A DESIRED SPEED SELECTION MODEL BASED ON PERCEIVED COST MINIMIZATION CONCEPT

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ABSTRACT

1. Objective: It has been established that drivers have their desired speed. As might be expected, the desired speed or the distribution of desired speed is strongly connected with safety and convenience on road traffic. While the relationships between desired speed of drivers and road traffic environment conditions (RTECs; e.g. road width, sight distance, weather…) have been concerned, the mechanism of the desired speed selection (DSS) behaviour was hardly discussed in the past. A DSS model based on well-defined behavioural concept may allow a proper prediction of desired speed when changing RTECs. This study aims to develop a DSS model based on perceived cost minimization concept.
2. Data/Methodology: This study firstly formulates a DSS model regarding each driver on an ordinary road section which has certain RTECs. The model is based on perceived cost minimization concept considering the trade-off between perceived accident cost and perceived delay cost. Secondly the DSS model is linked with the distribution of desired speed. Third, the estimation method of DSS model, using “Tobit model”, is introduced because the desired speeds of following cars’ drivers can actually not be observed. As a case study, finally, the DSS model is estimated based on the data collected on the 36 road sections which have various RTECs.
3. Results/Findings: In linking the DSS model with the distribution of desired speed, it was found that when defining a random variable which determines the weight of perceived accident cost as log-normal distribution, the distribution of desired speed can be log-normal distribution too. In the case study, the goodness of fit of DSS model estimated was relatively high (R2 = 0.81). Also, the effects of RTECs on the driving speed selection behaviour were found quantitatively as well as the fact that desired speeds of the drivers in the morning peak period were higher because of their higher perceived delay costs.

4. Implications for Research/Policy: This study has implications for both researches and policies. From the result, the goodness of fit was relatively high and the RTECs affecting the DSS behaviour were reasonable, indicating that the proposed DSS model is valid and has enough applicability to the prediction of desired speeds. However, the one parameter affecting perceived accident cost in DSS model was fixed because the number of parameters is overabundance. In further study, the driving experiment is needed in order to set a proper value of the parameter.

Keywords: desired speed selection, desired speed distribution, perceived cost, driving behaviour

INTRODUCTION

In road traffic engineering field, it has been said that each driver, in general, has his/her free speed or *desired speed*. Desired speed means the speed which a driver selects under a certain road condition without the effects of other road users (e.g. a leading vehicle). In micro traffic simulations, desired speed of each vehicle is often assigned as a basic parameter (e.g. Nakamura and Hiramatsu (2000)). It is important to clarify quantitatively the relationships between desired speed and various *road traffic environment conditions* (RTECs) particularly for analysing the characteristics of traffic flow or the formation process of traffic platoon and evaluating the convenience of drivers. On the other hand, desired speed will closely be relevant to road traffic safety. For example, the curve section on which some drivers might select their desired speed exceeding the limit of safe speed. In a residential area, also, the RTECs under which drivers might select excessive high speed lead to the issue of traffic safety including pedestrians or bicycles. Therefore, it is needed to analyse the relationships between desired speed and RTECs for evaluating road traffic safety.

Although it has been pointed out that desired speed or desired distribution speed (DSD) are related to RTECs, there have been few discussion about the mechanism of how drivers select their desired speed. However, there must be any behavioural principle in the background of *desired speed selection* (DSS). If the discussion of DSS mechanism is developed on the basis of perceived cost minimization concept which will be proposed in this paper, the logical meaning can be added to the prediction of desired speed when RETCs is changed. In addition, drivers' benefit or cost associated with any improvement of RETCs may be able to be estimated and introduced into the evaluation of the improvement of RETCs.

This paper aims to develop a DSS model based on explicit behavioural principal. At first, the DSS model of each driver under a certain RETCs is formulated based on the perceived cost minimization concept considering the perceived accident cost and the perceived delay cost. Secondly, it is showed that the formulated DSS model can be associated to DSD. Next, the estimation method of the model parameters is discussed. Finally, as the discussion of model applicability, the model parameters are estimated based on the data collected on the two-way roads that have various RETCs.

REVIEW OF PREVIOUS STUDIES

As a previous study on desired speed, for example, Tarko (2009) analyses the relationships between desired speed and RETCs by using the observed speeds of free-driving (i.e. no-following) vehicles as desired speed data. This method is sufficient in the situation where the traffic is low or there are almost free-driving vehicles. However, it creates the problem that the desired speed is underestimated in the situation where the traffic is heavy or there are many following vehicles. This is because the vehicles which have higher desired speed are likely to follow the leading vehicle by comparison with the vehicles which have lower desired speed. That is, only the observed speed data of free-driving vehicles means the biased speed data in which the speed data of vehicles which have higher desired speed are excluded.

Reflecting such a situation, there have been some studies to try to estimate DSD. Botma and Bovy (2001) proposed the estimation method that the observed vehicles is firstly divided, by using a certain threshold value of headway time, into two groups, e.g. the free-driving vehicles as *uncensored* data and the following vehicles as *censored* data, and then DSD is estimated by applying the concept of the *tobit model*. Hoogendoom (2005) firstly estimated the probability of following with respect to each observed headway time by using a *composite headway-time distribution model*, based on the viewpoint that the state, free-driving or following, is different for each vehicle even if the observed headway times are same. Hoogendoom (2005) then proposed a method for estimating DSD considering the probability of following. Catbagan and Nakamura (2007) applied the Hoogendoom's method to the data observed on a two-way road segment, and analysed the relationships between DSD and various RTECs such as whether or vehicle type. Nakamura and Kita (2002) considered the probability that higher desired speed vehicles catch up to slower desired speed vehicles, and proposed a method for estimating DSD based on the distribution of driving speed and the distribution of platoon size at two points on a simple road segment. Shiomi at el. (2010) more quantitatively considered the phenomenon that the probability that a vehicle catches up to the leading vehicle depends on the desired speed of the vehicle, and proposed a method for estimating DSD based on the data of driving speeds and platoon sizes observed at two points on a simple road segment on which passing is constraint. Shiomi at el. (2010) also proposed a method to inversely estimate the distribution of platoon size at the end point of a certain length of road segment, given DSD, the length of the road segment and headway time at the start point of the road segment.

