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DEVELOPMENT OF SENSITIVITY TERM IN CAR-FOLLOWING MODEL CONSIDERING PRACTICAL DRIVING BEHAVIOR OF PREVENTING REAR END COLLISION

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Abstract: In this study, the deceleration model and the sensitivity term were developed by considering actual driving behaviors to prevent rear end collisions in the car-following situations, especially in deceleration situations. Test vehicles capable of measuring the speed, acceleration, and spacing between the vehicles were used to collect data in the field survey. The deceleration model developed by linear regression has a high coefficient of determination (0.932) and for the goodness-of-fitness test of the sensitivity term, the chi-square test was performed under 95% confidence level. The results ($\chi^2 = 59.74 < \chi^2_{0.05} = 68.24$) showed that the sensitivity term has practical significance. According to the results, the factor that determines the drivers' characteristics in deceleration situations is the lapsed time until the driver starts to respond to the given stimuli. The results indicate that the lapsed time until driver reaction corresponds to the α value, which represents the drivers' characteristics in the GM model.

Key Words: deceleration model, sensitivity term, car-following, rear end collision

1. INTRODUCTION

The basic concept of car-following theories is the relationship between Stimuli and Response. In the classic car-following theory, the stimuli are represented by the relative speed of following and leading vehicle, and the response is represented by the acceleration (or deceleration) rate of the following vehicle. During the last 50 years, various car-following theories have been studied in terms of from the earlier deterministic relationships to the recent stochastic relationship.

The most significant improvement in the theory was achieved when the reaction time and sensitivity parameter, which can show the level of responsiveness, were considered. The GM model integrated previous car-following models and the research team developed five generations of car-following models, all of which took the form of $response = func(sensitivity, stimuli)$. The difference in the different levels of models was the representation of sensitivity.

Many researches have been conducted to develop the reliable sensitivity term, but they just focused on finding the values of the parameters of the sensitivity term. The GM model considered driving behaviors by introducing m and l exponents and α in the sensitivity term, but did not explain the factors that affect these parameters.

In actuality, a driver does not directly respond to the relative velocity between the vehicles, but rather to the amount of risk of rear end collision he perceives from the spacing, the velocity, and the probability of a collision. Accordingly, the stimuli to the response in the car following situation is the risk of a rear end collision perceived by the drivers on the basis of their experiences.

In this study, the deceleration model and the sensitivity term were developed and deduced based on these concepts.

2. LITERATURE REVIEW

2.1 Car-Following Theory

Reushel (1950) and Pipes (1953) gained the public acceptance of their car-following theory in the early 1950's for the first time, and since then, many have studied this theory.
The classic car-following theory is classified into two conceptual models. The first one was established by Chandler, Herman, and Montroll (1958), and they proposed a conceptual framework like equation (1).

$$\text{Response} = F(\text{sensitivity}, \text{stimuli}) \tag{1}$$

They also suggested that drivers exert acceleration or deceleration in proportion to "Force" meaning the relative speed. From this concept, they developed the linear model like equation (2) on the assumption that the driver of the following vehicle controls the accelerator (or brake) to keep zero relative speed to the leading vehicle.

$$M_n a_n(t+T) = \lambda v_{(n-1)/n}(t) \tag{2}$$

where,

M_n : Mass of n_{th} vehicle
$a_n(t+T)$: Acceleration of n_{th} vehicle after reaction
$v_{(n-1)/n}(t)$: Relative speed of $(n-1)_{th}$ to the n_{th} vehicle in time t
T : Response delay of a driver
λ : Sensitivity Term

Gazis, Herman, and Rothery (1961) suggested that the earlier car following model should be amended by reflecting psychological factors represented by equation (3)

$$\text{Response} = \text{Sensitivity} * \text{Stimuli} \tag{3}$$

In equation (3), the mass of vehicle was deleted and the response of a driver, the sensitivity term and the stimuli, are denoted as $a_n(t+T)$, λ and $v_{(n-1)/n}(t)$ respectively. The equation (3) is important because it introduces the psychological factor into the car-following theory. Hence, the need for an appropriate function that could express the sensitivity of a driver began to be recognized.

