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DESIGN AND EVALUATION OF INTELIGENT VEHICLE CRUISE CONTROL SYSTEMS USING A VEHICLE SIMULATOR

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ABSTRACT–This paper presents evaluation and comparisons of manual driving and driving with intelligent cruise control (ICC) systems. An intelligent vehicle cruise control strategy has been designed to achieve natural vehicle behavior of the controlled vehicle that would make human driver feel comfortable and therefore would increase driver acceptance. The evaluation and comparisons of the ICC and manual driving have been conducted using real-world vehicle driving data and an ICC vehicle simulator.

KEY WORDS : Intelligent cruise control, Stop-and-go, Human driver, Time gap, Time to collision, Vehicle

1. INTRODUCTION

Vehicle longitudinal control for application to automated highway systems and driver assistance systems has been in progress for several decades. Driver assistance systems (DAS) like Adaptive Cruise Control (ACC) and Stop-and-Go (SG) have been active topics of research and development since the 1990's with significant progresses in sensors, actuators, and other enabling technologies (Fancher *et al.*, 2000; Hedrick *et al.*, 1991; Venovens *et al.*, 2000; Weinberger and Bubb, 2000; Yamamura *et al.*, 2001; Yi and Kwon, 2001) The goal of a vehicle cruise control system such as ACC and SG is a partial automation of the longitudinal vehicle control and the reduction of the workload of the driver at low vehicle speeds all the way down to zero velocity in busy urban traffic as well as at high speeds in highways. Since the DAS always work with a human driver co-existing, the ACC or SG system must be useful to the driver and the system's operation characteristics need to be similar to normal driving operation of the human driver. Therefore, the first step in designing a vehicle-following control strategy for application to ACC and/or SG systems is to analyze driving behavior characteristics of human drivers (Yi and Kwon, 2001).

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Human drivers' driving characteristics in various scenarios has been analyzed and based on the analysis a control system capable of modeling those characteristics accurately has been constructed to provide natural vehicle behavior in low-speed driving (Yi and Kwon, 2001). The time gap (TG) and the time-to-collision (TTC) have been used in the analysis of driving behavior characteristics when following a preceding vehicle (Yi and Kwon, 2001). Driver behavior in adjusting the clearance during vehicle following was analyzed by focusing on the target clearance deviation for application to an ACC design (Bose and Ioannou, 2001). A longitudinal driver model has been developed based on real-world driving data and has been used to evaluate the impact of ACC vehicles on traffic flow (Shiler *et al.*, 1987). An adaptive-fuzzy controller for ACC has been proposed by Holve *et al.* (1995). The type of driver parameter has been introduced and has been used to adapt the controller for enhancement of the driver acceptance (Holve *et al.*, 1995). Comparisons between ACC and manual driving and a general procedure for creating string-stable ACC systems were presented by Fancher *et al.* (2000).

In this paper, a vehicle cruise control strategy based on human drivers driving characteristics has been presented. Human drivers driving patterns have been investigated using real-world driving test data obtained from 125 participants. The control algorithm has been designed to incorporate the driving characteristics of the human drivers and to achieve natural vehicle behavior of the controlled vehicle that would feel comfortable to the human driver. The vehicle longitudinal control algorithm developed in our previous research (Lee and Yi, 2002; Yi *et al.*, 2002) has been extended based on the analysis to incorporate the driving characteristics of the human drivers into the control strategy. Vehicle following characteristics of the cruise controlled vehicle have been investigated using a validated vehicle simulator. The vehicle following characteristics of the cruise controlled vehicles have been compared to those of the manual driving.

2. ICC VEHICLE SIMULATOR

Figure 1 shows hardware configuration of ACC driving simulator which is developed for this study.

