Characterization of Expert Drivers' Last-Second Braking and Its Application to A Collision Avoidance System

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***Abstract*—Expert drivers' deceleration patterns in last-second braking will be formulated using the perceptual risk index for the approach and proximity of a preceding vehicle as examples of comfortable braking patterns. It will be shown that the formulated braking pattern can generate a smooth deceleration profile uniformly for many approach conditions. In addition, the brake initiation timing of expert drivers will be successfully formulated using a modified index. Finally, an automatic braking system for collision avoidance will be proposed, based on the formulated brake initiation model and the deceleration pattern. Twenty-five expert drivers will experience the automatic braking installed in an experimental car. It will be shown that the proposed system can generate a smooth profile and realize secure brake patterns, based on the drivers' subjective evaluation.**

***Index Terms*—Automatic braking system, braking behavior collision avoidance, deceleration model**

I. Introduction

THE goal of this research is to develop a collision avoidance system by automatic braking to reduce rear-end crashes or mitigate the damage in such crashes. Pre-crash safety systems (PCSs) that activate when a crash is imminent have been successfully commercialized to mitigate rear-end crashes. In order to decrease the number of rear-end crashes further, it is important to have another collision avoidance system that can be activated in an earlier stage of a risky situation. In order to develop an acceptable system, it is important to determine the characteristics of comfortable deceleration since discomfort can easily occur if the automatic braking system activates earlier than the driver expects.

A number of research studies have focused on braking behavior in car-following situations. Lee [1] developed a theoretical framework of drivers' longitudinal control based on time-to-collision (TTC) associated with visual input. Goodrich et al. [2] characterized braking behavior in the phase plane of TTC vs. Time-Headway (THW). Kondoh et al. investigated risk perception based on TTC and THW [3]. Their findings imply that drivers determine the timing of brake initiation and deceleration patterns based on their own perceptual risk. LeBlanc et al. [4] investigated drivers' last-second braking to establish a methodology of designing a warning system and trigger timing of a collision avoidance system. On the other hand, the car-following driving models have been derived in traffic flow engineering such as the GHR model [5] and Gipps model [6]. These studies focused on deceleration and acceleration behavior as flow in the traffic environment and not on each braking behavior's characteristics.

On the other hand, there are many research studies on design and evaluation of driver assistance system with automatic brake. For example, Kaempchen et al. proposed an approach for calculating trigger time of emergency brake considering physically possible trajectories of vehicles based on situation assessment [7]. In addition, some studies have evaluated the Adaptive Cruise Control (ACC) system using such car-following models as Gipps' model [8]. There are research studies dealing with comfortable longitudinal control. Hiraoka et al. derived a car-following model for realizing a comfortable ACC system, applying the minimum jerk theory to longitudinal vehicle behavior [9]. Ferrara et al. proposed a sliding mode longitudinal control to realize bounded jerk and to avoid frequent changes between use of the accelerator and the brake[10]. Wu et al. propose a driver model that estimates deriver comfort in longitudinal control [11]. In order to realize collision avoidance system working in earlier stage of a risky condition, another method to determine brake timing and the deceleration profile is needed by considering drivers' perceptual risk.

This paper derives an expert drivers' last-second braking model based on the drivers' perceptual risk and considers the design of a collision avoidance system by applying the derived model. We have proposed a performance index of approach and alienation K_{dB} as an index related to the driver's perceptual risk of a preceding vehicle [12]. In this paper, an expert driver's

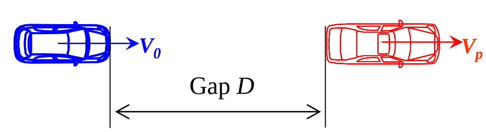

Fig. 1. Car-Following Situation.

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deceleration pattern in last-second braking will be formulated using the proposed index, and the results will be applied to a brake-assistance system. First, an expert driver's braking behavior in a car-following situation will be measured on an auto manufacturer's test course. The deceleration patterns will be formulated by a simple mathematical model by extracting an expert driver's braking characteristics. It will be shown that the formulated braking pattern can uniformly generate a smooth deceleration profile for a wide range of approach conditions of relative velocity and brake initiation timing uniformly. In addition, initiation timing of last-second brake will be characterized using another version of the index K_{dB_c}. A formula to determine initiation timing of last-second braking will be derived based on this index. Using these characterizations of braking behavior, a control method for a braking assistance system will be derived. A system using this control method will be installed in a real car, and the brake initiation timing and braking profile will be evaluated by subjective rating.

II. Evaluation Index Relating Approach and Proximity

There are many indices for evaluating drivers' risk perception of rear-end collision, including TTC, THW as summarized in the literature [13]. We have proposed the following evaluation index based on the driver's visual input. Suppose that we follow a car in the same lane, as depicted in Fig. 1. In such a situation, the driver evaluates the risk of approaching the preceding car appropriately and is able to drive safely by operating the pedals and the steering wheel, based on the perceived results. So far, we have hypothesized that drivers detect the approach of the preceding car, perceive the risk by area changes on the retina, and determine the degree of deceleration based on this change; thus, an evaluation index of approach and proximity (K_{dB}) has been derived [12].

Figure 2 presents a schematic image of the area change of a preceding car on the driver's retina when a car is approaching. The area on the retina is proportional to $1/D^2$, where D denotes the gap between the two cars. Its time derivative K can be written as

$$K(V_r, D) = \frac{d}{dt}\frac{1}{D^2(t)} = -2\frac{V_r(t)}{D^3(t)} \quad (1)$$

where

$$V_r(t) = V_p(t) - V_o(t) = \frac{d}{dt}D(t) \quad (2)$$

where V_r denotes the relative velocity; V_p denotes the velocity of the preceding car; and V_o denotes the velocity of the driver's own car with respect to ground. Assuming the threshold to detect the approach of the preceding car at D = 100m and V_r = -0.025m/s (=-0.09km/h) yields

$$K_0 \equiv K(-0.025, 100) = 5\times10^{-8} \ \ [1/\mathrm{m^2 s}] \quad (3).$$

K_{dB} is defined as eq. (4), which is the logarithm form of K to the base 10 so that K_{dB} = 0dB when $K = K_0$, according to Weber's law to represent human sensation characteristics.

