Effect of Activation Timing of Automatic Braking System on Driver Behaviors

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***Abstract*—Automatic braking systems have been studied to prevent rear-end crashes. Commercialization of such system is not so widespread since it is pointed out that drivers' over-reliance or over-trust on the system by introducing such a system could lead to unsafe driving behavior and crashes. On the other hand, the authors proposed a deceleration control method of the collision avoidance system based on the driver's perceptual risk of collision. The system has the advantage to generate deceleration profile automatically even when the braking timing of the system is changed. In this paper, effect of the braking timing of the system on the driver's behavioral changes that may reflect over-trust on the system will be investigated. The driving simulator experiments will show that the braking timing close to the driver's timing might cause smaller THW in the following situation and smaller TTC at emergency situations. In addition, it will be shown that the over-trust may be prevented by making the braking timing will be delayed than the driver's timing.**

Keywords-Automotive safety; Collision avoidance system; Driver behavior;Reliance

I. INTRODUCTION

Various driver assistance systems have been proposed to avoid rear-end crashes caused by driver's distraction etc. Automatic braking systems that judge the collision risk to the lead vehicle and start to decelerate have been developed to mitigate collision damage or to avoid collisions to the leading vehicle[1],[2],[3]. It is expected that such collision damage mitigation system (CDM) and pre-crash system(PCS) is effective to mitigate crash damage or reduce crash itself. However, it has been pointed out that such collision avoidance system by automatic braking may lead drivers to their unexpected behaviors including over reliance or over-trust to the system if the onset timing of the automatic braking is inappropriate. The activation timing of the system and deceleration method need to be investigated to avoid over-trust on the system. For example, Suzuki et al. investigated the activation timing from the viewpoint of interference between the driver and the system braking [4]. In addition, a method to reduce over-reliance on the system was proposed from the viewpoint of discomfort of the driver [5].

On the other hand, the authors have proposed an automatic braking system for collision avoidance based on the driver's perceptual risk of collision. The system has an advantage that activation timing of the automatic braking can be changed by changing a parameter in the control method that allows the system to generate deceleration profile uniformly without any complex calculation. This feature allows deceleration assistance from mild braking like an ACC system in the safer situation to the hard braking like a pre-crash safety system in crash imminent situations.

In this research, effect of the activation timing of the automatic braking system on the driver's behavioral changes in the normal situations and crash imminent situations will be investigated using driving simulator. The relationship between the activation timing and the change of driving behavior in the car-following situations and emergency situations will be investigated toward establishing design methodology for collision avoidance system.

II. AUTOMATIC BRAKING SYSTEM BASED ON DRIVERS' PERCEPTUAL RISK MODEL.

The proposed system aims that the vehicle equipped with the system starts to decelerate automatically to avoid collision if the driver does not decelerate or decelerates insufficiently even in a high risk situation against the lead vehicle by driver's failure etc [6].

A. Activation timing of automatic braking system

In our previous research, expert drivers' braking behaviors in last-second braking was investigated [7]. In the research, a collision risk index ϕ given by eq.(1) was derived

$$\phi(V_L, V_r, D) = 10\log_{10}\left(4\times 10^{7}\times\frac{-V_L + aV_P}{D^3}\right) - b\log_{10} D - c \qquad (1)$$

where V_L, V_r and D denote velocity of a lead vehicle, relative velocity and gap of two vehicles, respectively. The timing of the expert driver's last-second braking was modeled as $\phi = 0$.

In the proposed automatic braking system, the system's braking is activated when inequality (2) is satisfied

$$\phi > \phi_0 \qquad (2)$$

where ϕ_0 denotes offset to change the timing. A large positive ϕ_0 denotes late braking.

B. Deceleration control algorithm

Command for oil pressure of the brake system is given as eq.(3) after activation of the system's braking, satisfying eq.(2).

$$G = \max\{K_p (V_r^d(D) - V_r(t))\ ,\ d_d\} \tag{3}$$

where K_p and d_d denote the feedback gain and the brake pressure by the driver, respectively. A scalar V_r denotes the desired relative velocity defined as eq.(4).

$$V_r^d(t) = V_r(t_{bi})\delta^3(t)\exp\left\{3(1-\delta^3(t))\right\} \tag{4}$$

where t_{bi} denotes time at the brake initiation timing and $\delta(t)$ is defined as eq.(5).

