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An Analysis on the Driving Behavior Considering the Trade-off between Safety and Travel Utility

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Abstract: Driving behavior such as speed reduction is needed for risk aversion while driving although the behavior leads to the decrease in travel utility. In this paper, a driving behavior model applying “Subjective Risk” and “Driving Utility” is proposed as a fundamental study for the evaluation of traffic safety measures considering the trade-off between safety and travel utility. Then, the mechanism of the changes in “Driving Behavior”, “Subjective Net-Utility”, and “Social Net-Benefits” due to the changes in traffic environment is proved. Finally, the applicability of the model is confirmed with the data observed at non-signal intersections. It is found that the model can be applied to comparing the level of “Subjective Risk” and that the assumption is verified.

Key Words: *Driving Behavior, Evaluation of Safety Measures, Subjective Risk, Driving Utility*

1. INTRODUCTION

Traffic accidents have been still a serious social problem. In Japan, the number of traffic accident fatalities fell below 10 thousand in 1996 and has been decreasing rapidly. However, there were still extremely high numbers in 2007: 832,454 accidents; 5,744 fatalities; and more than one million injuries (White Paper, 2008). Therefore, implementations of effective and efficient traffic safety measures are needed, which require the appropriate evaluations of the effects of the safety measures.

Traffic safety measures should be evaluated by considering the trade-off between safety and travel utility. Traffic safety measures are generally employed in order to reduce the vehicle speed, to increase the driver’s concentration level or hazard perception level, to reduce the frequency of accidents or the cost of injury or damage caused by an accident. However, the vehicle speed reduction leads to the increase of travel time cost, and the driver’s concentration increment produces the increase of mental load. Therefore, the evaluation of traffic safety measures considering both traffic safety and travel utility is essential in implementing the effective and efficient traffic safety measures.

In addition, driving behavior such as reducing speed may also be related to the trade-off between traffic safety and travel utility. A driver who perceives some hazard will choose some risk avoidance behavior such as reducing speed. For example, when a driver consciously perceives high risk with a narrow view, the driver may immediately reduce the speed; if not, vice versa. On the other hand, for the driver who has the strong will to reach travel destination in time, the level of the speed reduction to avoid the hazard may be small. In other words, drivers may comprehensively determine the optimal driving behavior by considering the trade-off between the safety level to avoid the hazard and the convenience level to avoid the reduction of travel utility due to the hazard avoidance.

However, few studies have analyzed safety and travel utility jointly. In this paper, “Net-Utility Maximization Model” is proposed. This model focuses on the driving behavior from hazard perception to behavior decision, based on the assumption that drivers perform optimal driving behavior by considering the trade-off between safety and travel utility. Then, the mechanism of the changes in “Driving Behavior”, “Subjective Net-Utility”, and “Social Net-Benefits” due to the changes in traffic environment is proved. Moreover, the applicability of the model is confirmed with the data collected by video observation at non-signal intersections.

2. REVIEW OF PREVIOUS STUDIES AND DIRECTION OF THIS STUDY

Jørgensen and Wentzel-Larsen (1999) offered a driving behavior model for analyzing the effect of warning sign installations at dangerous curves on safety and total driving cost (monetary cost including safety and travel utility). The features of the model were as follows:

1) Total driving cost is defined as the sum of time cost (travel utility cost) and accident cost (safety cost), and it is assumed that drivers chooses their speed so as to minimize the subjective total driving cost.
2) There is clear distinction between the objective safety cost and the subjective safety cost.

Although the expedient of the evaluation of traffic safety measures considering both safety and travel utility was discussed by focusing on the difference between the objective cost and the subjective cost, the canonical model of driving behavior was just assumed tenaciously and was not applied to actual phenomenon.

Yamaguchi et al. (2005); Suzuki et al. (2005); and Nakamura et al. (2006) proposed an evaluation index for the signalized intersection considering both traffic conflict and delay by defining the conflict risk and delay risk concerned with users, and analyzed the index quantitatively with observed data. In addition, they discussed the forecast of impacts due to the change in operation of intersection, and compared the performance between roundabouts and signalized intersections. However, the difference between the objective evaluation and the driver’s subjective evaluation was not pointed out.

In this paper, in accordance with the previous studies, an alternative driving behavior model which considers both safety and travel utility is proposed. Then, the mechanism of the changes in "Driving Behavior", "Subjective Net-Utility", and "Social Net-Utility" due to the changes in traffic environment is presented qualitatively.

In addition, in this paper, the model is examined empirically with the driving behavior data observed at non-signal intersections. In this context, Kanda et al. (2002) analyzed 140 crossing accidents between two cars at non-signal intersections by using Variation Tree Analysis, and investigated unsafe driving behavior of drivers (e.g. passing the intersection with the prediction that there is no crossing vehicle). But they did not consider the relationships between driving behavior and traffic environment conditions of the non-signal intersections. In contrast, Ito et al. (2004) analyzed the relationships between traffic environment conditions of non-signal intersections (e.g. traffic volume or sight distance) and driving behavior there by using Structural Equation Model. However, since the model was remained to be liner model, there were not sufficient theoretical bases. In this paper, in accordance with the previous studies, the relationships between driving behavior and traffic environment conditions of non-signal intersections are analyzed by considering the trade-off between safety and travel utility which can be felt by drivers, at non-signal intersections in a residential area.

