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Analysis of Braking Behaviors in Car Following Based on A Performance Index for Approach and Alienation

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Abstract—**A new index is proposed to evaluate danger situation in car following based on the hypothesis that drivers are performing approach detection and deciding braking behavior with change of area of a preceding car on the retina. Based on the index, braking behaviors in car following situation is analyzed. The experimental results of a test driver with a real car with constant relative velocity to preceding car show that the braking behaviors can be characterized using the index and the gap. In addition, the results of laboratory experiments using a driving simulator support the results of the real car experiments. We conclude that the drivers' deceleration behavior in moderate danger levels can be characterized well in phase plane of the proposed index and the gap. Furthermore, we also show brake initiation timing can be characterized well based on the index modified by taking preceding car speed into account from the experimental results with a test driver.**

I. INTRODUCTION

It is important to investigate the sequences of the situations to the crashes and driver status and characteristics in each stage to realize driver support systems that avoid crashes in early stage of danger situation. In order to mitigate the risk of crash, methods to detect distracted, inattentive, and other unsafe driving situations are important.

There are many efforts to explore the method to detect drivers' error with many fashions. Many methods are developed to detect drivers status using driver inputs such as steering [1] and throttle [2] because it seems easier to detect directly in the case of application to real vehicle. Also, there are many researches to utilize mathematical model to detect errors. Shibata et al.[3] proposed a method to detect distracted driving based on error between the outputs of model defining safe driving and actual outputs of the driver. Asao et al.[4] attempt to describe difference between normal driving and physically distracted driving caused by large body movements as the change of parameters in the driver-vehicle closed-loop model. On the other hand, there are also many efforts to detect errors based on human behaviors directly, for example, using direction of the head[5] and eyeblink[6] to detect driver's unsafe condition.

The purpose of this research is to evaluate the physical danger level by approach of a preceding car in longitudinal direction in car following situation and its perceptual risk of the situation, to elucidate driving behavior associated with the situation and to apply the results to the design of driver support system. To investigate rear-end crashes, deceleration behavior is important. A lot of researches have been conducted on drivers behavior especially deceleration behaviors in car following situation. Lee [7] have offered theoretical framework of drivers longitudinal control based on TTC (Time-To-Collision) as a pioneer research on driving behavior associated with visual input. After that many discussion have been done for this, for instance, Morita et al.[8] have concluded by statistical comparison that brake initiation timing should be determined using inverse of TTC.

Moreover, on the deceleration behavior, Goodrich et al. [9] characterize the behavior in a phase plane of TTC vs. THW (Time-Headway). On the other hand, we can find literatures that investigate the risk perception based on TTC and THW [10]. These imply that drivers determine the timing of brake initiation and deceleration patterns based on their own perceptual risk.

In this research, we explore the possibility to characterize a driver's status and driving behavior in car following situation by considering relationship between the visual input and the behavior associated with the input in order to assess safety, comfort, and reliance of the driver support system and apply to optimal design of such systems including collision warning system and collision avoidance system. Namely, it is reasonable to evaluate driver's status based on the vehicle's behavior as the output of the driver-vehicle system by introducing a new index related to visual input because visual input affects directly on driver's operation and vehicle's behavior.

Wada et al.[11] have introduced a new index based on the changes of area of preceding vehicle on a retina to evaluate the driver status and characterizing the behavior in car following situation. The index is based on a hypothesis that drivers perceive the preceding car's approach and evaluate its emergency level and operate the vehicle based on the area changes on their retina. In [11], it has been shown that safe and normal driving behaviors of experimental results with real cars and micro data of traffic accidents with rear-end collisions as danger status can be distinguished using the proposed index. In addition, based on the basic laboratory experiments assuming preceding-car-following situation, it has been also shown that the proposed index reflects changes of the danger level, visual capability, and arousal level of the drivers.

