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A Driver-Adaptive Stop-and-Go Cruise Control Strategy

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Abstract – *A driver-adaptive stop-and-go (SG) cruise control strategy is proposed. The control strategy has been designed to incorporate the driving characteristics of the human drivers and to achieve natural vehicle behavior of the SG controlled vehicle that would feel comfortable to the human driver. Vehicle following characteristics of the SG vehicle with the driving behavior parameter estimation have been investigated using real-world vehicle driving test data and a validated simulation package. The vehicle following behavior of the SG vehicle with the adaptive control strategy is quite close to that of manual driving. It can be expected that a more natural and more comfortable vehicle behavior would be achieved by the use of the driver-adaptive SG control strategy.*

Keywords: Adaptive Cruise Control, Clearance, Time-Gap, Time-to-Collision, Vehicle.

1 Introduction

Vehicle longitudinal control for application to automated highway systems has been in progress for several decades. Driver assistance systems (DAS) like ACC (Adaptive Cruise Control) have been active topics of research and development since the 1990's with significant progresses in sensors, actuators, and other enabling technologies [1-5]. The goal of a Stop and Go Cruise (SG) system 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. 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 SG systems is to analyze driving behavior characteristics of human drivers [1].

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 [1]. 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 [1]. Driver behavior in adjusting the clearance during vehicle following was analyzed by focusing on the target clearance deviation for application to an ACC design [11]. 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 [12]. An adaptive-fuzzy controller for ACC has been proposed by Holve, et al. [13]. The *type of driver* parameter has been introduced and has been used to adapt the controller for enhancement of the driver acceptance [13].

In this paper, a driver-adaptive control strategy for stop-and-go systems is proposed. Human drivers driving characteristics have been analyzed using real-world driving data. The vehicle longitudinal control algorithm developed in our previous research [14,15] has been extended based on the analysis to incorporate the driving characteristics of the human drivers into the control strategy. A driving characteristic parameters estimation algorithm has been developed. The driving characteristics parameters of a human driver have been estimated during manual driving using the recursive least-square algorithm and then the estimated ones have been used in the controller adaptation. The vehicle following characteristics of the SG vehicles with and without the driving behavior parameter estimation algorithm 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.

Figure 1 shows a test vehicle used in this study. The vehicle is equipped with a millimeter wave (MMW) radar sensor, accelerometers, a brake pedal force sensor, a data logging computer and a display monitor. Range and range rate have been measured using the MMW radar sensor. 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).

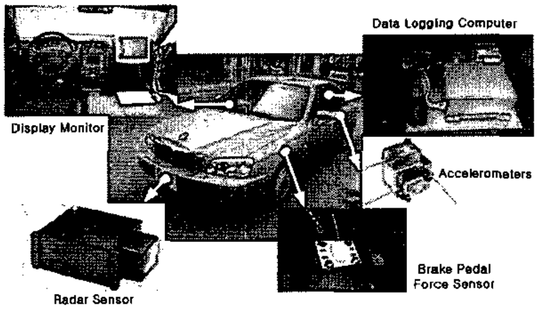


Fig. 1 Test vehicle for analysis of driving behavior characteristics of human drivers

Of the alternative spacing policies for vehicle following, constant time gap policy and constant clearance policy have received considerable attention in the literature [9,15]. It has been revealed from the analysis of the vehicle driving test data that a combination of the constant time gap policy and the constant clearance policy [14] can represent the driving behavior of human drivers. The actual clearance, c, of human drivers during front vehicle following in the driving tests can be modeled as follows:

$$c = v_p \cdot \tau + c_0 \tag{1}$$

where τ is the time gap, and c_0 is the minimum clearance to be maintained when the vehicle speed is zero. Time-gaps for twenty human drivers are compared in Fig. 2. The square and triangle indicate mean values for male and female drivers, respectively. The upper and lower bars indicate the maximum and minimum values of the time-gap when the inverse TTC is less than ε which is a small constant.