3. CONCEPT OF DRIVING BEHAVIOR MODEL

3.1 Assumption of Driving Behavior

In this paper, the driver's behavior decision flow is assumed as shown in Figure 1.

1) **Perception of Traffic Environment:** A driver perceives some traffic environment conditions denoted by E.
2) **Perception of "Subjective Accident Risk":** Then, the driver perceives "Subjective Accident Risk" denoted by R_S, which is defined as the excepted accident cost (that is, the product of the subjective probability of getting involved in an accident and the subjective unit accident cost). R_S is a function of driving behavior denoted by x.
3) **Evaluation of Driving Behavior:** The driver instantly evaluates driving behavior x by considering both "Subjective Accident Risk" denoted by R_S and "Driving Utility" denoted by U_S (defined as the travel benefit felt by the driver when a certain driving behavior x is taken).
4) **Decision of Driving Behavior:** The driver determines "Subjective Optimal Driving Behavior" denoted by x_S^*, as the result of evaluation described at **3)**.

3.2 Assumption of Social Evaluation Index

In this paper, "Social Accident Risk" denoted by R_{Scl} and "Social Benefit" denoted by U_{Scl} are assumed as the social evaluation indices given in response to the result of taking x. "Social Accident Risk" is defined as the social expected accident cost including external effects (that is, the product of the objective probability of getting involved in an accident and the social unit accident cost). "Social Benefit" is defined as the social travel benefit including external effects.

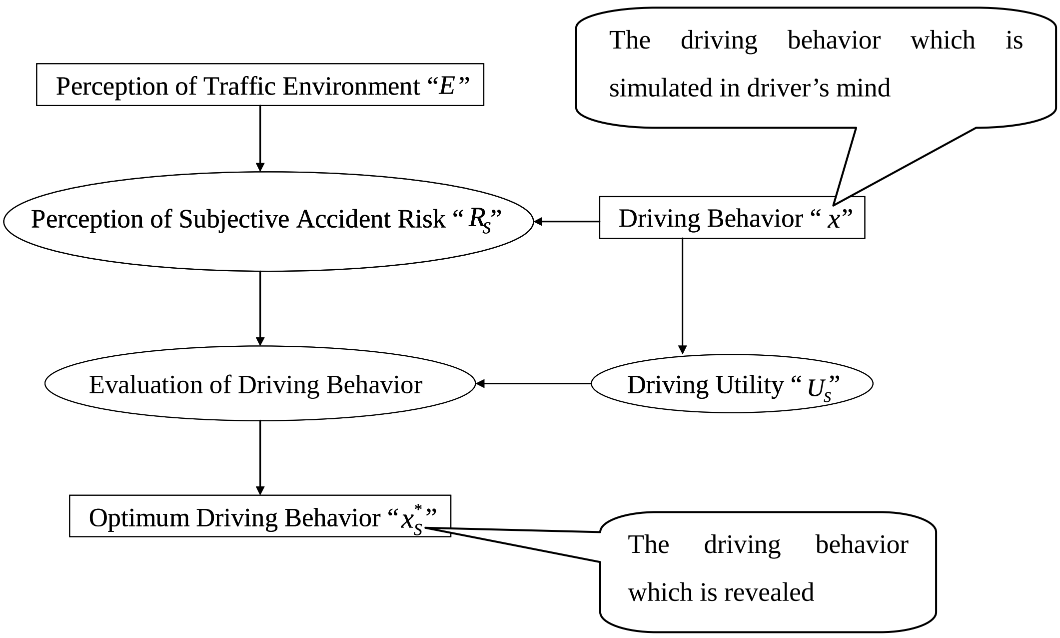


Figure 1 Driver's decision flow of Driving Behavior

3.3 Accident Risk Model

"Subjective Accident Risk" R_S and "Social Accident Risk" R_{Scl} are assumed to be functions of driving behavior and traffic environment as Equation (1) and Equation (2), respectively. In a narrow street, for example, R_S and R_{Scl} can be generally increased as the speed increases, and their relationships also can be affected by the traffic environment conditions such as one-way regulation. The curves of changing R_S and R_{Scl} are shown in Figure 2. Increasing type functions with increasing marginal risk are also assumed as the curves of changing accident risk due to the change in speed, as expressed in Equation (3). These assumptions are based on the reason that the function with same curve ($R = ax^b, a > 0, b > 1$) is used in the previous study (Jørgensen and Wentzel-Larsen, 1999), and the idea can be compatible with actual phenomenon. In addition, it is assumed that the inclination of R_{Scl} is bigger than that of R_S, as expressed in Equation (4), because R_{Scl} which includes the external effects can be more sensitive to the change in speed.

$$R_S = R_S(x, E) \tag{1}$$

$$R_{Scl} = R_{Scl}(x, E) \tag{2}$$

$$\frac{\partial R_S}{\partial x} > 0,\ \frac{\partial^2 R_S}{\partial x^2} > 0 \ \text{and}\ \frac{\partial R_{Scl}}{\partial x} > 0,\ \frac{\partial^2 R_{Scl}}{\partial x^2} > 0 \tag{3}$$

$$\frac{\partial R_S}{\partial x} < \frac{\partial R_{Scl}}{\partial x} \tag{4}$$