$$\delta(t) = \left(D(t) - D_{conv}\right) / \left(D(t_{bi}) - D_{conv}\right) \tag{5}$$

A scalar D_{conv} denotes the target converged gap. It has been shown that D reaches D_{conv} if the desired relative velocity is realized. The automatic braking is turned off when the inequality (6) is satisfied.

$$V_r(t) \geq 0 \tag{6}$$

III. EXPERIMENTAL MEDHOD

A. Experimental Appratus

A fixed-based driving simulator shown in Fig.1 was utilized in the experiments. There are three screens to display the road environment. A center screen is 100inch and the screens of both sides are 80inch. Computer graphics of the road environment is generated by World Tool Kit (Sense 8) that is C language library set based on Open GL. Vehicle dynamics are calculated by CarSim software (MSC corp.). The proposed automatic braking system was installed in the driving simulator in the experiments.

Figure 1. Driving simulator

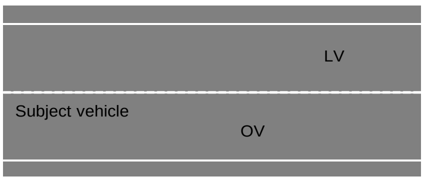


Figure 2. Experimental scenario

B. Experimental Scenarios

The test track was a straight road of 3000m in its length with two lanes in each direction as shown in Fig.2. In every driving scenario, a lead vehicle (LV) runs in the left lane. Participants were instructed to follow the LV in the normal situation. The other vehicle (OV) runs behind the participant's car in the right lane. The mean velocities of the LV and OV were 40km/h with some fluctuations. A risky event of sudden deceleration of the LV with -0.3G or -0.7G, or sudden cutting-in of the OV occurs in a scene to activate automatic braking. As the comparison, there are conditions without any risky event in a scene. Beep-like sound is displayed from the speakers when the automatic braking is activated.

C. Experimental Procedure

At the beginning, the participants drove the simulator to get used to driving the simulator without any automatic braking system. Function of the automatic braking was explained to the participants before the experiments.

Each participant was instructed to follow the LV in left lane as usual and avoid collision to the LV by braking if needed. The participants were also instructed to read a digit number displayed in the left side of the screen aloud to imitate high workload in the real road traffic. The number was updated in every 2s. There are six conditions in braking timing as ϕ_0= -2, -1, 0, 1, 2 and no system. The condition of ϕ_0= -2 has the earliest braking timing and ϕ_0= 2 denotes the latest timing. In each braking timing condition, the participants experienced 25 risky events including -0.3G, -0.7G sudden deceleration, cut-in, and no event as shown in Table1. The participants experienced 5 events in a run. Thus, the number of the runs was 5 in each braking timing condition. The order of the risky events was randomized in a braking timing condition. The experiments started from the no system condition, then the participants experienced the system with different initiation timing in the following order; ϕ_0= 0, -2, 1, -1, and 2 for all participants. Thus, the order effect was not eliminated. Totally, each participant experienced 150 events.

Five healthy male students aged 21 to 23 who gave informed consent participated in the experiments. All of the participants had the driving license.

TABLE I. NUMBER OF TRIALS

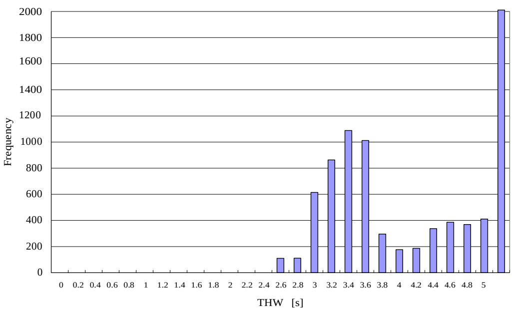
Braking Timing	Sudden decel.		Cut-in	No event
	-0.3 G	-0.7 G		
ϕ_0= -2	5	5	10	5
ϕ_0= -1	5	5	10	5
ϕ_0= 0	5	5	10	5
ϕ_0= 1	5	5	10	5
ϕ_0= 2	5	5	10	5
No system	5	5	10	5
Total	30	30	60	30

IV. EXPERIMENTAL RESULTS

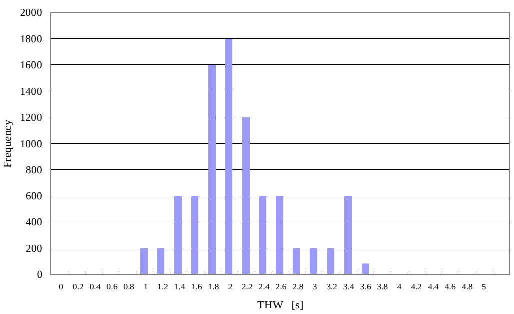
The experimental data was analyzed by dividing into two situations: (i) the car-following situation where the SV follows the LV before the risky events and (ii) the emergency situation where the SV experiences the risky events.

