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Automatic Braking Method for Collision Avoidance and Its Influence on Drivers Behaviors

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ABSTRACT: Collision avoidance system with automatic braking has been developed to prevent rear-end crashes. It is pointed out that driver's behaviors could be changed by introducing such collision avoidance systems. Thus, it is important to understand the driver's behavioral changes with such systems and to apply the results to its better design for effective use of the assistance system. On the other hand, a deceleration assistance control for collision avoidance based on driver's perceptual risk has been proposed. This 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. In this paper, an automatic braking method in which the activation timing is changed by its individual differences was introduced. The effect of the braking activation timing of the system on the driver's behavioral changes was investigated using a driving simulator experiment. The results demonstrated that the activation timing strongly affect the drivers behavior in time headway in following situations and drivers' braking timing when the lead vehicle's sudden deceleration as well as the gazing behavior in preparation of lane-changing operation.

KEY WORDS: Collision avoidance system, Automatic braking, Driver behavior

1. Introduction

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 safety system (PCS) is effective to mitigate crash damage or reduce crash itself. However, it is pointed out that changes of driver's behaviors are concerned when such braking systems are equipped[4]. Therefore, it is important to understand changes of driver's behaviors and to apply the results to design of such collision avoidance systems.

An automatic braking system for collision avoidance based on the driver's perceptual risk of collision has been proposed[5][6]. The brake-activation timing of the proposed system is determined by driver's last-second braking model. Thus, this system has an advantage that the activation timing of the automatic braking can be tuned by changing a parameter in the braking model that allows the system to generate deceleration profile uniformly without any complex calculation. This feature allows us automatic braking from mild braking like an ACC system in the safer situation through the hard braking like pre-crash safety system in crash imminent situation. Therefore, the deceleration assistance control for collision avoidance adaptive to individual driver can be realized.

In this research, a new automatic braking method for collision avoidance adaptive to individual driver considering the each driver's brake initiation timing will be introduced. The effect of the activation timing of the automatic braking system on the driver's behavioral changes in the hurried driving situation will be investigated using a driving simulator.

2. Automatic Braking System Based on 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 due to driver's error etc. The proposed system is an extended version of the system proposed in [5] and [6].

2.1. Initiation Timing of Automatic Braking System

In our previous research, expert driver's braking behaviors in last-second braking were investigated[7][8]. In the research, a collision risk index ϕ was derived as eq.(1),

$$\phi(V_r, V_p, D) = 10\log_{10}\left(\left|\alpha V_p - V_r\right|\right) - \beta\log_{10} D + \gamma \tag{1}$$

where V_p, V_r and D denote velocity of a preceding vehicle, relative velocity and gap of two vehicles, respectively. Scalars α, β, γ are determined by the least square method or other method to fit the experimental results for each driver. Thus, the timing of each 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

$$\phi > \phi_0 \tag{2}$$

where ϕ_0 denotes an offset to change the timing. A positive ϕ_0 denotes later braking than that by the driver's own timing.

2.2. Targeted gap to lead vehicle

Function ϕ can be regarded as driver's perceptual risk of collision. Then let us define the vehicle status at the termination of automatic braking control Ω_{conv} as eq.(3).

$$\Omega_{conv} = \left\{\left[V_r, V_p, D\right] \mid \phi(V_r, V_p, D) = \Delta\phi\right\} \tag{3}$$

Namely, the risk function satisfies $\phi = \Delta\phi$ at the converged status, where $\Delta\phi$ denotes the safety margin that should be positive. Let us consider the vehicle status at the converged status. It is supposed V_r=0 at the converged status. Then, the gap at the converged status, D_{conv} is given by eq.(4).

$$D_{conv} = \left[10^{\gamma-\Delta\phi} \times (\alpha V_p)^{10}\right]^{\frac{1}{\beta}} + \Delta D \tag{4}$$

Namely, D_{conv} is determined by specifying V_p. As seen from equation, D_{conv}=0 at V_p=0. A scalar ΔD was putted to make the positive gap ΔD in such situations.

