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A SELECTION METHOD OF EVALUATION INDEX ON THE QUALITY OF TRAFFIC SERVICE BASED ON DRIVERS' PERCEPTION

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A SELECTION METHOD OF EVALUATION INDEX ON THE QUALITY OF TRAFFIC SERVICE BASED ON DRIVERS’ PERCEPTION

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ABSTRACT

This paper proposes a method to select an evaluation index on the quality of traffic service (QOS) based on drivers’ perception. At first, data on the microscopic driving environment within the field of vision surrounding the driver at each point along a road section as well as on the macroscopic traffic conditions were obtained from a micro-simulation analysis. Then, the section-basis utility, as the section-basis QOS, was estimated from the microscopic driving environment data based on the structure of a driver’s perception. Using this data, we clarified the relationships between the macroscopic traffic condition indices and section-basis utility. Based on the relationships, we showed the validity of “the logarithm of traffic density” as the QOS-index which substitutes for the QOS, and proposed a practical equation for estimating the section-basis utility from the logarithm of traffic density. We verified the validity of the QOS-index and proposed an equation for estimating the QOS, by showing the internal relationship with the driver’s perception.

Keywords: quality of traffic service, drivers’ perception, QOS-index, practical equations, utility model, driving environment

1. INTRODUCTION

In order to promote drivers’ satisfaction while driving, it is important to adopt measures to improve the quality of traffic service (QOS) directly during road planning and traffic management. The QOS describes how well a traffic stream operates from a driver’s perspective. There are a wide range of road-based services, varying from those involved with the traffic function to scenery. The QOS shows an operational performance of traffic service which is one of the main functions a road should provide, and one which road administrators can control. For example, in performance-based planning policy, the QOS can be used as a road performance target in road planning and design, and road design and traffic operation schemes are adopted in order to achieve the performance target.

However, it is impossible to observe and measure the QOS perceived by a driver in the field. We have to estimate it using some methods. A number of studies have been made on a selection of QOS-index which is an evaluation index on the QOS, and proposed various indexes. For example, the Highway Capacity Manual (HCM) has selected “traffic density” from the “macroscopic traffic condition data”, such as average speeds and traffic volume, which can be easily obtained from a traffic detector, as the QOS-index for basic freeway segments (TRB, 2011).

However, it is not the macroscopic traffic condition but the “microscopic driving environment” within the driver’s field of vision at each point along a road section that the driver can recognize. This means that the QOS should be based on the microscopic driving environment, according to the structure of drivers’ perception. However, in previous studies, the QOS was related to macroscopic traffic indices without clarifying the relationships between the microscopic driving environments and QOS. HCM has used traffic density as a QOS-index for basic freeway segments and defined the level of service (LOS) based on it for over 20 years, but little is known about the theoretical relationship between the QOS, the macroscopic traffic condition, and the microscopic driving environment. Therefore, it has not been proven that the traffic density, a macroscopic traffic condition index which drivers cannot perceive directly, is a valid substitute for the QOS perceived by drivers. The proposal of a QOS-index and an equation for estimating the QOS which have been objectively proven to be consistent with drivers’ perception is a hot issue in road planning and traffic management using the QOS concept.

In this paper, we propose a method to select a QOS-index based on drivers’ perception from the macroscopic traffic condition data. At first, we clarify the relationships between the QOS based on microscopic driving environment and the macroscopic traffic condition data related with the microscopic driving environment, and then the QOS-index and a practical equation for estimating the QOS were selected. In estimating the QOS based on the microscopic driving environment, a series of structure models we proposed in an earlier study are employed (Kita and Kouchi, 2011a). According to the method of this paper, the validity of a QOS-index and a practical equation for estimating the QOS is verified objectively by showing internal conformity with drivers’ perception.

The organization of this paper is as follows. Section 2 presents issues regarding the selection of an evaluation index and models concerned with QOS estimation developed in our earlier studies. In section 3, we propose the methods to select a QOS-index and an appropriate equation for estimating the QOS. After section 4, we select a QOS-index and a practical equation for estimating the QOS. Section 4 presents data collected using microsimulation analysis which assumes basic highway segments. In section 5, the relationships between the macroscopic traffic condition data and QOS are clarified, and the QOS-index which substitutes for the QOS is selected. Then, a practical equation which approximates the QOS with the QOS-index is proposed. Section 6 presents conclusions.

2. BACKGROUND

2.1. Issues regarding QOS-index selection

HCM 2010 defined the four characteristics that service measures, as a QOS-index, should exhibit: i) they should reflect travelers’ perceptions; ii) they should be useful for operating agencies; iii) they should be directly measurable in the field; iv) and they should be estimable given a set of known or predicted conditions (TRB, 2011). HCM defines service measures for each traffic facility, and has used traffic density as a service measure for basic freeway segments and defined the LOS based on the degree of traffic density for over 20 years. However, it has not been clarified whether the traffic density can reflect the QOS perceived by drivers adequately. In other words, the traffic density, as a service measure, can meet conditions ii) - iv), but it has not yet been clarified whether it can meet condition i).

Therefore, a great deal of effort has been focused on QOS-index selection using driving experiments, laboratory experiments, group interviews, etc. For example, De Arzoza and McLeod (1993) proposed “average speed” and Flannery and Jovanis (2001) proposed “time-of-delay” as QOS-indexes. Regarding factors which affect the QOS, Hall et al. (2001) stated that the travel time most markedly influences the QOS, and safety, information, and, maneuverability also influences the QOS. Washburn et al. (2004) suggested that factors such as pavement conditions and driving manners are also important, although the main factor that influences drivers’ perceptions of QOS is the traffic density. Hostovsky et al. (2004) showed that factors which affect the QOS are travel time in urban areas, and maneuverability in non-urban areas. Choocharukul et al. (2004) suggested that the heavy-vehicle mix rate is a negative index for drivers other than truck drivers, while the opposite is the case for truck drivers. These studies showed the diversity of factors which affect the QOS, and provided useful information.

