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HUMAN-CENTERED DESIGN OF A STOP-AND-GO VEHICLE CRUISE CONTROL

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ABSTRACT–This paper presents design of a vehicle stop-and-go cruise control strategy based on analyzed results of the manual driving data. Human drivers driving characteristics have been investigated using vehicle driving data obtained from 100 participants on low speed urban traffic ways. 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 under low speed stop-and-go driving conditions. Vehicle following characteristics of the cruise controlled vehicle have been investigated using a validated vehicle simulator and real driving radar sensor data.

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

1. INTRODUCTION

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, 2004; Fenton and Bender, 1969; Germann and Isermann, 1995; Hedrick *et al*., 1991; Venhovens *et al*., 2000; Weinberger and Bubb, 2000; Yamamura *et al*., 2001). The goal of a vehicle cruise control system such as ACC and SG is 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 (Bose and Ioammou, 2001). 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 (Chien *et al*., 1994). 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 (Yamamura *et al*., 2001).

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 (Lee and Yi, 2002; Pipes, 1953). 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 driver behavior in adjusting the clearance during vehicle following was analyzed by focusing on the target clearance deviation for application to an ACC design (Iljima *et al*., 2000; Lee and Yi, 2002). A longitudinal driver model has been developed based on real-world driving data and has been used to evaluate the performance charateristics of controlled vehicles (Peng, 2002). An adaptive-fuzzy controller for ACC has been proposed by Holve *et al.* (2005). The type of driver parameter has been introduced and has been used to adapt the controller for enhancement of the driver acceptance. Comparisons between ACC and manual driving and a general procedure for creating string-stable ACC systems were presented by Fancher *et al.* (2004).

In this paper, a stop-and-go 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 100 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 in low speed stop-and-go driving situations. The cruise control strategy presentd in this study can be used in traffic situations such as congested highway traffic and dense urban traffic ways. The vehicle

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longitudinal control algorithm has been developed to incorporate the driving characteristics of the human drivers into the control strategy (Rajamani *et al.*, 1998; Shladover, 1978). Vehicle following characteristics of the cruise controlled vehicle have been investigated using a validated veicle simulator. The vehicle following characteristics of the cruise controlled vehicles have been compared to those of the manual driving.

2. DRIVING CHARACTERISTICS OF HUMAN DRIVERS

Human drivers driving characteristics have been analyzed using real-world driving data. The objectives of the analysis are to find good characteristic parameters of the human drivers and to develop a vehicle following control algorithm which provides natural vehicle behavior that would feel comfortable to the driver. 125 human drivers driving data have been collected using a vehicle equipped with sensors for ranges, range rates and visual images of preceding vehicles and human drivers driving inputs such as throttle, brake and steering.

Figure 1 shows a test vehicle used in this study. The vehicle is equipped with a millimeter wave (MMW) radar sensor, a laser radar, a CCD camera, accelerometers, a brake pedal force sensor, a steering angle sensor, a yaw rate sensor, a data logging computer and a display monitor. Range and range rate have been measured using a MMW radar and a laser radar. Vehicle speed, engine RPM, turbine speed of the torque converter, throttle position and gear status have been obtained from engine control unit (ECU) via CAN (Controller Area Network).

2.1. Human Driver's Range Clearance Characteristics

Measured clearance data of 100 human drivers for low speed stop-and-go urban driving are analyzed in this study. Of the alternative spacing policies for vehicle following, constant time gap policy and constant clearance policy have received considerable attention in the literature. Steady following has been defined as a following situation with small relative velocity. The inverse of the time to collision (TTC^{-1}) has been used to define the driver's steady following situations in this study.