3.4 Driving Utility Model

"Driving Utility" U_S and "Social Benefit" U_{Scl} can be functions of driving behavior and trip attributes denoted by z, as expressed in Equation (5) and Equation (6), respectively. Meanwhile, in this paper, the trip attributes is supposed to be constant for simplification. In a narrow street, for example, U_S and U_{Scl} can be increased as the speed increases. The curves of changing U_S and U_{Scl} are shown in Figure 3. Increasing type functions with decreasing marginal utility which are same as common utility theory are also assumed as the curves of changing driving utility and social benefit affected by change in speed, as expressed in Equation (7). It is also assumed that the inclination of U_{Scl} is bigger than that of U_S, as expressed in Equation (8), because U_{Scl} which includes the external effects can be more sensitive to the change in speed.

$$U_S = U_S(x, z) \tag{5}$$

$$U_{Scl} = U_{Scl}(x, z) \tag{6}$$

$$\frac{\partial U_S}{\partial x} > 0,\ \frac{\partial^2 U_S}{\partial x^2} < 0 \ \text{and}\ \frac{\partial U_{Scl}}{\partial x} > 0,\ \frac{\partial^2 U_{Scl}}{\partial x^2} < 0 \tag{7}$$

$$\frac{\partial U_S}{\partial x} < \frac{\partial U_{Scl}}{\partial x} \tag{8}$$

3.5 Net-Utility Maximization Model

It is assumed that the driver chooses "Subjective Optimal Driving Behavior" x_S^* by maximizing "Subjective Net-Utility" denoted by N_S, which is obtained as the difference of R_S and U_S.

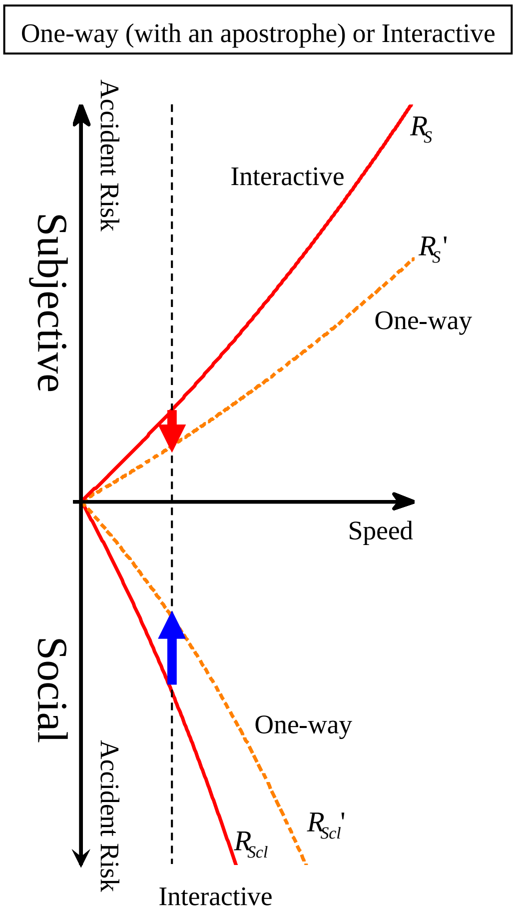


Figure 2 Changing "Accident Risk"

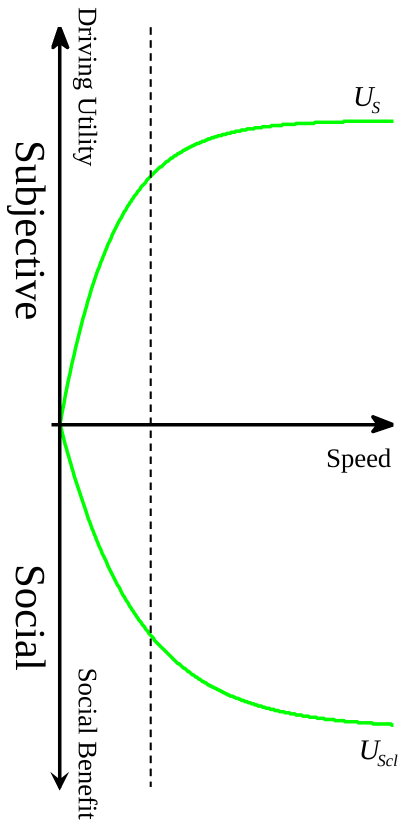


Figure 3 Changing "Utility" and "Benefit"

$$N_S = U_S - R_S \tag{9}$$

$$\begin{aligned} x_S^* &= \arg\max N_S \\ &= \arg\max\{U_S(x,z) - R_S(x,E)\} \end{aligned} \tag{10}$$