Edie (1961), Newell (1960), Gazis, Herman, and Rothery (1960) studied nonlinear car-following model considering the human factor, and especially Gazis et al (1960) stated that although it is difficult to find a reliable non-linear model which can represent real car-following conditions, only a nonlinear model can reflect real car following situations.

The research team of General Motors integrated previous car-following models, and arranged them into five generations of car-following models, all of which took the form of Response = Sensitivity * Stimuli. With this conceptual base, they derived the generalized car-following equation by introducing generalized exponents into the sensitivity term.

$$a_n(t+T) = \frac{\lambda_{l,m}[v_n(t)]^m}{[x_{(n-1)./n}(t)]^l}\, v_{(n-1)./n}(t) \tag{4}$$

where,

m, l : Parameters for speed and distance headway

$\lambda_{l,m}$: Constants showing the characteristics of a driver

Equation (4) is better known as the GHR model because Gazis, Herman, and Rothery (1960) introduced the parameters m and l into the sensitivity term of the car-following model. For this equation, they also classified the traffic flow conditions into congested and non-congested conditions in analyzing the relation of variables used in analyzing traffic flow.

2.2 Sensitivity Term

Greenshields (1934) established the basis of the car-following equation that could induce the equation of state for the steady flow by presenting the sensitivity term as the square of the inverse of the distance headway.

Edie (1961) proposed a modified sensitivity term by adding a speed factor into Greenshields' model, $\lambda = c\,\dot{x}_{n+1}/s^2$, and this equation came to be basis of the sensitivity term of the GHR model shown in equation (5). He showed that with this sensitivity term, characteristics of traffic situations such as stability of traffic flow and steady-state flow characteristics could be explained.

$$\lambda = \frac{\lambda_{l,m}\,\dot{x}_{n+1}^m(t+T)}{[x_n(t)-x_{n+1}(t)]^l} \tag{5}$$

May and Keller (1967) calibrated the parameters of the sensitivity term in the GM 5th Model by setting $m = 1, l = 3$, and they also showed that if the parameters did not have integer values, they would be approximately equaled to $m = 0.8, l = 2.8$.

Keiichi Sato and Hideo Igarashi (1972) induced a macroscopic traffic flow equation from the car-following equation and classified it into two models. The first one is the Exponential non-linear model, which can be derived from equation (5) when $m = 1, l > 1$ and one of the representative models of exponential non-linear model is the Underwood's model. The second one is the N-power curve model, which was derived from equation (5) when $m = 0$. In this model, if $l = 1$, the model becomes the Greenberg's model, and if $l > 1$, then it becomes the Greenshield's model and Drew's model.

Heyes and Ashworth (1972) introduced a new model to look into the relationship between stimuli and response. In their model, the stimuli and the sensitivity term were denoted as $\Delta v / \Delta x^2$ and Δt^p, respectively, and the sensitivity term was estimated as 0.8 based on the survey field data of the Mersey tunnel in UK.

Treiterer and Myers (1974) calibrated the parameters of sensitivity in GM model with the data collected from an aerial photograph, and they developed two distinct models for acceleration and deceleration, respectively, to consider the imperfection and heterogeneity of human behaviors.

Ceder and May (1976) classified the traffic flow conditions into two groups, congested and non-congested condition, and for each group, they estimated the parameters, l, m from a large data base of real data. Ceder (1976, 1978) modified the GHR model by substituting the sensitivity term with equation (6), and S, A in equation (6) denote 'distance headway in a congested situation', 'constant that varies with traffic flow conditions' respectively.

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$$\frac{A^{-S/\Delta x}}{\Delta x^2} \tag{6}$$

Aron (1988), who tested drivers' response in various traffic conditions, classified the drivers' responses into 3 types: deceleration, constant speed, and acceleration responses.

Ozaki (1993) investigated the sensitivity term with the data filmed from a 32 story building, and he analyzed the time series data under ten seconds due to the technical limitation of video film. From this analysis, he showed that the driver has a different sensitivity for acceleration and deceleration.