However, the suitability of those indices as substitutes for the QOS perceived by drivers has not been clarified, because the structure of drivers’ perception of the QOS is not mentioned explicitly in the decision process. As the QOS describes the conditions of the traffic stream from the driver’s perspective, in order to verify the validity of the QOS-index, the relationships between the microscopic driving environments which can be perceived by the driver and QOS need to be clarified based on the structures of QOS perception. Furthermore, the microscopic driving environment within the field of a driver’s vision at each instance while driving needs to be related to the macroscopic traffic conditions which the driver cannot perceive directly but can be easily obtained. Based on the ideas mentioned above, we can relate the macroscopic traffic conditions with the microscopic driving environment, and so the macroscopic traffic condition data can be connected with the QOS directly.

Ko et al. (2006) revealed the necessity of considering microscopic driving environments when measuring the QOS using field data. They pointed out that most of the studies concerned with the QOS put more weight on the relationships between the macroscopic traffic conditions and QOS, although the relationship between the QOS and microscopic driving environment should be established. They related traffic stream and LOS estimated from the traffic density employing a method in the HCM to each car using “speed” and “acceleration noise” as parameters of the traffic flow quality of each car, and the traffic density as a macroscopic traffic condition variable. As a result, they showed that the same traffic flow quality exists at different LOS, and the QOS estimated from the macroscopic traffic condition variable was shown to be unable to express the variety of driving environments which drivers face.

It follows from what has been reviewed that the validity of the QOS-index is not verified in previous studies, because those studies deal with the relation between macroscopic traffic indices and the QOS without verifying the relationship between the microscopic driving environment, macroscopic traffic conditions, and QOS.

2.2. Estimation of the QOS based on driver’s perception

In order to appropriately select the QOS-index which reflects drivers’ perceived QOS and an equation for QOS estimation, at first, the QOS needs to be based on the microscopic driving environments. Kita (2001) proposed a methodological framework for QOS evaluation based on drivers’ perceptions. The basic idea of this framework was that the total QOS of a certain road section can be understood by processing QOS for the driving environment at each point in the section. Also, as for the QOS at each point, Kita (2001) pointed out that the utility derived from the driving actions corresponds to the ceiling of QOS to the driver, if a driver chooses the most desirable driving actions under a given driving environment at each instance. From the above, the author viewed the “essence of QOS” as “desirability felt by drivers regarding the traffic service”, and proposed the idea of estimating the QOS in terms of a driver’s utility. Using that idea, we can comprehensively estimate the QOS by considering influencing factors, such as maneuverability, safety, and so on. Based on the framework, Kita and Kouchi (2011a) proposed a serial model to estimate the section-basis QOS from the microscopic driving environments based on drivers’ perception: “instant utility model”, “order effect model”, and “min-average model” (See Fig.1). As these models are employed to estimate the QOS based on the microscopic driving environment in this paper, we present an outline of the models below.

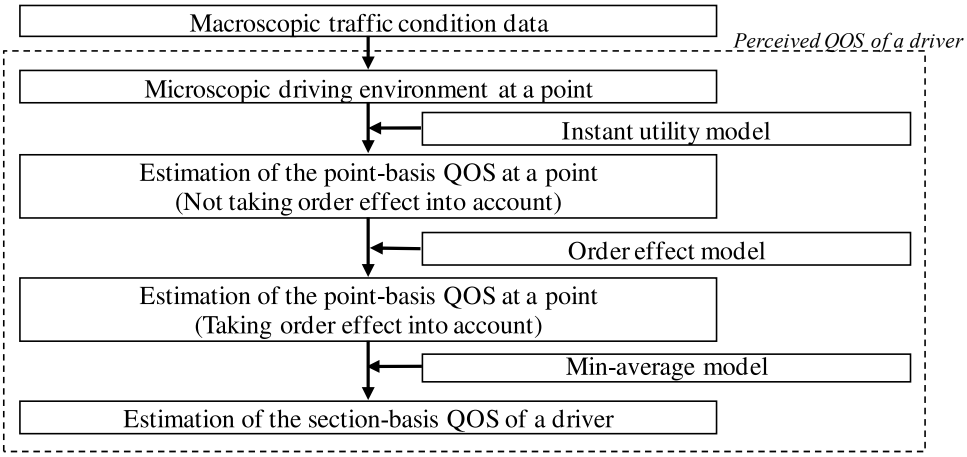

Figure 1 – Structure of the methodology to estimate the perceived QOS

(1) Instant utility model

The instant utility model assumes that a driver chooses the most desirable driving action to improve the driving environment on the assumption that he/she adopts utility-maximizing behavior. The model estimates the driving action a_i which the driver j chooses, and instant utility of a chosen driving action at the instance t, ${U_{instant}}_j^t$, as the QOS perceived by the driver j. In this paper, we employed the equations and parameters as follows:

$$U_{instant\,j}^{\ t} = \max_{a_i} \{U_{instant\,ji}^{\ t}\} \tag{1}$$

where $U_{instant\,ji}^{\ t}$ is the utility to each of the four alternatives, $a_i \in A(i=1,\dots,4)$, that consists of maintaining speed, acceleration, deceleration, and changing lanes of a driver j at the instance t. The driver's utility regarding each of the four alternatives, $U_{instant\,ji}^{\ t}$, is assumed as follows:

$$U_{instant\,ji}^{\ t} = V_{instant\,ji}^{\ t} + \varepsilon \tag{2}$$

where $V_{instant\,ji}^{\ t}$ is the deterministic parts of the point-basis utility taken by the driver j for the driving action $a_i \in A(i=1,\dots,4)$ at the instance t, and ε is the error term which follows an independent and identical Gumbel distribution. Deterministic parts, $V_{instant\,ji}^{\ t}$ for each driving