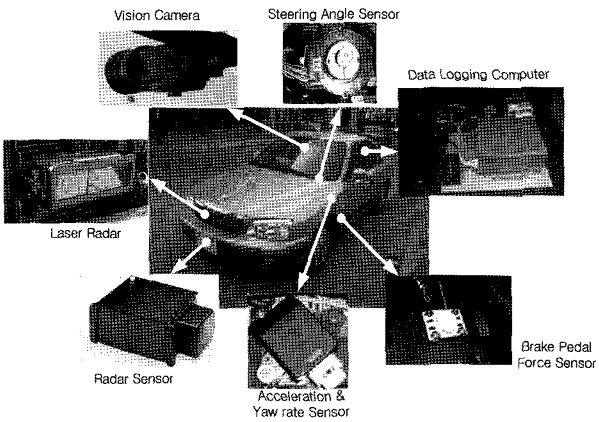


Figure 1. Test vehicle for analysis of driving characteristics of human drivers.

The time to collision (TTC [sec]) is defined as

$$TTC = \frac{c}{v_s - v_p} \tag{1}$$

where c is the range clearance between the preceding and subject vehicles, v_s is the subject vehicle velocity, and v_p is the peceding vehicle velocity. In a case that the preceding vehicle velocity is constant, the subject vehicle speed converges to the preceding vehicle speed and the subject vehicle follows the preceding vehicle at nearly a constant time gap. Therefore the human driver's steady following situations can be defined as a situation with small value of the inverse of the time to collision (TTC^{-1}), i.e.,

$$|TTC^{-1}| \le \varepsilon$$

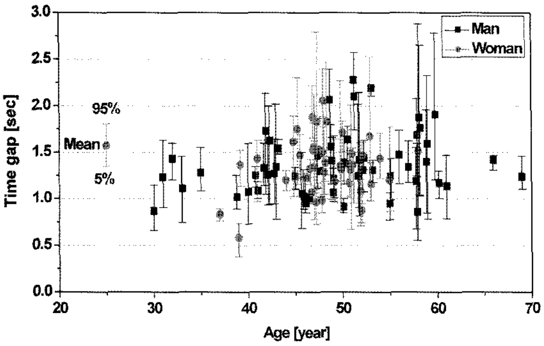
In this study $\varepsilon = 0.05$ has been used.

A second order equation of the form given in equation (2) has been used to represent the relationships relating clearance and vehicle speed in the steady following situations

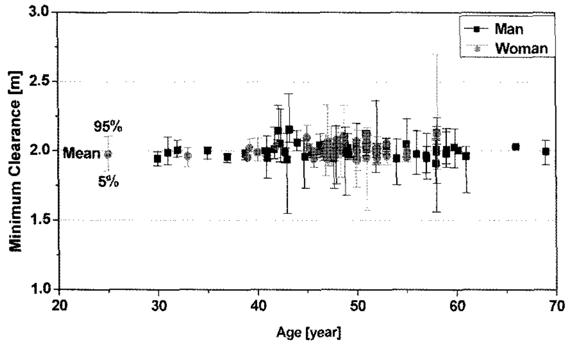
$$c = c_0 + \tau \cdot v + \gamma \cdot v^2 \tag{2}$$

where v is the vehicle speed, c_0 is the zero speed clearance, τ is the linear coefficient, and γ is the cubic coefficient. The relationships between the clearance and the vehicle velocity in steady following situations are investigated using the measured data obtained from the driving tests on busy uban traffic ways. It was found that there exist three types of human drivers' steady following characteristics. The three types can be characterized by the cubic coefficient, i.e., types of zero, positive, and negative γ. Although Fancher *et al.* (2000) illustrated that γ was less than zero for all the 143 drivers analyzed in their study, three different types of human drivers' following characteristics were observed in our study (Yi *et al.*, 2002; 2001; Yi and Kwon, 2001).