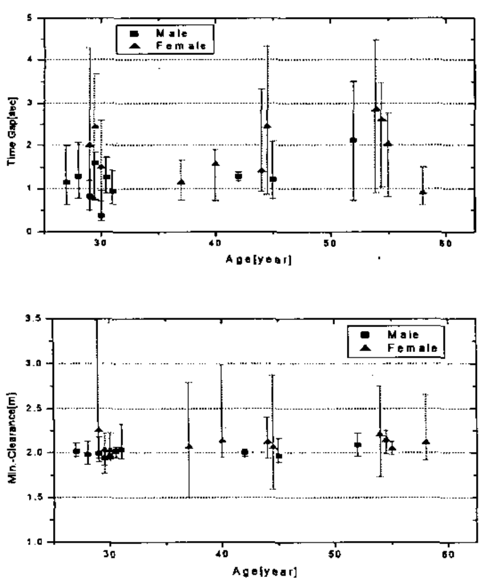


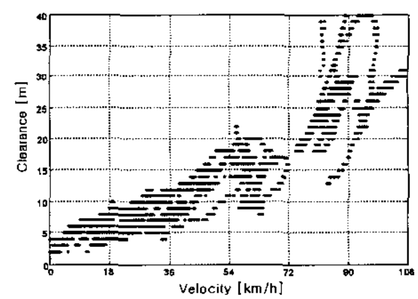
Fig. 2 Time-gap of human drivers

The estimated time gaps and minimum clearances for three drivers are compared in Table 1. Time gap varies from 0.67 to 1.70 seconds and the minimum clearance from 1.64 to 4.30 meters.

Table 1. Measured time gaps and minimum clearances

Human Driver	Time-gap [seconds]	Min. Clearance [m]
Driver_11	0.67	2.25
Driver_12	1.25	4.30
Driver_13	1.70	1.64

Based on the analysis of the driving test data, the driving scheme of a human driver can be figured out as illustrated in Fig. 3. The desired clearance of a driver can be represented as the solid line of the expression (1). It is interesting to note from the data shown in Fig. 3 (a) that the state space of the clearance and the velocity can be divided as three regions, i.e., pursuit (throttle control), dangerous (brake control) and comfortable (following) zones as shown in Fig. 3 (b). The desired clearance varies depending on the type of the drivers, road conditions, weather, etc. The SG cruise controller should be designed so that the natural vehicle behavior that would feel comfortable to the driver can be achieved. Therefore, the control scheme of the SG cruise controller should be similar to the driving scheme of the driver illustrated in Fig.3 (b). Since the characteristic parameters, the time gap and the minimum clearance, are driver dependent, they need to be adapted during manual driving in order to achieve natural vehicle behavior that would not feel strange to the driver.



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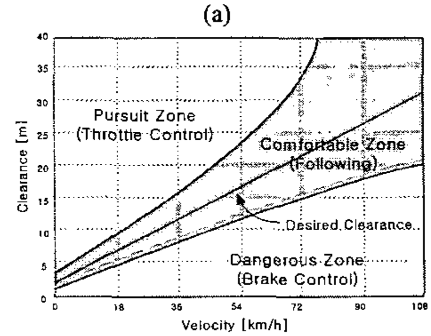


(b)

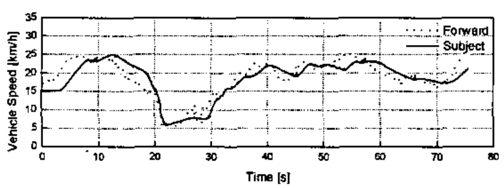
Fig. 3 Driving scheme of a human driver

Fig. 4 (a) shows a comparison of preceding and subject vehicle speeds during following. Fig. 4 (b) and (c) show the trajectories of the inverse of the time to collision

(TTC^{-1}) and the time gap (TG) during front vehicle following from 0 to 40 seconds and from 40 to 60 seconds, respectively. The time to collision is defined as

$$TTC = \frac{c}{v_c - v_p}. \qquad (2)$$

In a case that the preceding vehicle velocity is constant, the trajectory ultimately converges to $TG = TG_{desired}$ and $TTC^{-1} = 0$, and the host vehicle follows the preceding vehicle at nearly a constant time gap [1]. It can be observed from Fig. 4 (a) and (c) that the preceding vehicle velocity varies in a small range from 40 to 60 seconds and the trajectory remains in a small region in the TTC^{-1} - TG space during the period in which the preceding vehicle velocity does not vary significantly. Therefore the time gap maintained in this period can be considered as the desired time gap of the driver.