3.3. Deceleration Control Algorithm

Command for oil pressure of the brake system G is given as eq.(5) after activation of the system's braking, when satisfying eq.(2).

$$G = \max\{K_p(V_r^d(D) - V_r(t))\ ,\ \ d_d\} \tag{5}$$

where K_p and d_d denote the feedback gain and the brake pressure by the driver, respectively. A scalar V_r^d denotes the desired relative velocity defined as eq.(6).

$$V_r^d(t) = V_r(t_{bi})\,\delta^3(t)\exp\left\{3(1-\delta^3(t))\right\} \tag{6}$$

where t_{bi} denotes time at the brake initiation timing and $\delta(t)$ is defined as eq.(7).

$$\delta(t) = \left(\frac{D(t) - D_{conv}}{D(t_{bi}) - D_{conv}}\right) \tag{7}$$

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 (8) is satisfied.

$$V_r(t) \geq 0 \tag{8}$$

It should be noted that the velocity profile, eq.(6) was derived based on the expert driver's last-second braking model the perceptual risk model [5][6].

From these results, the activation flow of the proposed system is given as shown in Fig. 1

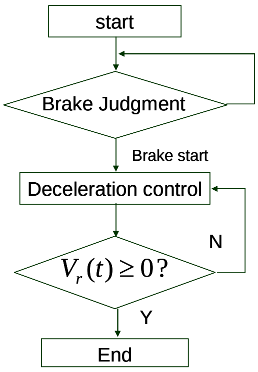


Fig. 1 The system flow of automatic braking system

3. Experimental Method

3.1. Experimental Apparatus

A fixed-based driving simulator shown in Fig. 2 was utilized in the experiments. There were three screens of 100inch to display the road environment. An additional 22inch monitor displaying a rear-side image was located behind the right side mirror of the cockpit, thus driver could see the image of the right rear-side road and vehicles displayed in the monitor through the side mirror as shown in Fig.3.

Computer graphics of the road environment was generated by World Tool Kit (Sense 8) that was C language library set based on Open GL. Vehicle dynamics were calculated by CarSim software (MSC corp.). The proposed automatic braking system was installed in the driving simulator in the experiments. In addition, beep-like sound was displayed from the speakers during the automatic braking was activated. An eye-mark recorder EMR-8B (NAC Image Technology Inc.) was used to measure gaze position of drivers. The gaze position of the dominant eye was measured for all participants. An orientation sensor MTx (Xsens Technologies) was used to measure the head motion of the drivers. The gaze position seen from the world-fixed frame can be calculated from the sum of the relative eye moment seen from the head measured by the eye-mark recorder and the head-yaw angle measured from the orientation sensor.

Fig. 2 Driving simulator

Fig. 3 Image of the right side mirror

3.2. The vehicle and course

The test course in the simulator was an oral track with straight roads of 1000m in their length as shown in Fig. 4. In each region illustrated as (1) through (4), the participants encountered the experimental scenario with other vehicle s as shown in Fig. 5. The velocity of lead vehicle (LV) was 40km/h with some fluctuations. Velocities of rear vehicles (RV) were from 65 to 75km/h. The gap between RVs was from 50 to 80m.

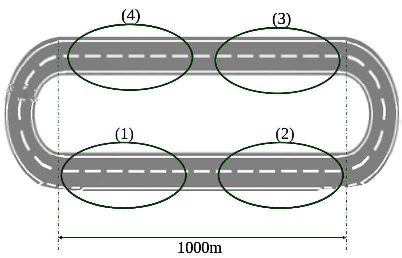


Fig. 4 Experimental course

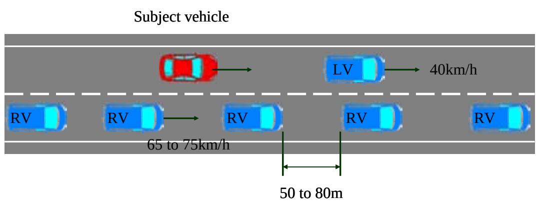


Fig. 5 Experimental scenario

3.3. Experimental Design

The participants drove in the driving simulator in the test truck and asked to follow the lead vehicle in the left lane of the two lanes in the same direction and taking over the lead vehicle when they felt the LV ran slow and wanted to take over it. The participants experienced driving in the simulator without any automatic driving, then experienced driving with the automatic braking system with the predetermined activation timing assigned for each participant as the experimental condition.