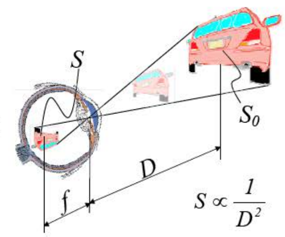

Fig. 2. Visual Input on Retina.

$$K_{dB} = \begin{cases} 10\log_{10}\left(\left|K / K_0\right|\right)\mathrm{sgn}(-V_r) \\ \quad = 10\log_{10}(|\,4\times10^7\times\dfrac{V_r}{D^3}\,|)\mathrm{sgn}(-V_r) \\ \qquad\qquad (|\,4\times10^7\times V_r/D^3\,|\geq 1) \\ 0 \qquad\qquad (|\,4\times10^7\times V_r/D^3\,|< 1) \end{cases} \quad (4)$$

Indices K and K_{dB} increase when the preceding car is approaching the driver's car, similar to the increase of the driver's visual input. Index K_{dB} increases when the driver does not react to the approaching of the preceding vehicle, regardless of the cause of risk (e.g., low arousal level or inattention, depending on driver's status). It has been demonstrated that K_{dB} can discriminate between braking behaviors of normal safe driving and those in crashes [12]. Appropriateness of the definition of K_0 is not investigated and it could be changed by driving experiences etc. This paper does not deal with the problem because it is not the main topics of this paper. Note that the definition does not affect the results of the analysis of braking behaviors.

III. Investigation of Expert Drivers' Braking Behaviors

A. Experimental Conditions

In order to formulate expert drivers' smooth deceleration patterns in last-second braking, the braking behaviors of test drivers of an auto manufacturer were measured on a test course. Participants were six skilled drivers aged 25 to 52yr (mean 46.3yr, Standard Deviation(SD) 9.9yr) who engaged in either product evaluation or research and development (R&D). A straight road in the test course was used. A midsize sedan was utilized in the experiments. This test car was equipped with an Frequency Modulation Continuous Wave (FMCW) milli-wave radar sensor to measure the gap between two vehicles and relative velocity at a 100ms sampling rate.

A preceding car runs at a constant velocity V_p, and the following car driven by the test driver approaches at a constant velocity V_o. The participants were instructed not to decelerate as long as they felt that a collision was avoidable with their normal deceleration behavior and to decelerate at their limit of normal braking operation. Experimental vehicle velocities V_p and V_o were [V_p , V_o] = [20, 30], [20, 40], [20, 60], [40, 80], [40, 100],

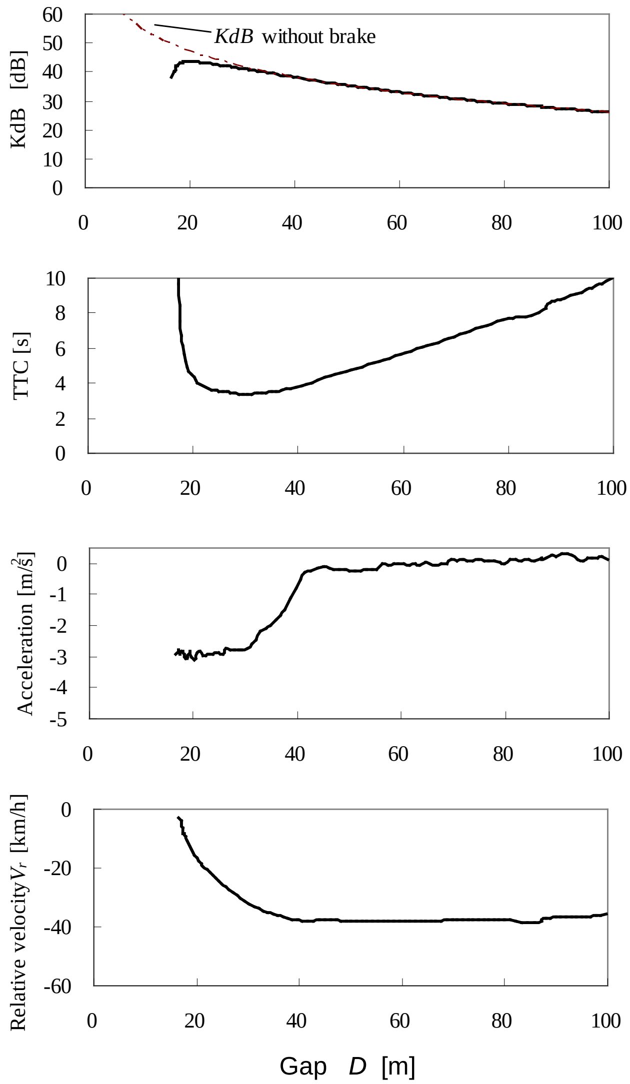

Fig. 3. Expert driver's braking behavior with $V_p = 40$, $V_o = 80$km/h.

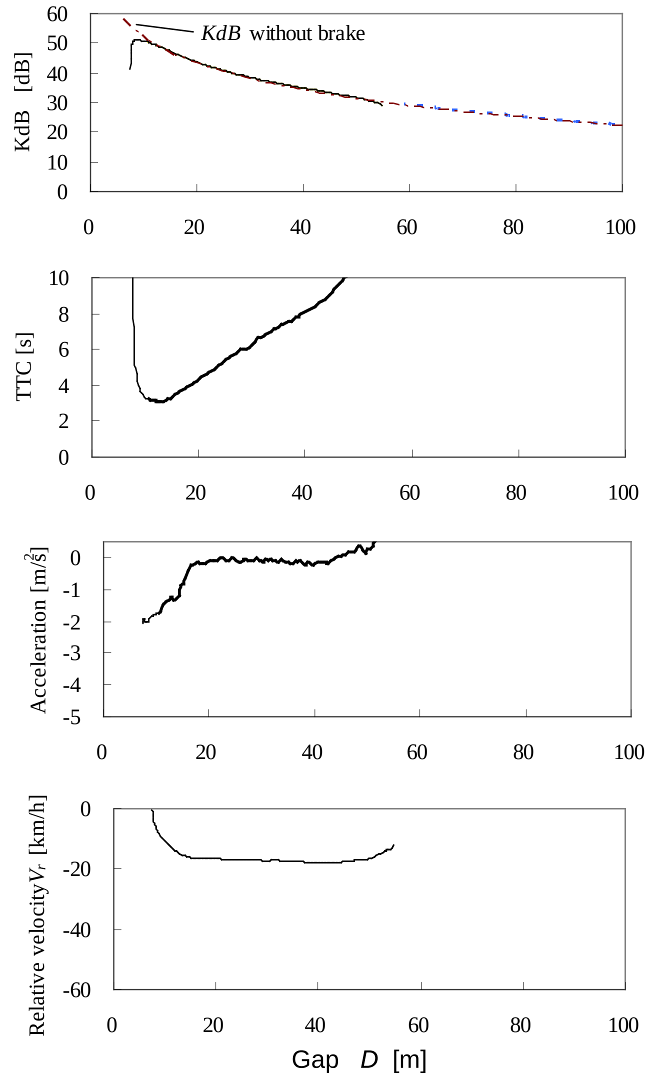

Fig. 4. Expert driver's braking behavior with $V_p = 23$, $V_o = 40$km/h.