Driving simulator which is developed for vehicle dynamic analysis or validation of controller consists of real-time controller which produces vehicles motion and responses in real-time, computers interfacing between driver and real-time controller and real-time rendering tool representing visual and audio information computed in real time and these subsystem must be integrated organically to succeed in real-time simulator. Nowadays driving simulator fulfilled these points somewhat already developed, but there is problems like not guaranteeing real time computation of motion because it doesn't adapt RCP, not computing real-time rendering and traffic in communication, so it can not be applied to real-time vehicle simulation or reduce realism during simulations.

Problems appeared in conventional driving simulator can be eliminated and improved in this study and utilize and maximize ACC driving simulator to test and validate controller of vehicles.

2.1. Configuration of ICC Vehicle Simulator

ACC driving simulator consists of real-time motion system,

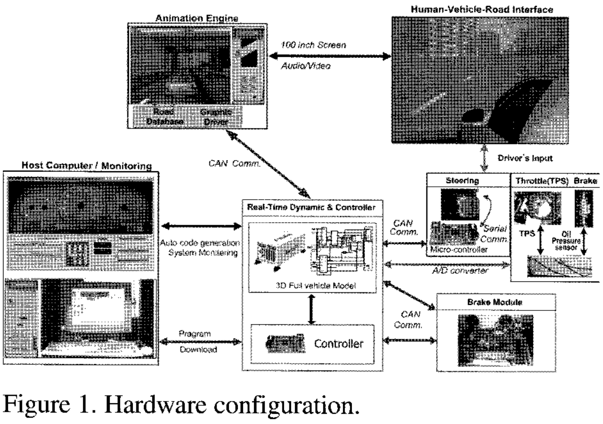


Figure 1. Hardware configuration.

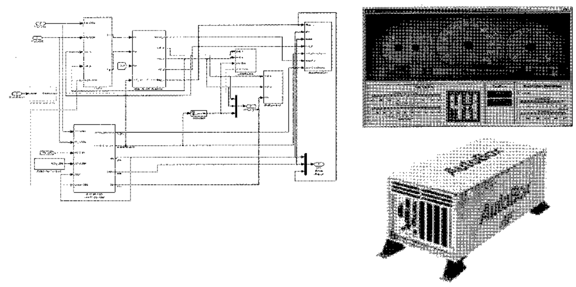


Figure 2. ACC simulation program and simulation engine.

visual & audio system, sensors which take driver's inputs and other subsystems.

2.1.1. Host computer

ACC algorithm is programmed with MatLab/Simulink of Mathworks as shown in Figure 2 and this program can be modified by host computer. Host computer also can compile, execute and download program to RCP device, AutoBox, through ethernet communication and control this program simulation tasking such as starting and stopping simulation, changing parameters, and monitoring and capturing simulation results in real-time.

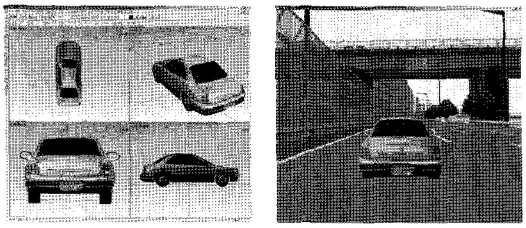
2.1.2. Simulation engine

Most important feature of ACC driving simulator is guaranteeing real-time performance because all the subsystems are designed and integrated considering real-time performance. ACC driving simulator has better real-time performance than conventional simulator which is based on workstation or PC and easy to use, flexible for modification of control parameters. The simulation engine, AutoBox (DS1005) of dSPACE, consists of Power PC 750 800 MHz processor and several data acquisition board (DS2201) and communication board (DS4302).

2.1.3. Graphic engine

Visual system is most important in assuring realism of vehicle simulator because driver can get all driving information. To guarantee of continuity and realism of image viewed in the screen, visual system and real-time rendering is very important facto, so it should be considered in the first stage of design. But driving environment models focused on the shape of the objects need excessive polygons, its material properties and visual characteristics like shades, brightness or darkness. So it costs too much time and efforts when we make model. Nevertheless this endeavor, complex shape information makes impossible to run in real-time rendering.