If γ is equal to zero, the clearance model represented by the equation (2) is the constant time gap policy. Although there exist three types of human drivers' steady following characteristics, it was found from the results obtained by processing the sets of human manual driving data for 100 different drivers that human driver's steady following characteristics would be well represented by the constant time gap policy. Time-gaps and zero speed clearances, i.e., minimum clearances, of male and female



(a) Time-gaps of human drivers



(b) zero speed clearnce of human drivers

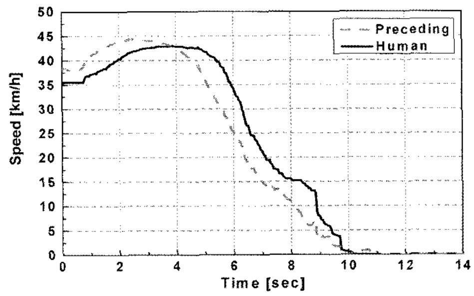
Figure 2. Time gap and zero speed clearnce of human drivers.

drivers were compared in Figure 2. The upper and lower bars indicate the 95th and 5th percentile values of the time-gap. Mean values of the zero speed clearance were approximately 2 meters and there was no significant difference between the male and female drivers.

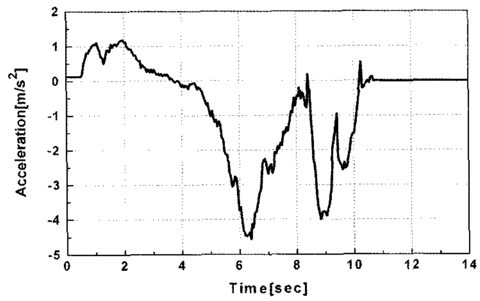
2.2. Human Driver's Time Delay

Human driver's time delay has been analyzed using the measured data for both deceleration-to-stop and stop-and-start situations, i.e., throttle-to-brake and brake-to-throttle switchings, respectively. Comparison of vehicle speeds, accelerations of subject vehicle, and human driver's throttle/brake inputs for a typical deceleration-to-stop case in an urban traffic way are shown in Figure 3. Same data for a typical stop-and-start situation are plotted in Figure 4. Typical time delays of the human drivers for throttle/brake switching are shown in Figure 3(c) and Figure 4(c).

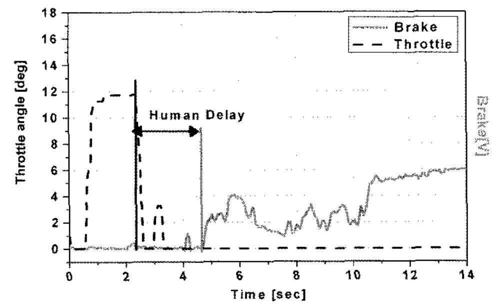
Time delay characteristics of the human drivers for both stop and start driving situations are summarized in Table 1. The mean values of the time delays for deceleration-to-stop and stop-and-start acceleration cases were 0.90 seconds and 0.81 seconds respectively. Five to ninety five percentile values and variance of the time



(a) Comparison of vehicle speed



(b) Acceleration of subject (human) vehicle



(c) Throttle and brake inputs

Figure 3. Deceleration to stop.

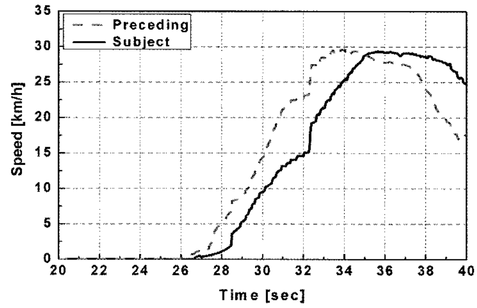
Table 1. Time delay characteristics of human drivers.

	Time-Delay [sec]					
	Mean	95%	75%	25%	5%	σ
Deceleration	0.90	1.53	1.42	0.54	0.25	0.20
Acceleration	0.81	1.61	1.02	0.46	0.31	0.18

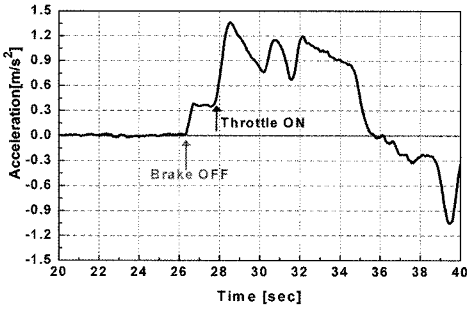
delays are summarized in Table 1.