[60, 70], and [60, 80]. These conditions were given as the target velocities for the experimenters and the participants; thus, some errors were included in the experimental results.

B. *Experimental Results*

Figures 3 and 4 illustrate participant A's deceleration behavior with $V_p = 40$, $V_o = 80$km/h, and $V_p = 23$, Vo = 40km/h as examples. These figures indicate that the driver decelerates to maintain the slope dK_{dB}/dD at brake initiation, as indicated in the $K_{dB} - D$ diagram. In addition, the peak deceleration is then maintained until $V_r = 0$, as indicated in the deceleration diagram as shown in Fig.3. Interestingly, K_{dB} patterns are almost linear even though deceleration, V_r, and TTC patterns are nonlinear. Similar patterns can be seen in other approaching conditions. In addition, all of the other participants' deceleration profiles in the $K_{dB} - D$ diagram exhibit a similar tendency (see Appendix for more results). Furthermore, it has been found that deceleration profiles of drivers including novices in a driving simulator exhibit a similar tendency [12].

IV. Formulation of Expert Drivers' Deceleration Profiles

A. *Characterization of Expert Drivers' Deceleration*

Expert drivers' brake behavior can be characterized as exhibiting the following two properties (Fig. 5).

Phase1) Index K_{dB} changes with the same slope $dK_{dB} / dD = dK_{dB}(t_{bi}) / dD$ as in phase I or the constant slope phase in Fig. 5.

Phase 2) Constant deceleration is maintained after peak deceleration until $V_r = 0$, as in phase II or the constant deceleration phase in Fig. 5.

We formulate the above properties as follows.

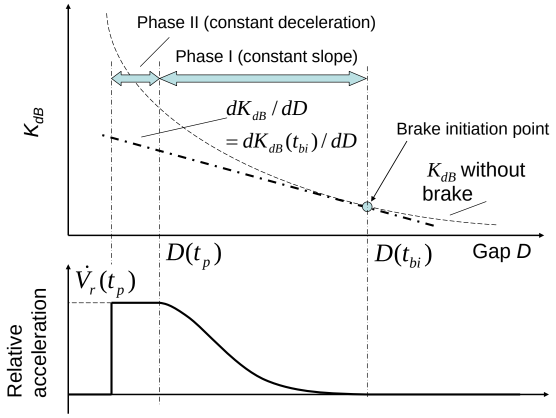

Fig. 5. Schematic image of an expert driver's deceleration model.

B. Deceleration Model of the Constant Slope Phase

Differentiating K_{dB} by gap D yields

$$\frac{dK_{dB}(t)}{dD(t)} = \frac{10}{\ln 10}\left(\frac{\dot{V}_r(t)}{V_r^{\,2}(t)} - \frac{3}{D(t)}\right) \tag{5}$$

Phase 1 can then be written as eq. (6).

$$\frac{dK_{dB}(t)}{dD} = \frac{dK_{dB}(t_{bi})}{dD} \tag{6}$$

Substituting eq. (5) into eq. (6) and solving by relative acceleration leads to deceleration profile model eq. (7).

$$\dot{V}_r(t) = \left(\frac{3}{D(t)} - \frac{3}{D(t_{bi})} + \frac{\dot{V}_r(t_{bi})}{V_r^{\,2}(t_{bi})}\right) V_r^{\,2}(t) \tag{7}$$

With Phase1, the definition of K_{dB} and eq. (6) leads to eq. (8).

$$\begin{aligned} K_{dB}(t) &= 10\log_{10}\left(4\times 10^{-7}\frac{-V_r(t)}{D^3(t)}\right) \\ &= \frac{10}{\ln 10}\left(\frac{\dot{V}_r(t_{bi})}{V_r^2(t_{bi})} - \frac{3}{D(t_{bi})}\right)(D(t) - D(t_{bi})) \\ &\quad + 10\log_{10}\left(4\times 10^{-7}\frac{-V_r(t_{bi})}{D^3(t_{bi})}\right) \end{aligned} \tag{8}$$

Solving eq. (8) by V_r(t) yields a profile of relative velocity as eq. (9).

$$V_r(t) = \frac{V_r(t_{bi})}{D^3(t_{bi})} D^3(t) \exp\left\{\left(\frac{\dot{V}_r(t_{bi})}{V_r^{\,2}(t_{bi})} - \frac{3}{D(t_{bi})}\right)(D(t) - D(t_{bi}))\right\} \tag{9}$$

Constant Relative Velocity Situation

For the sake of simplicity, we deal with approaching a preceding car driven at a constant velocity. In this situation, relative deceleration is zero until the following car's driver begins to brake. Substituting $dv_r(t_{bi})/dt = 0$ into eq. (7) yields eq. (10), and substituting it into eq. (9) yields eq. (11).

$$\dot{V}_r(t) = \left(\frac{3}{D(t)} - \frac{3}{D(t_{bi})}\right) V_r^{\,2}(t) \tag{10}$$

$$\begin{aligned} V_r(t) &= \frac{V_r(t_{bi})}{D^3(t_{bi})} D^3(t) \exp\left\{-\frac{3}{D(t_{bi})}(D(t) - D(t_{bi}))\right\} \\ &= V_r(t_{bi})\, d^3(t) \exp\{3(1 - d(t))\} \end{aligned} \tag{11}$$

Here $d(t) = D(t)/D(t_{bi})$.