MultiGen Creator is used to solve these problems. MultiGen Creator is the industry's leading software for creating highly optimized, high fidelity real-time 3D



(a) Graphic object (b) Real-time rendering

Figure 3. Graphic object modeling and rendering.

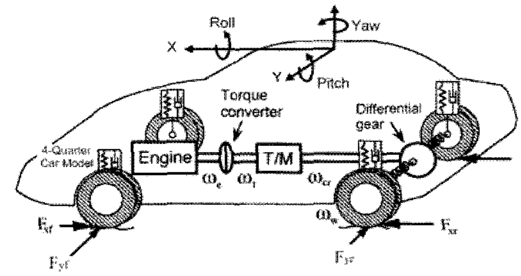


Figure 5. Full vehicle dynamic model.

content for use in visual simulation, urban simulation and other applications. The integrated and extensible toolset puts more interactive real-time 3D modeling power in your hands than any other modeler like 3D MAX or 3D STUDIO which is based on openGL. Mapping image and number of polygons from viewpoint also divided by level of detail. Objects modeled by 3D modeling tool require both powerful computer and real-time rendering tool. VEGA is used ad real-time rendering tool. To operate theses modeling tool and rendering tool, graphic engine consists of dual AMD opteron processor, Quadro Fx100 graphic subsystems.

Figure 3(a) shows the objects used in virtual environments and typical driving scenario is shown in Figure 3(b) as rendering images.

2.1.4. Input/Output systems

Driver's inputs can be measured by sensors such as brake pressures, throttle angle, and steering angle sensors as shown in Figure 4. Steering angle sensor which resolution with 0.5° and produce gray code with SSI (Synchronous Serial Interface) is absolute type encoder. TPS (Throttle Positioning Sensor) is installed this simulator to measure throttle angle and oil pressure sensor of Kyowa measure brake pressure. Electric DC motor also used to give driver feedback force when he press brake pedal.

Measured driver's inputs are transmitted by rapid control devices DS2201 and DS4302. DS2201 has 20 A/D channels, up to 12 bit resolution 8 D/A channels, up to 12 bit resolution and can receive throttle and brake inputs

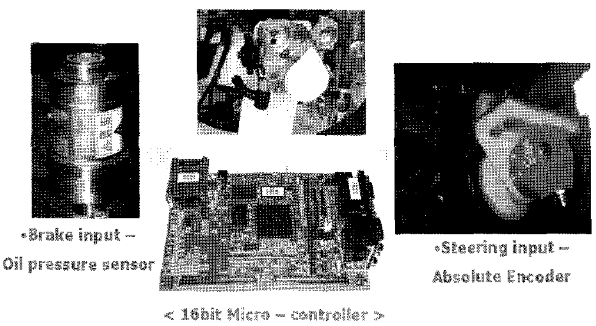


Figure 4. Drivers Input/Output system.

and deliver to simulation engine. DS4302 have 4 channels CAN (Control Area Network) signal which is transmitted and converted from gray code produced by 16bit C-167 family micro controller and also deliver vehicles position, orientation, viewpoint and motion of environment objects generated in simulation engine to graphic engine.

CAN communication, serial distributive network, developed by BOSH allowed certain ID to some necessary data among the subsystems' data and can share subsystems each other because it adapt signal transmitting by difference of voltage. So it does not influenced by noise and have high performance of error detection and most of all it guarantee the high speed of networking rather than Ethernet or RS-232C used in the conventional simulators. Real-time simulator can be possible by eliminating all obstacles to impede real-time simulation.

2.2. Validation of Vehicle Model

Most important factor of vehicle simulator is how it can be represented virtual environment with reality.

The full vehicle dynamic model performs real-time simulations in the driving simulator. Proposed vehicle model is consists of vehicle body, suspension, nonlinear tire model and power-train models as shown in Figure 5. Vehicle body with 6 degrees of freedom is connected to 4-quarter car suspensions with roll bar. The power-train model includes static engine and torque converter model, automatic transmission with gearshift map and driving shafts. Pacejka's tire model has been used to compute tire forces of each wheel (Ha *et al.*, 2003).