Table1 – Formulae of the instant utility model

Driving actions	Deterministic parts	PICUD
Maintaining speed	$V_{instant\,j1}^{\ t} = 0.010L_1^t - 0.116\lvert v_j^0 - v_j^t \rvert$	$L_1^t = \frac{(v_1^t)^2}{-2a} + s_0^t - \left\{ v_j^t \Delta t + \frac{(v_j^t)^2}{-2a} \right\}$ $L_2^t = \frac{(v_j^t)^2}{-2a} + s_0^t - \left\{ v_2^t \Delta t + \frac{(v_2^t)^2}{-2a} \right\}$
Acceleration	$V_{instant\,j2}^{\ t} = 0.010L_1^t - 0.116\lvert v_j^0 - (v_j^t + \Delta v) \rvert$	$L_1^t = \frac{(v_1^t)^2}{-2a} + s_0^t - \left\{ (v_j^t + 2.75)\Delta t + \frac{(v_j^t + 2.75)^2}{-2a} \right\}$
Deceleration	$V_{instant\,j3}^{\ t} = 0.010L_1^t - 0.116\lvert v_j^0 - (v_j^t - \Delta v) \rvert$	$L_1^t = \frac{(v_1^t)^2}{-2a} + s_0^t - \left\{ (v_j^t - 4.15)\Delta t + \frac{(v_j^t - 4.15)^2}{-2a} \right\}$
Lane changing	$V_{instant\,j4}^{\ t} = 0.010L_1^{\mathrm{nt}} + 0.057L_2^{\mathrm{nt}} - 0.116\lvert v_j^0 - v_j^{\mathrm{nt}} \rvert - 3.632$	$L_1^{nt} = \frac{(v_1^{nt})^2}{-2a} + s_0^{nt} - \left\{ v_j^t \Delta t + \frac{(v_j^t)^2}{-2a} \right\}$ $L_2^{nt} = \frac{(v_j^t)^2}{-2a} + s_0^{nt} - \left\{ v_2^{nt} \Delta t + \frac{(v_2^{nt})^2}{-2a} \right\}$

$V_{instant\,ji}^{\ t}$: deterministic parts of point-basis utility taken by the driver j for the driving action a_i ($i = 1, \dots, 4$) at time t
L_1^t : PICUD to the closest front-side vehicle at time t (m) L_2^t : PICUD to the closest rear-side vehicle at time t (m)
L_1^{nt} : PICUD to the closest front-side vehicle in the neighboring lane at time t (m)
L_2^{nt} : PICUD to the closest rear-side vehicle in the neighboring lane at time t (m)
v_j^0 : desired speed of the driver j (m/s) v_j^t : achieved speed of the driver j at time t (m/s)
v_j^{nt} : achieved speed of the driver j in the neighboring lane at time t (m/s)
Δv : speed change at time t (m/s) v_1^t : achieved speed of the closest front-side vehicle at time t (m/s)
v_2^t : achieved speed of the closest rear-side vehicle at time t (m/s)
v_1^{nt} : achieved speed of the closest front-side vehicle in the neighboring lane at time t (m/s)
v_2^{nt} : achieved speed of the closest rear-side vehicle in the neighboring lane at time t (m/s)
s_0^t : inter-vehicular distance (m) on the same lane at time t Δt : response time (0.75 sec)
s_0^{nt} : inter-vehicular distance (m) in the neighboring lane at time t a : degree of deceleration (-3.3 m/s^2)

action, a_i, are expressed in Table 1. The Possibility Index for Collision with Urgent Deceleration (PICUD) is an index that shows the risk of the vehicle suffering a rear-end collision with the closest front-side vehicle it is following when the driver of the closest vehicle brakes suddenly (Uno et al., 2002).

(2) Order effect model

Although $U_{instant\,j}^{\;t}$ is estimated independently from the traffic conditions at other points, there exists an “order effect”, which is one of the cognitive biases in actual driving. The “order effect” refers to the perception, after experiencing a prior stronger or weaker stimulus, of the strength of two stimuli as being different from each other, even though their actual strength is the same. The order effect model estimates the point-basis utility $U_{point\,j}^{\;t}$, as a point-basis QOS, from $U_{instant\,j}^{\;t}$ taking into account the order effect. Although Kita and Kouchi (2011a) developed the order effect model for each driver, we developed a representative model using aggregated data in this paper. The equation and parameters employed in this paper are as follows:

$$U_{point}{}^{t} = 1.96U_{instant}{}^{t} - 0.67(U_{instant}{}^{t} - U_{instant}{}^{t-1}) - 3.57 \tag{3}$$

(3) Min-average model

As the QOS is evaluated not at a point but in a section from a practical point of view, the section-basis QOS needs to be estimated from the point-basis QOS. The “min-average model” facilitates estimation of the section-basis QOS from the average score and worst score equivalent to the minimum score of each evaluation of the point-basis QOS of a certain road section. The equation and parameters employed in this paper are as follows:

$$U_{section} = \begin{cases} \overline{U}_{point} & if\ U_{point}^{1} = U_{point}^{2} = \cdots = U_{point}^{t} \\ 0.551\overline{U}_{point} + 0.603U_{point}^{Min} + 1.202 & otherwise \end{cases} \tag{4}$$

where $U_{section}$ is the section-basis utility, U_{point}^{t} is the point-basis utility at time t, $\overline{U}_{point}$ is the average point-basis utility at each point in the road section, U_{point}^{Min} is the minimum point-basis utility at each point in the road section.