A. Driving behavior in car-following situation

Fig.3 shows the participant A's examples of distribution of THW(Time Headway) in the car-following situation at the 5th run of no system and $\phi_0 = 0$ and 2 conditions. The change of the THW distribution is found by introducing the automatic braking system. In $\phi_0 = 0$ condition, the distribution of THW shifted to the left by comparing with the no system condition while the distribution in $\phi_0 = 2$ condition is similar with that in the no system condition.



(a) No system



A B C D E

Participants

2000
1800
1600

Figure 5. Mean THW of All Participants

(b) □ $\phi_0 = 0$ condition

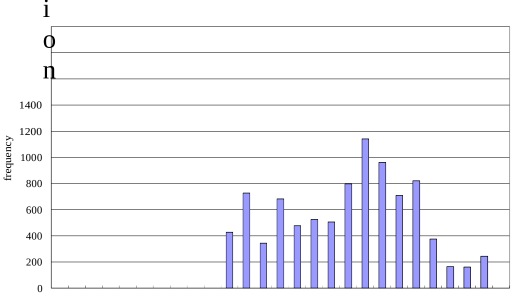


Fig.4 shows the mean THW of the participant A in the car-following situations with error bars representing SD. It is found that the mean THW tend to take the smallest value in the case of $\phi_0 = 0$ that means the timing of expert driver's brake timing. THW is increased with both larger and smaller ϕ_0. Please note that in the case of negative ϕ_0 like $\phi_0 = -2$, automatic braking starts to decelerate much earlier than the participants timing.

Fig.5 shows the mean THW of all participants in the following situations with the conditions of $\phi_0 = 0$ through 2 and no system. Conditions of ϕ_0 =-1 and -2 are eliminated. The results of two participants A and D have clear tendency that ϕ_0 = E e

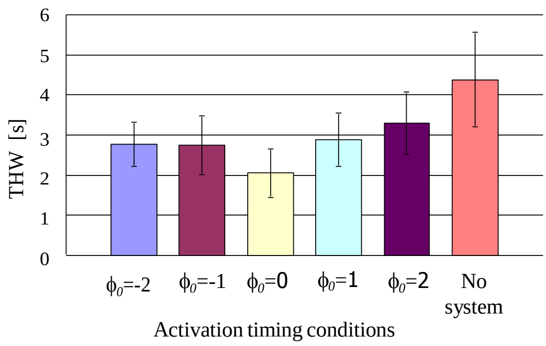
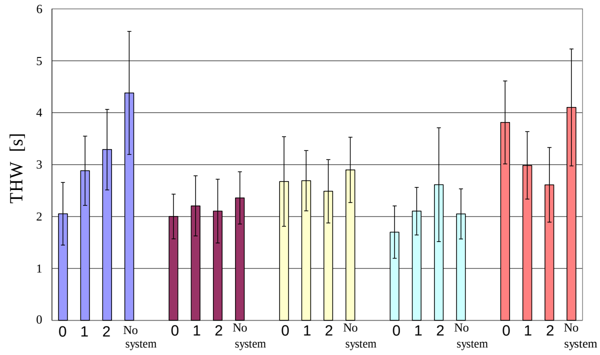


Figure 4. Mean THW (Participant A)



0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3 3.2 3.4 3.6 3.8 4 4.2 4.4 4.6 4.8 5

THW [s]

B. Driving behavior in emergency situation

Fig.6 shows the TTC at participants' brake initiation timing and that of automatic braking onset

