rho_1 & 0 \\ 0 & \rho_2 \end{bmatrix}, \quad R = [r]. \qquad (7)$$

The weighting factors, ρ_1, ρ_2 and r, have been chosen to achieve naturalistic behaviour of the controlled vehicle that would feel natural to the human driver in normal driving situation. In this study, alternative weighting factors have been used for low, medium and high speed ranges. Therefore, desired acceleration is represented by

$$a_*(t) = u(t) = -k_1(v_c(t)) \cdot (c_d(t) - c(t)) - k_2(v_c(t)) \cdot (v_p(t) - v_c(t))$$

$$a_{des}(t) = \begin{cases} a_{\max}(v_c(t)) & if \quad a_*(t) > a_{\max}(v_c(t)) \\ a_*(t) & if \quad a_{\min}(v_c(t)) \leq a_*(t) \leq a_{\max}(v_c(t)) \\ a_{\min}(v_c(t)) & if \quad a_*(t) < a_{\min}(v_c(t)) \end{cases} \qquad (8)$$

The control gains, k_1 and k_2, have been obtained by tuning the weighting matrices, Q and R. For the 'Control Mode-1', the maximum and minimum accelerations, a_{max} (•) and a_{min} (•), are determined based on the analysis of the driving test data (Yi, K. *et al*, 2007). In other words, the desired acceleration is computed using velocity-dependent optimal gain and restricted by acceleration limit for ride quality. In this study, the desired clearance defined by (9) has been used.

$$c_d = c_0 + \tau \cdot v_p \qquad (9)$$

where the c_0 is the zero-speed clearance, and τ is the linear coefficient. The zero-speed clearance and the linear coefficients can be adapted to make the steady-state following characteristic of an ACC/CA vehicle similar to that of manual driving. A recursive least square method for adaptation of the zero-speed clearance, c_0, and the linear coefficient, τ of human driver during manual driving, i.e., while the ACC is off, has been proposed by Yi and Moon (Yi, K. and Moon, I. 2006). Design parameters of the cruise control law, c_0 and τ, can be tuned to suit the driver.

In the case of the 'Control Mode-2', the desired acceleration is computed as the 'Control Mode-1' and acceleration limit extend to -4m/s^2. In order words, the desired acceleration of this mode can be larger than that of 'Control Mode-1'. Same as 'Control Mode-1', the desired clearance, c_d, is defined by (9).

$$a_*(t) = u(t) = -k_1(v_c(t)) \cdot (c_d(t) - c(t)) - k_2(v_c(t)) \cdot (v_p(t) - v_c(t))$$

$$a_{des}(t) = \begin{cases} a_*(t) & if\ a_*(t) > -4m/s^2 \\ -4m/s^2 & else \end{cases} \qquad (10)$$

In the case of the 'Control Mode-3', the desired acceleration, a_{des}, is computed using nonlinear functions that represent mapping from the indexes to the desired accelerations. The functions, $f_1(x)$ and $f_2(TTC^{-1})$, are obtained by confusion matrix method using on manual driving data. It has been revealed from the investigation of the manual driving data that the warning index is closely related with the driver's decision and vehicle acceleration behaviour in medium and high speed driving situations and the inverse TTC in low speed driving situations. These facts have been incorporated in the design of the desired vehicle acceleration, a_{des}, in severe braking situations. The desired acceleration is computed as

$$a_{des}(t) = W_1(v_c) \cdot a_1(x) + W_2(v_c) \cdot a_2(TTC^{-1}) \qquad (11)$$

where a_1(•) and a_2(•) are the functions defined by the warning index and the inverse TTC, respectively, and W_i is the weighting factor which is defined as a function of the vehicle speed.