3. METHODS TO SELECT A QOS INDEX AND A PRACTICAL EQUATION FOR QOS ESTIMATION

As shown in Fig.2, QOS-index, as a service measure, and a practical equation for QOS estimation are determined in four steps: i) Collection of data on the microscopic driving environment data related to the macroscopic traffic condition data; ii) Estimation of the section-basis utility based on the microscopic driving environment; iii) Analysis of relationships between the section-basis utility and macroscopic traffic condition data; iv)

Selecting the QOS-index and a practical equation for QOS estimation. As most of the previous studies put more weight on iii) and iv), it has not been clarified whether the QOS-index and a equation for QOS estimation can appropriately reflect the QOS perceived by drivers.

However, by relating these four steps with each other, we can select a QOS-index and an equation for estimating the QOS from the macroscopic traffic indices. Since the macroscopic traffic condition data, microscopic driving environment data, and section-basis utility have already been related, the QOS-index should be selected from the indices which have the highest relevance to the section-basis QOS.

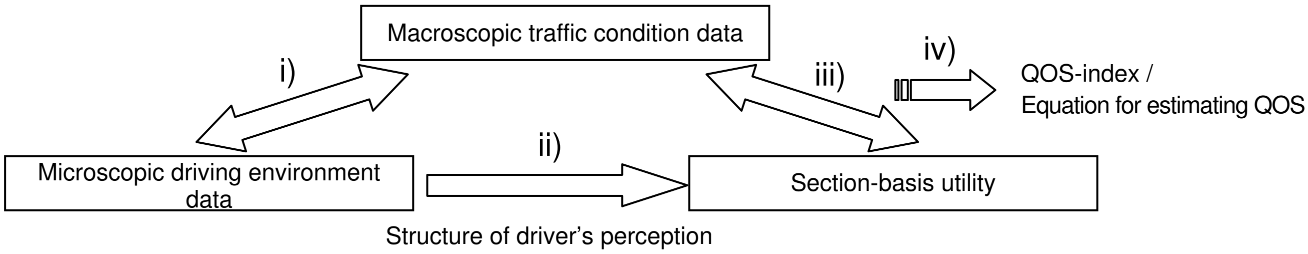

Figure 2 – Conceptual diagram of the methods to select the QOS-index and equation for QOS estimation

3.1. Collection of data on the microscopic driving environment

First, we have to obtain microscopic driving environment data related to the macroscopic traffic condition data. However, it is not easy to observe data concerned with microscopic traffic condition variables which drivers are facing while driving. For example, we can obtain microscopic driving environment data by recoding surrounding traffic conditions using a video camera installed in vehicles, but it is difficult to obtain a large amount of data from a practical point of view.

For the reasons mentioned above, Kita and Kouchi (2011b) proposed a method to estimate the distribution of the microscopic driving environment from macroscopic traffic condition data. In order to estimate the section-basis utility, it is necessary to obtain microscopic driving environment data at each point along the road section. Kouchi and Kita (2011) showed that the distributions of the point-basis QOS at each point are identical to the distribution of the point-basis QOS along the trajectory, when the traffic stream is a steady-state unsaturated flow using micro-simulation analysis. We can obtain microscopic driving environment data at each point from the macroscopic traffic condition data using those methods mentioned above under a steady-state unsaturated traffic flow. However, there is room for further study concerning the range of traffic conditions which we can apply to those methods of estimating microscopic driving environment data.

Another way to obtain such microscopic driving environment data involves micro-simulation analysis. Since we can obtain information on the behavior of individual vehicles using micro-simulation analysis, we can also obtain the microscopic driving environment data connected with the macroscopic traffic condition data.

In this paper, the microscopic driving environment data at each point and macroscopic traffic condition data are collected using a micro-simulation model calibrated to an urban expressway where a driving experiment to develop models for estimating the section-basis utility was conducted.

3.2. Estimation of section-basis utility

When selecting the QOS-index, the section-basis utility should be estimated using microscopic driving environment data at each point based on the structure of drivers' perception. As the microscopic driving environments which individual drivers face are different, the QOS of a certain section is also different among drivers. This indicates that the section-basis utility needs to be estimated for individual drivers. The section-basis utility of each driver can be estimated using the instant utility, order effect, and min-average models.

However, in fact, road planning and traffic management are not determined on the basis of the QOS evaluation of each driver. It is necessary to aggregate individual section-basis utility into a certain group. Therefore, the average section-basis utility of vehicles which pass a road section to be evaluated in a certain time is used as a basic case in this paper.

Furthermore, as the desired speed may affect the microscopic driving environment a driver faces, it may cause a difference in the section-basis utility. Therefore, the average section-basis utility of a group of vehicles divided by the desired speed is also calculated to examine how the desired speed influences the section-basis QOS.

3.3. Analysis of the relationships between the section-basis utility and macroscopic traffic indices

In order to select an appropriate QOS-index as a substitute for the section-basis utility and an equation for estimating the section-basis utility, the relationships between the section-basis utility and macroscopic traffic indices are examined in terms of identity, sensitivity, and uniqueness, and then we can clarify the validity of macroscopic traffic indices as the QOS-index. It goes without saying that the macroscopic traffic condition data used in this analysis needs to be related to the microscopic driving environments which determine the section-basis utility.

In this paper, we focus on the traffic flow rate, speed at a certain point, and traffic density obtained from a traffic detector, and examine the relationships between the section-basis utility and these macroscopic traffic indices.