C. Timing of Peak Deceleration of Phase 2

Peak relative acceleration can be obtained by substituting zero into the time derivative of relative acceleration as in eq. (12).

$$\dot{V}_r(t_p) = \frac{3}{2}\frac{V_r^{\,2}(t_p)}{\left(\frac{3}{D(t_p)} - \frac{3}{D(t_{bi})} + \frac{\dot{V}_r(t_{bi})}{V_r^{\,2}(t_{bi})}\right) D^2(t_p)} \tag{12}$$

where t_p denotes the timing of peak relative acceleration. Substituting eq. (7) into eq. (12) and solving it by gap D leads to the gap at the peak of relative acceleration, eq. (13).

$$D(t_p) = \frac{3 - \sqrt{6}/2}{\frac{3}{D(t_{bi})} - \frac{\dot{V}_r(t_{bi})}{V_r^{\,2}(t_{bi})}} \tag{13}$$

Thus, the gap with peak relative acceleration can be obtained uniquely by determining relative acceleration, relative velocity, and the gap at brake initiation.

Constant relative velocity situation

For the sake of simplicity, we deal with approaching a preceding car driven at a constant velocity, as before. Substituting $dV_r(t_{bi})/dt = 0$ into eq. (12) yields eq. (14), and substituting it into eq. (13) yields eq. (15).

$$\dot{V}_r(t_p) = \frac{\sqrt{6}}{2}\left(1 - \frac{\sqrt{6}}{6}\right)^5 \exp(\sqrt{6})\frac{V_r^{\,2}(t_{bi})}{D(t_{bi})} \tag{14}$$

$$D(t_p) = \left(1 - \frac{\sqrt{6}}{6}\right) D(t_{bi}) \tag{15}$$

Substituting eq. (15) into eq. (11) yields eq. (16).

$$V_r(t_p) = \left(1 - \frac{\sqrt{6}}{6}\right)^3 \exp\left(\frac{\sqrt{6}}{2}\right) V_r(t_{bi}) \tag{16}$$

D. Brake Timing Given Deceleration

Relative acceleration is equivalent to deceleration of the following car when the preceding car is driven at a constant velocity. We consider the constant deceleration phase after the deceleration peak. The relative velocity in the phase is represented as eq. (17), and the gap profile is represented as eq. (18).

$$V_r(t) = \dot{V}_r(t_p)(t - t_p) + V_r(t_p) \tag{17}$$

$$D(t) = \frac{1}{2}\dot{V}_r(t_p)(t - t_p)^2 + V_r(t_p)(t - t_p) + D(t_p) \tag{18}$$

Substituting $V_r = 0$ into eq. (17) yields brake termination timing t_f (eq. (19)).

$$t_f = t_p - \frac{V_r(t_p)}{\dot{V}_r(t_p)} \tag{19}$$

The gap D when braking is terminated is calculated as in eq. (20) by substituting eq. (19) into eq. (18).

$$D(t_f) = -\frac{1}{2}\frac{V_r^2(t_p)}{\dot{V}_r(t_p)} + D(t_p) \tag{20}$$

Eliminating t_p from eq. (20) by substituting eqs. (14), (15), and (16) yields eq. (21).

$$D(t_f) = \left(1 - \frac{\sqrt{6}}{6}\right)^2 D(t_{bi}) > 0 \tag{21}$$

It means that, in the approaching condition, collision can be avoided whenever deceleration eq. (14) is generated. However, in real driving conditions, a limitation of deceleration exists; thus, brake initiation timing can be calculated with eq. (22) by means of the deceleration limit by solving eq. (13) by $D(t_{bi})$.

$$D(t_{bi}) = \frac{\sqrt{6}}{2}\left(1 - \frac{\sqrt{6}}{6}\right)^5 \exp(\sqrt{6})\frac{V_r^2(t_{bi})}{\dot{V}_r(t_p)} \approx 1.03\frac{V_r^2(t_{bi})}{\dot{V}_r(t_p)} \tag{22}$$

Equation (22) indicates that if $V_r(t_{bi})$ is given, brake initiation timing can be determined from peak deceleration. The gap at brake initiation is inversely proportional to the peak deceleration. This implies that expert drivers can estimate brake initiation timing from the current relative velocity and preferable maximum deceleration based on environmental conditions (e.g., road conditions). Thus, our driver deceleration model seems to reflect expert human drivers' simple and skillful control scheme.

V. Characterization of Initiation Timing of Last-Second Braking

A. Derivation of the Judgment Line of Brake Initiation

The initiation timing of last-second braking obtained from the experiments in the previous section was analyzed. In the experimental results, a smaller K_{dB} at brake initiation was recorded at higher speeds of the preceding vehicle V_p. This result implies that with large V_p, drivers tended to drive more safely. Therefore, to take this phenomenon into account, we modify K_{dB} by adding a term related to V_p. For this purpose, K_{dB_c} is introduced.

$$K_{dB\_c}(a) = \begin{cases} 10\log_{10}\left(\left|4\times10^7 \times \dfrac{-V_r + aV_p}{D^3}\right|\right) \\ \quad (|4\times10^7 \times(-V_r + aV_p)/D^3| \geq 1 \text{ and } V_r \leq 0) \\ 0 \qquad\qquad (\text{else}) \end{cases} \tag{23}$$

Therefore, the term $-V_r$ of K_{dB} is replaced by $-V_r + a\,V_p$. Similar linear combination of relative velocity and vehicle's velocity with respect to ground can be seen in the definition of RF (Risk feeling) index [3]. It should be noted that K_{dB_c} is similar with a nonlinear transformation of combination of 1/TTC and 1/THW that are weighted by D [13]. The relationship between K_{dB_c} (a) and D at brake initiation follows a curved line with less scattering (Fig. 6). It should be noted that scalar $a = 0.2$ was determined by minimizing the scattering in this plane. Let us assume that the curve representing $K_{dB\_c}(a)$ at the time of brake initiation is approximated by eq. (24).

$$\phi(V_r, V_p, D) = K_{dB\_c}(a) - b\log_{10} D - c = 0 \tag{24}$$

Based on the least-square method, the following judgment line of brake initiation timing is obtained.

$$\phi(V_r, V_p, D) = K_{dB\_c}(0.2) + 22.66\log_{10} D - 74.71 = 0 \tag{25}$$

Equation (25) fits real brake initiation timing well as shown in Fig. 6.