Although there have recently been some studies on DSD as mentioned above, most of them only relate to the estimation of the DSD or the analyses with given DSD. Thus, there has hardly been the discussion about how the desired speed or DSD is determined. Matsuo et al. (2010), Matsuo et al. (2011) and Kagawa et al. (2012) have constructed driving behaviour models with the concept that drivers select their driving behaviour based on the trade-off between perceived safety and perceived convenience. Although Janssen and O'Neill (1977), Tenkink (1988), Jφrgensen and Wentzel-Larsen (1999) and Tarko (2009) discussed the mechanism of driving speed selection based on the trade-off between perceived safety and perceived convenience too, they did not focused on the relationships between the mechanisms or models and DSD.

This study will construct a DSS model in which the DSD is clearly linked to the behavioural principle based on the trade-off between perceived safety and perceived convenience. And more, the validity of the DSS model will be examined through the analyses on the relationships between RTECs and DSD by using the real data.

DESIRED SPEED SELECTION MODEL

Process of desired speed selection of drivers

This study assumed the process of DSS of drivers as shown in **Figure 1**, described below. A driver may firstly perceive the road traffic environment condition ***E***, which is a vector including various conditions such as road structure conditions, road surface conditions, weather condition, vehicle, etc.. Soon after, the driver may perceive the subjective dangerousness for the case of driving at a certain speed *v* on the road under the received RTECs. The subjective dangerousness, in this study, is thought to be the negative utility relating to the traffic safety, and called "*perceived accident cost*", denoted by *AC*, which is expressed by monetary term. On the other hand, the driver may also perceive the subjective convenience for the case of driving at a certain speed *v* on the road. In this study, the subjective negative utility relating to the traffic convenience is expressed by monetary term, and called "*perceived delay cost*", denoted by *DC*. Finally, the driver may select the subjective optimal desired speed *v** which minimizes the *perceived total cost* denoted by *TC* which consist of the *AC* and *DC*.

From next section, the behaviour from the perception of RTECs to the selection of desired speed will be specifically modelled on the basis of the total cost minimization concept.

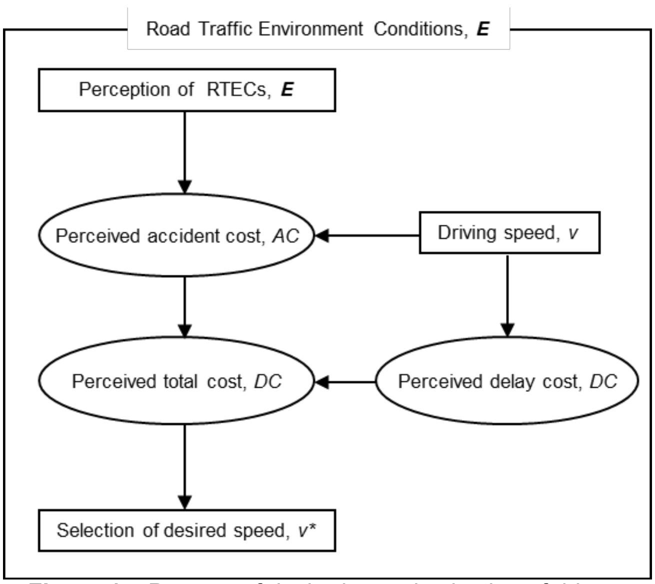

Figure 1 – Process of desired speed selection of drivers

Desired speed selection model for each driver

At first, ithe perceived accident cost per unit distance for the case of driving freely at a certain speed at a location *n* is denoted by AC_n [Yen/km] and defined as a function of the RTECs $\boldsymbol{E}_n$ and the driving speed *v* [km/h], where AC_n increases as the driving speed increases (see **Figure 2**), as follows:

$$AC_n = AC(v, \boldsymbol{E}_n), \tag{1}$$

where,

$$AC_n \geq 0, \qquad \frac{\partial AC_n}{\partial v} > 0.$$

On the other hand, the perceived delay cost per unit distance, denoted by *DC* [Yen/km], is defined as a function of the value of time of the driver, denoted by *w* [Yen/h], and the driving speed *v* [km/h], where *DC* increases as the driving speed decreases (see **Figure 2**), as follows:

$$DC = DC(v, w), \tag{2}$$

where,

$$DC \geq 0, \qquad \frac{\partial DC}{\partial v} < 0.$$

Moreover, the perceived total cost, denoted by TC_n [Yen/km], is defined as the sum of the AC_n and the *DC*, as follows:

$$\begin{aligned} TC_n &= TC(v, \boldsymbol{E}_n, w) \\ &= AC(v, \boldsymbol{E}_n) + DC(v, w). \end{aligned} \tag{3}$$

It is then assumed that the driver selects the subjective optimal speed, denoted by v^*, which minimizes the TC_n, and this subjective optimal speed v^* is defined as the desired speed of the driver (see **Figure 2**), as follows:

$$v^* = \mathrm{argmin}[AC(v, \boldsymbol{E}_n) + DC(v, w)]. \tag{4}$$

It is expressed in the Eq.(4) that the desired speed v^* is indirectly the function of the RTECs $\boldsymbol{E}_n$ through the function of AC_n. This implies that if the RTECs change (e.g. by widening of the road), the form of the function of AC_n changes, and in turn the optimal speed v^* giving minimum TC_n changes (see **Figure 3**). And more, it is shown in **Figure 3** that the AC_n^*, DC^* and TC_n^* which will be actualized if driving at v^* do change. This indicates the interesting characteristics that although the driving speed increases, the perceived accident cost decreases because RTECs are changes too.