In this paper, the deceleration behaviors are analyzed using the performance index and characterized since we originally have hypothesized that drivers determine the acceleration and deceleration behavior by the function of the proposed index. Namely, we investigate how the performance index can be utilized to characterize the braking behavior in car following situation. For this purpose, a test driver's driving a real car is analyzed in constant relative velocity conditions. Furthermore, experiments with the driving simulator are conducted in various following condition such as constant relative velocity and constant deceleration of preceding car. We will find that the drivers' deceleration pattern can be characterized well in phase plane of the proposed index and the gap between the rear of the lead vehicle and the front of the subject car. Furthermore, we also show brake initiation timing can be characterized well based on the index modified by taking preceding car speed into account from both experimental results of a real car.

II. PERFORMANCE INDEX FOR APPROACH AND ALIENATION

As shown in [11], by comparing change of distance, visual angle and area change on retina, the area change is the most sensitive. Thus, it seems reasonable to think that drivers detect the approach of the preceding car by its area changes.

We hypothesize that drivers detect the approach of the preceding car and sense the collision risk by its area changes on the retina and determine the operation of acceleration or deceleration based on it. Variable K is defined by eq.(1) as a variable proportional to the area change of the preceding car on the retina because the area of the preceding car on the retina is proportional to $1/D^2$.

$$K(V_r, D) = \frac{d}{dt}\left(\frac{1}{D^2}\right) = -\frac{2}{D^3} Vr, \qquad \cdots \quad (1)$$

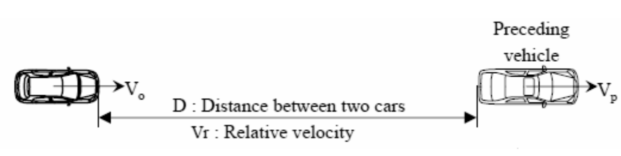


Fig.1 Car-following situation

where D and V_r=V_p-V_o represent gap between the rear of the lead vehicle and the front of the subject car and relative speed between two vehicles, respectively(Fig.1). Variable K changes in wide range for example it changes in the order of 10^6 corresponding to D=1 to 100[m]. Thus, in practical manner, we introduce logarithm expression of K. Assuming the threshold to detect the approach of the preceding car at D=100[m] and V_r=-0.1[km/h] yields

$$K_0 \equiv K(-0.1, 100) = 5 \times 10^{-8}. \qquad \cdots \quad (2)$$

Now KdB is defined as eq.(3) that is the logarithm form of K to the base 10 so that K_{dB} = 0[dB] when K=K_0.

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

We call this variable K_{dB} "performance index for approach and alienation" at the moment of the driver's operation such as deceleration and acceleration. Indices K and K_{dB} are increased when the preceding car is approaching relatively to own car as similar as increase of the driver's visual input. KdB is increased when the driver do not react for this regardless of cause of risky conditions such as low arousal level, inattention or other reasons depending on driver's status.

III. EXPERIMENTAL INVESTIGATION OF BRAKING BEHAVIOR

A. Experiments with a test driver

To characterize the deceleration behavior in normal safe driving, experiments are conducted with a test driver. A preceding car runs at constant velocity V_p and the following car driven by the test driver approaches at constant velocity Vo. The subject was instructed not to decelerate as long as he feels that the collision was avoidable with his normal decelerate behavior and to decelerate at his limit of normal braking operation. Three experimental conditions are utilized as the combinations of V_p and V_o.