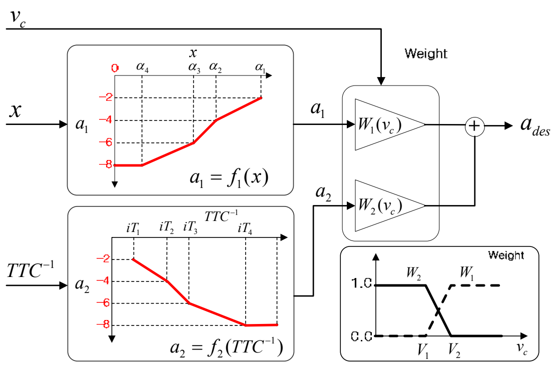


Figure.2 Design of the desired acceleration in severe braking situations

3. TUNING BASED ON MANUAL DRIVING DATA

In this study, using confusion matrix (Lee, K. *et al*, 2004), threshold values for the warning index and the inverse TTC are determined based on the analysis of the manual driving data. The manual driving data have been collected in no-crash driving situations by experienced drivers. In addition, these data included 62 severe braking test data. The acceleration is the actual variable and the warning index and the inverse TTC are the prediction variables. The warning index threshold values, $x_{th}(a)$, and the inverse TTC threshold values, $iT_{th}(a)$, for a given vehicle acceleration, a, are computed as follows.

$$x_{th}(a) = \arg\max_{i} \{ G_i \} \quad (i = 1,2 \cdots N)$$
$$iT_{th}(a) = \arg\max_{i} \{ G_i \} \quad (i = 1,2 \cdots N) \tag{12}$$

where G_i is defined as a function of the prediction variable, ϕ_i, as

$$G_i(\phi_i) = g\_mean_1 = \sqrt{TP \cdot P}$$
$$TP(a,\phi_i) = \left(\frac{D}{C+D}\right), \quad P(a,\phi_i) = \left(\frac{D}{B+D}\right) \tag{13}$$

The g_mean_1 computed for three acceleration values, -2 m/s^2, -4 m/s^2 and -6 m/s^2, with the warning index as the prediction variables are shown in Fig. 4. The threshold values obtained from the confusion matrix method are summarized in the Table 1. Therefore, the warning index threshold and the inverse TTC threshold can be used to determine driving situations. A driving situation is considered to be a severe braking situation when either the warning threshold, x_{th}, is smaller than 0.81 or the inverse TTC threshold, iT_{th}, is greater than 0.49. A driving situation is considered to be a normal following situation when neither the warning threshold, x_{th}, is smaller than 1.19 nor the inverse TTC threshold, iT_{th}, is greater than 0.21. Therefore, the warning index threshold and the inverse TTC threshold can be used to determine control mode. As summarized in Table 1, the threshold values of the warning index are determined as α_1=1.19, α_2=0.81 and threshold values of the inverse TTC are determined as iT_1 =0.21, iT_2=0.49.

Table. 1 Threshold values for x, TTC^{-1}

Acceleration	Warning index	Inverse TTC
-2 [m/s^2]	1.19	0.21
-4 [m/s^2]	0.81	0.49
-6 [m/s^2]	0.65	0.68

4. EVALUATION OF INTEGRATED ACC/CA SYSTEM

4.1 Comparisons between ACC/CA and Manual Driving

The proposed control strategy is compared with human manual driving. The human manual driving data have been collected using a test vehicle. The vehicle is equipped with a laser radar, a CCD camera, accelerometers, a brake pedal force sensor, a steering angle sensor, a yaw rate sensor, a data logging computer. Range and range-rate are measured using the radar and laser radar, respectively. Vehicle speed, engine RPM, turbine speed of the torque converter, throttle position and gear status are obtained from engine control unit and each sensor via CAN. Comparisons between controlled vehicle ('ACC/CA') and human driver's manual driving ('Human') in the case of closing on a slower moving preceding vehicle on a high speed city highway are shown in Figure. 3. The preceding vehicle and human driver data plotted in the Figure. 3 are measured values and the ACC/CA data are simulated under the same traffic situation. As shown in Figure. 3, the velocity, clearance and accelerations of the 'ACC/CA' are similar to those of manual driving.