On the other hand, "Social Net-Utility" denoted by N_{Scl} is obtained by Equation (11), and the driving behavior which maximizes N_{Scl} can be called "Social Optimal Driving Behavior" denoted by x_{Scl}^*, as expressed in Equation (12). As described above, however, x_S^* is taken actually, which is different from x_{Scl}^* as shown in Figure 4. Therefore, although the change of driving behavior can be predicted by "Subjective Net-Utility Maximization Model", the evaluation of the social desirability of driving behavior should be based on N_{Scl} whose value is evaluated at x_S^*. Also note that although x_{Scl}^* is smaller than x_S^* in Figure 4, it may be not always this case. However, x_{Scl}^* can be smaller than x_S^*, or, $x_{Scl}^* < x_S^*$ under two conditions: in general, **(a)** if $x = 0$ then the difference between R_{Scl} and R_S might be same as that between U_{Scl} and U_S, that is, $(U_{Scl} - U_S) = (R_{Scl} - R_S)$, or $(U_{Scl} - R_{Scl}) = (U_S - R_S)$, and if $x > 0$ then $(U_{Scl} - U_S) < (R_{Scl} - R_S)$, or $(U_{Scl} - R_{Scl}) < (U_S - R_S)$; and **(b)** the function form of N_S is same as that of N_{Scl} since the function forms of R_S and U_S are same as those of R_{Scl} and U_{Scl}, respectively.

$$N_{Scl} = U_{Scl} - R_{Scl} \tag{11}$$

$$\begin{aligned} x^*_{Scl} &= \arg\max N_{Scl} \\ &= \arg\max\{U_{Scl}(x,z) - R_{Scl}(x,E)\} \end{aligned} \tag{12}$$

Let us imagine, as an example, the situation where one-way regulation is forced as a traffic safety measure at a narrow street. As shown in Figure 5, if the effect of one-way regulation on the value of R_S is relatively small, then the values of x^*_S and N_S can be modestly increased with the decrease in R_S, and then N_{Scl} can be increased. In contrast, as shown in Figure 6, if the effect of one-way regulation on the value of R_S is substantially large, then x^*_S can be increased drastically with the decrease in R_S, and then the decrease in N_{Scl} can be occurred. This is a situation where the driver places too much trust in the increase of traffic safety.

In Figures 5 and 6, as mentioned above, the mechanisms of the changes in "Driving Behavior" and "Social Net-Utility" due to the change in a certain traffic environment condition are indicated, based on the specific assumptions of function form. If different function forms are assumed, it is also possible to describe the both cases where "Social Net-Utility" is either increasing or decreasing. Therefore, the effect of the change in a certain traffic environment condition by implementation of traffic safety measures depends on the function forms of "Subjective Risk" and "Driving Behavior". Hence, to find the function forms or parameters clearly is needed in order to evaluate the traffic safety measures appropriately.

4. EVALUATION OF MODEL APPLICABILITY AT NON-SIGNAL INTERSECTION

4.1 Model Formulation

"Subjective Net-Utility Maximization Model" is formulated here in order to evaluate the model applicability, which is targeted for driving behavior at non-signal intersection.

"Subjective Accident Risk" and "Driving Utility" are formulated by using the exponential function, as expressed in Equation (13) and Equation (14) which are consistent with the model forms assumed in Equation (3) and Equation (7), respectively. To simplify, the entering speed to intersection is supposed to be driving behavior x, and the traffic environment factor which is set as explanatory variable is restricted to only one factor E. In addition, the second term in Equation (13) is used in order to set $R_S = 0$ when $x = 0$.

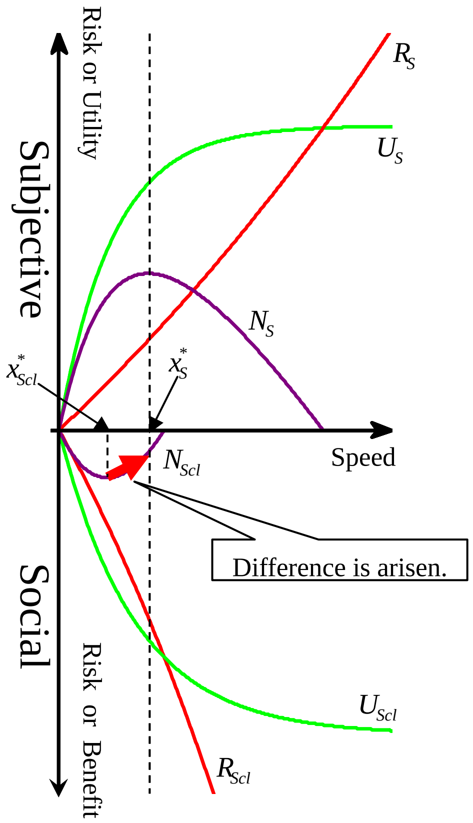
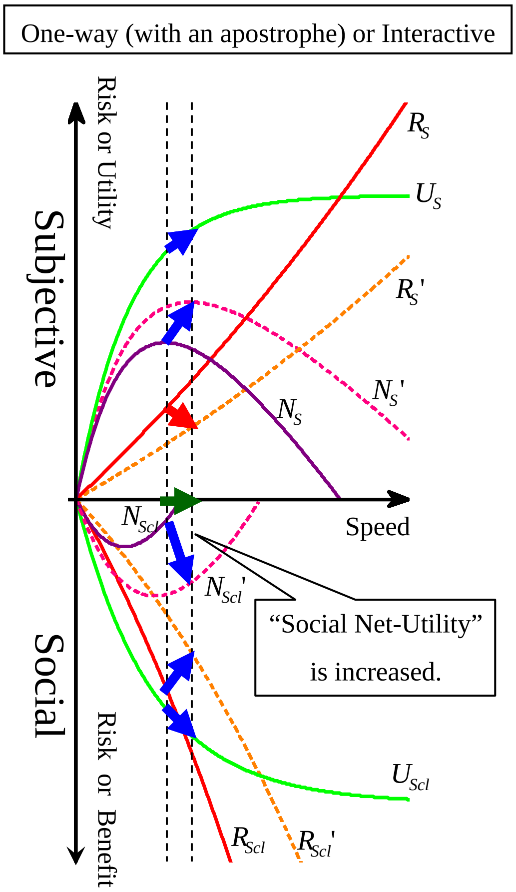