There were three levels in the condition of system activation timing as ϕ_0= -1, 0, 1. The condition of ϕ_0= -1 denotes the earliest braking timing and ϕ_0= 1 denotes the latest timing. In this research, the brake initiation timing of participants was measured on another day in advance to identify the timing of ϕ_0=0. This realized the automatic braking adaptive to the individual difference of the braking timing.

Each participant assigned to an activation timing level. Five participants were assigned to each level of braking timing. Total number of the participants were fifteen.

Driver behaviors during following LV and in emergency when LV was decelerating were compared with and without the braking system.

3.4 Participants

Fifteen healthy male students aged 21 to 23 who gave informed consent participated in the experiments. All of the participants had the driving license. The mean year of experience in driving for activation timing conditions of ϕ_0 = -1, 0, and 1 were 2.2 yr (SD 1.1), 2.5 yr (SD 1.4), and 2.3 yr (SD 0.9), respectively.

Each participant was assigned to an activation timing condition so that the distribution of the mean braking timing were as same between conditions as possible. As a results, the mean TTC (Time to Collision) at braking timing of the participants measured in the preparation experiments in the V_L=40km/h, V_r=40km/h condition for each activation timing condition was as follows: 3.0s (SD 0.6) with ϕ_0 = -1, 2.8s (SD 0.3) with ϕ_0 = 0, and 2.9s (SD 0.4) with ϕ_0 = 1. The repeated-measures ANOVA revealed that no significant differences among the activation timing conditions($F(2,8)=2.770$, p=.171.).

3.5. Experimental Procedure

The experimental trials were composed of three phases: 1) practice phase, 2) non-hurried phase, 3) no system phase in hurrying, and 4) with-system phase in hurrying.

1) Practice phase: at the beginning, the participants drove the simulator to get used to driving simulator without any automatic braking system. Each participant was asked to drive in the test track for three laps. The participants experienced three trials in the phase.
2) Non-hurried phase: then the experiments started from the no system condition without hurried driving situation. Each participant was asked to drive in the test track for three laps while the driving time for three laps was measured. The participants experienced three trials in the phase.
3) No system phase in hurrying: then, the hurried driving trial was started, where each participant was instructed to reach goal point earlier than the predetermined time that was determined by subtracting 40s from the driving time in the non-hurried condition. In order to give the participants the time pressure, the experimenter read the time from the start point aloud every 30s. Each run was terminated when LV decelerated or when the laps was reached to three. The participants experienced three trials in the phase.
4) With-system phase in hurrying: finally the participants drove with the automatic braking control after explanation of the braking system and experience of the activation of the system with the hurried situation. Time pressure was also given. Each run was terminated when LV decelerated or when the laps was reached to three. The participants experienced three trials in the phase.

For every driving trials from phase 2) to 4) above, each participant was instructed to drive about 60km/h and follow the LV as shown in Fig. 5. Each participant was also instructed to overtake the LV by changing the lane if the participants felt that LV ran slow. At that time, each participant was instructed not to collide with RV. The drivers experienced such scenarios at the four areas of the test track per lap as shown in Fig. 4.

During the experimental driving, LV was decelerates suddenly once a run. The timing of the sudden deceleration of LV was randomized to prevent from the participant's anticipation and the participants were instructed to avoid collision to the LV by braking. The deceleration of LV was fixed as -0.3G (-2.94m/s^2). A run ended when the participants experienced the sudden deceleration of LV in the run. The participants experienced three runs, thus each participant experienced 6 deceleration of LV, for three without the system and three with the automatic braking system.