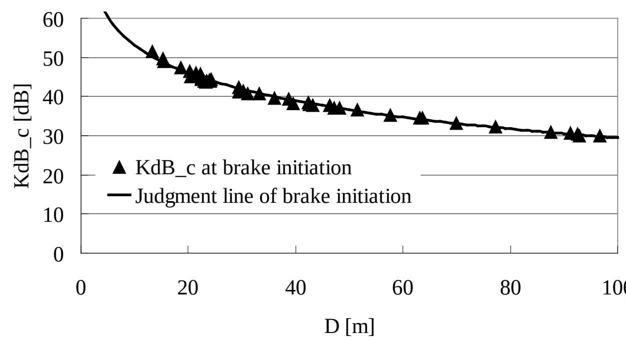

Fig. 6. K_{dB_c} at brake initiation and judgment line.

B. Effectiveness of the Judgment Line of Brake Initiation

In order to demonstrate the effectiveness of the judgment line of brake initiation, we compare brake initiation timing of crash data and that of normal safe driving.

<u>Analysis of Brake Initiation Timing of Crash Data</u>

We analyzed the velocity of the following car and that of the preceding car at the moment of crash, as well as the velocity of the following car and the headway distance at the moment of the driver recognized a danger, based on the data of 342 rear-end crashes from 1993 to 2003 collected by the Institute of Traffic Accident Research and Data Analysis (ITARDA). The data is collected by interviewing drivers after crashes. The index values are calculated from the data by the following procedure.

1) Assume that the relative velocity at the moment the driver recognizes danger can be calculated by (the velocity of the preceding car at the moment of crash) – (the velocity of the following car at the moment the driver recognizes danger).
2) Suppose that the headway distance of driver's danger recognition from 0 through 10m is treated as 7.5m because the distance less than 10m is provided as a group. In addition, the velocity of the following vehicle at that time from 0 through 25km/h is treated as 12.5km/h because the velocity less than

25km/h is provided as a group.

3) The index K_{dB_c} is calculated from the preceding car's velocity and the relative velocity at the driver danger recognition given in 1) and the headway at that time.

Note that the data points lacking velocities or distance are removed from the analysis, resulting in 214 of the 342 data points being effective.

<u>Analysis of Brake Initiation Timing of Normal Safe Driving</u>

A course including both limited access roads and other general roads that required 1.5h of driving was selected. Five males participated (one in his twenties, two in their thirties, one in his forties, and one in his fifties). The participants were instructed to drive in their usual manner to maintain safety. A midsize sedan was utilized in the experiments. The test car was equipped with an FMCW milli-wave radar sensor to measure the gap between two vehicles and the relative velocity. Vehicle state variables (e.g., the subject car's velocity and acceleration, brake oil pressure, and video images of the front view) were also recorded. The K_{dB_c} values at brake initiation determined by brake oil pressure onset were calculated from the recorded relative velocity, the test car's velocity, and the gap between the two vehicles. A total of 276 data points were extracted.

Figure 7 compares brake initiation timing of the crash data with that of normal safe driving in the $K_{dB\_c} - D$ plane. The judgment line of brake initiation successfully discriminates crash data and normal safe driving. The rate of the plots for normal driving that are located above the line is 0.0072. On the other hand, the crash data is not plotted below the line.

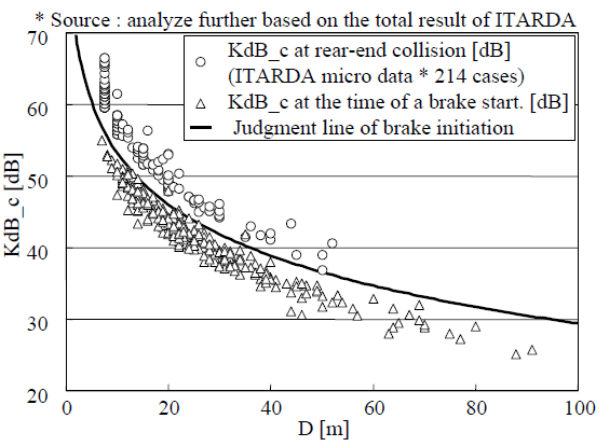

Fig. 7. Discrimination between Crash Data and Normal Safe Driving by the Judgment Line of Brake Initiation.

VI. Proposal of Automatic Braking Control based on the Driver's Deceleration Model

A. Determining when to Initiate the System's Braking

In the previous section, the driver's brake initiation timing can be modeled as the brake judgment line. Here, a method is proposed to apply the model to brake initiation judgment for an automatic braking system. The brake-judgment model obtained in the previous section is an averaged result of the drivers' brake initiations. Thus, the driver might over-trust the system and not brake because the system starts to brake automatically just when the driver starts to brake, if the model is employed as the brake initiation algorithm without any change. In addition, individual differences occur in brake initiation timing. For example, aggressive drivers start to brake later than mild drivers. Thus, it is important to consider individual differences in brake initiation judgment in order to avoid discomfort.

Therefore, brake initiation is determined from eq. (26) by adding an offset of the line Δc to eq. (25) as follows:

$$\phi(V_r, V_p, D) \geq \Delta c \qquad (26)$$

where Δc is determined by considering individual differences. In the remaining part of this paper, the offset Δc is chosen by trial and error. Establishing a systematic manner to determine is an important future study..

B. Deceleration Pattern Generation Method

<u>Characterization of the Constant Slope Feature</u>

As derived in the previous section, expert drivers' deceleration behaviors were modeled using the constant-slope feature (Phase 1) and the peak-hold feature (Phase 2). The peak-hold feature is difficult to install in the automatic braking system due to its lack of robustness against situational changes. Thus, we consider applying the constant-slope feature to generate a deceleration profile for the automatic braking system.

From eq. (10), dV_r/dt reaches zero when $V_r = 0$; otherwise, dV_r/dt always takes a positive value (i.e., deceleration). In addition, from eq. (11), V_r reaches zero when D goes to zero; otherwise V_r always takes a negative value because $V_r(t_{bi}) < 0$ is assumed. From these results, the derived deceleration profile results in collision with $V_r = 0$ under the given assumptions, as long as the calculated deceleration can be generated; that is, the state uniquely converges to its equilibrium point $[V_r, D]^T = [0, 0]^T$.