3.4. Selecting the QOS-index and a practical equation for QOS estimation

According to the results regarding the relationships between the section-basis utility and macroscopic traffic indices, the QOS-index and a practical equation for estimating the QOS are determined. The QOS-index is determined on the condition that the changing behavior of the traffic index is identical to that of the section-basis utility. Both the macroscopic traffic indices, such as the speed and traffic density, and the new indices based on the macroscopic traffic indices, such as the square of traffic density, can be the QOS-index. Then, a practical equation for estimating the QOS which approximates the section-basis utility by the QOS-index is derived.

In this paper, we propose the QOS-index and a practical equation for estimating the QOS targeting all traffic which pass a road section to be evaluated in a certain time, namely a representative driver, and targeting the groups divided by the desired speed.

4. DATA COLLECTION

4.1. Microscopic driving environment data

A micro-simulation analysis was carried out using VISSIM under the following conditions to obtain microscopic driving environment data. As shown in Fig.3, a basic segment of 8km road with two lanes in one direction was modeled in the simulation. In the simulated road section, the target section to collect microscopic driving environment data was 5 km from 2- to 7-km from the start point of the road section, and, in order to realize saturated flow, a bottleneck point was placed at 500 m downstream of the end of the target section.

The vehicle type was passenger car, for which the desired speed ranged from 60 to 110 km/h according to the normal distribution. In the simulation, the desired speed assigned to each vehicle was constant over the section. Each run lasted 3,600 sec, including a warm-up period, and the evaluation period was 5 min from 2,400 to 2,700 sec. The step size during the simulation was 0.5 sec. The macroscopic traffic condition data, namely the traffic volume and average speeds, were collected at the halfway point, 2,500-m from the start point of the target section. The data which were the components of the microscopic driving environment, the location and speeds of the closest front and rear-side vehicles and the subject vehicle, were collected when the subject vehicle passed from every data collection point placed at 250-m intervals.

The simulation was done in ten cases with a different input traffic volume from 1,000 to 5,000 veh/h at 500-veh/h intervals, i.e., 1,000 veh/h, 1,500 veh/h, etc. The subject vehicles were selected as those which passed the halfway point of the target section, the 2,500-m point, from 2,400 to 2,700 sec.

Figure 4 shows the Q-V diagrams of simulated traffic conditions collected from 1,800 to 3,600 sec and the actual traffic conditions collected by a traffic detector from 6:00 to 18:00 on a weekday on a four-lane urban expressway. Both traffic flow rates were based on the traffic volume in 5 min. As shown in Fig.4, simulated traffic conditions are mostly matching with actual traffic conditions, but the difference in simulated traffic conditions between the cruising lane and passing lane are smaller than the actual one. It is because traffic is composed of passenger vehicles only in the simulation. However, in reality, heavy vehicles are mixing with passenger vehicles on cruising lane and causing influence on the traffic capacity. As we focus on the proposal of selection method of QOS-index for passenger vehicle drivers in this paper, we regard simulated traffic conditions as representations of actual ones roughly.

In this paper, microscopic driving environment is described as a combination of the space headway and the relative speeds of surrounding vehicles. As for the space headway, the front-side vehicle was assumed to maintain its speed after passing from the point for detecting traffic conditions, and the space headway was calculated by multiplying the headway (s) by the front-side vehicle’s speed (m/s) minus the vehicle length (m).

The microscopic driving environment data at each point were obtained by using above mentioned data corresponding to different macroscopic traffic conditions at 2,500-m point.

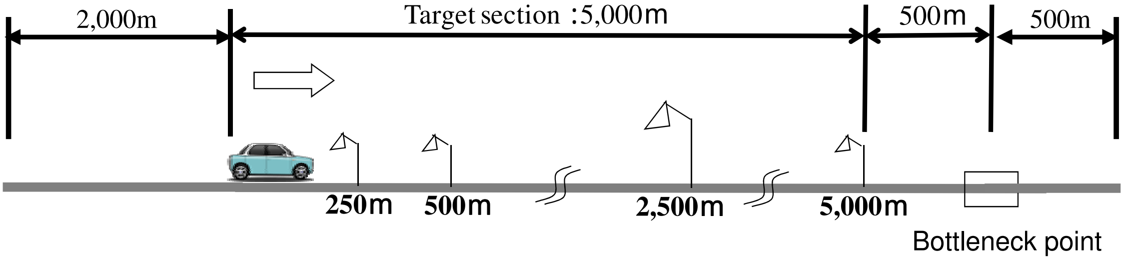

Figure 3 – Outline of the simulated road section

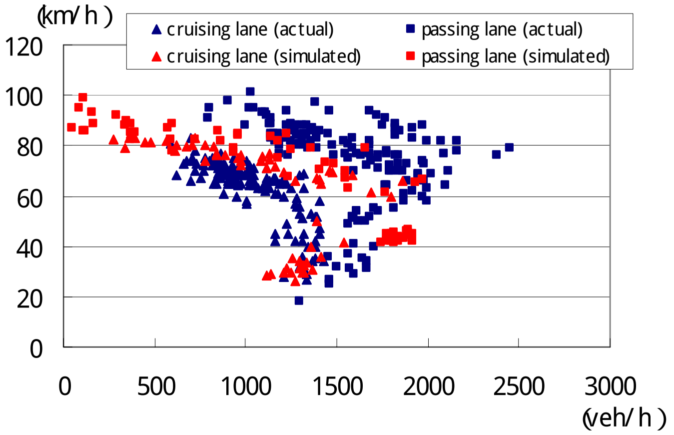

Figure 4 – Q-V diagram of simulated and actual traffic conditions

4.2. Estimation of the section-basis utility

Applying the microscopic driving environment data obtained from the micro-simulation analysis to the instant utility model and order effect model, the point-basis utility of each vehicle at each point was estimated. There were 21 evaluations.