3.6. Analysis method of gaze position of drivers

Gaze position at every moment was calculated by the sum of the relative visual angle seen from the head-fixed frame measured the eye-mark recorder and the head yaw angle measured by the orientation sensor.

The gaze position at the every moment was classified as “rear-view” or “front-view”. The gaze position was classified into rear-view when it was in a certain region around right side mirror. Otherwise, the gaze position was classified into front-view. Then, the time duration in which the gaze position was continuously classified as rear-view was calculated as continuous rear-view time Δt according to [9].

4. Experimental Results

4.1. Drivers behavior with ϕ_0 = -1

<u>THW and rear-view time in car-following</u>

Time headway (THW) during following the LV was collected and analyzed as a measure of drivers behavior in car-following situation. Fig. 6 shows the mean THW between the LV and SV in the car-following situation with error bars representing SD. No significance difference was found in THW by the repeated-measures ANOVA ($F(1,14)$=.012, p=.913).

The continuous rear-view time Δt was collected during following the LV. Fig.7 shows an example of distribution of Δt in a participant. As seen from the figure, the distribution of the Δt was changed by introducing the system, that is, frequency of large Δt was increased with the system. Seventy-five percentile value of Δt was calculated from the results of each participant. The mean of 75 percentile values of Δt is given in Fig.8. The repeated-measures ANOVA revealed significant difference ($F(1,14)$=6.599, p=.022), the rear-view time Δt was increase by introducing the system of ϕ_0 = -1.

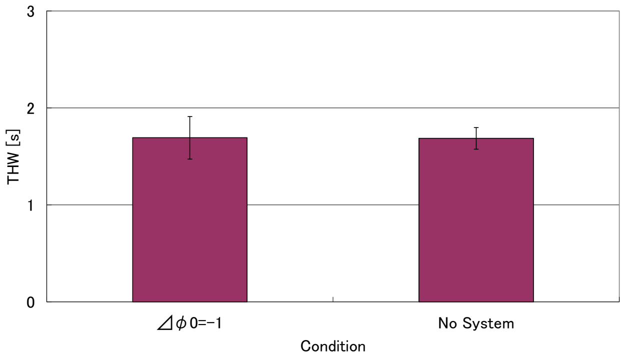
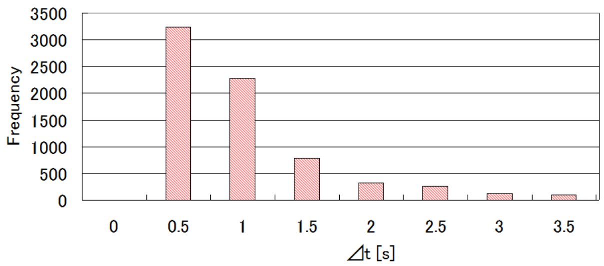
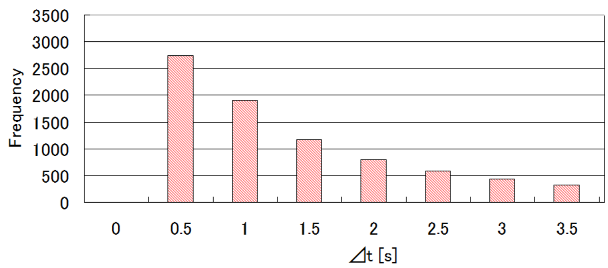


Fig. 6 Mean THW in ϕ_0 = -1



(a) No system



(b) With system

Fig. 7 Distribution of Δt (participant A)

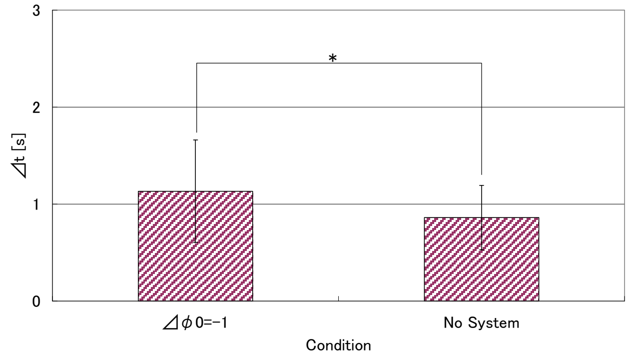


Fig. 8 Average of 75 percentile values of Δt (ϕ_0 = -1)