Figure 8 illustrates the calculated results of eqs. (10) and (11) with $V_r(t_{bi})$ = -20km/h without relative deceleration until brake initiation. The two lines in each graph denote $D(t_{bi})$ = 25m and 50m. A smooth deceleration profile can be obtained with only the simple calculation of eq. (11). It should be noted that the deceleration profile is asymmetric in time. At the beginning of brake initiation, a relatively large jerk is generated and leads to a secure system. However, in the final stage of the deceleration, the jerk is relatively small in order to provide comfortable assistance. It should be noted that a method to generate smooth deceleration profile based on the minimum jerk theory proposed by Hiraoka et al.[9] for smooth and comfortable ACC systems generates a symmetric deceleration profile.

<u>A Method to Generate a Deceleration Profile for Automatic Braking Control</u>

The smooth profile obtained from the constant-slope feature has an equilibrium point $[V_r, D] = [0,0]$ (i.e., collision occurs at $V_r = 0$). Thus, a method to generate a safer deceleration profile for the automatic braking system is needed. A safer velocity profile $V_r^d(t)$ is determined by adding an offset in the gap D to the velocity profile, so that $V_r = V_{r}\_offset>0$ is realized at $D = 0$.

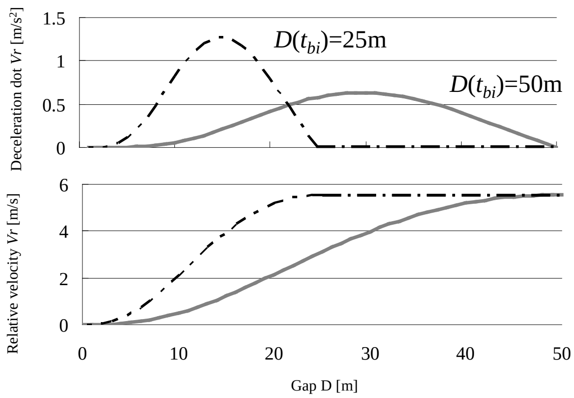

Fig. 8. Deceleration profile of the constant-slope feature.

$$V_r^{\,d}(D) = \frac{V_r(t_{bi})}{D^3(t_{bi})} D^3(t) \exp\left\{ -\frac{3}{D(t_{bi})}(D(t) - D(t_{bi})) \right\} + Vr\_offset \frac{D(t_{bi}) - D(t)}{D(t_{bi})} \tag{27}$$

$$= V_r(t_{bi}) d^3(t) \exp\{3(1-d(t))\} + Vr\_offset(1-d(t))$$

With this offset, $V_r = 0$ is realized with gap $D>0$ (i.e., no collision). Figure 9 presents examples of the results with V_r_offset = 1m/s for three V_r conditions.

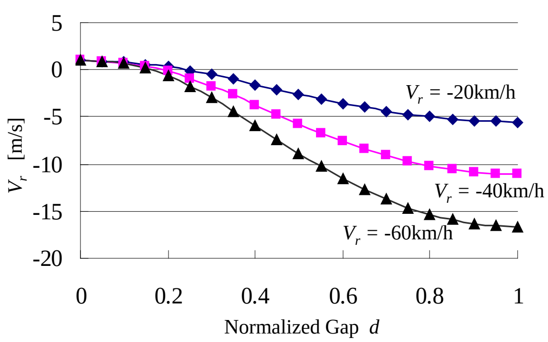

Fig. 9. Safer velocity profile with offset.

C. *Procedure of Automatic Braking Control*

We propose a new automatic braking system based on the derived driver deceleration model. The proposed system decelerates the vehicle automatically and avoids collision if the driver does not decelerate or decelerates too slowly, even in a high risk situation, such as the preceding vehicle's approaching. Brake initiation timing and the deceleration profile play important roles in achieving an effective system. In particular, automatic braking should start as early as possible to realize smooth and safe deceleration, as long as the driver does not feel discomfort and does not begin to over-trust the system.

The following control method has thus been obtained (Fig. 10).

1) ϕ□(V_r, V_p, D) is calculated in real time from measured $V_r(t)$, $D(t)$, and $V_p(t)$ or $V_o(t)$. Brake control starts when the judgment criteria of inequality (26) is satisfied.

2) The desired deceleration can be determined by the deceleration profile model (eq. (27)).

3) The brake control terminates if V_r >= 0.

An acceleration command is generated from the given velocity profile by the following simple method.

$$G = -k_p (V_r^{\,d}(D) - V_r(t)), \tag{28}$$

where k_p is the feedback gain.

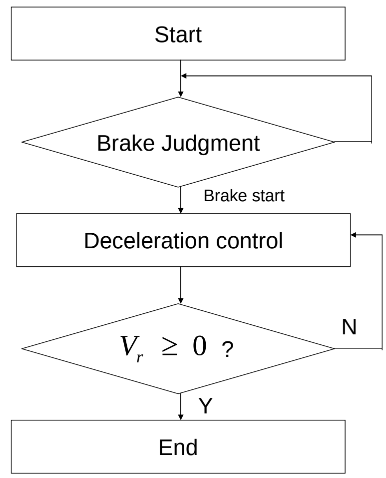

Fig. 10. System flow of automatic braking control.

D. *Simulation Results of the Proposed Automatic Braking Control*

Some numerical simulations are performed with the sequences given in Fig. 10 in order to show effectiveness of the proposed braking method. In all simulations, V_r_offset in the velocity profile of eq. (28) is set to 1m/s, and the offset of brake initiation timing Δc in eq. (27) is set to 0.

Figures 11 and 12 illustrate the response of the proposed control method when approaching a preceding vehicle at a constant relative velocity. In Fig. 11, the driver's vehicle driven at V_o = 60km/h approaches the preceding vehicle being driven at V_p = 40km/h. In Fig. 12, the simulation condition is given by V_o = 60km/h and V_p = 0km/h (i.e., the preceding vehicle stops). As seen in both figures, smooth velocity profiles are realized, and collision is avoided.

Figure 13 illustrates the simulation results when the preceding vehicle suddenly decelerates in order to show the effectiveness and robustness of our proposed method. In the initial state, the following vehicle and the preceding vehicle are driven at 40km/h with gap D = 30m. At t = 2s, the preceding vehicle starts to decelerate in -2m/s^2, then stops. Results indicate that the proposed deceleration method can realize smooth deceleration and avoid collision even with deceleration of the preceding vehicle.