2.2.1. Longitudinal motion

Vehicle test data have been used to validate the driving simulator. Figure 6 shows a comparison between vehicle test data and simulator driving data with just throttle input and Figure 7 shows response with throttle and brake inputs. When vehicle speed is increased and decreased similar to the actual vehicle test results, drivers response is quite similar in longitudinal direction.

2.2.2. Lateral motion

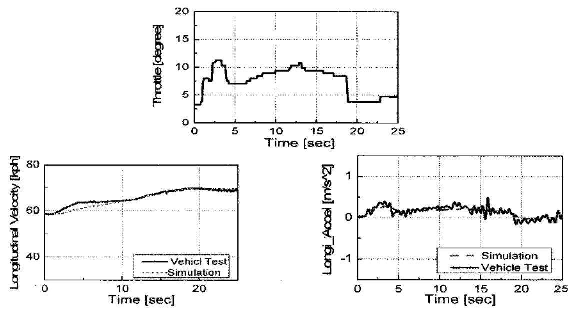


Figure 6. Vehicle longitudinal response with no brake.

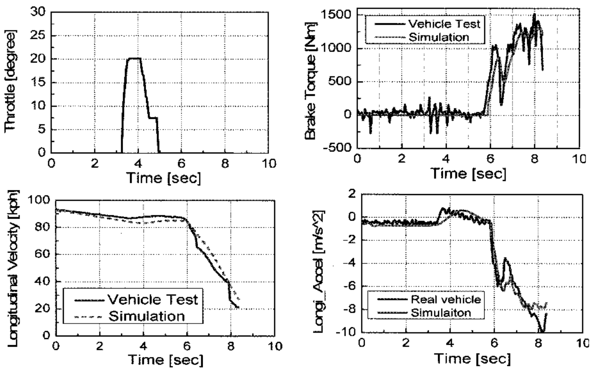


Figure 7. Vehicle longitudinal response with brake.

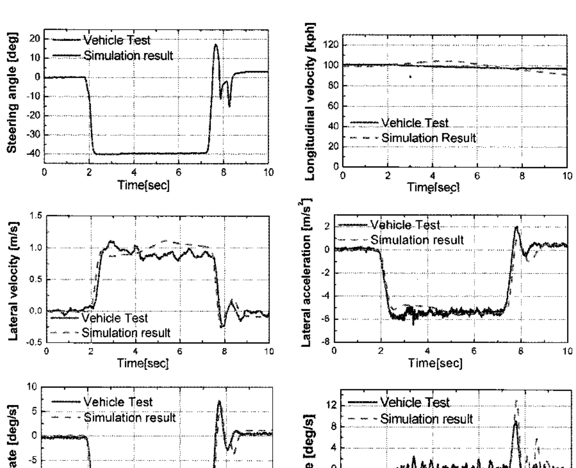


Figure 8. Vehicle lateral response with step steer.

Step steer test is conducted to examine the vehicle lateral responses. The driver who performs the test on a driving simulator keeps an approximately 100 kph similar to actual test data. The magnitude of a steer angle is 40 deg and keeping for 5 sec. Figure 8 shows that the step steer input results as time histories. And vehicle responses, lateral velocity, lateral acceleration, yaw rate, roll rate are also quite similar to the actual test results as shown.

The comparison between the driving simulator and vehicle test results both longitudinal and lateral direction shows that proposed simulator is very feasible for describing actual vehicle dynamic behaviors.

3. VEHICLE FOLLOWING CONTROL DESIGN

ACC systems should be acceptable to drivers. In order to be acceptable to human drivers and passengers, the ACC systems need to be constructed to provide smooth naturalistic vehicle behavior similar to naturalistic driving of the human drivers. A vehicle cruise control strategy has been designed based on the analysis of human drivers driving characteristics. Human drivers driving patterns have been investigated using real-world driving test data obtained from 125 participants. The vehicle longitudinal control algorithm has been designed to incorporate the driving characteristics of the human drivers and to achieve natural vehicle behavior of the controlled vehicle that would feel comfortable to the human driver.