2.3 Collision Avoidance Model

Kometani and Sasaki (1959) tried to improve the traffic dynamic theory of Pipes (1953) and found the fundamental equation of traffic dynamics. They also showed that the safety of the following vehicle with respect to rear end collision when the lead car is in sinusoidal motion can be quantified by introducing a safety index. Through this study, they established the basic concept of the collision avoidance model in car-following situations.

Gipps (1981) made a significant improvement in collision avoidance study. To mimic similar car-following behavior to real situations, he gave limitations to drivers' abilities and the performance of vehicles, and with this hypothesis, he calculated the speed of following vehicle required for safe following. Considering reaction time and sensitivity term, he developed a realistic simulation model with real data collected from field survey, but did not calibrate the parameters.

Touran et al (1999) developed a crash model to evaluate the safety of the AICC (Autonomous Intelligent Cruise Control) system and examined the function of this equipment to show how it controls a vehicle to prevent crash. He also tested the field survey with four consecutive vehicles, and through this survey, he showed that under the given hypothesis, a vehicle with AICC could reduce the possibility of collision with a leading vehicle.

One of the various collision avoidance models, which have been researched to find an appropriate Simulation model, is CARSIM developed by Benekohal and Treiterer (1989). This model consists of two algorithms, which are the following algorithm without speed variation and the acceleration (or deceleration) algorithm. In the 'following' algorithm, both the control algorithm of the distance headway and the collision restraint algorithm are considered and in the 'acceleration (deceleration)' algorithm, various acceleration (deceleration) rates are applied to the model according to 5 types of traveling conditions. Especially, by assigning 12 types of reaction time to each driver randomly, they tried to simulate the variety of the drivers as well as the various acceleration and deceleration patterns in car-following.

3. MODEL DEVELOPMENT

In this chapter, based on the deceleration model developed by assuming that the risk of rear end collision is a stimulus to a driver, a new sensitivity term is proposed to compare with that of the earlier car-following model.

3.1 Deceleration Model

(1) Stimuli and Response
The GM model says that a driver of the following vehicle accelerates (or decelerates) in response to the stimulus of relative speed, but in real car-following situations, especially in the deceleration condition, a driver responds not to the speed difference but to the perceived risk of rear end collision caused by the speed difference. In other words, a driver recognizes the level of risk from the current traveling speed, distance headway, and the probability of collision. And then, he/she follows the leading vehicle only within the region of risk he/she can bear.

If the driver recognizes large risk, the driver would decelerate quickly; if the driver recognizes small risk, then decelerate slowly. If the leading car decelerates, the following car driver would select a proper reaction time and deceleration rate to prevent rear end collision according to his/her experiences. Hence, all drivers have their own reaction area with respect to reaction time and deceleration rate, and they follow the leading vehicle to a proper distance considering their reaction area.

For instance, when the leading vehicle decelerates at some rate in the car-following situation, the driver of the following vehicle will choose one of the response sets, (a_f, t_r) from his/her experience, and then he/she will decelerate at that rate to minimize the risk of rear end collision as shown in Figure 1. If this empirical decision is wrong, that is to say, if he/she selects the response set of $c_1(a_f^1, t_r^1)$ the driver would recognize a larger risk than before, so he/she will choose an even higher deceleration rate with lower reaction time like $c_2(a_f^2, t_r^2)$.

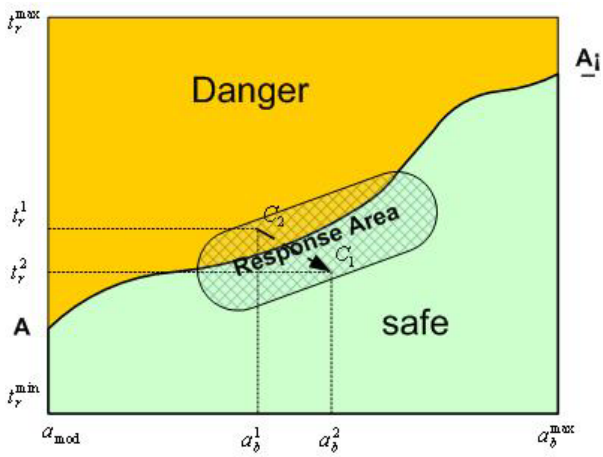

Figure 1. Response Area

The driver of the following vehicle follows the leading car and tries to retain proper following situation by employing this continuous selection process. Therefore, to some stimuli, a driver has his/her own response area, which is learned from his/her experience, and in general car-following conditions, most drivers try to follow the leading vehicle within their response areas. Consequently, the knowledge about the response area of a driver for various car-following situations can help us to identify the car following behavior of the driver.