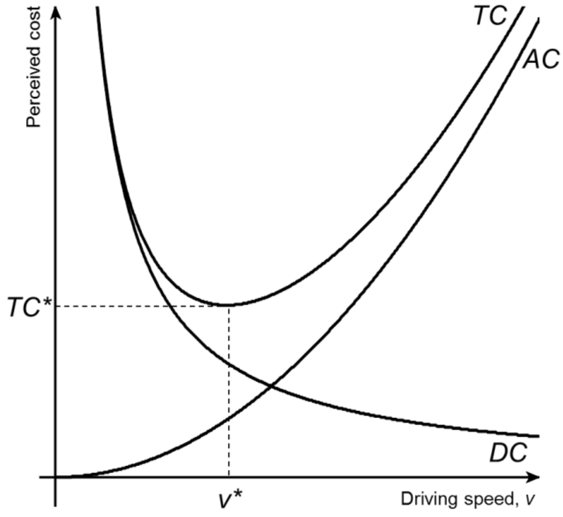

Figure 2 – Image of the DSS model based on the perceived total cost minimization concept

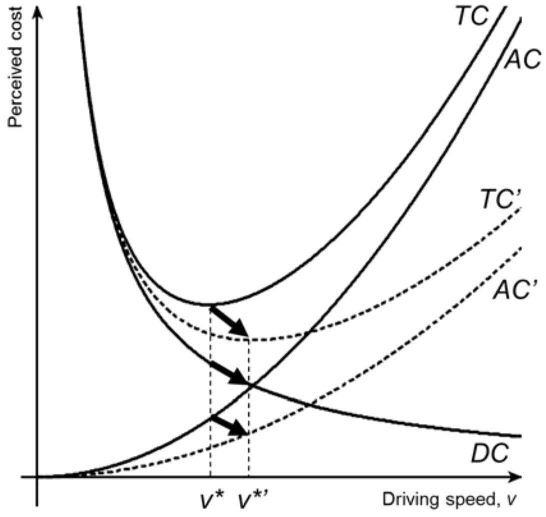

Figure 3 – Change of the desired speed and perceived total cost associated with the change of RTECs

Formulation of the desired speed selection model

Based on the concept defined above, the function form of the TC_n, a main part of the DSS model, is specified as follows:

$$TC_n = A_n \cdot v^{\beta} + \frac{w}{v}, \tag{5}$$

where,

$$A_n = A(\boldsymbol{E}_n, \boldsymbol{\alpha}) > 0; \qquad \beta \geq 0;$$

$\boldsymbol{\alpha}$ (vector) and β are parameters. The 1st term and 2nd term of the RHS of the Eq.(5) correspond to the AC_n and DC in the Eq.(3), respectively. A_n is a function of the $\boldsymbol{E}_n$ (e.g. liner function), which can be interpreted as the variable providing the weight of the change in the AC_n against the change in the DC with one unit change in v. Then, by using the first order condition, the desired speed v_n* which minimizes the can be derived as follows:

$$v_n^* = \left(\frac{w}{\beta \cdot A_n}\right)^{\frac{1}{\beta+1}}. \tag{6}$$

Association of the DSS model with the desired speed distribution

It is quite natural that the perception of the dangerousness and the weight of the perceived dangerousness corresponding to the perceived convenience are different for individual drivers. However, the all attributes of individuals cannot be observed. Therefore, the A_n in Eq.(5) is defined as a random variable, denoted by $\tilde{A}_n$, which allows the desired speed v_n* to be a random variable too, denoted by $\tilde{v}_n$*, and to interpret the distribution of the $\tilde{v}_n$* as the DSD. In this regard, it is supposed that the PDF of is denoted by $f_{An}(A|\boldsymbol{\alpha},\boldsymbol{E}_n)$ and the expectation, $E(\tilde{A}_n)$, is dependent on $\boldsymbol{E}_n$. If denoting Eq.(6) by $g(A_n)$, the inverse function can be expressed as follows:

$$g^{-1}(v_n^*) = A_n = \frac{w}{\beta \cdot (v_n^*)^{\beta+1}}. \tag{7}$$

Thus, the PDF of the DSD v_n* can be derived by applying variable transformation as follows:

$$f_{vn}^*(v) = f_{An}\left(g^{-1}(v)\right) \cdot \left|\frac{dg^{-1}(v)}{dv}\right|. \tag{8}$$

The algebraic manipulation mentioned above shows that the DSD can be derived from the DSS model for individual drivers.

It will be useful to suppose the distribution form of $\tilde{A}_n$ to be a log-normal distribution, due to the two reasons below:

1. A_n is assured to absolutely be non-negative, satisfying the constraint of the model. This is clearly because of the non-negativity of log-normal distribution;

2. Eventually, $\tilde{v}_n$* follows a log-normal distribution (see Appendix 1), assuring the v_n* to be non-negative too and simplifying something such as the parameter estimation. This is because of the reproducing property of log-normal distribution (see Ang and Tang, 2006).

According to the reasons, this study supposes the distribution form of $\tilde{A}_n$ to be a log-normal distribution and the expectation is specified as a log-liner function. Therefore, the value of A_n corresponding to a driver *i* at location *n* is expressed as follows:

$$A_{ni} = \alpha_0 \cdot \prod_k E_{nk}^{\alpha_k} \times \varepsilon_i, \tag{9}$$

where, ε_i is the probability error term following the log-normal distribution with the expected value $E(\varepsilon)$=1 and the dispersion parameter ζ.

Also, the value of time, w_i, may be different for some conditions such as time period. Thus, w_i is specified as the log-liner function as follows:

$$w_i = W \cdot \prod_m Z_{im}^{\gamma_m}, \tag{10}$$

where, *W* is the standard value of time [Yen/hr]; Z_{im} are the conditions relating to the value of time; and γ_m are the parameters.

Before estimating the parameters of DSS model (i.e. Eq.(6) into which Eq.(9) and Eq.(10) are substituted) based on real data, the estimation method will be examined in the next chapter.

EXAMINATION OF THE ESTIMATION METHOD OF DSS MODEL

In the parameter estimation of the DSS model, RTECs are used as the explanatory variables and desired speed are used as the objective variable, which thus requires the desired speed data of drivers under various RTECs. However, there is the problem that the following vehicles' desired speeds cannot be observed. Therefore, this study estimates the DSS model parameters by using a method to which the *Tobit model* is applied, proposed by Botam and Bovy (2001). That is, observed vehicles are firstly divided into free-driving vehicles or following vehicles by a certain threshold index, and the observed driving speeds of free-driving vehicles and following vehicles are defined as *censored data* and *uncensored data*, respectively. Then, the parameters which would maximize the log likelihood function below are estimated:

$$\mathrm{LL}(\boldsymbol{\theta}) = \sum_{n}\sum_{i}\left[(1-\delta_{ni})\cdot\ln\left(f_{vn}^{*}(v_{ni}|\boldsymbol{\theta})\right) + \delta_{ni}\cdot ln\left(1-F_{vn}^{*}(v_{ni}|\boldsymbol{\theta})\right)\right], \quad (11)$$

where, v_{ni} is the observed speed of individual driver i at a location n; δ_{ni} is the dummy variable which takes 0 if the vehicle i is a free-driving vehicle and takes 1 if the vehicle i is a following vehicle; $f_{vn}*(\cdot)$ and $F_{vn}*(\cdot)$ are PDF and CDF of the assumed distribution of the desired speed $\tilde{v}_n*$, respectively; and $\boldsymbol{\Theta}$ is the parameter vector of DSS model, i.e. $\boldsymbol{\alpha}$, β, $\boldsymbol{\gamma}$, ζ. This method is, in this study, called "*Standard Tobit estimation (STE)*".