Figure 4 Concept of “Net-Utility Maximization Model”



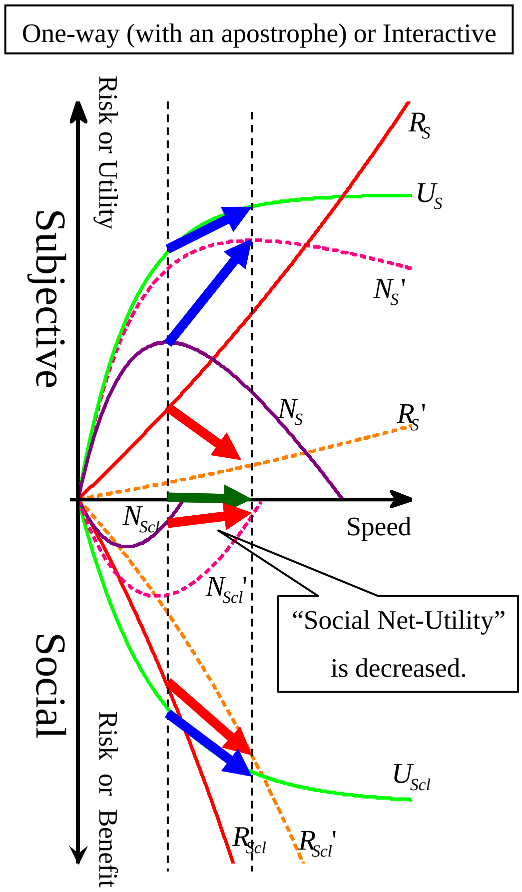


Figure 5 Impacts of change E (1)

Figure 6 Impacts of change E (2)

$$R_S = e^{\alpha \cdot x + \beta \cdot E} - e^{\beta \cdot E} \tag{13}$$

$$U_S = 1 - e^{-\gamma \cdot x} \tag{14}$$

where α, β, γ : parameter

The values of x_S^* is obtained as Equation (15). Then, a liner form formula is derived by integrating the coefficients of the explanatory variable, as expressed in Equation (16).

$$\begin{aligned} x_S^* &= \arg\max(U_S - R_S) \\ &= \frac{-\beta}{\alpha + \gamma} \cdot E + \frac{1}{\alpha + \gamma} \cdot \log\left(\frac{\gamma}{\alpha}\right) \end{aligned} \tag{15}$$

$$x_S^* = A \cdot E + B \tag{16}$$

where
$$\begin{aligned} A &= \frac{-\beta}{\alpha + \gamma} \\ B &= \frac{1}{\alpha + \gamma} \cdot \log\left(\frac{\gamma}{\alpha}\right) \end{aligned} \tag{17}$$

It can be possible to find the driver's comprehensive evaluation structure of safety and travel utility by estimating the values of parameters specifying the driving behavior, with the behavior data observed at multiple places that have various traffic environment conditions.

4.2 Data Collection

The database of driving behavior was obtained by using video observation at various non-signal intersections for the estimation of the model. Outline of the observation is as follows:

- **Study Intersections:** 18 non-signal intersections crossing narrow streets in residential area in Toyohashi city, Japan. All of these intersections have a main approaches (that is, a driver on this approach has the right-of-way) and a secondary approaches (with stop regulation), and these approaches are intersecting crisscross. And, the right-of-way is based on the priority rules, where vehicles on the secondary approaches give way to vehicles on the main approaches. The examples of the intersections are shown in Figure 7.
- **Observation Method:** respective vehicles accessing to the intersection from the secondary approach were recorded by using video cameras, and then individual driving behavior and traffic conditions are measured by inspection.

- **Measurement Item (Driving Behavior):** the entering speed to intersection (average speed of a vehicle in the segment between the stop line and 30 meters behind it).
- **Measurement Item (Traffic Environment Condition):** the direction of the object vehicle, the presence or absence of other vehicle and/or pedestrian when the object vehicle is entering into intersection, various types of traffic volume, the approach width, lateral sight distance, the presence or absence of curve mirror, and one-way traffic or interactive traffic.
- **Observed Day and Time:** weekdays during 13.10.2006 ~ 27.10.2006, 7:00 ~ 9:00, 16:00 ~ 18:00.