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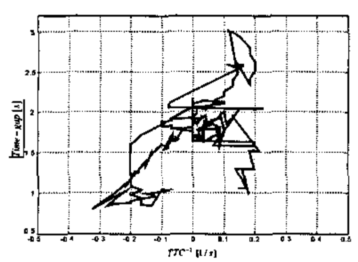

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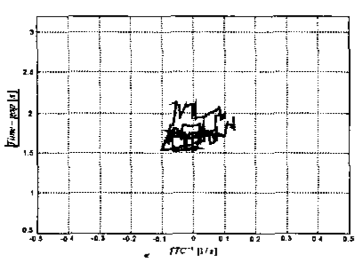


(c)

Fig. 4 Comparison of preceding and following vehicle velocities and Time gap versus the inverse TTC trajectories during vehicle following

3 Driver Adaptive Control Strategy

A two-step design approach has been used in the design of the vehicle longitudinal control algorithm. Firstly, the desired acceleration has been designed based on the distance control algorithm. Secondly, the throttle/brake control laws were designed so that the actual vehicle acceleration tracks the desired acceleration profile.

For a stop-and-go vehicle, the vehicle following control objective is to track any bounded acceleration and velocity of its predecessor with a bounded spacing and velocity error and to maintain a minimum safe clearance when the vehicle stops. The desired clearance, c_d , is defined as follows:

$$c_d = v_p \cdot \tau + c_0 \qquad (3)$$

where τ is the time gap, and c_0 is the minimum clearance to be maintained when the vehicle speed is zero. The desired acceleration of the SG vehicle is designed based on the clearance and relative speed measurements as follows:

$$a_{des} = -k_1(c_d - c) - k_2(v_p - v_c) \qquad (4)$$

where k_1 and k_2 are the gains, c is the actual clearance, and v_p and v_c are the velocities of the preceding vehicle and the controlled, i.e., the SG vehicle, respectively. The gains can be chosen by alternative design methods and the gains has been determined using a design method based on optimal control theory.

Figure 5 shows a block diagram of the vehicle longitudinal control algorithm with driving behavior parameter estimation for application to S&G cruise control. The driver parameter adaptation algorithm estimates the time gap and minimum clearance of the driver using the measures clearance and preceding vehicle velocity. The estimated values are updated during the driver drives the vehicle and kept constants when the vehicle is controlled by the controller. The desired acceleration is computed based on the preceding vehicle velocity, the estimated time gap and minimum clearance. Control inputs to the throttle/brake actuators are determined by the throttle/brake control algorithm so that the vehicle acceleration tracks the desired acceleration as closely as possible.

As described in section 2, the driving behavior characteristics of the human drivers can be parametrized using the time gap and minimum clearance. Therefore, the desired clearance can be modified to incorporate the driving characteristics of a human driver into the control algorithm as follows:

$$c_d = v_p \cdot \hat{\theta}_1 + \hat{\theta}_2 \qquad (5)$$

where $\hat{\theta}_1$ and $\hat{\theta}_2$ are the estimated time gap and minimum clearance, respectively. They are computed during the human driver drives the vehicle, i.e., during manual driving, using the recursive least-square algorithm as follows:

$$\hat{\theta}(k)=\begin{cases}\hat{\theta}(k-1)+P(k)\varphi(k)\left(y(k)-\varphi^{T}(k)\hat{\theta}(k-1)\right) & if\,|TTC^{-1}|\le\varepsilon\\ \hat{\theta}(k-1) & otherwise\end{cases}$$

$$,\qquad \hat{\theta}(0)=\hat{\theta}_0 \qquad (6)$$

$$P(k)=\frac{1}{\lambda}\left(p(k-1)-\left(\frac{p(k-1)\varphi(k)\varphi^{T}(k)P(k-1)}{\lambda+\varphi^{T}(k)P(k-1)\varphi(k)}\right)\right),$$

$$P(0)=P_0>0 \qquad (7)$$

$$y(k)=\varphi^{T}(k)\cdot\theta(k), \qquad (8)$$

$$\varphi^{T}(k)=[\varphi_1\ \ \varphi_2]=\left[v_p(k)\ 1\right], \qquad (9)$$

$$\theta(k)=\begin{bmatrix}\theta_1\\ \theta_2\end{bmatrix}=\begin{bmatrix}\tau\\ c_o\end{bmatrix}, \qquad (10)$$

where λ is forgetting factor, $y(k)$ is the actual clearance measured by the millimeter wave radar sensor and $v_p(k)$ is the velocity of the preceding vehicle and is computed from the controlled vehicle velocity and relative velocity measurements. Since the driving behavior characteristic parameters, τ and c_0, are time varying depending on the driver type, road conditions, and weather, etc, the least-square with forgetting factor algorithm has been used to prevent covariance wind-up problem.