B. Experimental results

As shown in Figs.2 and 3, the driver decelerates to maintain the slope dK_{dB}/dD at the brake initiation timing for all conditions and then peak deceleration is kept until V_r=0 is realized. Interestingly, K_{dB} patterns are almost linear even though deceleration, Vr and TTC patterns are nonlinear. Dotted lines in the figures illustrate simulation results using the feature that the braking behavior completely satisfies dK_{dB}/dD=$K_{dB}(t_{bi})/dD$ where t_{bi} denotes time at brake initiation and peak of the deceleration is held given the same brake initiation timing as the experimental results. In the simulation, V_p, V_o at the initial status and TTC at brake initiation are extracted from the experimental results and used in the simulation. The experimental results and the simulation results coincide well. Similar behavior can be seen with the condition of V_p=40, V_o=100[km/h], TTC=4.75[s] (no figure). Thus, the feature of

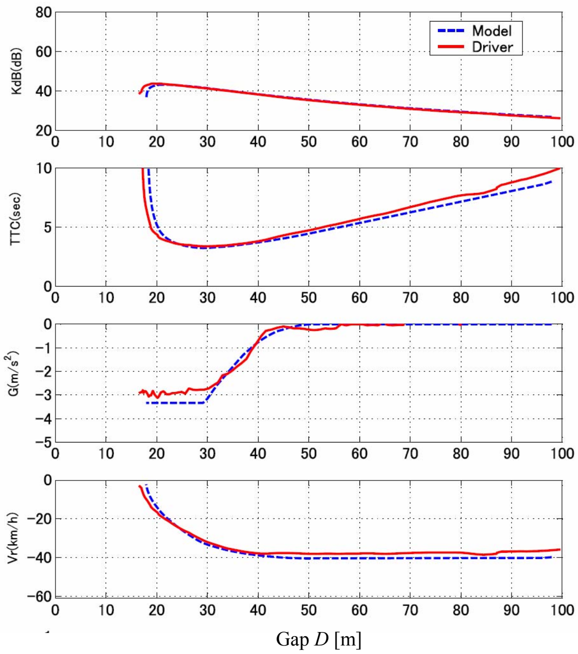


Fig.2 Test driver's deceleration behavior and simulation results Vp=40, V_o=80[km/h], TTC=4.5[s]

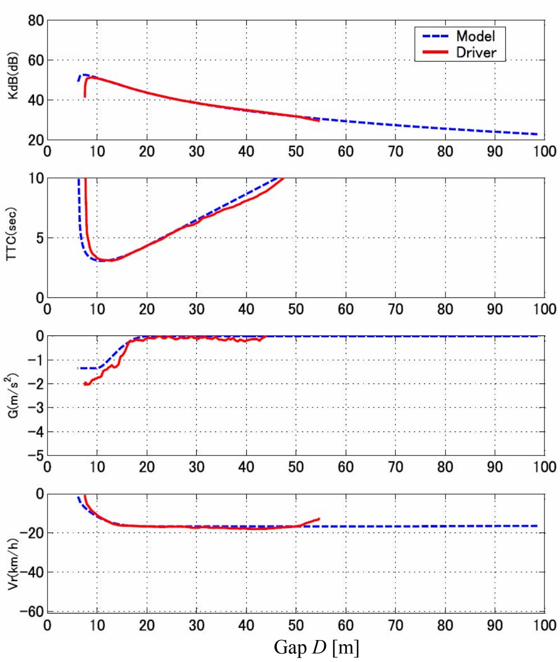


Fig.3 Test driver's deceleration behavior and simulation results Vp=23, V_o=40[km/h], TTC=4[s]

dK_{dB}/dD=const then peak hold of deceleration is validated. As a result, possibility of characterization of deceleration behavior in plane of D and K_{dB} is shown.

IV. Simulator Experiments in various Situation

Experiments with normal drivers are conducted using a driving simulator to investigate whether characterization with a test driver given in the previous section can be applied to general drivers in various situations.

A. *Experiments in approaching of preceding car with constant speed*

Experiments in approach of the preceding car with constant velocity are conducted to show whether the characteristics obtained in the previous section with a test driver can be obtained in the normal drivers. Also, by preparing the normal and the low μ conditions, we investigate the possibility to express such situations using the proposed model and characterization.