Two steps design approach has been used in the design of vehicle speed and clearance control. Firstly, the desired acceleration of the subject vehicle has been designed using velocity information and range clearances that measured using a radar sensor. Secondly, the throttle-brake ontrol laws were designed so that actual subject vehicle acceleration tracks the desired acceleration profile. Since the torque converter plays an important role in the stop-and-go driving situations, torque converter dynamics has been accounted in the design of the throttle-brake control law(Lee and Yi, 2002).

3.1. Design of Desired Acceleration Profile

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

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

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, $u=-k\cdot x$, are chosen to minimize the cost function:

$$J = \int_0^{\infty} \left(x^T Q\, x + u^T R\, u\right) dt] \quad (2)$$

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

$$Q = \begin{bmatrix} \rho_1 & 0 \\ 0 & \rho_2 \end{bmatrix}, \quad R = [r]. \quad (3)$$

The weighting factors, ρ_1, ρ_2 and r, have been chosen to give a tradeoff between performance and ride comfort and to obtain smooth naturalistic vehicle behavior. In this study, alternative weighting factors have been used for low, medium and high speed ranges.

Desired acceleration is represented by

$$a_{des}(t) = \begin{cases} a_{max}(v_c(t)) & if \quad a_*(t) > a_{max}(v_c(t)) \\ a_*(t) & if \quad a_{min}(v_c(t)) \le a_*(t) \le a_{max}(v_c(t)) \\ a_{min}(v_c(t)) & if \quad a_*(t) < a_{min}(v_c(t)) \end{cases} \quad (4)$$

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

where $k_1(\cdot)$ and $k_2(\cdot)$ are the gains as a function of the subject vehicle speed, $v_c(t)$, c_d is the desired clearance, c is the actual clearance, v_p and v_c are the velocity of the preceding vehicle and the velocity of the controlled vehicle, $a_{max}(\cdot)$ and $a_{min}(\cdot)$ are the maximum acceleration and the minimum acceleration (i.e. the maximum deceleration) as a function of the vehicle speed. The gains can be chosen by alternative design methods and have been determined using a design method based on optimal control theory in this study. In this study, the desired clearance defined by the equation (5) has been used

$$c_d = c_0 + \tau \cdot v_p \quad (5)$$

where the c_0 and τ were determined from the analyzed results for human drivers manual driving data. Design parameters of the cruise control law such as c_0, τ, $a_{max}(\cdot)$ and $a_{min}(\cdot)$ have been tuned so that the behavior of the cruise controlled vehicle is similar to those of human manual driving under all the traffic situations, i.e., both high-speed highway traffic and dense urban traffic (Pipes, 1953).

In an emergency driving situation such as a case that the Stop-and-Go Cruise control algorithm proposed in this paper can not prevent the vehicle-to-vehicle distance from dropping to an unsafe level, a warning should be provided to the driver and a collision avoidance brake control algorithm which generates a large controlled deceleration to avoid a collision or to reduce the severity of accidents should be used.

3.2. Throttle-Brake Control Law

The throttle/brake controller controls the throttle/bra-ke actuators such that the vehicle acceleration tracks the desired acceleration, which is designed in previous research. Depending on the desired acceleration that the controlled vehicle must follow, the controller applies throttle or brake control. Throttle-brake switching has been determined using a switching line which has been obtained from zero-throttle acceleration data of the vehicle (Zhou and Peng, 2004). The switching line indicates the vehicle acceleration (the minimum acceleration, a_{min}) when the throttle is closed (α=0) for a given vehicle velocity. The minimum acceleration line has been used as a switching line in the throttle/brake controls. The controller applies throttle control when $a_{des} \ge a_{min} + h$ or brake control when $a_{des} \le a_{min} - h$ for a given vehicle speed. Switching logic with a boundary layer is necessary to avoid frequent switching between throttle and brake controls.