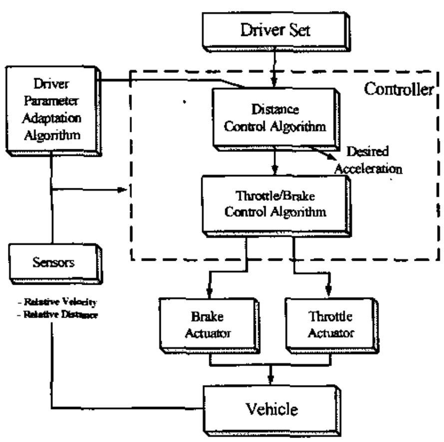


Fig. 5 A block diagram of the vehicle longitudinal control algorithm with driving behavior parameter estimation

As illustrated in section 2, since the time gap when the trajectory remains in a small region in the TTC^{-1} - TG space can be considered as the desired time gap of the driver, the estimated parameters, $\hat{\theta}$, are updated only when TTC^{-1} is small, i.e.,

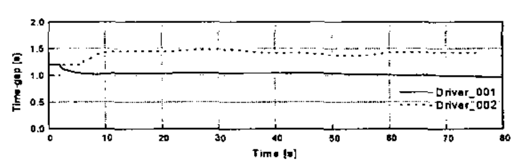
$$|TTC^{-1}|\le\varepsilon \qquad (11)$$

where ε is a small constant. In this study $\varepsilon=0.05$ has been used.

4 Evaluation of the Driver-Adaptive Controller

Vehicle following characteristics of the SG vehicle with the driving behavior parameter estimation have been investigated using vehicle driving test data and a validated simulation package [15,17]. Since it is not easy to reconstruct exactly the same driving situations such as the preceding vehicle speed profile and initial conditions, etc., in actual vehicle tests, the preceding vehicle speed profiles measured in the manual driving tests have been used in the SG vehicle simulations and then the vehicle following characteristics of the SG vehicles with and without the driving behavior parameter estimation algorithm have been compared to those of the manual driving.

Fig. 6 shows the time histories of the estimated characteristics parameters for two human drivers and estimation signals. The estimated time gaps for driver 1 and driver 2 converge to 0.89 seconds and 1.42 seconds, respectively. It has been shown in Fig. 6 (b) that the estimated minimum clearances are 2.1 and 1.6 meters for the driver 1 and 2, respectively.



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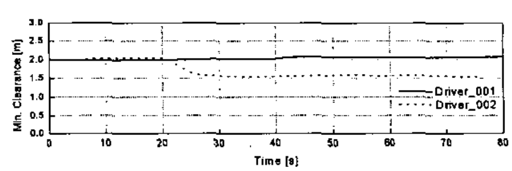


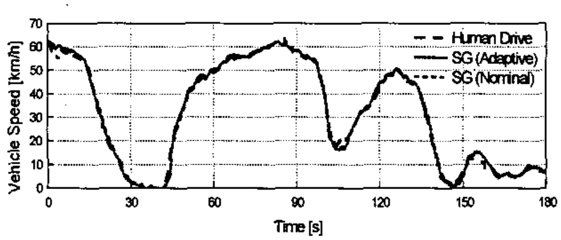
(b)

Fig. 6 Time histories of the estimated characteristics parameters for two human drivers and estimation signals

Figure 7 shows comparisons of vehicle speeds and clearances in a case of vehicle following. 'Human Drive' indicates the manual driving test data. 'SG (Adaptive)' and 'SG (Nominal)' indicate simulation results for the controlled vehicle with the adaptive control law and the one with the control law without adaptation, respectively. The preceding vehicle speed used in the SG vehicle simulation study is the measured one in the manual driving tests. In the case of the 'SG (Nominal)', the constant 'nominal' time gap of 1.2 seconds and minimum clearance of 2 meters have been used. The nominal values have been used in vehicle tests for the evaluation of the performance of the ACC/SG vehicle [14,15]. In the case of the adaptive control, the estimated time gap of 0.86 seconds and the estimated minimum clearance of 2.28 meters have been used. The control gains, k_1 and k_2, have been chosen, firstly, using optimal control theory and, then, fine-tuned in the vehicle tests taking into account ride comfort of the controlled vehicle [14].