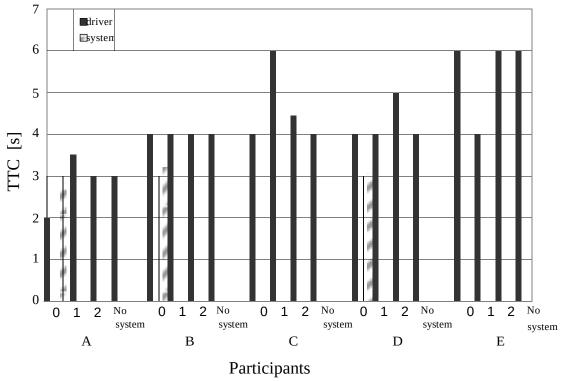
(c) $\phi_0 = 2$ condition

Figure 3. Distribution of THW in the car-following situation

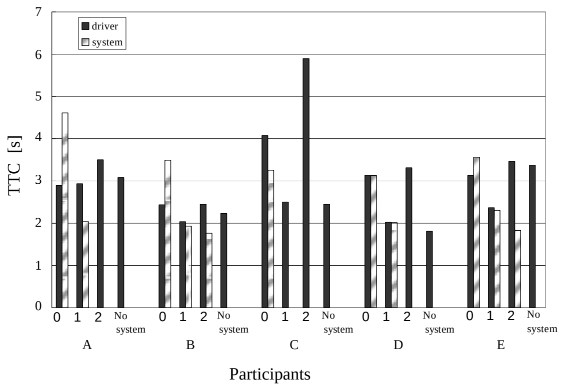
timing against the lead vehicle sudden deceleration with -3m/s^2 and 7m/s^2 at 5th trial. It is found that frequency of the system activation is lower at the 3m/s^2 conditio. At 3m/s^2 condition, system activated only

$\phi_0 = 0$ condition and that is seen only for participants A, B, and

C. In the timing condition of $\phi_0 = 1$ and 2, the drivers are always step the brake pedal earlier than the system or the same timing while no clear tendency is found in $\phi_0 = 0$ condition.



(a) dV_L/dt = -3m/s^2



(b) dV_L/dt = -7m/s^2

Figure 6. TTC at driver's brake initiation and that of system activation the emergency situation

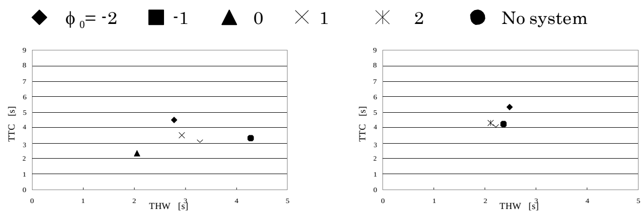
C. *Relationship between THW in car-following and TTC at driver's brake onset in emergency*

Fig.7 shows relationship between mean THW in the car-following and TTC at driver's brake initiation timing for 3m/s^2 deceleration condition. Positive correlation can be found in some participants even though the regression coefficients would be different for each participant. Namely, TTC at brake initiation in emergency could be decrease when the mean THW in car-following is small. In participant A, TTC is smaller than those of the other participants even though the mean THW is not so different from the others. This implies the delay of the participant's braking reaction. The similar tendency can be seen at the 7m/s^2 deceleration of the LV while the regression coefficients would be different from that at 3m/s^2 deceleration.

V. CONCLUDING REMARKS

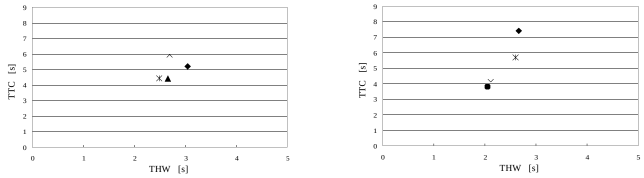
Effect of the activation timing of the automatic braking system on the driver behaviors was investigated. In some participants, the activation timing close to the driver's braking timing leads to decrease of THW in the car-following situation. TTC at driver's brake initiation decreases at that situation. From the fact that the driver starts to brake earlier than the system's deceleration in ϕ_0 = 1 and 2, the proposed deceleration control method might avoid driver's over-reliance on the system by choosing later onset timing of automatic braking.

As a future study, mechanism of the behavioral change in both the normal car-following situation and the emergency situation by introducing the error of the automatic braking system. Then, optimal timing that minimizes behavioral changes will be investigated considering individual differences.



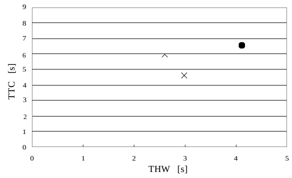
(a) Participant A

(b) Participant B



(c) Participant C

(d) Participant D



(e) Participant E

Figure 7. Mean THW in car-following vs TTC at driver's brake initiation at 3m/s^2 deceleration of LV

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