In order to examine the validity of the estimation method, the method was applied to the virtual observed data generalized from a simple micro traffic simulation in which a certain DSD parameters were set up previously. It should be noted that the DSD parameters to be estimated in this examination were the expectation and the standard deviation. In the simple traffic simulation, one simple road section with one lane per one direction without overtaking was supposed and two things below were assumed, similar to the assumption in Shiomi et al. (2010):

1. Each vehicle has their desired speed and drive at the desired speed when free-driving. The desired speed of each vehicle is determined by drawing from a given DSD;

2. Each vehicle keeps driving at the desired speed until it caches up to the forward vehicle. After the headway time is less or equal to a given threshold value, the vehicle keeps the headway time and driving at the same speed of the forward vehicle's speed.

Figure 4 and **Figure 5** illustrated the estimation error rates against the ratio of following vehicles for the case of estimating the expectation and the standard deviation under the all combination of the conditions shown in **Table 1**, where the distribution form of DSD was the log-normal distribution and the threshold value of the following headway time was 4 seconds (because generally said it takes 3 ~ 5 seconds). Also, the results were aggregated by the ratio of following vehicles by 0.2, and the RMS of each group is shown in **Table 2**. With regards to the expectation, while the simple means of the observed speeds substantially became underestimation as the ratio of following vehicles increases, the values estimated by the STE were slightly smaller but still underestimation where the ratio of following vehicles was over 0.6. This may be because the STE does not consider the facts that the vehicles with slower desired speed are likely to be the leading vehicle of bigger platoons (meaning the number of vehicles in the platoon is larger) and the vehicles with higher desired speed are likely to belong to bigger platoons. Therefore, the estimation method with the weight of the platoon size was tried by modifying the log-likelihood function as follows:

$$\mathrm{LL}'(\boldsymbol{\theta}) = \sum_{n}\sum_{i}\left[\frac{(1-\delta_{ni})}{N_{PLT}}\cdot\ln\left(f_{vn}^{*}(v_{ni}|\boldsymbol{\theta})\right) + \frac{\delta_{ni}\cdot\left(S_{PLT,ni}-1\right)}{N_{PLT}}\cdot ln\left(1-F_{vn}^{*}(v_{ni}|\boldsymbol{\theta})\right)\right], \quad (12)$$

where,

$$N_{PLT} = \sum_{n}\sum_{i}\left[(1-\delta_{ni}) + \delta_{ni}\cdot\left(S_{PLT,ni}-1\right)\right];$$

$$\sum_{n}\sum_{i}\left[\frac{(1-\delta_{ni})}{N_{PLT}} + \frac{\delta_{ni}\cdot\left(S_{PLT,ni}-1\right)}{N_{PLT}}\right] = 1;$$

$S_{PLT,ni}$ is the size or the number of vehicles of the platoon the vehicle belongs, e.g. it takes 5 if the vehicle belongs to a platoon consists of 5 vehicles including the leading vehicle. This method is, in this study, called "*Weighted Tobit estimation (WTE)*". Similar to the case of STE, the estimation error rates against the ratio of following vehicles and RMS for WTE are also calculated by the simple traffic simulation and shown in **Figure 4**, **Figure 5** and **Table 2**. With respect to the expectation, while the error rates for the case that the ratio of following vehicles is 0.6~0.8 were around 10% for STE, those for WTE were reduced to around 5%. However, the error rates for WTE when the following vehicle ratio is over 0.8 were still high. This may because the sample size of free-driving vehicles becomes quite small.

With regards to the standard deviation, on the other hand, both STE and WTE became underestimation as the following vehicle ratio increases. However, the relationships between the error rates and following ratio were almost liner form. Thus, there might be the way to compensate the error linearly after the estimation.

From the examination above, WTE will be applied to the case study in the next chapter, giving priority to the WTE's estimate accuracy although the theoretical base is not enough.

Table 1 – Condition of micro traffic simulation for the examination of the estimation method

Expectation of DSD [km/h]	40, 60, 80, 100
Standard deviation of DSD [km/h]	3, 6, 9
The number of vehicles generalized [veh]	100, 1000, 10000
Observing point (distance from vehicle generating point) [m]	0, 1000, 5000, 10000, 100000
SEED value of random number	Two numbers

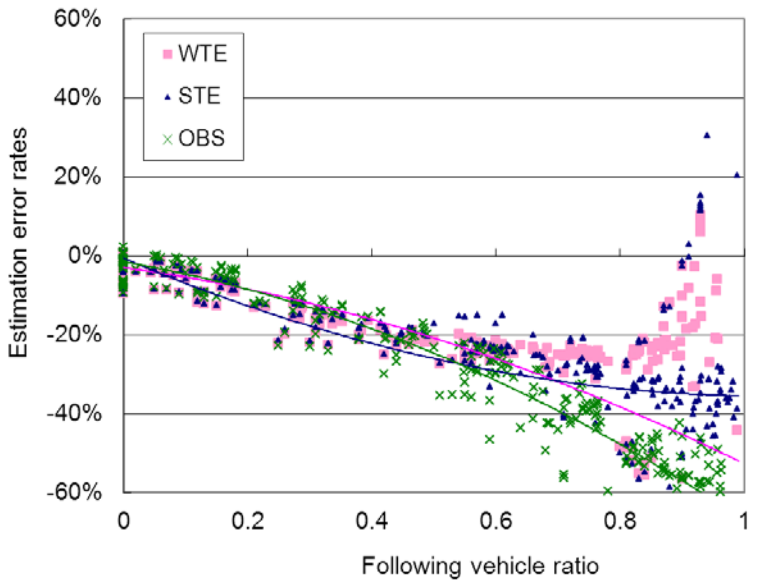

Figure 4 – Estimation error rates of the expectation of DSD against the following vehicle ratio