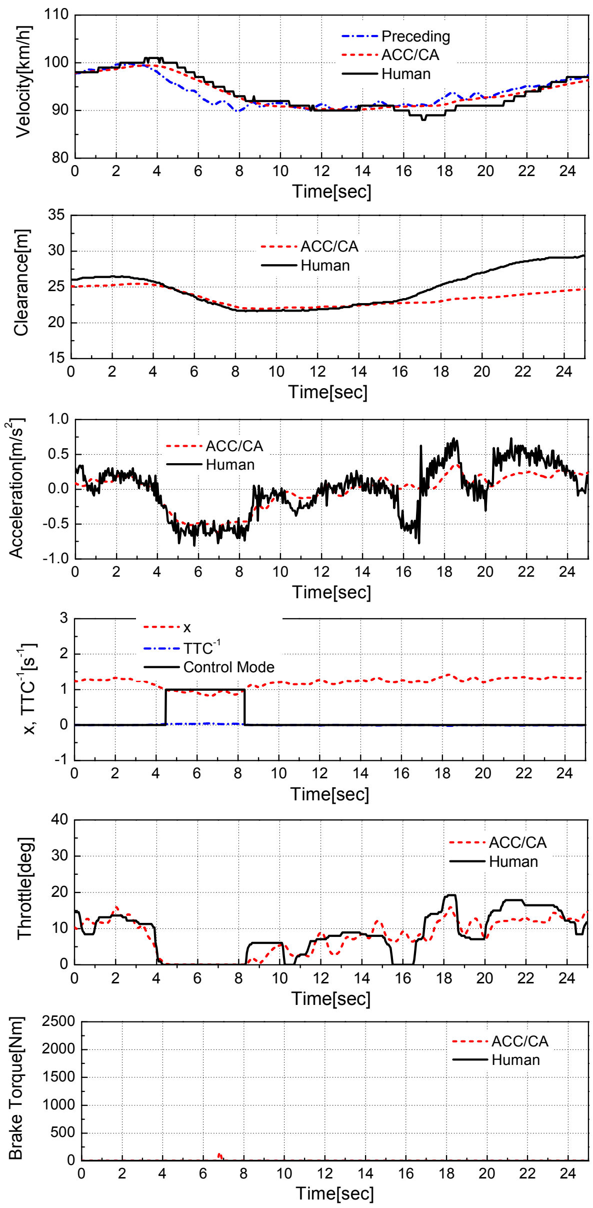


Figure.3 Comparisons between ACC/CA control and human driving at high speed on a city highway.

4.2 Hardware-in-the-Loop System

This paper describes an investigation on the Brake-ECU HiLS (Hardware-in-the-loop Simulation) System for verification of an ACC/CA system. Since vehicle tests are expensive and time consuming, it is necessary to establish an efficient and low-cost development system. HiLS system consists of the host computer, target computer, ACC/CA controller and brake hardware module using ESC module. The host computer downloads nonlinear model of vehicle and driving scenarios to target computer and monitors signals in CAN network.

In this study, xPC-target is used as target computer. The target computer implemented the vehicle motion at real-time. The brake hardware module consists of a brake pressure control unit, front / rear brake calipers and hydraulic system of ESC module. Brake HiLS system prevents the error that occurs in modeling of the hydraulic system of vehicle, and has an advantage of developing controller for ACC/CA System by using an interface which is same as real test vehicle environment.