(2) Deceleration Behaviors

To understand the relation between stimuli and response in a deceleration situation, let us think of two vehicles which have the traveling trajectory shown in Figure 2.

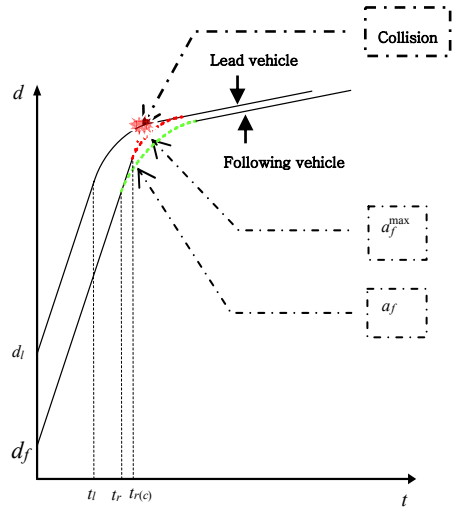

Figure 2. Relation between Response Time and Deceleration Rate

In Figure 2, t_l, t_f, t_c, $h = d_l - d_f$, t_m, a_f and $a_f^{\max}$ denote 'time at which leading vehicle begins to decelerate', 'time at which a driver of following vehicle begins to decelerate', 'time at which a driver can prevent rear end collision only if he/she decelerates at maximum deceleration rate', 'distance headway at time 0', 'duration time of maximum deceleration', 'deceleration rate at which the driver of the following vehicle should choose at t_f to avoid rear end collision', and 'maximum deceleration rate at which the driver of the following vehicle should choose at t_c to avoid rear end collision' respectively.

In Figure 2, as the leading vehicle decelerates at time t_l, the distance headway between the two vehicles shortens, and hence, the driver of the following vehicle comes to perceive the risk of rear end collision. In this situation, the deceleration behavior of the following vehicle depends on t_f and accordingly, to follow leading vehicle while minimizing the risk of rear end collision, the driver should increase the deceleration rate from a_f to $a_f^{\max}$ as $t_f \to t_c$. From this point of view, the level of the deceleration rate chosen by the driver of the following vehicle is related to $t_f, t_c, a_f^{\max}$ and the critical reaction time is represented as follows;

$$t_f(c) = t_l - t_c \tag{7}$$

In fact, the distance headway and the speed of the following vehicle also affect the deceleration rate, but the effects of these factors are considered in determining t_f and t_c. Thus, the deceleration rate which the driver chooses can be expressed as a function of such variables as t_f, t_c and $a_f^{\max}$.

$$a_f = f(t_f, t_f(c), a_f^{\max}) \tag{8}$$

The most important factor in equation (8) is $t_f(c)$, which is calculated from the relationship among the speed of both vehicles, spacing, and maximum deceleration rate. In this study, $t_f(c)$ is calculated by the EXCEL program at every second.

(3) Data Collection

To validate the relationship among factors related to the deceleration rate of the following vehicle, a field survey was performed on the straight roadway at Tong-Il Hill in Gyeonggi-do. To minimize the error caused by imperfection and heterogeneity of human behaviors, the field survey was performed for 20 test drivers of different driving skill levels with two test vehicles equipped with a tachometer and laptop computer system capable of measuring the speed, acceleration, and spacing between the vehicles. The data collected from the tachometer depended on vehicle specifications such as the wheel size and driving gear of the transmission and the like, which were provided by ROTIS Inc.

To obtain a reliable model, field survey should be performed under various traffic conditions, but in this study, it was performed in a specific driving condition because of the restraints of the survey environment, test equipment, and safety. The survey was performed in three different situations, namely when the following vehicle follows the leading vehicle at 30 km/h, the drivers of the following vehicles were instructed to respond to the stimuli from the leading vehicle with three responses such as immediate reaction, general reaction, and slightly delayed reaction.