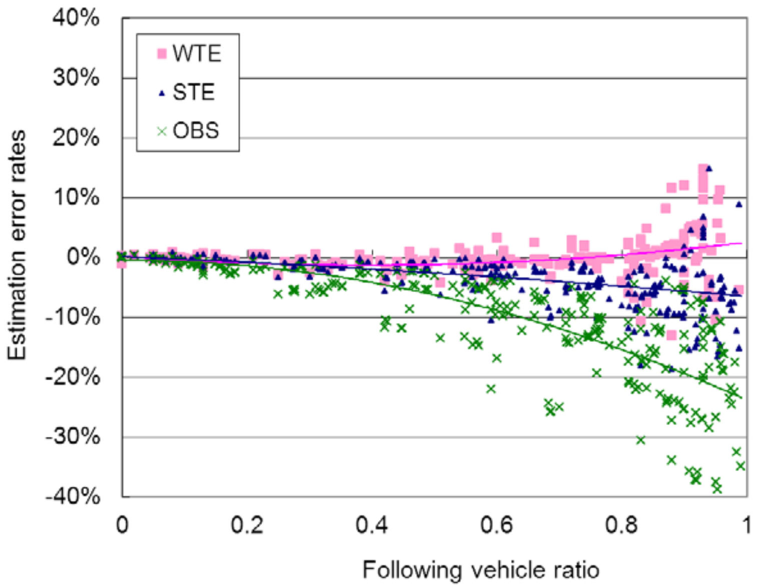

Figure 5 – Estimation error rates of the standard deviation of DSD against the following vehicle ratio

Table 2 – RMS of Estimation error rates of DSD parameters (Expectation and standard deviation)

Following vehicle ratio	Expectation			Standard deviation		
	OBS	STE	WTE	OBS	STE	WTE
0.0~0.2	0.9	0.4	0.4	4.1	4.9	5.0
0.2~0.4	4.1	1.5	1.2	15.4	15.6	16.6
0.4~0.6	8.5	3.3	1.7	26.4	21.9	22.7
0.6~0.8	12.2	4.6	1.3	39.6	48.6	41.4
0.8~1.0	22.0	8.3	5.6	58.4	47.8	66.9

OBS: Mean and sd of observed speed; STE: Standard tobit estimation; WTE: Weighted tobit estimation

CASE STUDY

Data collection

In order to examine the applicability of the proposed DSS model, video observations were conducted. The target locations were 19 simple road segments (36 directions including 2 one-way roads), where the road sizes were two lanes per one direction or smaller (see **Figure 6** as examples). Note that they were chosen so that there were no effects of signalized intersections. The video observations were conducted on some weekdays during March ~ April in 2011. From the video data, some indices including the point speeds, headway times and vehicle types of individual vehicles were collected. Although there were some ways to judge if the each vehicle state was free-driving or following, the constant headway time value, 4 second, was used as the threshold value (i.e. following if the headway time < 4 seconds). Also, the various RTECs of the all directions of all targeted road segments were collected. **Figure 7** illustrates the histograms of observed speeds of the following vehicles and the free-driving vehicles, and **Table 3** shows the main RTECs used in this case study. It is indicated in the histograms that while there were some free-driving vehicles with very high speeds, the free-driving vehicles with respectively low speeds were often indicated. This is because there were low traffic and thus were low following vehicle at the smaller road segments, but their desired speeds tends to be low due to the smaller size of the road segments. Also, **Figure 8** shows the mean observed speed of each targeted location, indicating that the mean speeds varied from 30km/h to 60km/h.

It should be noted that the road lengths were not included in the RTECs in this study since the road segments far from intersections were previously chosen. The posted speed limits were also not used in the analysis, considering the fact that there were some road segments with no speed limit in the residential areas and the fact that the correlation between the posted speed limits and the road widths were high. And more, the observed data affected by other road users such as pedestrians, bicycles, entering and exiting vehicles from side areas, etc. were rejected since this study aimed to analysed DSS behaviour. Although the speed selection behaviour with pedestrians and bicycles is no doubt important too, it was needed to adequately consider the interactions with the pedestrians and bicycles. Thus, this study stayed in the analyses of DSD behaviour.

Figure 6 – Examples of observed road segments

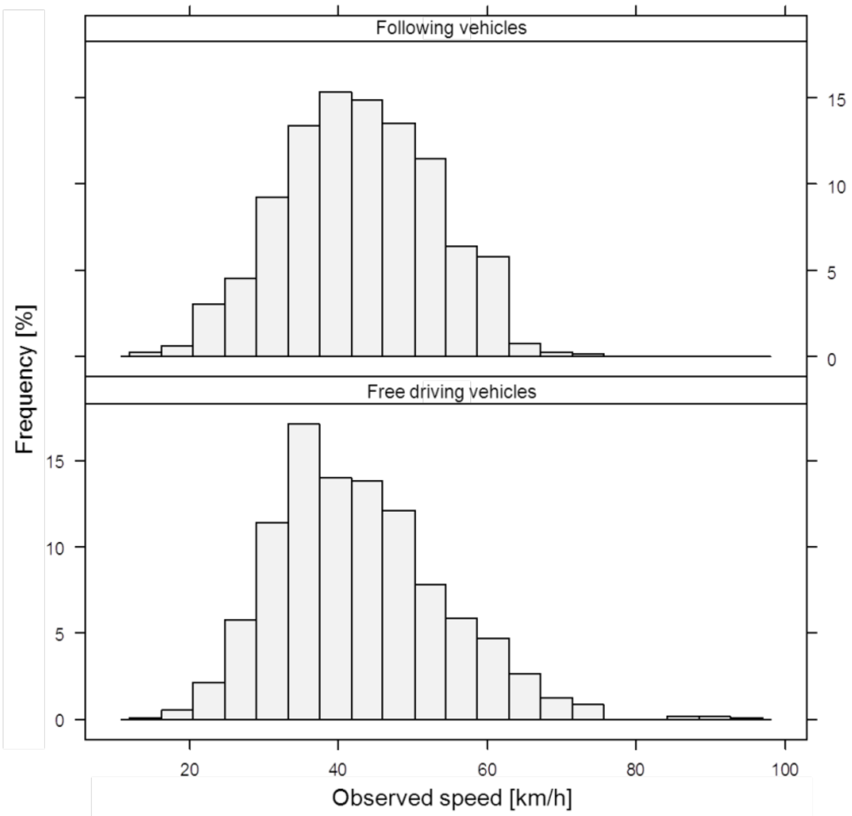

Figure 7 – The observed speed distributions of following vehicles and free-driving vehicles