Applying the point-basis utility to the min-average model, the section-basis utility of each vehicle was estimated. As in the on-road experiment conducted by Kita and Kouchi (2011a), a driver verbally classified the section-basis QOS in terms of “dissatisfaction” using an 11-level score from -10 to 0: -10 for “conditions with heavy stress and extreme dissatisfaction”, -5 for “conditions with stress but otherwise tolerable”, and 0 for “conditions enabling stress-free driving”, the value of section-basis utility also ranged from -10 to 0.

5. RESULTS

5.1. Overall trend

Table 2 shows the relationships between the macroscopic traffic indices and section-basis utility. We focused on the traffic flow rate, speed, and traffic density among macroscopic traffic indices. The traffic flow rate was based on the traffic volume in 5 min. As for the section-basis utility, the average, maximum, minimum, and standard deviation of each traffic condition group are shown in Table 2.

As presented in Table 2, the higher the traffic density and the lower the speed, the lower the section-basis utility. However, according to the standard deviation of the section-basis utility, there is dispersion in the section-basis utility, even if the macroscopic traffic conditions are mostly the same. In this paper, as we employed the same order effect and min-average models for each driver, it appears that the reason for this dispersion is the difference in the desired speed and the microscopic driving environment, which are used in the instant utility model.

As the desired speed may affect the microscopic driving environment, we organize the section-basis utility for each desired speed, as shown in Table 3. It is shown that the standard deviation of the section basis utility becomes small when grouping based on the desired speed. This result shows that it may be effective to examine the section-basis QOS in terms of the desired speed.

Table2 – Outline of the data on traffic conditions and section-basis utility

Item	Data									
Traffic flow rates [veh/h/lane]	300	510	780	1,044	1,254	1,404	1,626	1,518	1,554	1,584
Average speed [km/h]	84.6	82.2	79.4	80.2	66.9	68.7	62.5	40.9	39.7	38.2
Traffic density [veh/km/lane]	3.5	6.2	9.8	13.0	18.7	20.4	26.0	37.1	39.1	41.5
Section-basis utility [Average]	-1.4	-2.1	-2.7	-2.9	-4.0	-3.7	-5.7	-6.0	-6.5	-6.3
Section-basis utility [Maximum]	0.0	0.0	0.0	-0.8	0.0	0.0	-2.1	-3.6	-3.1	-3.6
Section-basis utility [Minimum]	-3.2	-4.5	-5.5	-5.5	-6.2	-6.0	-8.0	-8.6	-9.1	-8.8
Section-basis utility [Standard deviation]	0.8	1.0	1.1	0.9	1.2	1.1	1.0	1.1	1.1	1.0

Table 3 – Outline of the section-basis utility for each desired speed class

Desired speed	Section-basis utility										
below 80 km/h	Average	-1.1	-1.3	-1.8	-2.1	-2.7	-2.6	-4.7	-5.2	-5.5	-5.5
	Maximum	-0.2	-0.6	0.0	-0.8	0.0	0.0	-2.1	-3.6	-3.1	-3.6
	Minimum	-2.4	-2.1	-3.3	-3.9	-4.0	-4.1	-5.8	-6.4	-7.0	-6.8
	Standard deviation	0.6	0.4	0.7	0.7	1.1	0.9	0.7	0.8	0.8	0.8
80 - 90 km/h	Average	-1.2	-1.9	-2.5	-2.7	-4.1	-3.9	-5.7	-6.1	-6.4	-6.3
	Maximum	0.0	0.0	0.0	-1.1	-2.5	-2.0	-4.6	-4.3	-4.1	-4.5
	Minimum	-2.7	-3.2	-4.0	-4.2	-4.9	-4.9	-6.7	-7.1	-7.7	-7.5
	Standard deviation	0.8	0.8	0.8	0.6	0.4	0.5	0.5	0.7	0.8	0.8
90 - 100 km/h	Average	-2.0	-2.6	-3.4	-3.5	-4.9	-4.6	-6.6	-6.9	-7.2	-7.1
	Maximum	-1.3	-0.5	-1.5	-1.8	-3.7	-4.0	-5.6	-5.0	-5.1	-5.4
	Minimum	-2.8	-3.8	-4.7	-4.8	-5.6	-5.6	-7.5	-8.0	-8.6	-8.4
	Standard deviation	0.6	0.9	0.7	0.6	0.3	0.4	0.5	0.7	0.8	0.8
above 100km/h	Average	-2.7	-3.6	-4.4	-4.1	-5.7	-5.3	-7.2	-7.7	-7.9	-7.7
	Maximum	-2.4	-2.5	-3.3	-3.2	-5.0	-4.6	-6.4	-5.7	-6.2	-6.5
	Minimum	-3.2	-4.5	-5.5	-5.5	-6.2	-6.0	-8.0	-8.6	-9.1	-8.8
	Standard deviation	0.4	0.6	0.6	0.7	0.3	0.4	0.4	0.7	0.7	0.8

5.2. Relationships between the section-basis utility and macroscopic traffic indices

Figures 5, 6, and 7 show the relationships between traffic flow rates and the section-basis utility, speed at a certain point and the section-basis utility, and traffic density and the section-basis utility, respectively. On the graph, “x” in gray indicates the section-basis utility of individual vehicles, and the red square represents the average section-basis utility under each macroscopic traffic condition.

As for the relationships between the traffic flow rates and section-basis utility, there are two section-basis utility values for the same traffic flow rates, namely unsaturated and saturated, as shown in Fig.5. In the road section where the traffic demand exceeds capacity, it is difficult to approximate the section-basis utility by traffic flow rates, because the section-basis utility is not uniquely determined by the traffic flow rates.