To filter the noises caused by data conversion from the tachometer, the non-flatness of the surface and the difference of driving distance, two correction steps were chosen. At first, the difference between the traveling distance by a vehicle and the distance in the map was corrected by the average dividing method. The noise produced by data conversion was filtered by eliminating abnormal data, and then the noise of the data which has no abnormal point was filtered by using the wavelet tool in Matlab.

(4) Data Collection and Analysis

With the field data, the relationships between deceleration rate and related factors were analyzed. The results showed that the deceleration rate was linearly related to the "reaction time/critical reaction time", as shown in Figure 3.

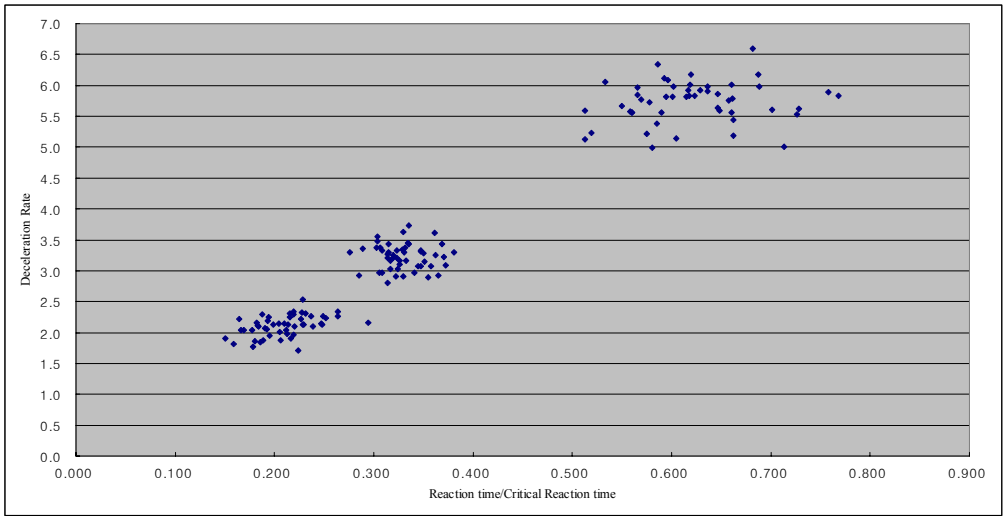

Figure 3. Scatter Diagram of Reaction time

In Figure 3, the field data has three different areas of distribution because of the three different test conditions. The distance among each distribution area is not uniform because the test drivers did not respond exactly to the three different requests during the test. Figure 3 shows the first order linear relationship between deceleration rate and reaction time/critical reaction time and the model could be formulated by regression analysis based on equation (9).

$$a_f = \beta_0 \times \frac{t_f}{t_f(c)} + \beta_1 \tag{9}$$

Table 1. Results of Regression Analysis

	Coefficient	SD	t-statistics	P-value
Intercept	0.586	0.070	8.420	2.999E-14
X variable	7.36	0.164	44.986	3.211E-88

Table 2. Results of Regression Analysis (ANOVA)

	Degree of Freedom	Sum of squares	Mean of squares	F-statistics
Regression	1	255.856	255.856	2023.747
Residual	148	18.711	0.126	
Sum	149	274.568		

To check the statistical significance of the model, f-test and t-test were performed. The F-statistics was 2023.747 ($> F_{0.05} \approx 3.84$) and the t-statistics of intercept and x variable were 8.420, 44.986($> t_{0.05} \approx 1.976$), respectively. Moreover, the Coefficient of Determination was 0.932 and the adjusted one was 0.931 so the estimated model has statistical significance.
As a result, the estimated model is as follows;

$$a_f = 7.36 \times \frac{t_f}{t_f(c)} + 0.586 \tag{10}$$

As mentioned in section 3.2, if a driver responds to the stimuli with the critical reaction time, he/she should exert deceleration at a maximum rate to avoid rear end collision. According to equation (10), the deceleration rate that is required when a driver responds with the critical reaction time is 7.94, which is similar to the maximum deceleration rate of the test vehicle in slow traffic conditions. Especially, the drivers should decelerate considering a buffer distance to follow the leading vehicle safely, so the intercept reflects this buffer distance considered by the drivers.