1) *Experimental method*

A driving simulator with real car's cockpit is utilized. In the experiments, a 17inch LCD is attached in front of the subjects to utilize high resolution image even though our simulator has a 100inch screen at front and two 70inch screens at two sides for usual driver behavior researches. The distance between the LCD and the subject's eye is 0.3[m].

Three levels of relative velocity V_r-20, -40, -60[km/h] and two levels of road friction, that is, normal road with μ=1.0 and low μ road with μ=0.2 imitating icy road. Number of the trials are 5 per each condition. Subjects are 4 males from 21 to 23 years old. Road μ is announced to the subjects in advance. The subjects utilize the acceleration pedal and brake pedal but not steering wheel even the subjects grasp a steering angle during the experiments.

The experimental procedure is as follows:

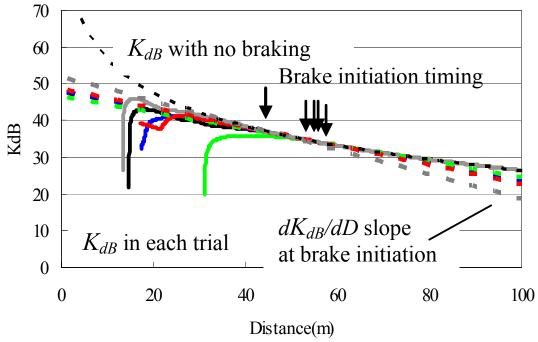
1) At the initial state, the gap is D=200[m]. Through each trial, the subject's car runs at V_o=80[km/h] and the preceding car runs so that the relative velocity V_r is one of the value.

2) The subjects are instructed to decelerate in their normal way against to the approaching to the preceding car.

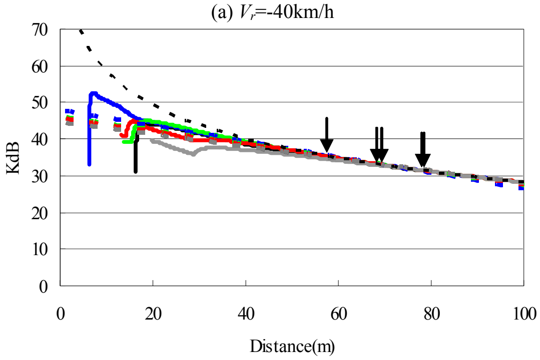
2) *Experimental results*

Fig.6-(a), (b) represent the gap D vs. the index K_{dB} for subject TA with μ=1.0. The dotted curved line in each graph represents transition of K_{dB} with no braking situation. Linear dotted lines represent the slopes dK_{dB}/dD at brake initiation points of every trial illustrated by down arrows. Every K_{dB} transitions go along the dK_{dB}/dD slope at the brake initiation timing for all relative velocity conditions.

This tendency can also be found in V_r=-20km/h condition and the other three subjects (no figure). These tendencies coincide with the experimental results of the test driver in a real vehicleFig.7 represents D vs. K_{dB} for the subject TA

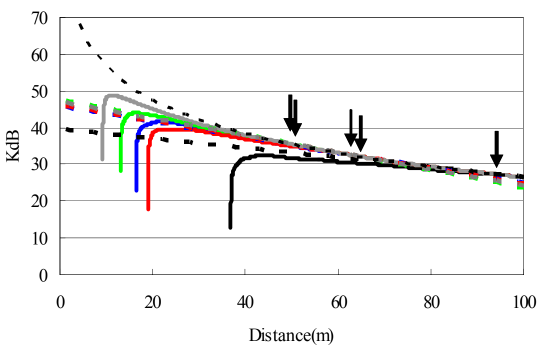


(a) V_r=-40km/h

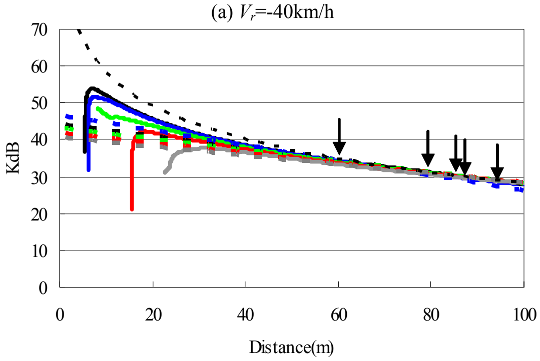


(b) V_r=-60km/h

Fig.4 KdB and gap D (μ=1.0)