Table 3 – Main road traffic environment conditions (RTECs) used in this study

RTECs	Mean, etc.	Standard deviation
Road width [m]	5.3	1.05
Left shoulder width [m]	0.8	0.53
Total road width [m] (road width + both shoulder width)	7.0	1.25
Presence of left sidewalk	8 dir / 36 dir	-
Presence of centre line	22 dir / 36 dir	-
Pedestrian traffic [people/h]	21.5	32.0
Bicycle traffic [bicycle/h]	33.3	49.6
Entering and exiting vehicle traffic	72.6	57.1
Residential area	10 dir / 36 dir	-
Business area	14 dir / 36 dir	-
Rural area	12 dir / 36 dir	-

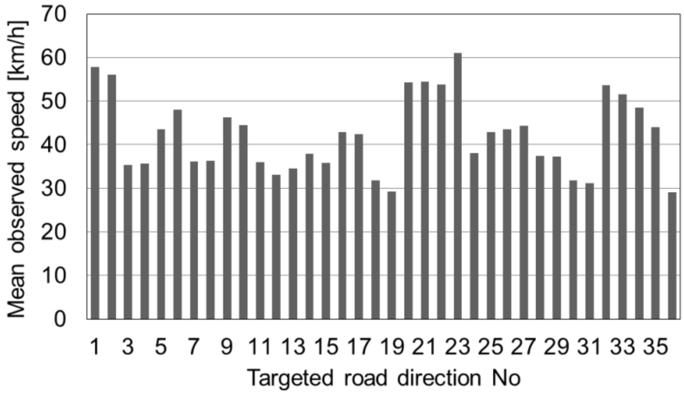

Figure 8 – Mean observed speeds by targeted road directions

Result of parameter estimation

The DSS model parameters, $\boldsymbol{\alpha}$, β, $\boldsymbol{\gamma}$, ζ, were estimated based on the data collected by the video observations, where 3000Yen/h was used as the standard value of time, W since 60Yen/min is usually used for road planning in Japan. It should also be noted that since the expectation of $\tilde{A}_n$ was defined as a log-linear function of the $\boldsymbol{E}_n$, the dummy variables in $\boldsymbol{E}_n$ were to be not [1 if absence and 2 if presence] rather than [0 if absence and 1 if presence]. In addition, since the number of the parameters was excess, the parameter β was fixed to be 1.0 and the other parameters were estimated. This meant the function form of the perceived accident cost, AC_n, was to be liner. Estimation method was the STE, and the BFGS method (i.e. quasi-Newton method) was used for the calculation of maximizing the log-likelihood function.

As the result of the parameter estimation with trial and error, the rational and valid model was found. **Table 4** shows the results and **Figure 9** illustrates the comparison between the mean observed desired speeds and the predicted expectations by the DSS model for each targeted road direction. It should be noted here that although the only observed speed of free-driving vehicles should be used for calculating the mean observed desired speed, there would be biased results because the vehicles with low desired speed is likely to be a leading vehicle of platoons. In the comparison in **Figure 9**, therefore, the mean of observed speeds of only the vehicles not belonging to platoons (i.e. only free-driving vehicles except for leading vehicles) were used as the mean observed desired speeds.

It is indicated in **Figure 9** that the expectations of desired speed were slightly overestimated. This may be because the vehicles with headway time less than 4 seconds were judged as following vehicles, leading to that some vehicles even actually not following might be wrongly judged as following vehicles. However, the correlation coefficient was very high, 0.91, meaning that the structure of the desired speeds corresponding to the difference of the RTECs was mostly explained.

It should be explained for seeing **Table 4** that if the coefficient parameters, α_k, were positive value, the driver's perceived accident cost, AC_n, increases as the explanatory variables increases, and then the desired speed, v_n*, in turn decreases, according to Eq.(9). On the other hand, if the coefficient parameters, γ_m, were positive value, the driver's perceived delay cost, *DC*, increases as the explanatory variables increases, and then the desired speed, v_n*, in turn increases, according to Eq.(10). **Table 4** also shows the elasticity of desired speed corresponding to the each explanatory variable (see Appendix 2). The results indicate these things below.

- "Road width" had the largest elasticity of desired speed, and the perceived accident cost of drivers decreased as the road width became wider. The effect of "Left shoulder width" was similar to the road width but smaller. The perceived accident cost also tended to decrease if there was left sidewalk. These facts can be explained by that on the wider roads, drivers does not need to pay attention to the horizontal wobble increasing with driving speed, and there will be the spatial and temporal space to response to sudden crossings of pedestrians.

- In this study, the targeted road segments were divided into three types of area, residential area, business area and rural area. The parameters of "Residential area dummy" and "Business area dummy" were positive value, indicating that the perceived accident cost was higher on the road segments in the residential and business area than in the rural area. This may be because of the narrower sight distance, the higher density of electric poles, etc. in the residential and business area in comparison with the rural area. For considering these facts in detail, the explanatory variables such as the density of buildings or the density of electric poles are required.

- The perceived cost was tended to increase as the pedestrian traffic became grater. This may be because the drivers would drive carefully if they had known there were a lot of pedestrians.

- The vehicle type also affected the DSS behaviour. In this study the observed vehicles were divided into three vehicle types, normal size vehicles, heavy vehicles and kei-cars. The results indicated that the desired speeds of heavy vehicles and the kei-cars were lower than those of the normal size vehicles. Regarding the heavy vehicles, the perceived accident cost tended to be higher probably because of the vehicle characteristics such as the wider vehicle width and the difficultly to decelerate rapidly. Regarding the kei-cars, the moderate difficulty to drive at high speed might decrease the desired speed.