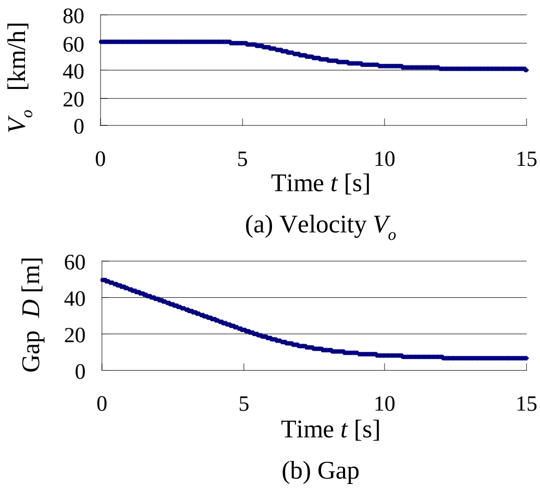

Fig. 11. Simulation results ($V_p = 40$, $V_o = 60$km/h).

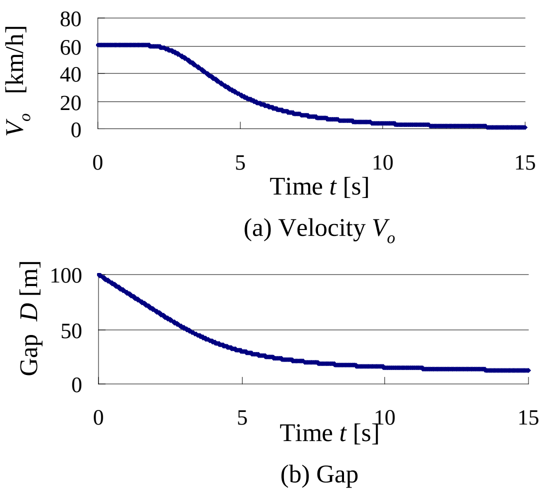

Fig. 12. Simulation results ($V_p = 0$, $V_o = 60$km/h).

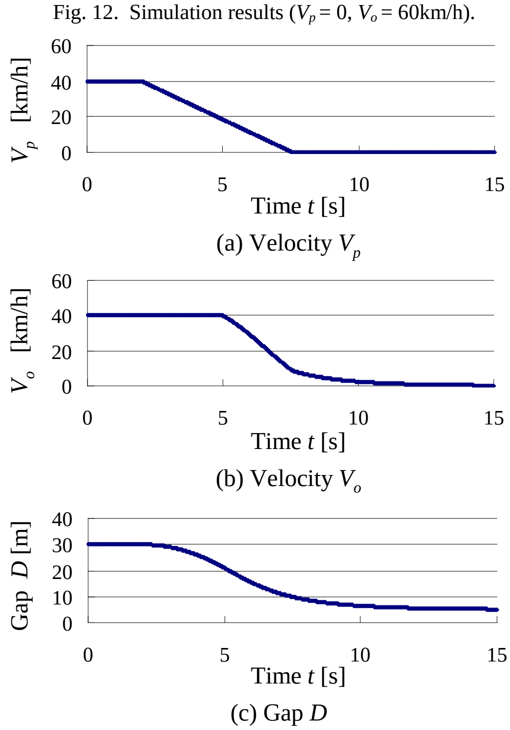

Fig. 13. Simulation results for sudden deceleration ($V_p = V_o$=40km/h, dV_p/dt = -2m/s^2)

VII. Evaluation of the Proposed Automatic Braking Control

The proposed control method is installed in a midsize sedan and subjectively evaluated by drivers from an auto manufacturer on a test course. A straight road in the test course was used. Twenty-five skilled drivers aged 38 to 70yr (mean age 54.2yr, SD 7.93yr) who were not involved in this research participated in the experiments.

Figure 14 illustrates the vehicle's behavior in the experiments as an example. The subject car driven at 90km/h approaches the preceding vehicle being driven at a constant velocity of 50km/h in the initial state. The proposed system starts to decelerate automatically, based on the proposed algorithm, and the relative velocity of the two vehicles converges to zero. As seen in the figure, smooth braking was realized to avoid collision.

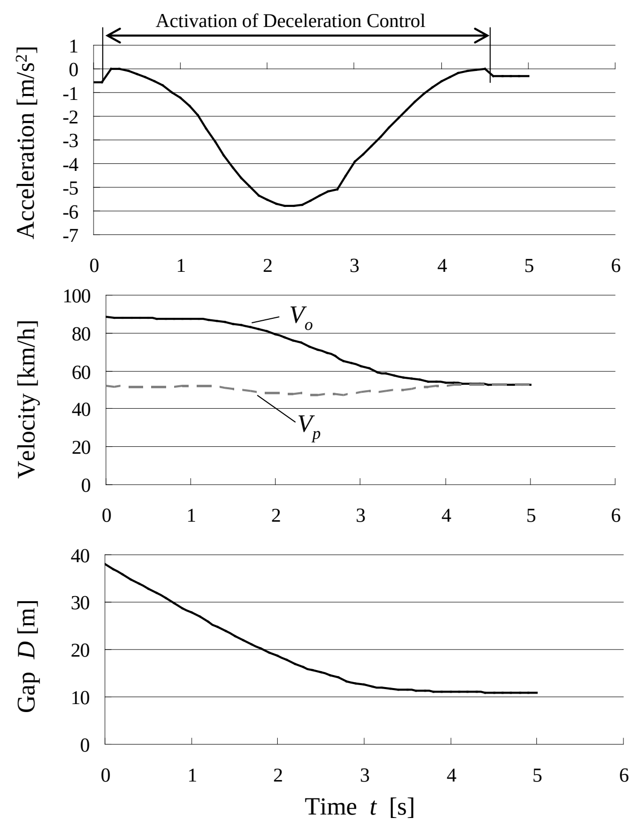

Fig. 14. Experimental Results: Vehicle Behavior

A. *Evaluation of Brake Initiation Timing*

Participants were asked to comment on the braking timing of the brake assistance system. The experimenters used three categories: earlier than, almost the same as, and later than the driver's own timing. In this experiment, Δc = 1dB was employed to avoid excessive dependence on the system. This is based on an assumption that a driver does not excessively depend on the system if the system starts to decelerate moderately later than the driver's timing since the driver feels discomfort. There were two conditions of constant relative velocity, V_p = 60km/h and V_o = 100km/h, and sudden deceleration with dV_r/dt = 1m/s^2 from $V_o = V_p$ = 60km/h with initial distance $D_0 = D(t <= t_{bi})$ (mean 19.4m, SD 3.7m).