(a) V_r=-40km/h



(b) V_r=-60km/h

Fig.5 K_{dB} and gap D (μ=0.2)

with low μ (=0.2). Every K_{dB} transitions also go along the dK_{dB}/dD slopes at the brake initiation timing and the brake initiation timings are earlier than higher μ condition. This tendency can also be found in V_r=-20km/h condition and the other three subjects (no figure).

As the result, the strategies of drivers such that the gap and deceleration are changed considering environmental conditions such as preceding car motion and road surface can be expressed by the change of K_{dB} and D.

B. Experiments in approaching of preceding car with constant deceleration

Experiments in sudden approach of the preceding car with constant deceleration in car following situation are conducted to show whether the characteristics of deceleration behaviors obtained in the previous section of constant relative velocities can be also obtained in relatively higher danger levels.

1) Experimental method

The experimental setup and the subjects are same as those of the previous section. The procedure is as follows:

1) The subject's car runs at constant velocity of 80[km/h] to maintain the initial gap D_0(20, 40, 60m) automatically.

2) The preceding car decelerates suddenly at random timing at deceleration 1 or 3m/s^2.

3) The subject is instructed to brake in their ordinary way against the deceleration of the preceding car.

2) Experimental results

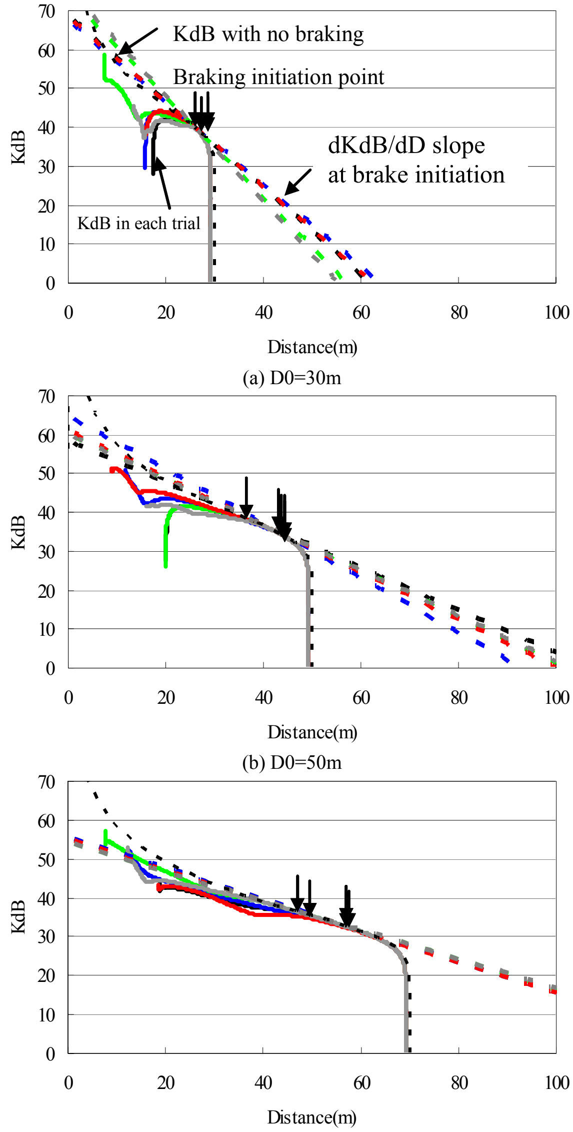
Fig.6 represents the gap D vs. the index K_{dB} for the subject TA with the deceleration of 3[m/s^2]. It should be noted that the transition patterns of K_{dB} in no braking different from those in the approaches at the constant relative velocity.