- "Morning peak dummy" is the variable representing if the data were observed during 7:00AM ~ 10:00PM or not. The parameters were negative value, indicating that the desired speeds of the vehicles driving in the morning peak tended to be higher than those in the other time periods. This fact can be interpreted as that the drivers in the morning peak hurried, i.e. they had the higher value of time than the drivers in the other time periods. By using Eq.10, The value of time was calculated to be 1.28 times of the standard value of time (3000Yen/h), that is 3826Yen/h.

Table 4 – Result of the estimation of DSS model

Explanatory variable	Parameter		p-value	Elasticity of desired speed
Constant	α_0	1.88	0.000	-
Road width [m]	α_1	-1.10	0.000	0.55
Left shoulder width [m]	α_2	-0.23	0.000	0.11
Left sidewalk dummy	α_3	-0.13	0.002	0.065
Residential area dummy	α_4	0.51	0.000	-0.26
Business area dummy	α_5	0.47	0.000	-0.24
Pedestrian traffic [people/h]	α_6	0.082	0.000	-0.041
Heavy car (vehicle type) dummy	α_7	0.069	0.035	-0.034
Kei-car (vehicle type) dummy	α_8	0.10	0.060	-0.052
Morning peak (7:00~10:00) dummy	γ_1	0.35	0.000	0.18
Dispersion parameter	ζ	0.39	0.000	-
	β	1.0		-
Standard value of time [Yen/h]	W	3000		-
Sample size	2214			
Adjusted ρ^2	0.16			

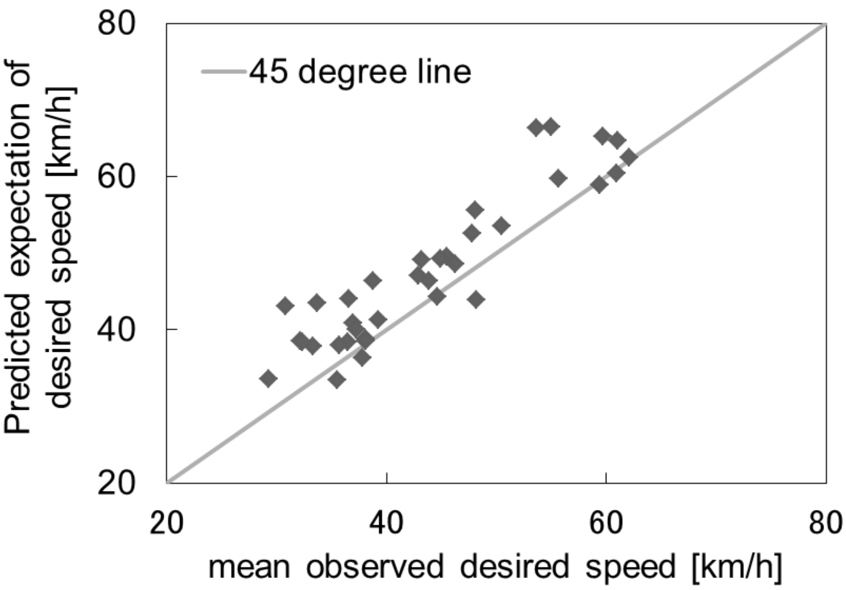

Figure 9 – Relationships between the predicted expectations by estimated model and mean observed desired speeds of the vehicles not belonging to platoons

Sensibility analysis

Finally, the expectations of the desired speed under the condition shown in **Table 5** were calculated by the estimated DSS model. **Figure 10** illustrates the results by road width, area (rural area or residential area) and time period (morning peak or not).

It is presented that as the road width become wider, the desired speed increases while the slop decreases. This model form can be thought of as reasonable since the desired speed will not increase drastically even if the road width becomes considerably wider. Also, the desired speed on a 5m width residential road is roughly 37km/h for the morning peak and roughly 33km/h for the other periods. Similarly, the desired speed on a 8m width rural road is roughly 64km/h for the morning peak and roughly 71km/h for the other periods. These results will not be strange or be valid.

Considering the results so far, a certain level of applicability of the proposed DSS model was confirmed by the high goodness of fit, the rational sign of the estimated parameters and the rational reasonable results in the sensibility analysis although some problems such as the excess number of parameters and the slight overestimation of the desired speed are remaining.

Table 5 – Conditions for the sensitively analysis of the estimated DSS model

Explanatory variables	Rural road	Residential road
Road width [m]	3m ~ 9m	3m ~ 9m
Left shoulder width [m]	0.80	0.10
Left sidewalk dummy	1	2
Residential area dummy	10	10
Business area dummy	1	2
Pedestrian traffic [people/h]	1	1
Heavy car dummy	1	1
Kei-car dummy	1	1
Morning peak dummy	1 or 2	1 or 2

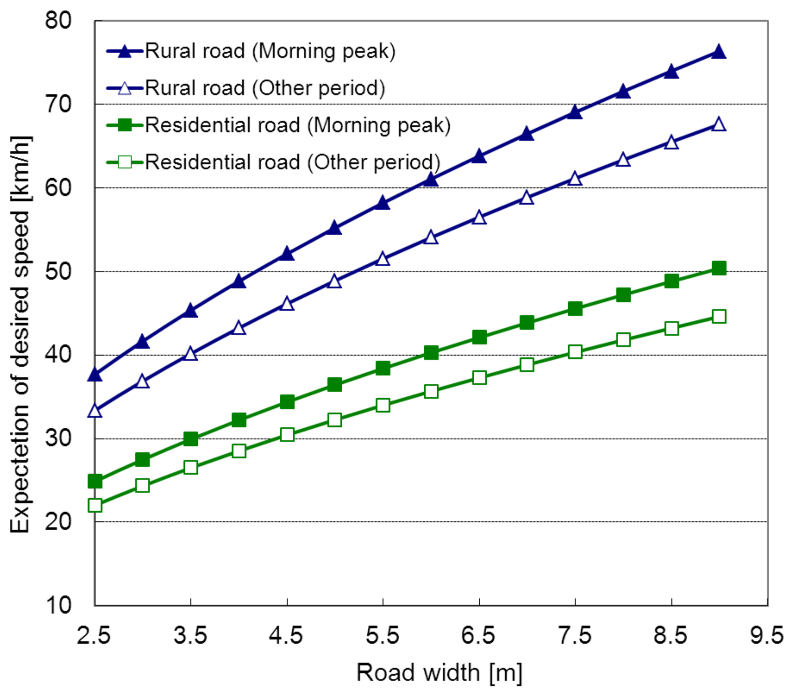

Figure 10 – Sensitively of the desired speed corresponding to the change in RTECs