<u>TTC at braking by driver at sudden braking of LV</u>

The TTC at participant's brake initiation timing according to the sudden deceleration of the LV was collected. The mean TTC is given in Fig. 9 with error bars representing SD. The repeated-measures ANOVA revealed the significant difference ($F(1,14)$=16.227, p=.001), TTC at participant's brake initiation timing was increased by introducing the automatic braking system of ϕ_0 = -1.

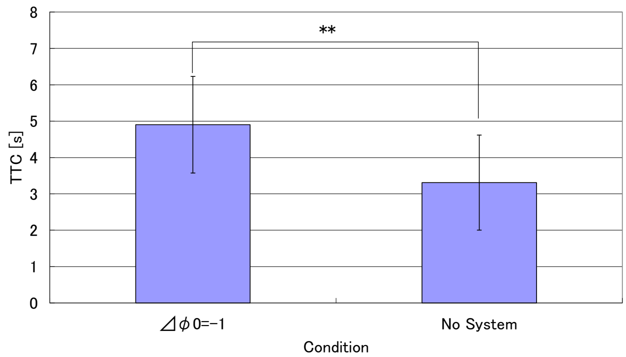


Fig. 9 Mean TTC at driver's brake initiation (ϕ_0 = -1)

4.2. Drivers behavior with ϕ_0 = 0

<u>THW and rear-view time in car-following</u>

Fig. 10 shows the mean THW between the LV and SV in the car-following situation with error bars representing SD. No significance was found in THW by the repeated-measures ANOVA ($F(1,14)$=.113, p=.742).

Fig.11 shows the mean of 75 percentile values of Δt. The repeated-measures ANOVA revealed no significant difference ($F(1,14)$=.004, p=.952).

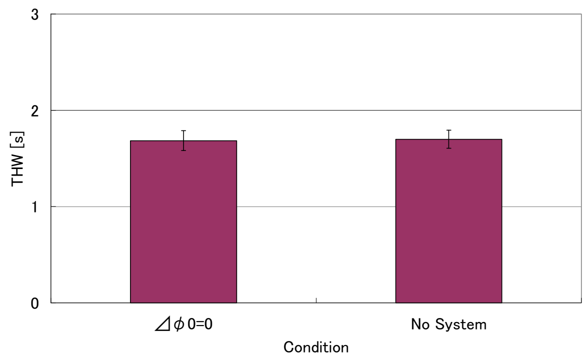


Fig. 10 Mean THW in ϕ_0 = 0

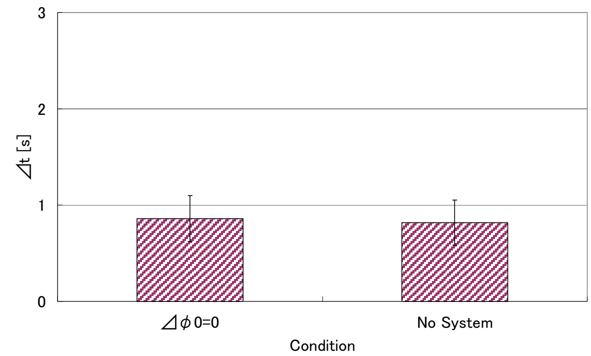


Fig. 11 Average of 75 percentile values of Δt (ϕ_0 = 0)

TTC at braking by driver at sudden braking of LV

The mean TTC in the sudden deceleration of LV is given in Fig.12 with error bars representing SD. The repeated-measures ANOVA revealed the significant difference (F(1,14)=18.450, p=.001), TTC at participant's brake initiation timing was decreased by introducing the automatic braking system of ϕ_0 = 0.