A throttle control law has been derived under a no-slip condition of the driving wheels. At a low level of acceleration, wheel slip is quite small. The no-slip assumption has been incorporated in previous throttle/brake control designs for vehicle longitudinal control in Intelligent Cruise Control or in Automated Highways (Fancher *et al.*, 2000; Holve *et al.*, 1995; Shiler *et al.*, 1987). The torque converter pump and turbine speed ratio varies significantly in low-speed and stop-and-go driving situations and the torque converter plays an important role in those cases. Therefore, torque converter dynamics should be considered in the development of the throttle control law.

When the desired acceleration, a_{des}, for a given vehicle velocity is greater than the switching line, i.e., the throttle control region, the desired turbine torque of the transmission, $T_{t,des}$, is computed from the equations of motions for the vehicle as follows:

$$\begin{aligned} T_{t,des} &= R_g T_{s,des} \\ &= R_g \cdot r \cdot [M_v(a_{des} + K_p e_a + K_i \textstyle\int e_a dt) + F_L] \\ e_a &= a_{des} - a \end{aligned} \quad (6)$$

where R_g is the gear ratio from the turbine to the wheels, $T_{s,des}$ the desired shaft torque of the driving axle shaft, r the effective tire radius, M_v the vehicle mass, K_p and K_i gains, a the actual acceleration of the vehicle, and F_L the driving resistance load.

The desired engine speed, $\omega_{e,des}$, is computed from the desired turbine torque, $T_{t,des}$, using a torque converter map as follows

$$\omega_{e,des} = TCM^{-1}(\omega_t, T_{t,des}) \quad (7)$$

where TCM^{-1} indicates the inverse torque converter map. The torque converter map can be obtained from torque converter test results and is provided by torque converter manufacturers. It provides relationships between the turbine torque, T_t, the pump torque, T_p, the pump speed, ω_p, which is identical to the engine speed,

ω_e, and the turbine speed, ω_t, as follows:

$$T_t = TCM\ (\omega_e,\ \omega_t) \tag{8}$$

The desired throttle angle for the desired engine speed, $\omega_{e,des}$, is computed from the desired net engine torque, $T_{net,des}$, using the engine map as follows:

$$\alpha_{des} = EM^{-1}(\omega_e,\ T_{net,des}) \tag{9}$$
$$T_{net,des} = T_p(\omega_e,\ \omega_t) + K_e(\omega_{e,des} - \omega_e)$$

where EM^{-1} is inverse engine map and K_e the gain. Typically the engine map is provided by the engine manufacturer as a lookup table. Since engine dynamics are represented as follows:

$$J_e\frac{d\omega_e}{dt} = T_{net}(\omega_e, \alpha) - T_p(\omega_e, \omega_p) \tag{10}$$

It can be shown that the following engine dynamics can be obtained using the throttle control law (9) and the engine speed, ω_e, tends to the desired engine speed with first order dynamics of the following forms:

$$\tau_e\frac{d\omega_e}{dt} + \omega_e = \omega_{e,des} \tag{11}$$

where $\tau_e\left(=\frac{J_e}{K_e}\right)$ is the time constant.

It has been recognized that the control law with large gains results in a very jerky driving behavior due to the torque production delay of the engine. The gains, K_p, K_i, and K_e, have been tuned so that the effect of model errors and engine torque production delay on the control performance is minimized. The throttle angle has been controlled using a stepper motor to minimize the error between the actual and the desired throttle angles.