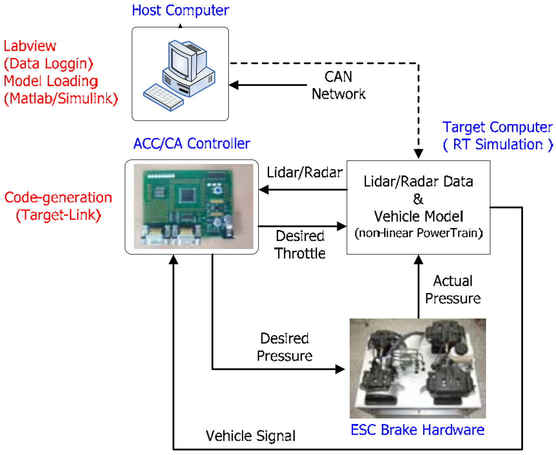
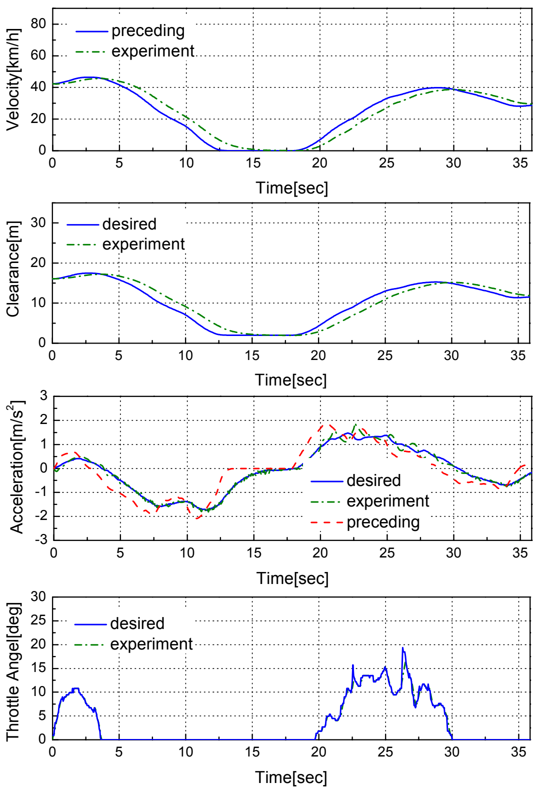


Figure. 4 Configuration of HILS system

The ACC/CA controller has been successfully tested using the HiLS system. Test results obtained using the HiLS system in low speed driving scenarios with stop-and-go situation show that the HiLS system can be a useful tool for the evaluation of the ACC/CA system in the laboratory. As shown in Figure. 5, the preceding vehicle velocity varies between 0 and 40 km/h and the subject vehicle velocity is close to the preceding vehicle velocity.



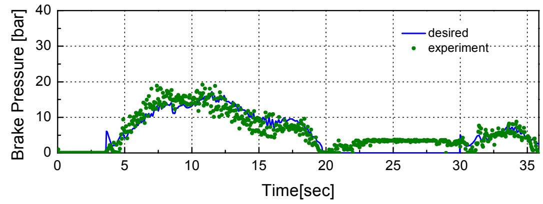


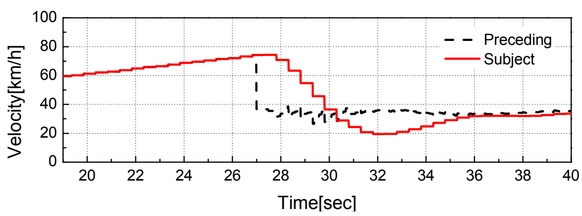
Figure.5 HILS test result: cruise control at stop-and-go situations

5. VEHICLE TEST

Figure. 6 shows the test vehicle, a Hyundai-motors Azera used in this study. The vehicle is equipped with a laser radar, an accelerometers, ESC module, wheel speed sensor and wheel pressure sensor, etc. Engine RPM, turbine speed of the torque converter, throttle position and gear status are obtained from engine control unit via CAN. The integrated ACC/CA system included upper-lever controller and low-level controller is implemented by dSPACE hardware (Micro-AutoBox). In order to tracks the desired acceleration, the controller manipulators throttle actuator by voltage level and sends brake command to ESC controller which is connected with vehicle's ESC module using CAN communication.