Next, regarding the relationships between the speed at a certain point and section-basis QOS, the lower the speed, the lower the section-basis utility, as shown in Fig.6. However, the sensitivity of the speed to the traffic conditions is poor when the speed exceeds a certain level. This is evident from the fact that the speed does not continue to increase even if the traffic conditions improve. For that reason, although the speed does not change so much, especially in the high- and low-speed ranges, the microscopic driving environment changes because the space headway changes, and this leads to a change in the section-basis utility. In this case, the speed does not appropriately reflect the difference in the section-basis utility. Concerning the relationships between the traffic density and section-basis utility, as shown in Fig.7, the higher the density, the lower the section-basis utility, and the section-basis utility can be uniquely identified by the traffic density.

From the above results, it seems reasonable to conclude that the traffic density is the most suitable variable to approximate the section-basis utility among those three macroscopic traffic indices.

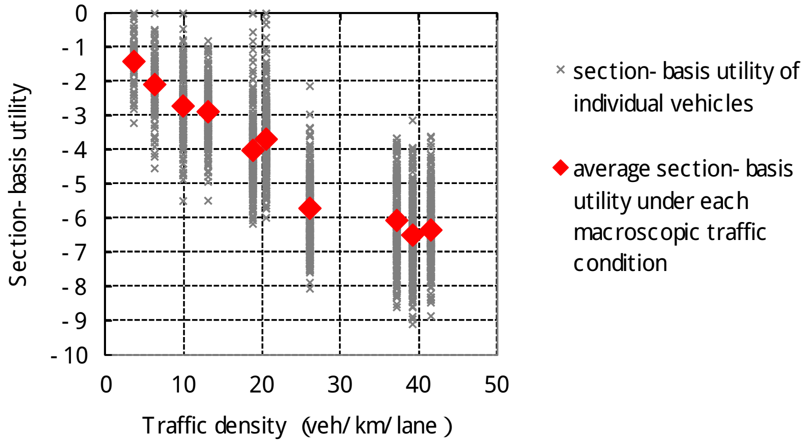

Figure 5 – Relationships between the traffic flow rate and section-basis utility

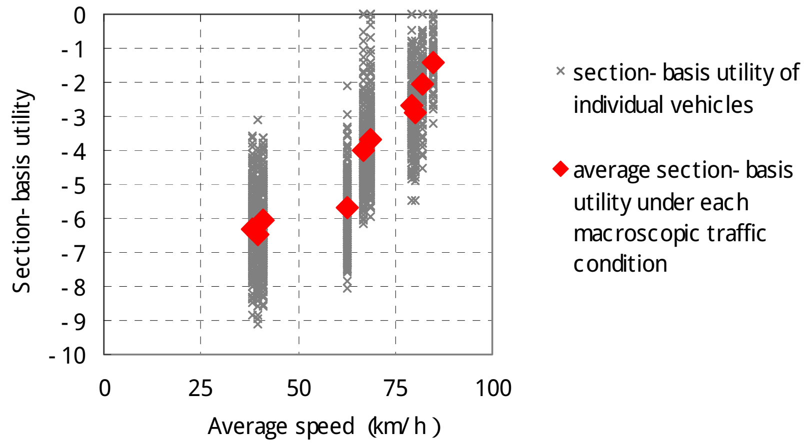

Figure 6 – Relationships between the speed and section-basis utility

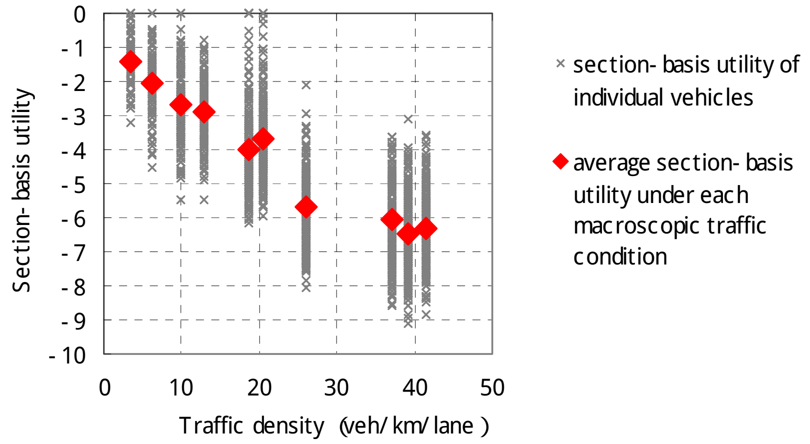

Figure 7 – Relationships between the traffic density and section-basis utility

5.3. Selecting the QOS-index and a practical equation for QOS estimation

From the above results, the traffic density is the most suitable substitution index for the section-basis utility. However, as shown in Fig.7, the traffic density and section-basis utility are non-linear. Therefore, we derived a practical equation which has “the logarithm of traffic density” as an explanatory variable:

$$U_{section} = -2.182 \ln(k) + 2.016 \qquad (R^2=0.92) \qquad (5)$$

where k is the traffic density. Equation (5) appears to provide a fairly good representation, and we have come to the conclusion that the most suitable evaluation index, as the QOS index of basic segments of an expressway, is the logarithm of the traffic density.

Figure 8 shows the relationships between the traffic density and section-basis utility based on Eq. (5). The value of the section-basis utility at -5 indicates a condition with stress otherwise tolerable, and 25 veh/km/lane is approximately equivalent to it based on Eq. (5).