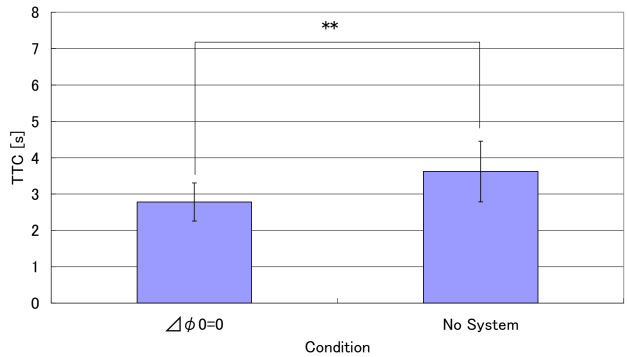


Fig. 12 Mean TTC at driver's brake initiation (ϕ_0 = 0)

4.3. Drivers behavior with ϕ_0 = 1

THW and rear-view time in car-following

Fig. 13 shows the mean THW between the LV and SV in the car-following situation with error bars representing SD. Significant difference was revealed in THW by the repeated-measures ANOVA (F(1,14)=9.800, p=.007), the THW was decreased by introducing the system of ϕ_0 = 1.

Fig. 14 shows the mean of 75 percentile values of Δt. Significant difference was shown (F(1,14)=5.161, p=.039) by the repeated-measures ANOVA, Δt was increased by the system of ϕ_0 = 1.

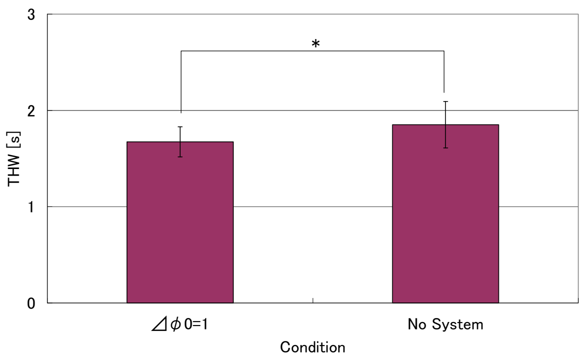


Fig. 13 Average of THW

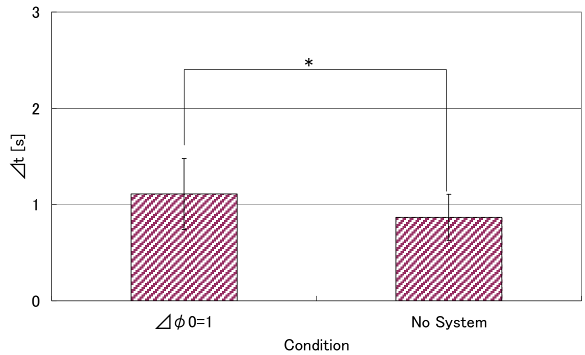


Fig. 14 Average of 75 percentile values of Δt (ϕ_0 = 1)

TTC at braking by driver at sudden braking of LV

Fig. 15 shows the average of TTC at participant's brake initiation timing against the lead vehicle sudden deceleration. the significant difference was shown(F(1,14)=5.655, p=.032), TTC at participant's brake initiation timing was increased by the system of ϕ_0= -1 setting.

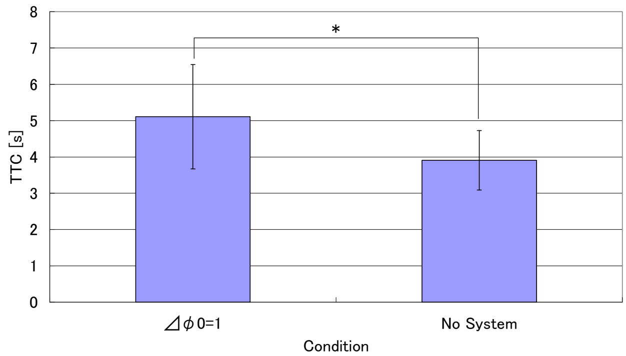


Fig. 15 Mean TTC at driver's brake initiation (ϕ_0 = 1)

4.4. Comparison of brake initiation timing of drivers and system

Table 1 shows the percentage of runs where drivers initiated braking earlier than system for all participants when LV decelerated. Conditions ϕ_0 = -1 and 0 have similar number, the system initiated braking earlier than the drivers in the many trials. On the other hand, the driver did earlier than the system in all trials with ϕ_0 = 1 setting.