As shown in Fig.6-(c), every K_{dB} transitions go along the dK_{dB}/dD slope at the brake initiation timing for the relatively safer conditions, that is, larger gap. On the other hand, Figs.6-(a) and (b) show the subject decelerates in larger deceleration than those along with the slope dK_{dB}/dD at brake initiation timing in such relatively dangerous situations with smaller gaps while some plots go along the slope. This implies that drivers tend to take safer behaviors in such dangerous situations. On the other hand, the experimental results at deceleration of 1[m/s^2] (no figures) do not have tendency along the slope dK_{dB}/dD. It is understood that low deceleration results in many options to be taken by a driver in such safe situations.

V. Analysis of Brake Behavior Based on the Index

A. Modeling of Deceleration Profile

Based on the driver's deceleration profile especially early stage of braking, another expression is provided using common physical parameters presenting vehicle motion. Consider the feature of K_{dB} is increased along its tangential line at the brake initiation point. The index K_{dB} is a continuous function of V_r and D. Assume that dV_r/dt is continuous at brake initiation timing. This yields that V_r and



(a) D0=30m

(b) D0=50m

(c) D0=70m

Fig.6 KdB and D in constant deceleration conditions

D are smooth, say, continuously differentiable by time. Then, K_{dB} is required to be a smooth function. So, K_{dB} is smooth at braking initiation point, say, K_{dB} is changed along dK_{dB}/dD at the brake initiation timing.

Assume that $4\times10^7 V_r / D^3 \le -1$. Then the feature of K_{dB} is increased along dK_{dB}/dD at brake initiation timing yields the followings.

$$\frac{dK_{dB}(t)}{dD} = \frac{10}{\log_e 10}\left(\frac{\dot{V}r(t)}{Vr^2(t)} - \frac{3}{D(t)}\right) = \frac{dK_{dB}(t_{bi})}{dD}$$

where t_{bi} denotes the time when starting brake action. Solving this by $\dot{V}r(t)$ yields the following equation.

$$\dot{V}r(t) = \left(\frac{3}{D(t)} - \frac{3}{D(t_{bi})} + \frac{\dot{V}r(t_{bi})}{Vr^2(t_{bi})}\right)Vr^2(t) \qquad \text{.........(4)}$$

This is a simple function of D, V_r and deceleration of the preceding car.

B. Analysis of Brake Initiation Timing Based on the Modified Speed Term

From the experimental results Section III-A, brake initiation timing is analyzed. By looking at relationship between KdB at brake initiation and D, smaller K_{dB} is recorded at higher speed of the preceding vehicle V_p. This implies that at the situation with large Vp, drivers tended to drive more safely. So, to take this phenomenon into account, we modify K_{dB} by adding a term relating to V_p. For this purpose, K_{dB_c} is introduced as follows:

$$K_{dB\_c}(a) = \begin{cases} 10\log_{10}(|4\times10^7 \times \dfrac{-V_r + aV_p}{D^3}|)\mathrm{sgn}(-V_r + aV_p) & (|4\times10^7\times(-V_r + aV_p)/D^3| \ge 1) \\ 0 & (|4\times10^7\times(-V_r + aV_p)/D^3| < 1) \end{cases}$$

. ··(5)