CONCLUSIONS

This study aimed to introduce a desired speed selection (DSS) model based on a clear behavioural principle. Firstly, the DSS model for individual drivers on a simple road section was formulated in the basis of the perceived total cost minimization concept. It was then shown that the DSS model can be associated with the desired speed distribution (DSD), by assuming the variable which affects the weight of the perceived accident cost to be a random variable. It was also ensured that if the distribution form of the random variable is a log-normal distribution, the DSD will be a log-normal distribution and eventually the value of the desired speed will surely take non-negative values.

Secondly, the estimation method of the parameters of DSD or proposed DSS model was improved. As a case study, then, the parameters of the DSS model were estimated based on the observed speed data on the simple road segments with various road traffic environment conditions (RTECs). As the result, the certain level of the applicability of the proposed DSS model was found according to the high goodness of fit, the rational sign of the parameters and reasonable results of the sensitively analysis. And more, it could be expressed not only the effects of the RTECs on the perceived accident cost, but also that the drivers during the morning peak period had higher desired speed probably due to their higher perceived delay cost.

However, some issues to be solved were also found. The first is the excessive number of parameters to be estimated. Particularly, beta is the parameter which affects the form of the perceived accident cost function. It will therefore be needed to give the appropriate value exogenously if cannot be estimated. For doing that, the approaches such as to measure the change in the perceived accident cost for the case the drivers drive at various speeds on a road with constant RTECs, by using driving experiments. The second issue is about the estimation method of the parameters of DSD. Although the weighted tobit estimation (WTE) proposed improved the estimation accuracy in comparison with the standard tobit estimation (STE), the theoretical evidence was not enough discussed. In addition, the estimation accuracy for the standard deviation was still not improved. Nakamura and Kita (2002) and Shiomi et al. (2010) proposed the estimation method using the observations at two points on a road section. However, the better way to estimate based on one point observation is needed in order to efficiently conduct the observation on several road segments with various RTECs. The third issue is relevant to the second. The expectations of DSD for the case applying the estimated DSS model to the real data tended to be overestimation. This may be because of the all or nothing judge if following vehicles or free-driving vehicles by the constant threshold headway time. It is therefore required some improvements such as to consider the probability to be following vehicles, which was proposed by Hoogendoom (2005).

APPENDIX

[1] Suppose the distribution form of $\tilde{A}_n$ is a log-normal distribution and the PDF is as follows:

$$f_{An}(A|\boldsymbol{\alpha},\boldsymbol{E}_n,\zeta)=\frac{1}{\sqrt{2\pi}\zeta}\frac{1}{A}exp\left[-\frac{1}{2}\left(\frac{lnA-\lambda}{\zeta}\right)^2\right],$$

where,

$$\lambda=A(\boldsymbol{E}_n,\boldsymbol{\alpha})-\frac{1}{2}\zeta^2,$$

$$\mathrm{E}(\widetilde{A_n}|\boldsymbol{\alpha},\boldsymbol{E}_n,\zeta)=A(\boldsymbol{E}_n,\boldsymbol{\alpha}),$$

$$\mathrm{Var}(\widetilde{A_n}|\boldsymbol{\alpha},\boldsymbol{E}_n,\zeta)=\left(A(\boldsymbol{E}_n,\boldsymbol{\alpha})\right)^2\cdot[exp(\zeta^2)-1].$$

Then, the PDF of the desired speed distribution, $\tilde{v}_n{}^*$, can be derived as follows:

$$f_{vn}^*(v|\boldsymbol{\alpha},\boldsymbol{E}_n,\zeta,\beta)=\frac{1}{\sqrt{2\pi}\zeta'}\frac{1}{v}exp\left[-\frac{1}{2}\left(\frac{lnv-\lambda'}{\zeta'}\right)^2\right],$$

where,

$$\lambda'=\frac{-ln\left(A(\boldsymbol{E}_n,\boldsymbol{\alpha})+\frac{1}{2}\zeta^2+lnw-ln\beta\right)}{(\beta+1)},$$

$$\zeta'=\frac{\zeta}{(\beta+1)},$$

$$\mathrm{E}(\widetilde{v_n^*}|\boldsymbol{\alpha},\boldsymbol{E}_n,\zeta,\beta)=exp\left(\lambda'+\frac{1}{2}\zeta'^2\right),$$

$$\mathrm{Var}(\widetilde{v_n^*}|\boldsymbol{\alpha},\boldsymbol{E}_n,\zeta,\beta)=\left(\mathrm{E}(\widetilde{v_n^*}|\boldsymbol{\alpha},\boldsymbol{E}_n,\zeta,\beta)\right)^2\cdot[exp(\zeta'^2)-1].$$

[2] The slops and elasticity of the change in the desired speed corresponding to the change in the RTECs can respectively be derived as follows:

$$\frac{\partial v_{ni}^*}{\partial E_{nk}}=-\frac{\alpha_k}{E_{nk}(\beta+1)}\cdot v_{ni}^*,\qquad \frac{\Delta v_{ni}^*}{v_{ni}^*}\bigg/\frac{\Delta E_{nk}}{E_{nk}}=-\frac{\alpha_k}{\beta+1}.$$

Similarly, the slops and elasticity of the change in the desired speed corresponding to the change in the individual characteristics can respectively be derived as follows:

$$\frac{\partial v_{ni}^*}{\partial Z_{im}}=\frac{\gamma_m}{Z_{im}(\beta+1)}\cdot v_{ni}^*,\qquad \frac{\Delta v_{ni}^*}{v_{ni}^*}\bigg/\frac{\Delta Z_{im}}{Z_{im}}=\frac{\gamma_m}{\beta+1}.$$

ACKNOWLEDGEMENTS

We acknowledge the support of the Japan Construction Information Center (JACIC), which is a General Incorporated Foundation, in funding this research project.

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