Table 1 Percentage of runs where drivers initiated braking earlier than system

Condition	Percentage
ϕ_0= −1	27
ϕ_0=0	20
ϕ_0=1	100

5. Discussion

In the ϕ_0= -1 condition, the TTC at brake initiation was increased while THW in the car-following was not changed. Continuous rear-view time was also increased. In addition, the system started automatic braking before the driver in this setting.

This implies that the timing of driver's braking became earlier by being triggered by the initiation of automatic braking or its sound indicating its activation. The participant might use the sound like a warning system to trigger the braking while it is thought that such early automatic braking may result in the annoyance.

In the ϕ_0= 0 condition, TTC at brake initiation was decreased while no significant differences were found in THW and the rear-view time. This implies that the setting ϕ_0= 0 that was matched to the driver's last-second braking might result in shorter TTC in the crash imminent situation.

In the ϕ_0= 1 condition, the TTC at the braking initiation was increased. The THW was decreased while the rear-view time was increased. In addition, the driver started braking before the system in this setting. From these results, it is thought that the ϕ_0= 1 setting has no risky effect on the driver's behavior in emergency.

Wada et al. investigated the effect of the similar automatic braking system as in the present paper but without any individual adaptation, on the driver's behavioral changes[10]. Itoh et al. investigated driver's behavioral to three automatic braking systems[4]. Wada et al. reported that THW in the car following was decreased when the system has the brake timing close to the driver's even though they did not show statistical significance due to small number of participants and employment of within-subject design [10]. Itoh et al. [4] demonstrated that the significant difference in the THW was shown in the car-following situation while no significant difference was found in THW in the present paper. This difference may be caused by the difference between the following situation. Itoh et al.[4] collected THW through the driving in the following lead vehicles while the present paper collected THW in a short time before overtaking operation. Itoh et al. [4] showed no significant difference in TTC while the present paper demonstrated that TTC was decreased significantly at ϕ_0= 0. It is suggested that in such a higher workload situations like lane changing, reliance on the system might be increased.

As pointed in Itoh et al.[4], decrease of the TTC at the emergency was risky rather than change in THW at car-following. From this viewpoint, ϕ_0 = 0 that imitates individual braking timing may change the driver's behavior in risky situation. Among three levels in activation timing, ϕ_0 = 1 was preferable from the viewpoint of behavioral changes in emergency while ϕ_0 = -1 is not realistic due to its annoyance by early interference. However, shorter THW may occasionally lead to risky situation. In order to clarify the effect of potential risk such as shorter THW in car-following on risky situation in emergency, attentional allocation of the driver could be a key. The continuous rear-view time was an index to see the attentional allocation in part. The rear-view time was increased significantly in the experiments. Wada et al. [9] demonstrated that the drivers allocate their gaze position in changing-a-lane situation according to the collision risk against the peripheral traffic appropriately. Thus, combination of the rear-view time and THW should be analyzed to understand behavioral changes by the braking system in detail.

6. Conclusion

This paper introduced an automatic braking method based on the drivers' perceptual risk of collision in which the activation timing can be changed by its driver's individual differences in braking timing. The effect of activation timing on driver's behavior was investigated. From the viewpoint of the braking timing in crash imminent, the experimental results suggest that the setting of ϕ_0 = 1 in which the system started to automatic braking later than drivers exhibited no bad influence on the drivers' braking behavior. On the other hand, it should be suggested that setting ϕ_0 = 0, which imitated identified individual driver's braking timing has risky effect.

As the future study, effect of the collision avoidance system on driver's attentioanl allocation will be investigated by combining the collision risk with the peripheral vehicles and gaze position characteristics.

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