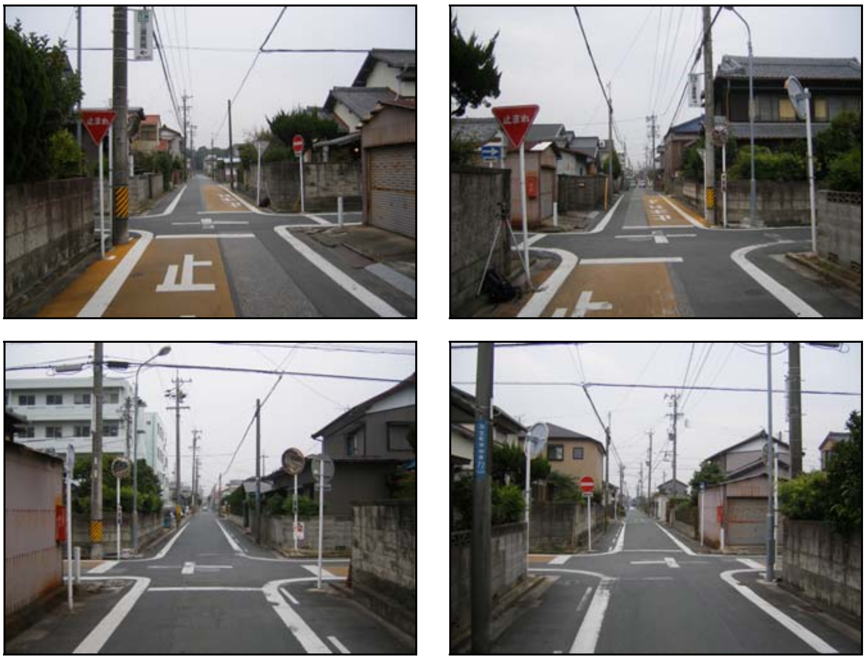


Figure 7 Examples of non-signal intersections studied in this paper

The data of 641 driving behavior in total are obtained. Table 1 shows the main items of the traffic environment conditions, and Figure 8 shows the average of the entering speed at each intersection measured by the video observation. Note that the traffic volume by direction is observed within 10 minutes independently of the video observation. Also, many “Crossing” vehicles (126 / 10 minutes) are observed at the intersection 18.

4.3 Estimation Result

Figure 9, Figure 10 and Figure 11 show the cumulative frequency curve of the entering speed of each vehicle by one-way traffic or interactive traffic, by the approach width, and by the observation time period, respectively. In Figure 9, it is indicated that the ratio of high entering speed vehicles with one-way traffic is higher than that with interactive traffic. In Figure 10, it is indicated that when the ratio of high entering speed vehicles is slightly higher as the approach width becomes wider, and the significant difference can not be seen. In Figure 11, it is indicated that the ratio of high entering speed vehicles observed in the morning is higher than that in the afternoon. Other clear relationships between the entering speed and the traffic environment conditions except for those shown in above figures are not found.

Table 1 Main items of traffic environment conditions of each intersection

Intersection	Traffic volume by direction (/ 10 minutes)				Road width (m)	One-way (=1) or Interactive (=0)	Observed time period
	Through	Opposite	Crossing	Pedestrian			
1	3	2	6	10	5.25	0	am
2	18	0	26	18	5.42	0	pm
3	14	3	17	12	4.96	0	am
4	8	2	13	12	4.43	0	pm
5	10	0	20	30	4.28	0	pm
6	18	17	13	15	4.29	0	pm
7	9	6	13	4	5.00	0	am
8	10	0	20	20	4.16	1	pm
9	8	18	6	24	4.54	0	am
10	15	0	21	8	4.79	0	pm
11	5	0	17	14	4.52	0	pm
12	6	0	7	16	4.69	1	pm
13	15	0	14	25	4.49	1	am
14	7	0	22	21	4.5	1	pm
15	18	0	26	12	4.09	1	pm
16	6	0	17	9	4.29	1	am
17	12	2	19	28	5.13	0	am
18	7	2	126	7	3.9	0	am
Average	10.5	2.9	22.4	15.8	4.6	---	---
Standard deviation	4.8	5.6	26.5	7.5	0.42	---	---