Figure.6 Configuration of test vehicle

Vehicle following tests have been using two vehicles: a preceding vehicle and a controlled vehicle. Test results are shown in Figure. 7. The initial vehicle velocity was 70 km/h and a cut-in vehicle with a velocity of 30 km/h has appeared in front of the subject vehicle at 27 seconds. The initial clearance between the subject and cut-in vehicle was about 30 meters. The warning index and the inverse TTC increase at instance and the control-mode changes from '0' to '2'. Because the control mode switches the severe-braking mode, the acceleration of controlled vehicle ranges to -6 m/s2 to avoid the collision. As indicated in the Figure. 7, throttle angle was set to be zero and the brakes were applied to reduce the velocity and to increase the clearance.



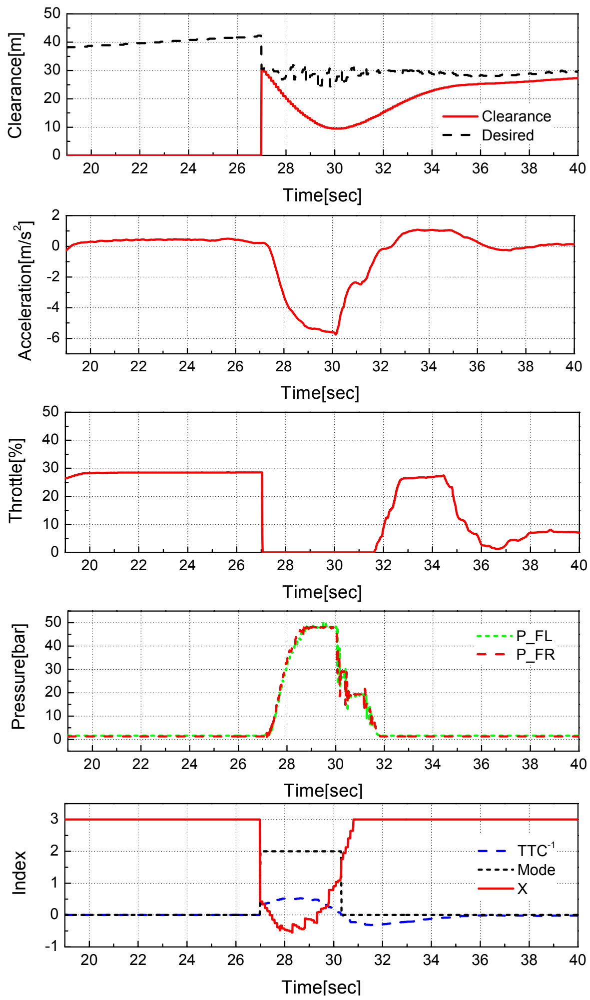


Figure 7. Vehicle test result: a severe cut-in case

6. CONCLUSIONS

An integrated algorithm for integrated ACC/CA system has been presented. The control algorithm has been designed to achieve naturalistic behaviour of the controlled vehicle that would feel natural to the human driver in normal driving situation and to achieve safe vehicle behaviour in severe braking situations in which large decelerations are necessary. In order to integrate the ACC system and CA system, the proposed algorithm makes the controlled vehicle operate in three possible modes: comfort, large-deceleration, and severe-braking mode. While in "comfort mode (Control Mode-1)", the control objective is to maintain the safety distance from the preceding vehicle and to feel natural to the driver. If the driving situation based on indexes is determined to "large-deceleration mode (Control Mode-2)", the ACC/CA system gives the driver warning signal and generates large deceleration. In the case of dangerous situation, the integrated ACC/CA system switches the control mode to the "severe-braking mode (Control Mode-3)", and generates emergency braking action. For the enhanced driver acceptance, the threshold values for x, TTC^{-1} for each driving mode are determined based on manual driving data.

It has been shown that the proposed control strategy can provide with natural following performance similar to human manual driving in both high speed driving and low speed stop-and-go situations and can prevent the vehicle-to-vehicle distance from dropping to an unsafe level in severe braking situations. The vehicle longitudinal control algorithm presented in this study can be a good solution to enhance driver acceptance of an integrated adaptive cruise control with collision avoidance system.

ACKNOWLEDGEMENTS

This work is supported by Hyundai Motor Company.

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