Function (8) shows that the deceleration rate is affected by the maximum deceleration rate considered by driver but in developing the model, the data on the maximum deceleration rate was not included. However, the regression results show that the coefficient of the x variable is almost equal to the maximum allowable deceleration rate in a slow traffic condition. Therefore, this result shows that the relationship between the independent variable and dependent variable is consistent with the theoretical hypothesis of the model.

3.2 Deducement of Sensitivity Term

As known in Figure 2, the deceleration rate that the driver selects to prevent rear end collision with the leading car is related to $t_f(c)$, t_f, $a_f^{\max}$. And this relationship was statistically proven in section 3.1. In equation (10), the coefficient of the x variable is almost maximum deceleration rate for the vehicle in a slow traffic condition, and the intercept can be deleted because it is negligible when trying to explain the trend of the deceleration by a driver.

$$a_f = a_f^{\max} \times \frac{t_f}{t_f^c} \tag{11}$$

To deduce the sensitivity term, the next two assumptions are required. First, deceleration is a response which is executed by a driver to avoid rear end collision with the leading vehicle. Second, the speed of both vehicles will be equal at the end of the deceleraton of the following vehicle. Especially, when the following vehicle decelerates at its maximum rate, the spacing between the two vehicles is close to 0.

In the right side of equation (11), $a_f^{\max}$ is determined by the performance and traveling speed of the following vehicle, t_f is related to the characteristics of driver and $t_f(c)$ is calculated from the factors related to traveling condition such as the speeds of both vehicles, spacing etc. To deduce the sensitivity term from equation (11) t_f^c should be expanded to the variables related to the traveling condition factors. Thus, if a driver begins to decelerate at the time of t_f^c, he/she should decelerate at the maximum rate to avoid rear end collision. In this case, the following equation should be satisfied.

$$v_l = v_f + a_m t_m \tag{12}$$

where,

v_l : Speed of leading vehicle (m/s)

v_f : Speed of following vehicle (m/s)

a_m : Maximum deceleration rate at the traveling condition (m/s^2)

t_m : Lapse time to the point when the speed of the following vehicle becomes equal to the speed of leading vehicle at the maximum deceleration rate (sec)

$$v_a(t^* + t_m) + h \approx v_b \cdot t^* + v_b \cdot t_m + \frac{1}{2} a_m \cdot t_m^2 \tag{13}$$

where,

h : spacing between two vehicles before deceleration

Substitute t with $t_f^c + t_m$ and the equation (13) will be as follows;

$$v_f \cdot t + h = v_f \cdot t + \frac{1}{2} a_m \cdot t_m \tag{14}$$

Expanding equation (14) for t_f^c, equation (14) will be as follows ;

$$t_f^c = \frac{\left\{ \frac{1}{2} a_m t_m^2 - h - (v_a - v_b) t_m \right\}}{v_a - v_b} = \frac{-2h - (v_a - v_b) t_m}{2(v_a - v_b)} \tag{15}$$

Substituting equation (15) for equation (11) and expanding equation (11) for a_f

$$a_f = \frac{2(v_l - v_f)t_f}{-2h - (v_l - v_f)} \cdot a_m \tag{16}$$

And expanding the equation (16) to the form of GM model yields;

$$a_f = \frac{-2t_f a_m}{(v_l - v_f)t_m + 2h} \cdot (v_l - v_f) \tag{17}$$

Comparing equation (17) with the GM model, the sensitivity term (λ) is expressed as;

$$\lambda = \frac{-2t_f a_m}{(v_l - v_f)t_m + 2h} \tag{18}$$

In equation (18), the fact that the sensitivity term deduced from the deceleration model here increases as a_f, t_f, t_m, and $(v_l - v_f)$ increase and h decreases is consistent with general deceleration behaviors.

3.3 Goodness of fitness Test

To validate the sensitivity term, field survey was performed for three drivers with three different reaction times in the same test environment of the field survey for deceleration model. According to the data collected from the survey, the average reaction time, standard deviation and number of data of each test driver for each situation are summarized in Table 3 and the average deceleration rate of each test driver is also summarized in Table 4.