The brake torque is applied only when the engine braking is not sufficient to follow the desired acceleration profile. When the desired acceleration for a given vehicle velocity is smaller than the switching line, i.e., the brake control region, the desired brake torque, $T_{b,des}$, is computed from the equations of the motion of the vehicle as follows:

$$T_{b,des} = -r(M_v a_{des} + F_L) + T_s \tag{12}$$

The shaft torque, T_s, is computed using the engine map as follows:

$$T_s = \frac{1}{R_g}T_{net}(\omega_e, 0) \tag{13}$$

Since the total brake torque is proportional to the brake pressure, the desired brake pressure, $p_{w,des}$, can be obtained by the equation:

$$p_{w,des} = \frac{1}{K_b}T_{b,des} \tag{14}$$

where K_b is the lumped gain for the entire brake system. K_b lumps all the uncertainties in the brake model from the brake pressure to the brake torque. The parameter, K_b, has been obtained from experimental data. A value of K_b=850 Nm/Pa was used and it provides a good fit to one set of the experimental results.

The brake actuator system dynamics are not negligible and the brake control system shows nonlinear characteristics. Therefore, a feed forward plus proportional-integral-derivative (PID) control law is used to control the brake pressure:

$$u = g^{-1}(p_{w,des}) + P\cdot e_p + I\cdot\int e_p dt + D\cdot e_p$$
$$e_p = p_{w,des} - p_w \tag{15}$$

where u means the applied duty input to the brake solenoid valve, p_w the wheel caliper pressure, P, I, D the gains and $g(\cdot)$ the function representing the relationship between the duty input to the brake solenoid valve and the steady state values of the brake pressure, i.e.:

$$p_w = g(u) \tag{16}$$

4. COMPARISONS BETWEEN ICC AND MANUAL DRIVING

The proposed cruise control strategies were compared to human drivers' manual driving. The performance of a cruise controlled vehicle with the proposed control strategy has been investigated via simulations using real driving data. Comparisons between human driver's manual driving and cruise control (ACC) in the case of

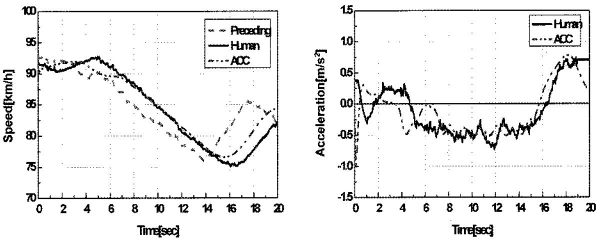


Figure 9. Comparisons between ACC and human driving at high speed.

Table 1. Closing accelerations.

	Acceleration[m/s²]		
	Preceding	Human	ACC
95%	–0.17	–0.33	–0.27
75%	–0.38	–0.39	–0.40
Mean	–0.44	–0.46	–0.43
25%	–0.51	–0.52	–0.49
5%	–0.62	–0.64	–0.51
Variance	0.02	0.01	0.01

closing on a slower moving preceding vehicle on a high speed city highway are shown in Figure 9. The preceding and human driver's data plotted in the Figure 9 are measured ones and the ACC data are simulated under the same following traffic situation. As shown in Figure 9, the speed, clearance and accelerations characteristics of the 'ACC' are similar to those of the manual driving. The closing acceleration characteristics of the preceding, manual driving and the ACC vehicles are summarized in Table 4. Mean, 25 percentile and 75 percentile values of the ACC are close to those of the human driver's manual driving.

5. CONCLUSIONS

Human drivers' driving behavior characteristics has been analyzed based on real-world driving data. A cruise control strategy has been investigated in comparison to the human drivers' manual driving. The control algorithm has been designed to incorporate the driving characteristics of the human drivers into the control algorithm and to achieve natural vehicle behavior of the cruise control vehicle that would feel comfortable to the human driver. The performance of the proposed cruise control strategy has been investigated using an ICC vehicle simulator based on rapid control prototyping. It has been shown that proposed control strategy can provide with naturalistic following performance similar to the human manual driving on both high speed driving and low speed stop-and-go situations. Investigation on the performance of the naturalistic driving with respect to string stability, and environmental and fuel economy considerations is the topic of our future researches.

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