It is illustrated in Fig. 7 (a) that vehicle speeds of the SG vehicle in both the adaptive and nominal cases are very close to that of manual driving. It can be noted from Fig. 7 (b) that the clearance of the adaptive SG vehicle is quite close to that of the manual driving while there exist noticeable differences between the clearance of the nominal SG vehicle and that of the manual driving.

Time histories of the throttle angle, brake torque and vehicle longitudinal accelerations for the case illustrated in Fig. 7 have been compared in Fig. 8 (a), (b) and (c), respectively. As can be seen in the Fig. 8 (a) and (b), the throttle and brake timing and magnitude of the SG controlled vehicle are similar to those of the manual driving. It can be noted from Fig. 8 (c) that also the acceleration characteristics are similar for both cases.



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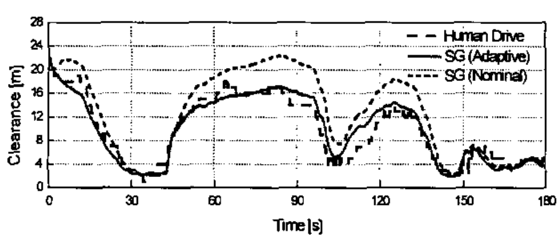

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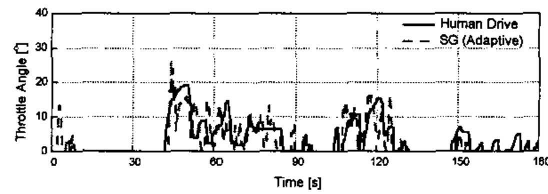
Fig. 7 Comparisons of vehicle speeds and clearances in a case of vehicle following



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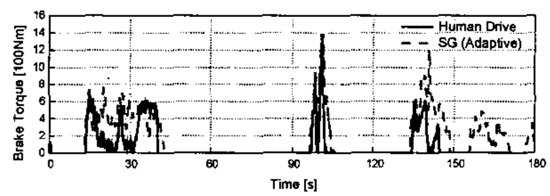

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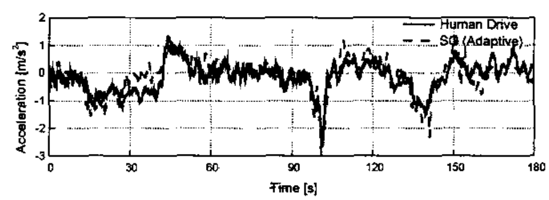

(c)

Fig. 8 Comparisons of time histories of the throttle angle, brake torque and vehicle longitudinal accelerations

RMS velocity and clearance errors between the controlled SG vehicle and the manual driving in the case shown in Fig. 7 are compared in Table 2. The errors indicate the deviation from the manual driving and a small error can be interpreted as driving characteristics similar to those of manual driving and more natural vehicle behavior. It has been indicated that 60 % of the RMS clearance error has been reduced by the use of the driver-adaptive control algorithm. Although a quantitative evaluation for the effect of the adaptive control on improving comfort of the driver or driver acceptance has not been performed, it can be expected that the more natural and more comfortable vehicle behavior would be achieved by the use of the driver-adaptive SG control algorithm.

Table 2. Comparison of RMS velocity and RMS Clearance Errors

	SG (Adaptive)	SG (Nominal)
RMS Velocity Error [m/s](%)	1.03 (88.1%)	1.17 (100%)
RMS Clearance Error [m](%)	1.19 (39.6%)	3.01 (100%)

5 Conclusions

Human drivers' driving behavior characteristics has been analyzed based on real-world driving data and a driver-adaptive control algorithm for vehicle stop-and-go systems has been developed. 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 SG controlled vehicle that would feel comfortable to the human driver. The driving characteristics parameters of a human driver have been estimated during manual driving using the recursive least-square algorithm and then the estimated ones have been used in the controller adaptation.

It has been shown that the behavior of the SG vehicle with the adaptive control algorithm is close to that of human driven vehicles and the difference between the clearance of the human-driven vehicle and that of the SG vehicle in vehicle following cases can be significantly reduced by the use of the driving behavior parameter estimation algorithm. It can be expected that the more natural and more comfortable vehicle behavior would be achieved by the use of the driver-adaptive SG control algorithm. Quantitative evaluation on the effect of the adaptive control on enhancing driver acceptance is the topic of future research.

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