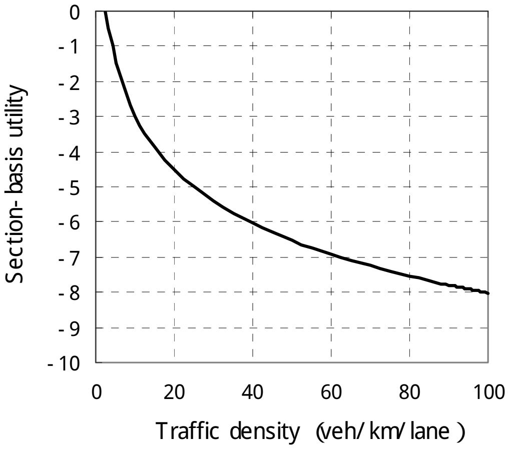

Figure 8 – Illustration of relationships between section-basis utility and the traffic density

Next, we tried to derive equations for estimating the QOS for each desired speed class, namely below 80, 80-90, 90-100, and above 100 km/h. Equations (6)-(9) were derived based on the average of the section-basis utility and logarithm of the traffic density for each desired speed class:

<Below 80 km/h> $U_{section} = -1.995\ln(k) + 2.366$ ($R^2=0.86$) (6)

<80 - 90 km/h> $U_{section} = -2.301\ln(k) + 2.384$ ($R^2=0.93$) (7)

<90 – 100 km/h> $U_{section} = -2.300\ln(k) + 1.591$ ($R^2=0.93$) (8)

<Above 100 km/h> $U_{section} = -2.218\ln(k) + 0.634$ ($R^2=0.92$) (9)

Figure 9 shows the relationships between the traffic density and section-basis utility based on Eqs. (6)-(9), in order to make it easier to understand intuitively by converting the logarithm of the traffic density into the actual traffic density. According to Fig.9, the higher the desired speed, the lower the section-basis utility under the same traffic density, and the difference in the section-basis utility among the desired speed classes becomes large if the traffic density is high. The difference in the section-basis utility among the desired speed classes is approximately 3 for the most deviating one. The traffic density which corresponds to -5, a condition with stress otherwise tolerable, is 40 veh/km/ln for below 80 km/h, 25 veh/km/ln for 80-90 km/h, 18 veh/km/ln for 90-100 km/h, and 13 veh/km/ln for over 100 km/h.

Although the road traffic and driver characteristics differ between Japan and the United States, the result of this paper was linked to the LOS of basic freeway segments, ranged from A to F, in the HCM. As shown in Fig.9, LOS B approximately corresponds to -5 to the driver whose desired speed is above 100 km/h, and LOS C approximately corresponds to -5 to the driver whose desired speed is 90-100 km/h.

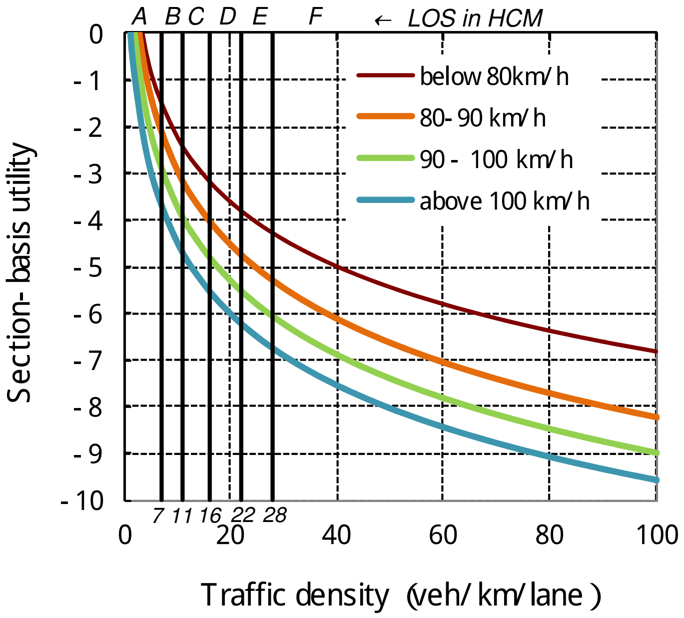

Figure 9 – Relationships between the traffic density and section-basis utility for each desired speed class

6. CONCLUSIONS

In this paper, we proposed a selection method of evaluation index, the QOS-index, and an equation for estimating the QOS based on the structure model for estimating the section-basis utility from the microscopic driving environment. According to the method proposed in this paper, the structure of a driver’s perception is considered explicitly, and the method makes it possible to show the validity of the QOS-index based on macroscopic traffic indices, such as average speeds and traffic density, which are not recognized by drivers but are easy to obtain by road administrators, and to select the most appropriate equation for estimating the QOS objectively. Then, the logarithm of the traffic density is selected as the QOS-index, based on the simulation analysis assuming basic expressway segments.

The significance of this study is that we can propose methods to select the QOS-index for evaluating QOS by showing internal conformity with drivers' perceptions, and comparing the explanatory power of each index. Also, as a result, we can show the validity of "traffic density" as the QOS-index in the HCM explicitly. Furthermore, we selected practical equations for each desired speed in consideration with the heterogeneity of the driver. The results of this paper provide an opportunity to promote discussions about the way to reflect the QOS perceived by the drivers in road planning, design, and traffic management from a practical viewpoint.

However, there remain some concerns. It seems that road alignment and heavy traffic influence the QOS, and that the traffic conditions and perspective of drivers are different in urban and rural areas. This means that there may be more factors which affect the QOS, and the QOS-index and practical equations proposed in this paper are different depending on those factors mentioned above. We need to clarify the scope of the application of the QOS-index and its practical equations by accumulating data on road alignment, traffic conditions, and regions. It is also shown that, even for the same macroscopic traffic conditions and desired speed, the microscopic driving environment which the driver faces is different. This indicates that there is a necessity to consider the QOS in a stochastic manner.

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