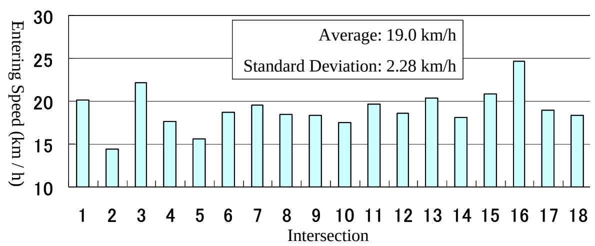


Figure 8 Average of entering speed by intersection

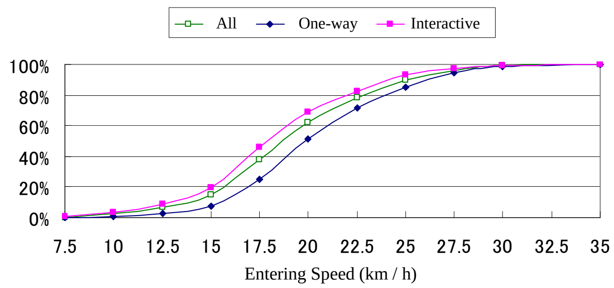


Figure 9 Entering speed by one-way regulation

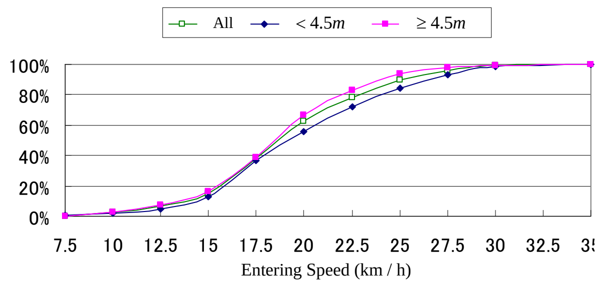


Figure 10 Entering speed by approach width

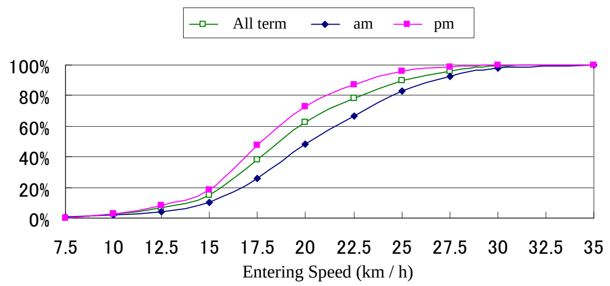


Figure 11 Entering speed by observed time period

As the result of calculation of the correlation coefficients between the traffic environment conditions and the average of the entering speed by grouping the data into two types of the observation, namely in the morning or in the afternoon, a certain degree of the correlation between one-way traffic or interactive traffic and the entering speed is indicated (in the morning: $r = 0.62$, in the afternoon: $r = 0.49$). Therefore, the parameters of Equation (16) is estimated by setting the presence or absence of one-way regulation as the dummy independent variable (namely, one-way traffic: $E = 1$, interactive traffic: $E = 0$), and by setting the entering speed as the dependent variable (x_S^*), respectively. Table 2 shows the estimation results. Note that although the driving behavior can be constrained by the priority rules at the intersection studied as mentioned above, it is assumed that the drivers choose their driving behavior by maximizing "Net-Utility" under the constraint. Also, here $\gamma = 0.1$ is configured for the simplification of the estimation. Since R_S and U_S are obtained relatively in this model, configuring the value of γ is just prescribed in the function form of U_S as a criterion for the estimation of the function form of R_S consistently. Thus, the relationships between R_S and U_S is not affected by changing γ.

Table 2 Results of parameter estimation (α and β are calculated from the value of A and B)

Parameter	am	pm
A	2.91	1.79
B	19.6	17.2
α	0.0113	0.0140
β	- 0.324	- 0.204
γ	0.1	0.1
Determination coefficient	0.39	0.24
Significance probability	0.099	0.148
Sample size	8	10

Figure 12 shows the curves of R_S, U_S, and N_S in the case of one-way traffic and in the case of interactive traffic by using the model estimated with the data observed in the morning. R_S with one-way traffic is lower than that with interactive traffic, thus N_S and x_S^* (subjective optimal entering speed) with one-way are higher than those with interactive. This probably indicates that since the drivers can drive without paying attention to the opposite vehicles, higher entering speed is taken. Figure 13 shows the curves of R_S, U_S, and N_S using both the model estimated with the data observed in the morning and those in the afternoon for only in the case of one-way traffic. R_S in the morning is lower than that in the afternoon. It can be presumed that, as for this reason, many drivers in the morning can be festinated comparatively although trip attributes (independent variable of U_S) is not considered here, thus R_S in the morning is relatively lower. In the real world, however, there seems to be no difference in R_S between in the morning and in the afternoon. Therefore, if it is assumed that R_S does not depend on observation period, N_S and x_S^* are higher in the morning than those in the afternoon because U_S in the morning is higher than that in the afternoon, as shown in Figure 14.