Table 3. Average Reaction Time of Test Drivers

Classification	Ave. time of Immediate reaction (SD, Num of data)	Ave. time of Usual Reaction (SD, Num of data)	Ave. time of Delayed Reaction (SD, Num of data)
Driver 1	0.56(0.06, 15)	1.01(0.06, 15)	1.91(0.13, 20)
Driver 2	0.70(0.07, 15)	1.04(0.08, 15)	1.98(0.15, 20)
Driver 3	0.67(0.05, 15)	1.02(0.10, 15)	1.98(0.15, 20)

Table 4. Average Deceleration Rate of Test Drivers

Classification	Ave. Deceleration Rate for Immediate Reaction (SD)	Ave. Deceleration Rate for Usual Reaction (SD)	Ave. Deceleration Rate for Delayed Reaction (SD)
Driver 1	2.17(0.17)	3.33(0.22)	5.71(0.24)
Driver 2	2.31(0.11)	3.35(0.17)	5.89(0.19)
Driver 3	2.25(0.18)	3.36(0.23)	5.84(0.38)

The results showed that the deceleration rates of drivers 1, 2, 3 became higher as the reaction time was delayed. Moreover, the model indicated no rear end collision as long as the spacing between two vehicles is over 0, but generally the drivers consider buffer spacing for minimum safety so drivers are likely to decelerate at a slightly higher rate than that predicted by the model.

To test goodness-of-fitness of the model under the 95% confidence level, the chi-square test was performed and the result ($\chi^2 = 59.74 < \chi^2_{0.05} = 68.24$) showed that the model deduced in this study provides results that are consistent with the behaviors of the driver of following vehicle.

4. CONCLUSIONS

Deceleration in the classic car-following model can be represented as the response to the stimulus of the relative speed between two vehicles. In this study, however, the deceleration model and the sensitivity term were developed based on the different concept of the stimuli; that is, the risk of rear end collision perceived by the driver of following vehicle is considered as the stimulus.

"Stability Analysis" which explains the rear end collision caused by unstable following vehicle also states a close relationship between reaction time and the response of acceleration/deceleration. Namely, the drivers who respond slowly have high acceleration or deceleration rates. On the other hand the, the drivers who are attentive to the car-following process are not likely to resort to sudden accelerations or decelerations except in emergencies. Accordingly, the car-following behaviors of a driver in deceleration situation can be expressed by the relationship between reaction time and deceleration. The data from field survey showed that the deceleration rates chosen by the drivers are closely related to the ratio of the critical reaction time and the reaction time of the driver of the following vehicle.
The results of regression analysis showed that the coefficient of determination (0.932) is very high and F-statistics and t-statistics of intercept and x variable are 2023.747 ($> F_{0.05} \approx 3.84$), 8.420, 44.986($> t_{0.05} \approx 1.976$), respectively. Accordingly, the estimated model has statistical significance.

The sensitivity term was deduced theoretically from the deceleration model, and goodness-of-fitness test of the model in the 95% confidence level showed that the sensitivity term is consistent with the behaviors of the drivers of following vehicles. Of the factors which constitute the sensitivity term, no one factor can explain the characteristics of driver theoretically. However, the model developed in this study found that the characteristics of the driver in the sensitivity term can be represented by the reaction time of the driver in response to the risk of rear end collision.

To develop a more reliable model, the data on reaction time of less than 1 second was required but in this study, due to the limitations of the equipment, the time unit of the data collected from field survey was 1 second from slow traffic conditions.

In the future, if more accurate equipment can collect more precise data than the present data , and safety related problem can be solved, the general deceleration model in various car-following situations can be developed. And based on the general model, the sensitivity term which can consider the general characteristics of drivers can be also deduced.

The sensitivity term developed in this study can help build the theoretical frame for analyzing the characteristics of traffic flow and the characteristics of the control algorithm used in advanced vehicles. And based on the sensitivity term, if the situations of car-following can be better understood, which can provide higher reliability for analyzing capacity, the traffic flow safety and so on. Moreover, this study proposed a significant new approach for developing the sensitivity term which has not changed for about a half century.

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