2.3. Acceleration Characteristics of Human drivers in Low Speed Stop-and-Go Driving Situations

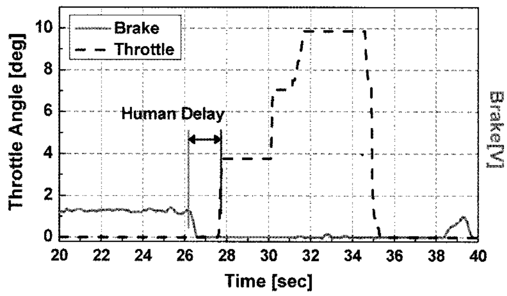
Closing accelerations on a slower moving preceding vehicle for low speed busy urban traffic cases have been computed from measured data. Stop-and-start accelerations on a faster starting preceding vehicle on a busy urbn



(a) Comparison of vehicle speed



(b) Acceleration of subject (human) vehicle



(c) Throttle angle and brake inputs

Figure 4. Stop-and-start.

Table 2. Stop-and-start accelerations on a faster starting preceding vehicle.

Acceleration [m/s^2]			
Region	Mean	95%	5%
Deceleration-to-Stop Acceleration	−1.92	−0.62	−3.21
Zero Throttle Accelerations	0.39	0.51	0.29
Stop-and-Start Accelerations	1.14	1.5	0.71

traffic way have been also computed. Comparison of preceding and subject vehicle speeds, accelerations of the subject vehicle, and human driver's throttle/brake inputs for a low speed case in a busy urban traffic way are shown in Figure 3. Closing acceleration characteristics for low speed cases and stop-and-start acceleration characteristics on a faster starting preceding vehicle are compared in Table 2. The data for the low speed case are all for speeds below 45 kph. It should be noted that the magnitude of the decelerations for stop is significantly large compared to that of the stop-and-start accelerations. Mean of the zero-throttle acceleration was 0.39 m/s^2. Mean value of the start accelerations was 1.14 m/s^2.

3. HUMAN-CENTERED VEHICLE STOP-AND-GO CRUISE CONTROL STRATEGY

The stop-and-go vehicle control algorithm has been designed based on the analysis of the manual driving data to incorporate the driving characteristics of the human drivers into the control strategy. A two step design approach has been used in the design of vehicle speed and clearance control. Firstly, the desired acceleration of the subject vhicle has been designed using velocity informations and range clearances that measured using a radar sensor. Secondly, the throttle-brake ontrol laws were designed so that actual subject vehicle acceleration trcks 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-brke control law.

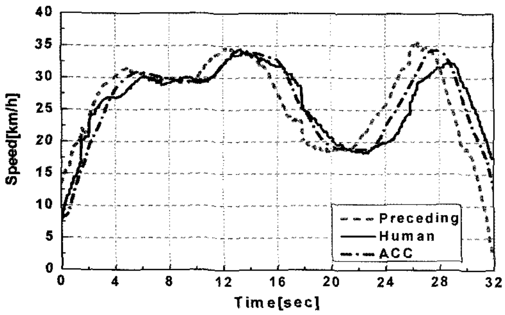
The control strategy is represented by

$$a_{des}(t) = \begin{cases} a_{\max}(v_c(t)) & if \quad a_*(t) > a_{\max}(v_c(t)) \\ a_*(t) & if \; a_{\min}(v_c(t)) \le a_*(t) \le a_{\max}(v_c(t)) \\ a_{\min}(v_c(t)) & if \quad a_*(t) < a_{\min}(v_c(t)) \end{cases} \tag{3}$$