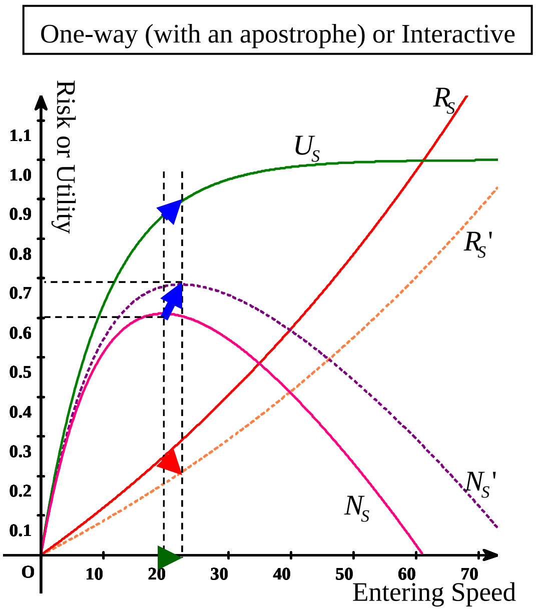


Figure 12 "Accident Risk" and "Utility" by one-way or interactive

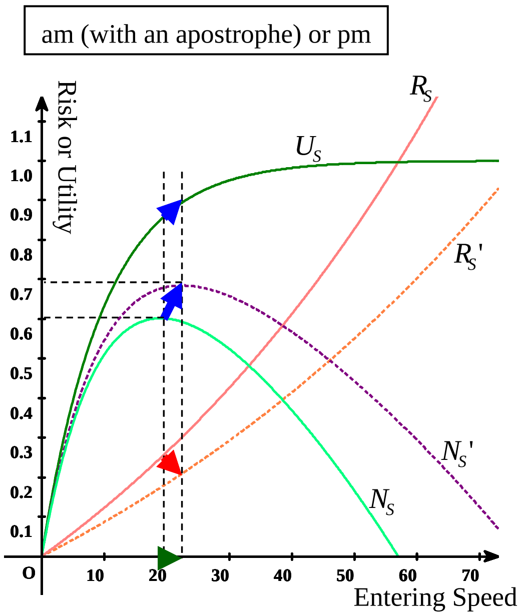


Figure 13 "Risk" and "Utility" by observed time period (1)

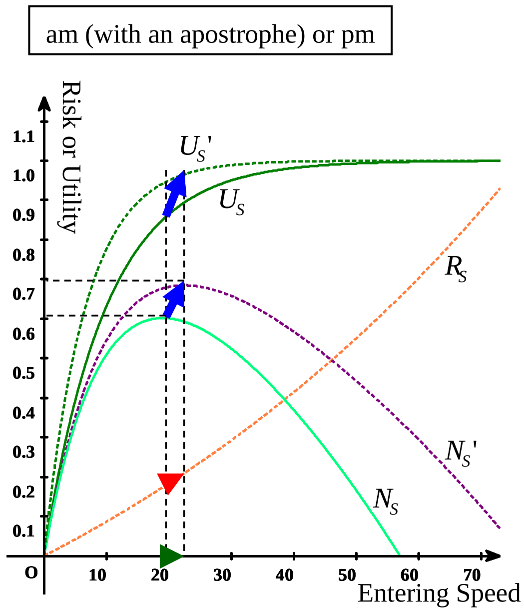


Figure 14 "Risk" and "Utility" by observed time period (2)

In Figure 15, the predicted values of average entering speed at respective intersections are plotted against the observed values as a scatter chart. Although they can be predicted partially, the adaptation is poor over 20 (km/h). In this study, the combination of traffic environment conditions is not considered because the number of the cases is small (18 cases). Therefore, the driving behavior is not explained sufficiently by this model, and the model applicability is not indicated clearly. However, there can be no incoherence between the model assumption and the actual phenomenon in a qualitative standpoint. Therefore, it is suggested that the concept of “Subjective Net-Utility Maximization Model” can be applied to the analysis and the evaluation of traffic safety measures, by improving the model such as reforming function form.

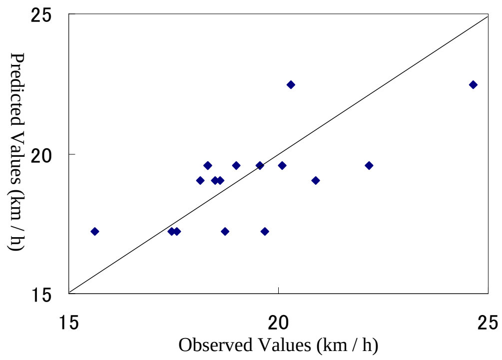


Figure 15 Goodness of the model (predicted and observed entering speed)

5. CONCLUSIONS

In this paper, “Subjective Net-Utility Maximization Model”, a driving behavior model which considers driver’s “Subjective Accident Risk” and “Driving Utility” jointly was proposed as a fundamental study for the comprehensive evaluation of traffic safety measures considering the trade-off between safety and travel utility. Then, by considering the difference between the driver’s subjective evaluation and the social evaluation of safety and travel utility, the mechanism of the changes in “Driving Behavior”, “Subjective Net-Utility”, and “Social Net-Utility” due to the changes in traffic environment was discussed qualitatively. Finally, the applicability of the formulated model was examined with the data observed at non-signal intersections in a residential area. It was found that this model can be applied to analyze the driver’s evaluations of traffic safety and travel utility relatively and the model assumption is consistent with the driving behavior in the real world.

However, in the study of applicability intended for the one-way regulation, the driving behavior was not sufficiently explained by the model due to the simplification reason that only one variable which expresses a traffic environment condition affecting driving behavior was employed as the independent variable of the model. As for future issues, to improve the model such as reforming the function form, to observe the driving behavior additionally, and to analyze trip attributes by using questionnaire, are pointed out. In addition, this study remains to formulate the “Subjective Accident Risk” model and “Driving Behavior” model. Therefore, it is required that “Social Accident Risk” and “Social Benefit” are quantified and formulated for the evaluation of the effects of traffic safety measures.

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