Twenty-one participants rated the braking timing of the system as later than their own braking (Fig. 15), indicating that the brake initiation timing with Δc = 1dB did not result in excessive dependency. However, the fact that four participants rated the system's braking timing as almost same as their own timing implies the need for a method that adapts to individual differences.

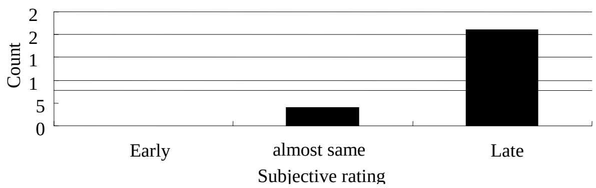

Fig. 15. Subjective Evaluation of Brake Initiation Timing.

B. *Evaluation of the Smoothness of the Deceleration Profile*

The participants were asked to comment on the smoothness and security of the deceleration profile. The experimenters used three categories: poorer than the driver's own braking, as good as the driver's own braking, and very good. In this experiment, Δc = -3dB was employed to collect detailed comments under safer conditions. The same two conditions as in the previous experiments were experienced by the participants.

All except one participant rated the smoothness and security of the deceleration profile as being as good as their own or very good (Fig. 16). Many commented that the control method realized very smooth deceleration.

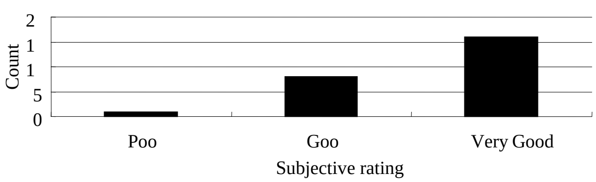

Fig. 16. Subjective Evaluation of the Braking Profile.

VIII. CONCLUSION

The deceleration behavior of expert drivers in last-second braking in a car-following situation were analyzed using our proposed K_{dB} and K_{dB_c} indices that reflect the driver's visual input and perceptual risk of a preceding vehicle. Braking profiles of expert drivers were formulated, and it was found that the formulated deceleration profile can generate smooth velocity and deceleration profiles for a wide range of approach situations without any complex calculation. In addition, the initiation timing of last-second braking was modeled as a braking initiation line with high accuracy. Based on these models, a new automatic braking system was proposed and installed in a real car. Subjective ratings of test drivers demonstrated that the system realizes comfortable and secure deceleration by means of brake initiation and deceleration profiles.

In this paper, we derived a new control method in an automatic braking system, based on expert drivers' braking behavior model. In addition, an offset to the brake judgment line was introduced for individual differences. Further investigation of personal adaptation to brake initiation timing is needed in future study because drivers may be sensitive to brake initiation timing, which could easily lead to discomfort. As another future study, the robustness of the method should be investigated, including emergency situations or a complex traffic environment. In addition, the influence of the system on traffic flow should be investigated, even though it seems that the negative effect is small, since our proposed method generates a smooth and human-like deceleration profile.

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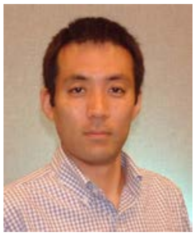

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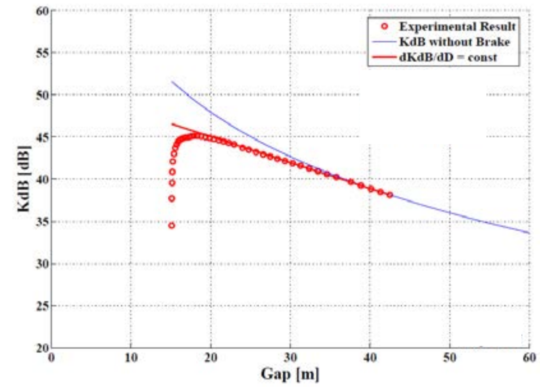
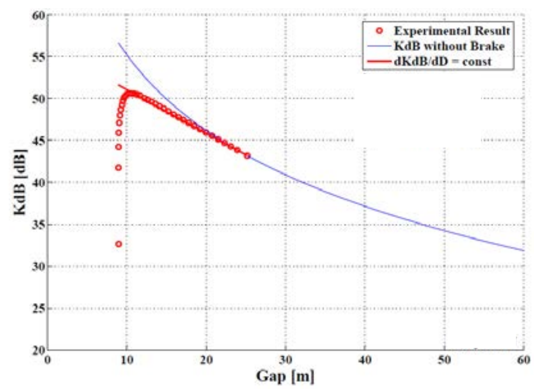
APPENDIX

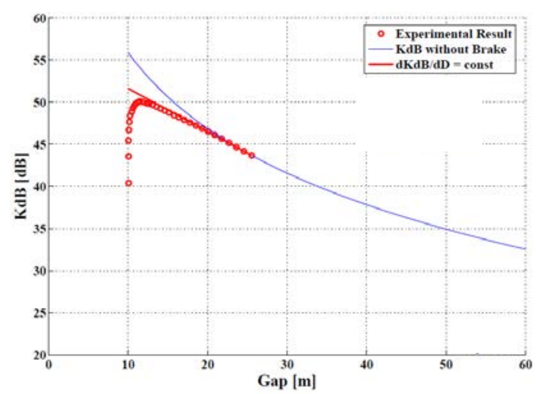
The following figures show the other examples of the experimental results in Section III. The same dK_{dB}/dD = constant feature appears in the other participants behaviors with various approaching conditions.



(a)Subject B, V_p=57, V_o=102km/h



(b) Subject B, V_p=19, V_o=49km/h



(c) Subject C, V_p=21, V_o=56km/h

Fig. Expert driver's braking behavior in K_{dB}-D diagram

Abstract: Expert drivers' deceleration patterns in last-second braking will be formulated using a perceptual risk index for the approach and the proximity of a preceding vehicle as examples of comfortable braking patterns. It will be shown that the formulated braking pattern can uniformly generate a smooth deceleration profile for many approach conditions. In addition, the brake initiation timing of expert drivers will be successfully formulated using a modified index. Finally, an automatic braking system for collision avoidance will be proposed based on a formulated brake-initiation model and a deceleration pattern. Twenty five expert drivers will experience the automatic braking that is installed in an experimental car. It will be shown that the proposed system can generate a smooth profile and realize secure brake patterns based on the drivers' subjective evaluation.

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