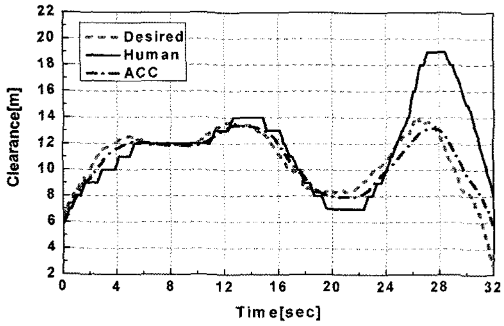
where $k_1(\cdot)$ and $k_2(\cdot)$ are the gains as a function of the subject vehicle speed, $v_c(t)$, c_d is the desired clearance, c is the actual clearance, v_p and v_c are the velocity of the preceding vehicle and the velocity of the controlled vehicle, $a_{\max}(\cdot)$ and $a_{\min}(\cdot)$ are the maximum acceleration and the minimum acceleration (i.e. the maximum deceleration) as a function of the vhicle 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 (4) has been used

$$c = c_0 + \tau \cdot v_p \tag{4}$$

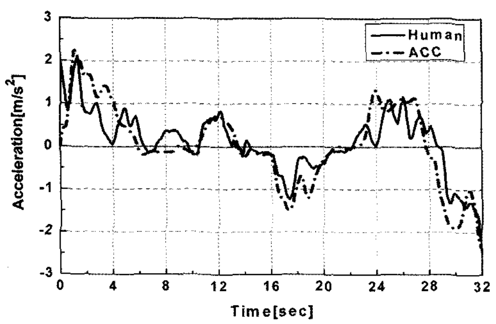
where the c_o and τ were determined from the analyzed results for human drivers manual driving data. All the design parameters of the cruise control strategy such as c_o, τ, $k_1(\cdot)$, $k_2(\cdot)$, $a_{\max}(\cdot)$, and $a_{\min}(\cdot)$ have been tuned so that the behavior of the cruise controlled vehicle is similar to those of human manal driving.



(a) Comparison of vehicle speeds



(b) Comparison of clearances



(c) Comparison of accelerations

Figure 5. Comparisons between cruise control and human driving at low speed on busy urban city traffic.

4. SIMULATION RESULTS

The performance of a cruise controlled vehicle with the proposed control strategy has been investigated via simulations using real driving data. Comparisons between huamn driver's manual driving and cruise control (ACC) in the case of low speed driving on a busy urban traffic way are shown in Figure 5. The preceding and human driver's data plotted in the Figure 5 are masured ones and the ACC data are simulated under the same following traffic situation. As shown in Figure 5, the speed, clearance and accerelartions characteristics of the 'ACC' are similar to those of the manual driving.

Table 3. Comparisons of acceleration characteristics for the stop-and-start situations.

	Acceleration [m/s^2]		
	Preceding	Human	ACC
95%	1.89	1.50	2.02
75%	1.56	1.43	1.38
Mean	1.28	1.14	1.11
25%	1.03	0.83	0.79
5%	0.52	0.71	0.43
Variance	0.17	0.27	0.22

Table 4. Comparisons of acceleration characteristics for the the deceleration-to-stop situations.

	Acceleration [m/s^2]		
	Preceding	Human	ACC
95%	–0.62	–0.45	–0.54
75%	–1.29	–1.17	–1.49
Mean	–1.92	–2.17	–1.87
25%	–2.79	–3.10	–2.58
5%	–3.21	–4.31	–3.12
Variance	0.71	1.5	0.62

Comparisons of acceleration characteristics between the manual driving and the ACC under the stop-and-start and the deceleration-to-stop on congested highway and/or dense urban traffic way are summarized in Table 3 and Table 4. The closing acceleration characteristics of the preceding, manual driving and the ACC vehicles for the stop-and-start situations are summarized in Table 3. Mean, 25th and 75th percentile values of the ACC are close to those of the human driver's manual driving. Mean and variation of the decelerations in deceleration-to-stop situations are very large compared to those of the stop-and-start situations. It is observed that the ACC leads to similar characteristics of the human manual driving.

5. CONCLUSION

A stop-and-go cruise control strategy has been designed. Human drivers' driving behavior characteristics has been analyzed based on real-world driving data. 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 via closed-loop simulations using data measured from a mmWave radar during test driving in low speed busy urban traffic ways and conjested city freeways. It has been shown that the proposed control strategy can provide with naturalistic following performance similar to the human manual driving.

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