Namely, the term of $-V_r$ of K_{dB} is replaced by $-V_r + a\,V_p$. Let us assume that $K_{dB\_c}(a)$ at brake-initiation timing is approximated in $K_{dB\_c}(a)$ vs D plane by the following equations:

$$K_{dB\_c}(a) - b\log_{10} D - c = 0 \qquad (6)$$

The coefficient a is determined so that the error of the approximated relationship eq.(9) is minimized in terms of least squares. Based on the least square method, a=0.3 is obtained for the test driver. With the $K_{dB\_c}(a)$, judgment line of brake initiation timing is obtained as follows:

$$K_{dB\_c}(0.3) + 23.76\log_{10} D - 76.96 = 0 \qquad (7)$$

Eq.(10) fits well to the real brake initiation timing as shown in Fig.9. Furthermore, Fig.10 illustrates errors from the judgment line of the normal driving and crash data from ITARDA. Probability that the error of the normal driving equals or is greater than 0 dB is 0.00694. On the other hand, for the crash data, probability that the error equals or is smaller than 0[dB] is 0. Therefore, the judgment line can distinguish the normal and crash data very well and be utilized trigger of driver support system.

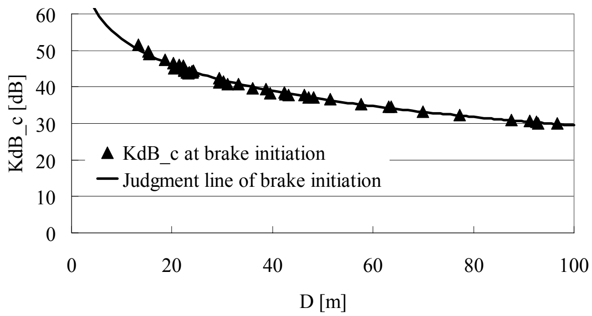


Fig.7 K_{dB_c} at brake initiation and judgment line

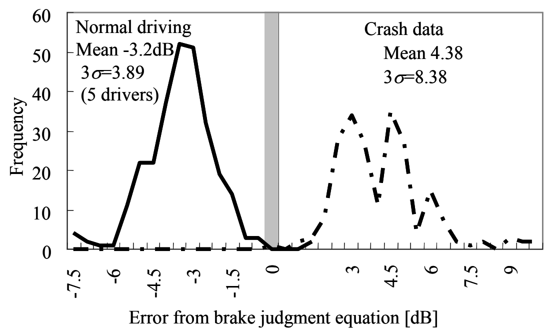


Fig.8 Histogram of error from brake judgment line

VI. CONCLUSIONS

A driver model of the deceleration behaviors in preceding-car-following situation has been developed by hypothesizing that drivers determine the acceleration and behavior by the function of the proposed index. It is found that the test driver decelerates along the slope dK_{dB}/dD at the moment of brake initiation and holding the peak deceleration until V_r=0.

Driving simulator experiments with various deceleration patterns have also shown that the same features along the slope dK_{dB}/dD can be seen also in the normal driver at the constant relative velocity situation even in the low friction road and sudden deceleration situation with moderate danger levels. It has been also shown that the changes of behavior due to change of environment such as earlier braking in low μ road can be explained by this feature. On the other hand, drivers take safer behaviors than the slope feature in more dangerous situation and drivers have many choices of deceleration patterns in much safer situations. This thought implies that the characterization of the deceleration in D-K_{dB} plane may be utilized for the definition and assess unsafe behaviors and also be applied to design of driver support system. Note that the fact that the characterization along dK_{dB}/dD can be found only in the moderate danger level is useful in terms of designing driver support system. This is because the moderate danger level occurs just before high danger level and detection of risky situation in such early stage works better in active safety technology. Furthermore, brake initiation timing was analyzed based on the modified index K_{dB_c} taking the speed of preceding car into account. With K_{dB_c}, judgment line of brake initiation was induced by the test driver's brake initiation. It was shown that the judgment line can distinguish the normal and crash data very well, thus, these results can be utilized for design of driver support system.

As a future study, we will conduct experiments with many participants with various attributes such as sex, age group, and driving experiences to show the validity of the proposed index and characterization. In addition, relationship between the index KdB and risk perception of human for an approaching vehicle will be investigated. Moreover, we will propose a method to realize safe and comfortable driver support systems.

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